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ENERGY AND QUALITY SIMULATION OF THERMAL PROCESSING

IN CANS AND RETORT POUCHES

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ENERGY AND QUALITY SIMULATION OF THERMAL PROCESSING IN CANS AND RETORT POUCHES

By

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ABSTRACT

ENERGY AND QUALITY SIMULATION OF THERMAL PROCESSING
IN CANS AND RETORT POUCHES

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Computer models were used to simulate temperature changes, microbial destruction, and nutrient degradation occurring in pouches and cans during thermal processing. The optimum shape for a retort pouch was determined using a least cost approach based on nutrient retention and material requirements. The models were developed for conduction heated foods and use the sufficient lethal kill method as the criteria for determining sufficient process time.

The 694.5 cm^3 pouches with various shapes and equivalent lethal kill had process times between 40.4 and 49.6 minutes, and nutrient retentions (thiamine) of 70.0 and 66.5 percent, respectively. A thinner profile pouch will have a shorter process time, with a much shorter cooling phase than a thicker pouch. The nutrient retention becomes lower and the processing time becomes longer as the container shape approaches a cube. The energy cost difference in processing equal volumes of food in pouches and cans is insignificant. The energy consumption is strongly influenced by the volume of material processed. Volumetric reduction, due to reduced liquid fill requirements, which may occur in pouch products can significantly reduce the energy required for thermal processing.

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NOMENCLATURE

AO, BO, CO = length, width, height of rectangular containers (cm)

C = concentration of spores per cm^3

C_0 = initial concentration of bacteria a time = 0 (spores per cm^3)

D = decimal reduction time, the time at a specified temperature (DN) necessary to destroy 90% of the organisms present in a given container (minutes)

DN = time to destroy 90% of a vulnerable factor at temperature TN

DTR = decimal reduction time at reference temperature TR (minutes)

f_h = time for the straight line portion of heating curve to transverse one log cycle (minutes)

FS value = the number of decimal reductions of the process

h = half height of cylindrical container (cm)

(i,j) = spatial nodes in the cylindrical coordinate system

k = constant

(m,n,k) = node location for Cartesian geometry used in rectangular model

NA, NB, NC = number of increments for rectangular container

r = radial distance from centerline (cm)

t = time (minutes)

T = temperature (°C)

T(i,j) = temperature at the node location (i,j) refers to cylindrical geometry

T(m,n,k) = temperature at the node location (m,n,k) refers to Cartesian geometry

T_c = temperature at the geometric center (°C)

TN = temperature corresponding to DTR (°C)

T_s = temperature at the surface (°C)

TR = reference temperature (°C)

T_∞ = steam temperature in retort (°C)

x, y, z = the Cartesian Coordinate axes

y = height from mid-plane (cm) for the cylindrical geometry

Z = reciprocal of the slope of a Thermal Death curve of an organism (C°)

ZN = thermal destruction constant for vulnerable factor (C°)

α = thermal diffusivity (cm^2/x)

Δh = spatial increment in the h direction (cm)

Δr = spatial increment in the r direction (cm)

Δt = time increment (minutes)

Δx = spatial increment in the x direction (cm)

Δy = spatial increment in the y direction (cm)

Δz = spatial increment in the z direction (cm)

I INTRODUCTION

1.1 General Remarks

The Federal Government and private industry are interested in the energy savings which may be achieved by processing food in a retort pouch as opposed to the traditional can. Food items need a certain degree of heating before they may be considered a commercially sterilized, "safe" product. The geometry of the retort pouch is favorable to heat transfer allowing reduced (compared to the can) energy inputs during processing. Other advantages of the retort pouch over the can include the following:

1. Less energy is required to manufacture the packaging material.
2. Packaging material is lighter in weight.
3. Geometry allows improved utilization of storage space.
4. Size and weight reduce transportation cost ($/ unit volume).
5. Reduction in overcooking (overheating) resulting in improved nutrient retention.

1.2 Objectives

This research was an analytical study with the following objectives:

1. To provide a literature review of the "state of the art" in retort pouch technology.

2. To conduct simulation studies to compare the energy cost and nutrient retention of conduction heating foods in various size pouches and cans of equal volume.

3. To compare the energy cost and nutrient retention of various size pouches and cans with different fill volume and equal drained weight.

4. To recommend an optimum pouch size based on nutrient content and a cost analysis.

II LITERATURE REVIEW

2.1 Pouch Construction and Characteristics

The retortable pouch is a lightweight, three-ply (polyolefin, polyester, and aluminum) container that will maintain integrity with temperatures above 121° C. The result of this material combination is a container that is impermeable to light, water vapor, and microorganisms. Each of the layers provides vital functions necessary for the integrity of the pouch. Polyolefin, the inner layer, is responsible for allowing the pouch to be heat sealed and it protects the aluminum layer from internal damage. The middle layer is aluminum which provides both a vapor and light barrier. Using aluminim is essential for maintaining a shelf life of over two years for most retort pouch products. Polyester film, the outer layer of the retortable pouch, protects the aluminum film from external mechanical damage and provides a surface suitable for printing.

A vacuum is created inside the retort pouch before it is fused closed. Vacuum packaging and heat sealing are important aspects of the pouch processing. The vacuum causes the pouch to conform to the product geometry. This allows for improved heat penetration and gives the soft pouch material a semi-rigid shape. The fused seal also precludes all movement of material in or out of the pouch (Wilson, 1978).

The food industry has been inundated with articles in journals and magazines proclaiming the advantages of the retortable pouch. Usually, the articles carry little technical information and often cite the billion dollar prepared food industry as the market potential. Most of the recent literature has appeared in trade journals as general information or advertising. The claims, which will be dealt with individually in the following paragraphs, are greatly improved product quality, light weight package material, reduced processing time, better use of storage space, and interference by the Food and Drug Administration (FDA) and United States Department of Agriculture (USDA).

Most of the initial work on the retort pouch techonology was supported by the United States Army. When the technology proved feasible the Army decided to covert all field rations to retort pouch containers. Subsequently, the food industry began to work on obtaining part of the guaranteed multi-million dollar market. With the influx of people came new ideas such as the retort tray and retortable cup (Banner, 1979). The standing pouch was also introduced. When this three-ply pouch is filled the bottom expands and may be used to support the pouch in an upright position. When empty, the standing pouch will require the same space as a regular pouch. The lower section of the pouch contains additional folds which allows the base to expand. This is a problem area because the folds and seams cause stress points that may lead to pinholes (small cracks in the aluminum layer which allow oxygen to enter the package).

2.2 Advantages of the Pouch

One advantage of the institutional pouch versus the number ten can (3.03 liters) is lower cost. The current (1979) price of a number ten can is 42¢ and the cost for the corresponding pouch is 21¢. The processor may be able to further reduce cost by using a smaller capacity pouch because pouch type products may require less brine or other liquid fill than do can products.

Retort pouch material offers significant energy savings when compared to other food containers. Manufacturing of the retort pouch requires less energy than that needed to make frozen food packages, glass containers, and tin-cans. Table 2.1 shows the energy requirements for manufacturing other containers (Schulz, 1978). The pouch currently costs less than the other containers. As energy prices continue to rise, the cost of a pouch will be increasing at a slower rate relative to the cost of the other containers. Another form of energy savings obtained by using a retort pouch is reduced processing requirements. The products packaged in pouches have a shorter cooking time than similar products packed in glass jars or tin-cans. The length of the processing time is dependant on the thickness of the pouch. A thinner profile will require less processing time because of the improved heat transfer to the slowest heating point. The improved processing times are quoted on Table 2.2. The energy required to thermally process frozen food is less than that required for a pouch. However, the refrigeration requirements during storage cause frozen foods to be very energy intensive. Overall, it has been reported that pouched food requires sixty percent less energy than frozen food (Lustucru's, 1979).

Due to the lightweight nature of the constituent materials, the pouch has an advantage over glass or tin. The retort pouch will weigh ten percent of a can and five percent of a glass container when empty (Lustrucru's, 1979). A full pouch with an equal quantity of food will weigh forty-five percent less than a full can (Rubinate, 1964). This weight reduction is based on foods with a large amount of fill water. Part of the weight savings is from using lighter container material, the other portion is reduced fluid in the pouch. A full pouch will contain about ten percent water while forty percent of the total can weight is water (Abbott, 1977). The reduced weight (30%) will save at least ten percent of the freight cost (Goldfarb, 1971).

Either empty or full, the retort pouches have less void space than stacks of cans or glass jars. Full pouches require twenty-five percent less space than cans (Rubinate, 1964). Pouches also require less space when empty. A 13.7 meter long tailer will hold under 200,000 227-gram empty cans. The same trailer would hold 2.3 million empty preformed pouches (Abbott, 1977). The combined effect of reduced warehouse space for empty and full pouches is partly offset by the fact that full pouches cannot be stacked as high as cans.

The U.S. Army has a "Meal-Ready to Eat" (MRE) program. The MRE program takes full advantage of the pouch which is well suited for individual servings, portion control, and product variety. The army has developed a menu with at least seventeen different meat, vegetable, and dessert items (Davis, 1972). Portion controlled, individual serving pouches are placed into separate cardboard cartons and shipped in larger boxes. It is possible for military personnel to carry an entire meal in the pocket of a field jacket.

The retort pouch can be fitted to the food producers needs. Pouches can be made from roll stock or purchased as preformed containers. The advantage of the preformed pouch is that the food processor only needs to seal one edge of the container. The advantage of roll stock is the flexibility concerning pouch size. However, better quality control is required due to the problems caused by the necessity of sealing all four sides of the pouch.

Table 2.1 The energy requirement for manufacturing container material for various types of containers (Schulz, 1978).

Container Type	Joules/container***
Retort Pouch	2.04×10^6
Frozen Food	2.97×10^6
Glass Jar	3.35×10^6
Tin Can	3.76×10^6

*** 227 grams (8 ounce) food container, material and label

Table 2.2 Improved processing time reported for retort pouches.

Rubinate, 1964	50% less than cans
Abbott, 1977	40% less than cans
Pereira, 1978	30-50% less than cans

Products processed in a pouch will have improved quality. The thin profile of the pouch reduces the cooking time required to obtain a commercially sterile product. Correspondingly, the shorter process time allows for better nutrient retention. Some nutrients are heat sensitive and easily degraded when processed for long periods of time. The geometry of the can causes much of the product to be over-cooked. This excess cooking destroys valuable nutrients. Over-cooking will cause needless cell damage to vegetables and meats which further reduces the quality. Periera (1978) showed improved firmness, color, and texture when using the pouch to process green beans as compared to cans. Another means of assuring product quality is to flush and vacuum pack the product. The flush and vacuum process is difficult for can processing and ideal for pouches. The pouch has a fused seal which inhibits oxygen transfer, and the soft nature of the pouch allows the vacuum to conform the pouch to the product geometry. This process will remove most free oxygen from the pouch which may chemically react with the product. This reaction may reduce the product quality by influencing the color, nutrient content, and texture. The tin-can does not have the positive seal of the pouch. A tin-can has a large headspace, and more free oxygen to reduce the product quality. The improved quality of the pouch products has been demonstrated in a preference test involving the free choice of meals (Schultz, 1978).

A hydrostatic cooker, commonly used with tin-cans, is suitable for retort pouch processing. The closing equipment utilized seals the pouch in the final stages of sterilization (Wilson, 1970). During processing, individual pouches are conveyed upright through the retort. The conveyor holds the pouches in such a manner than a one way valve is formed at the seal. The valve allows gases to leave the pouch and nothing is permitted to enter. This significantly reduces the free oxygen in the pouch headspace (Wilson, 1970). The normal closing operation involves vacuuming and sealing the pouch. In the hydrostatic process, the high temperatures drive all the free gases out of the product and only sealing remains. Eliminating the vacuum step allows more time for sealing which results in stronger seals (Wilson, 1970).

2.3 Disadvantages of the Pouch

The retort pouch is not the final answer to the food industries problems. The most significant factor against the pouch, compared to the can, is the slow vacuum and sealing machine speeds. There are several reasons for the slow equipment.

1. The industry is young and capital has not been available for machine development.

2. The army spent important lead time and money on the development of pouch materials instead of pouch processing equipment.

3. The soft nature of the pouch requires special handling.

4. The pouch is not as easy to convey as a can.

In order to compete with cans the line speed would need to be at least 400 pouches per minute, (Lemaire, 1978). It appears that the second generation of pouch filling and closing machines will have about half the speed needed to compete with cans (Table 2.3). The equipment cost is an important factor. A machine capable of closing 15 pouches per minute would cost $100,000 (Lemaire, 1978). To produce 100 pouches per minute would require a $1 million investment (Lemaire, 1978). Pinto (1978) suggested buying several low capacity durable machines rather than risking a high capacity unproven model.

Table 2.3 Equipment speeds for vacuum and sealing machines used with retort pouches.

Source	Pouches/Minute
Pinto, (1978)	10-15, 30-60
Lustrucru's, (1979)	25
Banner, (1979)	20-30 large pouches
Europe's (1979)	100
User, (1979)	50-60 (mid-1979), 250 (late-1979)

Labor is one of the more expensive inputs into the pouch processing system. Many meat items and institutional size pouches require hand filling. A commercial hand fill operation averaging four pouches per minute has been reported (Pinto, 1978). At this slow speed labor becomes a critical problem. Labor is required for several operations such as loading and unloading the racks which hold the pouches during retort processing. The total labor requirement in a production operation (pouch sealing to case loading) for 120 pouches per minute is 14 to 16 people (Lemaire, 1978).

Another problem with using the pouch has been government regulation. The Federal Government was initially concerned with the leaching of the bonding material into the food (Abbott, 1977). This problem has been solved by using the three-ply pouch material so "no adhesive" is used to seal the pouch. The inner lining of the pouch provides the heat sealing surface. After the material was approved, the United States Department of Agriculture (USDA) limited the amount of meat which could be processed in a pouch to 0.45 kg (about one pound). Andres (1979), who discussed this problem does not quote the USDA reasoning in the matter. The weight limit causes two problems. First, the family unit would have to buy several pouches of one item for a main dish. Secondly, the institutional market will have no number ten can equivalent pouches for meat products. The Food and Drug Administration has set no limits on pouch capacity. However, pouches must be placed in a carton for protection. Even with the additional cost of the carton, the total cost of the pouch product is less than that required for a comparable can and label (Andres, 1979).

One area of difficulty has been in obtaining high quality materials which could be used to make pouches. In the early 1970's a roll of pouch material frequently was not cut squarely and the variation in the width caused machinery problems related to pouch formation. There were also problems in obtaining pouch materials during 1974. The industry was very small and the raw plastic was not available during the oil embargo. As a result, hasty substitutions were made for the normal pouch materials. In one case, a degradable package was formulated and sold. Needless to say, there were difficulties (Donley, 1979). Even today, there is a limited number of suppliers and there are no industry standards used to judge the quality of pouch materials (Donley, 1979). Manufacturers estimate that 95 percent of the retortable film produced is good (Pinto, 1978).

The strength of the pouch seals have been tested by various methods. However, there are no industry standards as to the minimum strength. The U.S. Army ran numerous tests on the retortable pouches before they decided to adopt them in the "Meals Ready to Eat" program. Lampi et. al. (1976) gives a clear description of each test and the related standards. In summary:

1. Fusion test is a visual examination of the seal and weld of the inner lining.

2. Burst test determines the pressure required to break the pouch seal.

3. Visual examination grades the severity of lines, air pockets, and food materials in the area of the seal.

4. Infrared scanning measures differences in the seal thickness.

5. Caliper measurement determines variation in thickness not visible to the eye.

Although these tests are not industry standards, they could serve as valuable guides for the future.

Another problem related to the commercial development of the pouch products is the lack of marketing information. International Telephone and Telegraph Continential test-marketed a line of pouch products in 1977 but was forced to cancel the program due to an inability to keep up with consumer demand (Lemaire, 1978). ITT-Continential is expected to resume testing in mid-1979 (Banner, 1979). This is the first company to market the pouch on a large retail level to consumers. In contrast, Hormel Inc. has been operating in the speciality market for several years. The speciality market consists of government programs and special camping suppliers. Hormel offers eleven meat based products. Although the response has been favorable in the speciality market, the cost of $1.05 - 1.10 for 0.085 to 0.113 kg of product will not compete well in the general consumer market (Banner, 1979). In addition the consumer needs to be educated in the uses and advantages of the pouch. The distribution system must also adapt to the flexible pouch and carton.

The flexible nature of the pouch requires special handling during processing. Pouches cannot be placed directly into the retort because unrestrained pouches will fold, bend, and swell thus inhibiting uniform heat transfer. For this reason, retort pouches must be placed in a holding or restraining device. Small pouches can be placed in vertical racks, (Pflug et.al. 1965; Davis et.al. 1972) which enhances both heat penetration and heating medium circulation. Institutional pouches have an additional problem because of their large mass. The high weight places additional stress on the seams which may result in pin-holes. This problem is avoided by placing the large pouches on uniformly spaced horizontal racks. An overriding pressure is required for processing both large and small pouches to keep the pouch from excessive expansion during the heating process.

2.4 Methods of Measuring the Slowest Heating Point

The flexible nature of the pouch causes difficulty in measuring the slowest heating point. As the pouch expands during processing the slowest heating point may actually move. Three methods of inserting and holding the thermocouples in a pouch are available. The methods are gland (Davis et.al. 1972; Pflug et.al. 1963), gussed and lead (Pflug et.al. 1963). The gland method is most commonly used today. This method does not involve sealing the pouch around the thermocouple wires. Before filling the pouch a gland is attached to the pouch wall and the thermocouple wires are inserted through the gland into the pouch.

2.5 Conduction Heated Foods

Various methods for describing heat transfer in conduction heated canned foods have been well documented. Several computer simulation models are available for solving conduction heating problems in cylindrical containers (Hayakawa et.al. 1968; Manson et.al. 1967; Teixeira, 1978; Teixeira et.al. 1969). Herndon et.al. (1968; 1969; 1971) used computer derived tables to solve conduction heating problems in cans. Lenz and Lund (1977) describe the lethality-Fourier number approach to solving conduction heating problems in finite cylinders. Board and Steel (1978) used an "automated version" of Gillespy's method of solving heating problems. There are several books available which describe one or more methods in detail (Ball, et.al. 1957; Stumbo, 1965).

There is a limited amoung of published material on non-cylindrical conduction heated foods. Two of the most recent reports are given by Manson et.al. (1970, 1974). The first study deals with rectangular containers and the second study deals with pear-shaped (ham-shaped) containers. Both of these papers use a computer simulation approach to analize the problem.

The rectangular model can be applied to retort pouch processing and is discussed in greater depth later.

III THEORETICAL DEVELOPMENT

3.1 General Rate Equation

The general rate equation has been shown to be an affective analytical tool for describing the destruction of microorganisms. This equation has been useful in the analytical determination of "commercial sterility." Heat degradation of several quality factors can also be described as first-order rate processes. The general rate equation (at a constant temperature) may be described, in terms of bacterial concentration, as

$$dC/dt = -kC \qquad [1]$$

where

C = concentration of bacteria (spores per cm^3)

k = constant

t = time (minutes)

Integrating equation [1] and converting to common logarithms yield

$$C = C_0\, 10^{(-2.303 \times t/D)} \qquad [2]$$

where

C_0 = initial concentration of bacterial at time = 0 (spores per cm^3). The decimal reduction time is temperature dependant and specified by

D = decimal reduction time, the time at a specified temperature necessary to destroy 90 percent of a given organism (minutes) (Note $D = 2.303/k$)

$$dD/dT = -D/Z \qquad [3]$$

where

T = temperature (°C)

Z = thermal death constant for a particular organism (°C)

Integrating equation [3] and converting to common logarithmic yields

$$D = DTR\ 10^{2.303\frac{(TR-T)}{Z}} \qquad [4]$$

where

DTR = decimal reduction at reference temperature TR (°C)

TR = reference temperature (°C)

Substituting equation [4] into equation [2] to give C in terms of temperature gives

$$C = C_0\ 10^{(-2.303t/(DTR\ 10^{2.303(TR-T)/Z}))} \qquad [5]$$

Equation [5] determines the concentration of bacteria after holding at a specific temperature (TR) for time (t) when the initial concentration was C_0. Equation [5] may also be used to describe vitamin destruction and is best suited for small volumes with uniform temperature. To account for transient temperatures it is necessary to incorporate the differential equations of heat transfer. Heat transfer models for the can and pouch will be developed in the next two sections.

3.2 Rectangular Heat Transfer Model for Pouches

In order to simulate the pouch shape it is necessary to develop a rectangular heat transfer model. This model will predict the temperature at locations throughout the pouch. The pouch model uses the Fourier equation for 3-dimensional, transient, isotropic heat conduction, written as

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{T}{t} \qquad [6]$$

where

(x,y,z) are the three planes in a Cartesian Coordinate system

α = thermal diffusivity (cm^2/sec)

Using a finite difference method with the central difference formula (Karleker et. al., 1977), the differentials given in equation [6] may be rewritten as

$$\frac{\partial^2 T}{\partial x^2} = \frac{(T(m+1,k) - 2T(m,n,k) + T(m-1,n,k))}{\Delta x^2} \qquad [7]$$

$$\frac{\partial^2 T}{\partial y^2} = \frac{(T(m,n+1,k) - 2T(m,n,k) + T(m,n-1,k))}{\Delta y^2} \qquad [8]$$

$$\frac{\partial^2 T}{\partial z^2} = \frac{(T(m,n,k+1) - 2T(m,n,k) + T(m,n,k-1))}{\Delta z^2} \qquad [9]$$

$$\frac{\partial T}{\partial t} = T(m,n,k)^{(t+\Delta t)} - T(m,n,k)^{t} \qquad [10]$$

where

(m,n,k) are node points in the Cartesian Coordinate system

A Taylor series expansion is necessary to derive equations [7-9]. Using this technique an error of the order of $[(x)^2/12]$ is generated (Karleker, et. al. 1977). This error is negligible if small spatial and time increments are used in computation. Substituting equations [7-10] into equations [6] yields

$$\frac{T(m+1,n,k) - 2T(m,n,k) + T(m-1,n,k)}{\Delta x^2} + \frac{T(m,n+1,k) - 2T(m,n,k) + T(m,n-1,k)}{\Delta y^2}$$

$$+ \frac{T(m,n,k+1) - 2T(m,n,k) + T(m,n,k-1)}{\Delta z^2} = \frac{T(m,n,k)^{(t+\Delta t)} - T(m,n,k)^{t}}{\alpha} \qquad [11]$$

The boundary and initial conditions for cooking a pouch product are uniform initial temperature (equations [12-14]), surface temperature equal to retort temperature with time greater than zero (equation [15]) and center temperature reaches retort temperature as time approaches infinity (equation [16]).

$$\frac{\partial T}{\partial x} = 0 \qquad \text{at} \qquad t = 0 \qquad [12]$$

$$\frac{\partial T}{\partial x} = 0 \qquad \text{at} \qquad t = 0 \qquad [12]$$

$$\frac{\partial T}{\partial y} = 0 \qquad \text{at} \qquad t = 0 \qquad [13]$$

$$\frac{\partial T}{\partial z} = 0 \qquad \text{at} \qquad t = 0 \qquad [14]$$

$$T_s = T_\infty \qquad \text{at the surface, when } t < 0 \qquad [15]$$

T_s is the surface temperature (°C)

T_∞ is the steam temperature in retort (°C)

$$T_c = T_\infty \text{ at the center when } t >> 0 \qquad [16]$$

T_c = temperature at the geometric center (°C)

The heat transfer model required in the computer simulation of retort pouch thermal processing is based on equations [11 - 16].

3.3 Cylindrical Heat Transfer Model for Cans

This can model is a transient, cylindrical conduction heating model with isotropic material and uniform initial temperature. The general differential equation for a finite cylinder is

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial y^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad [17]$$

where

r = radial distance from centerline (cm)

y = vertical distance from mid-plane (cm)

Figure 3.1 describes the location of r and y with respect to the center of the container. Using a finite difference method with the central difference formulas the differentials of equation [17] may be rewritten as

$$\frac{\partial^2 T}{\partial r^2} = \frac{(T(i+1,j) - 2T(i,j) + T(i-1,j))}{\Delta r^2} \qquad [18]$$

$$\frac{\partial^2 T}{\partial y^2} = \frac{(T(i,j+1) - 2T(i,j) + T(i,j-1))}{\Delta y^2} \qquad [19]$$

$$\frac{\partial T}{\partial r} = \frac{T(i+1,j) - T(i-1,j)}{2\Delta r} \qquad [20]$$

$$\frac{\partial T}{\partial t} = T(i,j)^{(t+\Delta t)} - T(i,j)^{t} \qquad [21]$$

where i and j refer to spatial nodes in the cylindrical coordinate system.

Substituting equations [18-21] into equation [17] results in

$$\frac{(T(i+1,j) - 2T(i,j) + T(i-1,j))}{\Delta r^2} + \frac{T(i+1,j) - T(i-1,j)}{2r\Delta r} + \frac{T(i,j+1) - 2T(i,j) + T(i,j-1)}{\Delta y^2} = \frac{(T(i,j)^{(t+\Delta t)} - T(i,j)^{t})}{\alpha} \qquad [22]$$

At the centerline (r equals zero) and equation [22] is not valid because the second term is undefined. However, the $(1/r)(\partial T/\partial r)$ term can be determined by taking the limits as r goes to zero. Using ℓ 'Hopital's rule (Thomas, 1969), the $(1/r)(\partial T/\partial r)$ term is written as

$$\lim_{r\to 0} \frac{\frac{\partial T}{\partial r}}{r} = \frac{\partial^2 T}{\partial r^2} \qquad [23]$$

The second term in equation [22] can be substituted by equation [18] to describe the temperature at the centerline. This substitution yields

$$\frac{2(T(i+1,j) - 2T(i,j) + T(i-1,j))}{\Delta r^2} + \frac{T(i,j+1) + -2T(i,j) + T(i,j-1)}{\Delta y^2}$$

$$= (1/\alpha)(T(i,j)^{(t+\Delta t)} - T(i,j)^{t}) \qquad [24]$$

The boundary and initial conditions for the can model are uniform initial temperature (equations [25] and [26]), surface temperature equal to retort temperature with time greater than zero (equations [27] and [28]), and

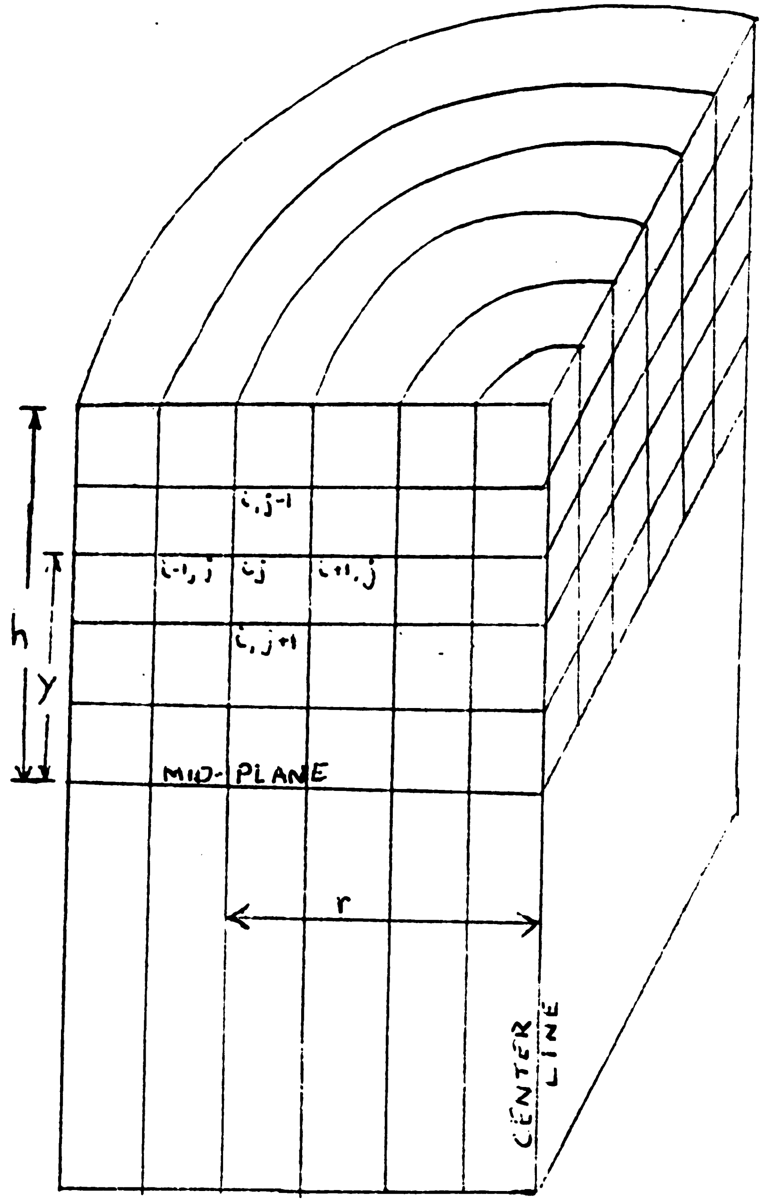

FIGURE 3.1 Labeling of nodes for finite cylinder used in the heat transfer simulation model.

center temperature reaches retort temperature as time approaches infinity (equation [29]).

$$\frac{\partial T}{\partial r} = 0 \qquad t = 0 \tag{25}$$

$$\frac{\partial T}{\partial y} = 0 \qquad t = 0 \tag{26}$$

$$T_s = T_\infty, \ r = R, \quad t > 0 \tag{27}$$

$$T_s = T_\infty, \ y = Y, \quad t > 0 \tag{28}$$

$$T_s = T_\infty, \ r = 0, \quad t >> 0 \tag{29}$$

The heat transfer model required in the computer simulation of the thermal processing of canned products is based on equations [22, 24 and 25-29.]

3.4 Thermal Diffusivity of the Food Models

The value of the thermal diffusivity of a food material is required to determine the temperature gradient within the product. For the pouch model the thermal diffusivity is based on the Heisler charts and the corresponding solutions for temperatures in a rectangular parallelepiped. The result is

$$\alpha = 0.933/4((1/AO)^2+(1/BO)^2+(1/CO)^2)\ f_h \tag{30}$$

where

AO,BO,CO are the lengths of the three sides of the parallelepiped.

f_h is the reciprocal of the slope of the straightline portion of the center point heating curve. f_h is based on the food properties (the value used is typical of those found for most foods).

The can model is based on a finite cylinder and the corresponding thermal diffusivity is

$$\alpha = 0.398/((1/r)^2 + (0.427/h^2))f_h \tag{31}$$

where

h = the half height of the container

IV METHODS

4.1 Can and Pouch Simulation Models

The retortable pouch model is based on a rectangular heat transfer model and the general rate equation to describe bacteria destruction and thiamine degradation. Equations [5,11-16] were programed by Manson et.al. (1970) and his computer model was adopted for use in this study. The can model is based on a cylindrical heat transfer model and the general rate equation in describing bacteria destruction and thiamine degradation. Equations [5,22,24,25-29] which compose the can model were programed by Teixeira et.al. (1969) and that computer model was also adopted for use in this study. The pouch and can models will allow for the simulation of a wide range of container sizes. The rectangular model simulated the retort pouch and involved thickness between 1.32 cm and 8.86 cm. Two volumetric capacities were considered in this study: 694.5 cm^3 and 70 percent of 694.5 cm^3 or 486.2 cm^3 . This variation in volume is based on the reduced fill water required in pouches as compared with cans (Abbott, 1977).

The 694.5 cm^3 volume is representative of medium can sizes and was calculated from the nominal dimensions of a NO. 2 can (307 x 409). The variation in pouch dimensions allowed for a comparison of the amount of container material required, food quality, process time, and energy utilization. The dimensional changes are also useful in validating the models. The cylindrical model was used to simulate various can shapes of equal volume (694.5 cm^3). The simulation studies of can shapes allowed the comparisons mentioned for the pouch to be made for the can. The purpose in simulating the thermal processing of pouches and cans was to compare the results and to make recommendations as to optimum container size. The can and pouch simulation models use the same basic assumptions and parameters. The pouch model will be described in detail so the functional characteristics of both models may be clearly understood. There were a number of temperature assumptions made in developing the computer simulation models. The assumptions may be summarized as follows:

1. Initial product temperature is 76.7° C (170° F).
2. Retort temperatures during cooking is maintained at 121° C (250° F).
3. Product is cooked in water maintained at 26° C (79° F).
4. Cooling is complete when the product center temperature equals 76.7° F (170° F).

4.2 Description of Pouch Model

A rectangular container is easily described in terms of its height, width, and thickness. Using the Cartesian Coordinate system, a grid is formed (Figure 4.1). Each grid location has a unique descriptor or variable name (i.e., (1,1,1,) or (2,4,1)). By symmetry, the bottom and top, the right and left side, and the front and back are all mirror images. Therefore, it is possible to generate the entire rectangular container from one-eighth of the original container. The coordinate (1,1,1) is the outermost corner, of the rectangle. Coordinate (NA,NB,NC) is the innermost corner (center of the container) and NA, NB and NC are the largest values of the spatial coordinates. Each grid point specifies a unique location within the rectangular container and has three values which define that point. Within the computer program there are three arrays which correspond to the grid network. Each grid point or the corresponding descriptor has a temperature value, a bacteria quantity, and nutrient level which are internalized for all locations and change during processing. Using the finite difference approach to solve the problem, the time is first increased by one unit. In order to find the temperature at descriptor (1,1,1) the retort temperature is checked, (three sides of this grid location face the retort medium) second the three internal sides are checked. Figure 4.2 shows the relationship between one grid location and the six surrounding locations. The temperature of the surrounding volume influences the temperature of the center location. A weighted average is used in determining the center temperature and a similar procedure is followed for the other grid points. If the grid was not uniformly spaced, each of the sides would be a different size and carry a different weighting. The weighting scheme is built into the model. After descriptor (1,1,1) is determined the temperature value of (1,1,2) is calculated. This process continues until descriptor (NA,NB, NC) has been determined at which point the processing time is checked. The time is increased by one unit and the cycle is repeated until the program is completed.

At this point, it is appropriate to discuss several terms which apply to the computer models. The terms are come-up time, heating time, decimal reduction or FS value, cooling time, and percent retention.

1. Come-up time is the period of time required for the retort to reach the desired processing temperature (121° C). This process is energy intensive because steam is used to flush the air out of the retort. The come-up time is assumed to be constant for equal volumes of product.

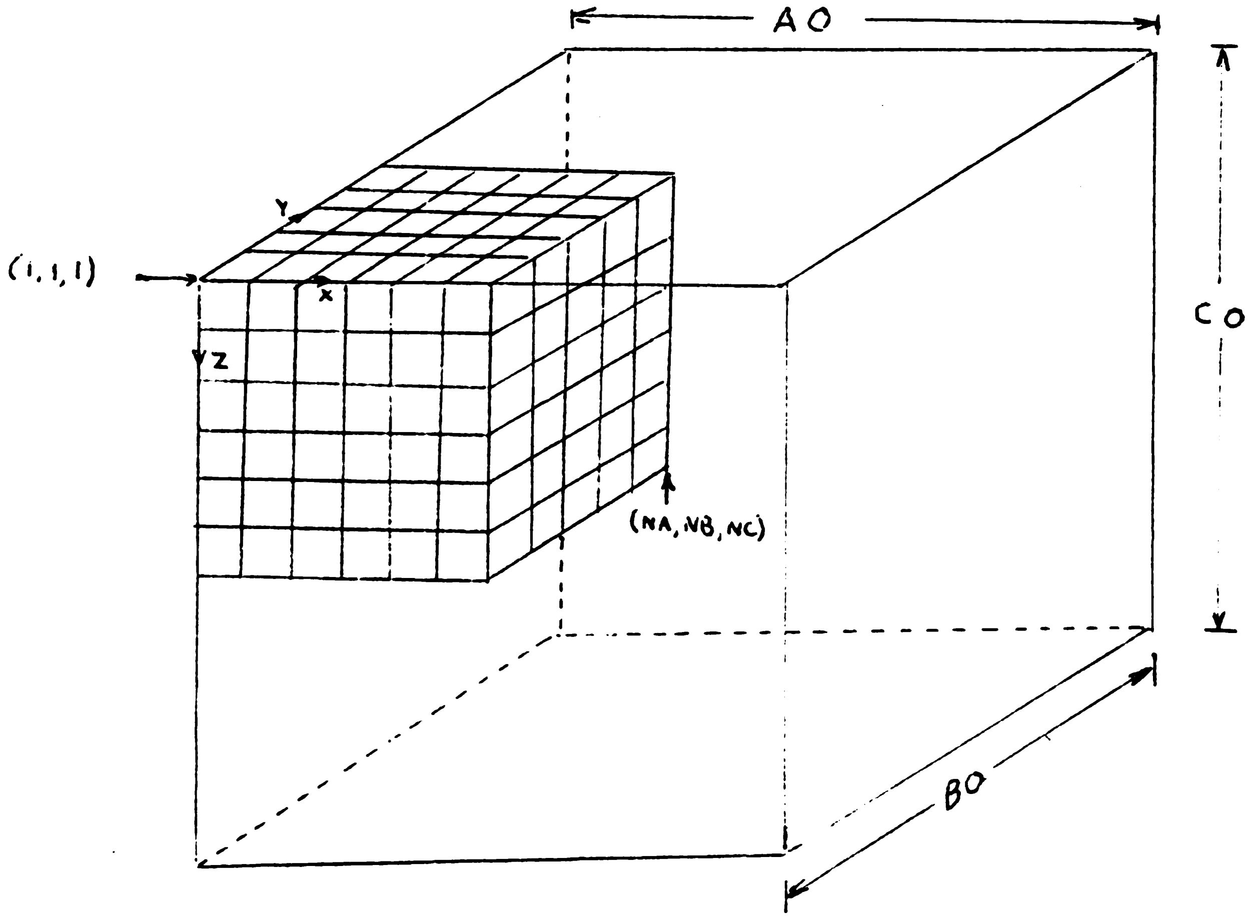

FIGURE 4.1 Labeling of nodes for a rectangular parallelpiped for use in the computer simulation model.

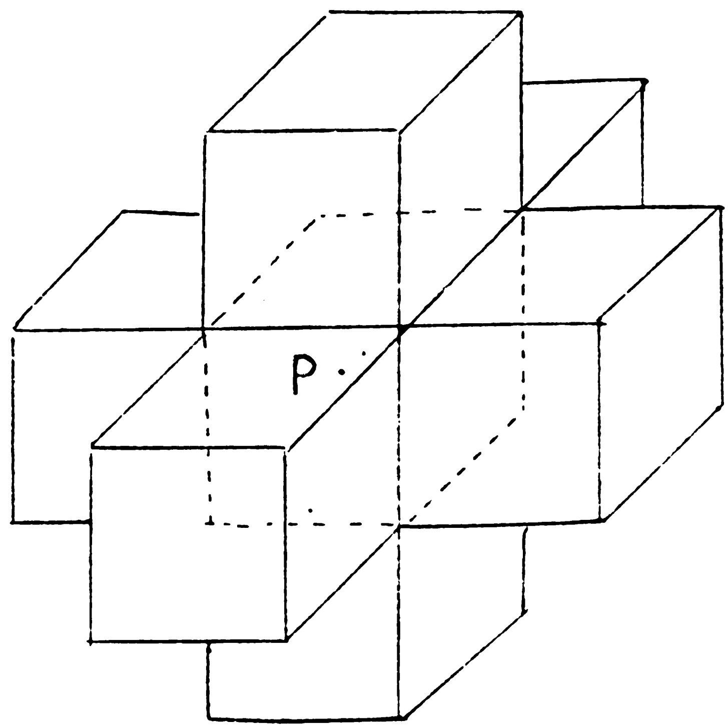

FIGURE 4.2 A view of a central cube with surrounding locations.

2. Heating time is the total time period that the steam is required. For the same amount of time and equal product the energy utilization is constant. The retort temperature during this phase is 121° C.

3. Decimal reduction (D) and FS value are time and temperature relationships based on equation [5] which corresponds to a 90 percent reduction in the bacteria level. The decimal reduction is the time period required at a specified temperature to achieve 90 percent destruction of an organism. The FS value is a measure of the magnitude of the process and provides a convenient number to gage the reduction of bacteria. If 90 percent of the bacteria are destroyed the FS value will equal 1.0. Should 99.9 percent of the bacteria be destroyed the FS value will equal 3.0. If the initial bacteria population was 100,000 spores per standard size container and a final population (after heating) of $8X10^{-5}$ bacteria per container is used as the cut-off value to stop the heating process. In order to yield an FS value of approximately 10.0 with the overprocessing (kill greater than $8X10^{-5}$ bacteria per container) during the cooling phase. The extra kill may be counted as a safety measure.

4. Cooling time is the time period required to cool the slowest heating point to an acceptable level (77° C). The cooling phase requires little energy, cool water, and time. The bacterial destruction which takes place during the cooling phase can be discounted or ignored depending on the method. The retort temperature during the cooling phase is 26° C.

5. Percent retention is the percent of the nutrient left after the processing has finished. The initial level is 100 percent. The percent difference between 70 and 65 percent, by convention, is 5 percent

of the original value. The modelled nutrient has the same decimal reduction and thermal destruction constant as thiamine (Manson et.al. 1970). Thiamine is heat stable vitamin found in food products (Clifcorn, 1948).

The computer models have three criteria for termination which are process time completed, sufficient lethal kill, or instability of the model. The stability criteria is discussed later. Completion of the scheduled process time is normally used to terminate the models. This assumes that the desired process time is known and that the FS value is the desired output. The FS value would then be compared to company standards and the process time would be adjusted accordingly. Normally, the data would be compared with experimentally determined values. Sufficient lethal kill or desired number of bacteria is another method of determining process time. The assumptions are the same as the completion of the scheduled process time method. The value specified for sufficient lethal kill will determine the heating time required to reach the desired bacterial level.

The sufficient lethal kill approach was taken in this study. Although, this method used an arbitrary bacteria kill, the approach provides useful information because heating time, cooling time, and the severity of the over-processing are all available for analysis. The FS value would be less than 10.0 if the product instantly cooled when the heating time was completed. As the FS value increases the lag time is lower or response time of the container is slower, and the quality decreases. The sufficient lethal kill method is useful in quantifying differences between various sizes and shapes of containers.

4.3 Model Adoption and Verification

Several changes were necessary to adapt each of the computer models discussed in section 4.2 to the sufficient lethal kill method. In order to adapt the rectangular model (Manson et.al. 1970) to the Michigan State University computer (Controlled Data Corporation Model 6500) changes were necessary because of undefined operand errors due to inappropriate dimension sizes and parameters. The program was also converted from natural log to the base ten log because the food industry has traditionally used base ten in calculating the thermal destruction of bacteria. The original program contained no explanation or comment statements. The revised program contains a variable list and comment statements.

Computer simulation models need to be validated against actual situations in order to be of value. The models are adapted from published research so it is not necessary to repeat the original work of data collection. However, it is important to match the published values for each model and to compare these against other values found in literature. Manson et.al. (1970) did not clearly state the manner of validation he considered for the rectangular model. He did quote both Stumbo (1965) and Ball et.al. (1957) in discussing his results. Table 4.1 shows the comparison between Manson and the revised pouch model used in this study. There is a difference of 0.5 percent between the two models. Manson's model uses a combination of base ten and base e and the rounding error involved in the conversion accounts for the discrepancy.

The pouch model has a built in stability criteria which is based on the size of the container, the corresponding size increment, and the time increment. The general stability equation for a one-dimensional forward difference system is (Holman, 1976)

$$\frac{(\Delta x)^2}{\alpha\Delta t} = 2 \qquad [32]$$

This equation can be rearranged to yield

$$0 = 1 - \frac{2\alpha\Delta t}{(\Delta x)^2} \qquad [33]$$

Expanding equation [33] for three dimensions results in

$$0 = 1 - \frac{2\alpha\Delta t}{(\Delta x)^2} - \frac{2\alpha\Delta t}{(\Delta y)^2} - \frac{2\alpha\Delta t}{(\Delta z)^2} \qquad [34]$$

Equation [34] was programmed into the rectangular model. The pouch model is unstable when the time increment is 0.4 minutes with the largest space increment equal to 1.8 cm. The number of space increments was not changed from Manson's model and the time increment was raised to 0.2 minutes.

The cylindrical model (Teixeira et.al. 1969) required major modifications. Several important statements were missing and comment statements occasionally were faulty. The line continuation makers were not placed in column 6 and were inconsistent. Several statements were invalid and needlessly repeated. In general, the program used unnecessary steps and tended to make things more complicated. One example is the repeated use of three level (positive, zero, negative) IF Statements, when a simple (greater than) IF Statement would be sufficient. Lines with statement labels 8 and 9 in Teixeira et.al. (1969) are given as examples of inappropriate statements. The can model was modidified in order to perform bacteria and quality determinations during one program execution. A partial stability criteria based on equation [33] was also added. As published the model will not run, it is

TABLE 4.1 The validation of rectangular model comparing the original model to the revised model.

	Percent Retention	FS value
Manson	68.04	9.18
Orlowski (Revised Manson Model)	67.66	9.12

TABLE 4.2 The validation of cylindrical model comparing Problem 2 in Teixeira et.al. (1969) and the revised model.

	Percent Retention	FS value
Stumbo	---	5.45
Manson/Zahradnik	---	5.28
Teixeira (10X10)**	46.0*	5.34
Teixeira (5X5)**	---	5.06
Orlowski (Revised Teixeira model)	45.0*	5.22

*Based on DN = 188 minutes ZN = 25 C°

DN = decimal reduction time of the thiamine, the time at a specified temperature necessary to destroy 90 percent of the nutrient (minutes at 120° C)

ZN = thermal destruction constant for thiamine (C°)

** Number of spatial increments

assumed that a rough draft of the model was published.

In order to validate the corrections made in the model, problem number 2 in Teixeira et.al. (1969) was considered. Teixeira validated his model against Manson and Zahradrik and Stumbo as referenced by Teixeira et.al. (1969). The results of the current study (Table 4.2) fall within the accepted range.

The numerical stability of the can model is most sensitive to changes in the time increment. When the time increment is large (0.20 minutes with a radial increment (Δr) of 0.44 cm and a height increment (Δy) of 1.16 cm) the system becomes unstable and unacceptable oscillation occurs. The exact level of instability was not determined. The time increment used in the can model is the same as that used by Teixeira, 0.125 minutes with a 0.51 cm radial and 0.43 cm height increment for the 5.08 cm radius and 8.57 cm height can. Manetsch (1977) and Karleker et.al. (1977) discuss the importance of the time interval in relation to the stability of the model.

4.4 Comparison of the Can and Pouch Models

A comparison between the pouch and can models provided the necessary linkage between the models. The comparison is based on extreme rectangular and cylindrical shapes. Table 4.3 contains a listing of the various size pouches and cans used to compare the two models. (Appendix C contains the complete computer print-outs of selected sizes.) As the rectangular shape is changed from a pouch to a cube the thiamine retention is reduced by 4.2 percent. The same trend is noticed for cylindrical containers changed from a shaft to a squat can. The rectangular shape can be made thinner or more compact than the cylindrical shape, simply as a matter of geometry (with a constant volume and reasonable dimensions).

The values are consistent between the two models. The pouch has better retention and the cube poorer retention than the squat can. Correspondingly, the longer and thinner cylindrical shaft has better retention than the shorter and thicker square shaft. Without the positive comparison between models there would be no purpose in comparing further results.

A summary of the various can and pouch sizes which were simulated is listed in Tables 4.4 and 4.5. Regular pouches are considered to be those which have a volume equal to 694.5 cm^3 and the small pouches are those which have a reduced volume equal to 486.2 cm^3. A square pouch has equal length and width and a rectangular pouch has a length three times the width. The container sizes considered ranged between 35.0 and 1.3 cm for any side, height, or radius. This variation allowed for a comparison between a wide spectrum of container sizes. The stability criteria of the models inhibited extreme dimensional changes.

TABLE 4.3 Comparison between models using extreme container sizes and a constant volume of 694,5 cm^3.

Shape	Dimensions	FS value	Percent Thiamine Retention
Pouch	$1.90X19.11^2$	9.91	69.95
Cube	8.86^3	10.98	65.72
Square Shaft	$26.90X5.08^2$	10.49	67.49
Squat Can	5.08X8.57**	10.42	66.53
Cylindrical-Shaft	2.54X34.26**	9.97	68.65

** radius by height

TABLE 4.4 Dimensions of the container simulated by the retort pouch processing model*

Thickness (cm)	Length (cm)	Width (cm)	Type
1.90	19.12	19.12	Square
1.90	11.04	33.11	Rectangular
2.54	16.54	16.54	Square
2.54	9.55	28.64	Rectangular
3.17	14.80	14.80	Square
3.17	8.55	25.64	Rectangular
3.81	13.50	13.50	Square
3.81	7.79	23.38	Rectangular
5.08	11.69	11.69	Square
5.08	6.75	20.25	Rectangular
8.86	8.86	8.86	Cube
26.90	5.08	5.08	Square Shaft
1.33	19.12	19.12	+ Square
1.33	11.04	33.11	+ Rectangular
1.78	16.54	16.54	+ Square
1.78	9.55	28.54	+ Rectangular
2.22	14.80	14.80	+ Square
2.22	8.55	25.64	+ Rectangular
2.67	13.50	13.50	+ Square
2.67	7.79	23.38	+ Rectangular
3.56	11.69	11.69	+ Square
3.56	6.75	20.25	+ Rectangular
7.86	7.86	7.86	+ Cube

* Each container has the same volume (694.5 cm^3), unless noted by a (+).

+ These containers have a volume of (486.2 cm^3).

TABLE 4.5 Dimensions of the containers simulated by the can processing model.*

Radius (cm)	Height (cm)
2.54	34.26
2.94	25.58
3.17	22.00
3.50	18.05
3.81	15.23
4.37	11.58
5.08	8.57
5.38	7.64
5.89	6.37
6.35	5.48
6.60	5.07
7.61	3.81

* Each container has the same volume (694.5 cm^3)

V RESULTS

5.1 Pouch Simulation Results

The simulation results for regular (694.5 cm^3) and small pouch (486.2 cm^3) are given in Table 5.1 The regular size pouches had retention values between 69.95 and 65.72 percent which correspond to 1.90 cm thickness (thinnest pouch) and a cube with each side being 8.86 cm in length. The FS value varied from 9.91 for the thinnest pouch to 10.98 for the cube. The relationship between FS value and total time is consistent being 40.40 and 45.80 minutes for the thinnest pouch and the cube, respectively. The thinner pouch is expected to have reduced process time and improved quality, which is confirmed by the model. Increasing the pouch thickness while maintaining a constant volume will increase the process time (Figure 5.1) and the bacterial kill during the cooling phase with the same volume. The increase in pouch thickness will also cause a decrease in the percent retention of nutrients (Figure 5.2) The process time can be reduced 2.2 minutes and the nutrient retention improved by 3.8 percent by using a 1.90 cm thick square pouch in place of a 5.08 cm thick square pouch.

5.2 Comparison of Square and Rectangular Pouches

The reason for comparing square and rectangular pouches is the fact that pouches are basically confined to these shapes. The difference in processing time between a square pouch and a rectangular pouch

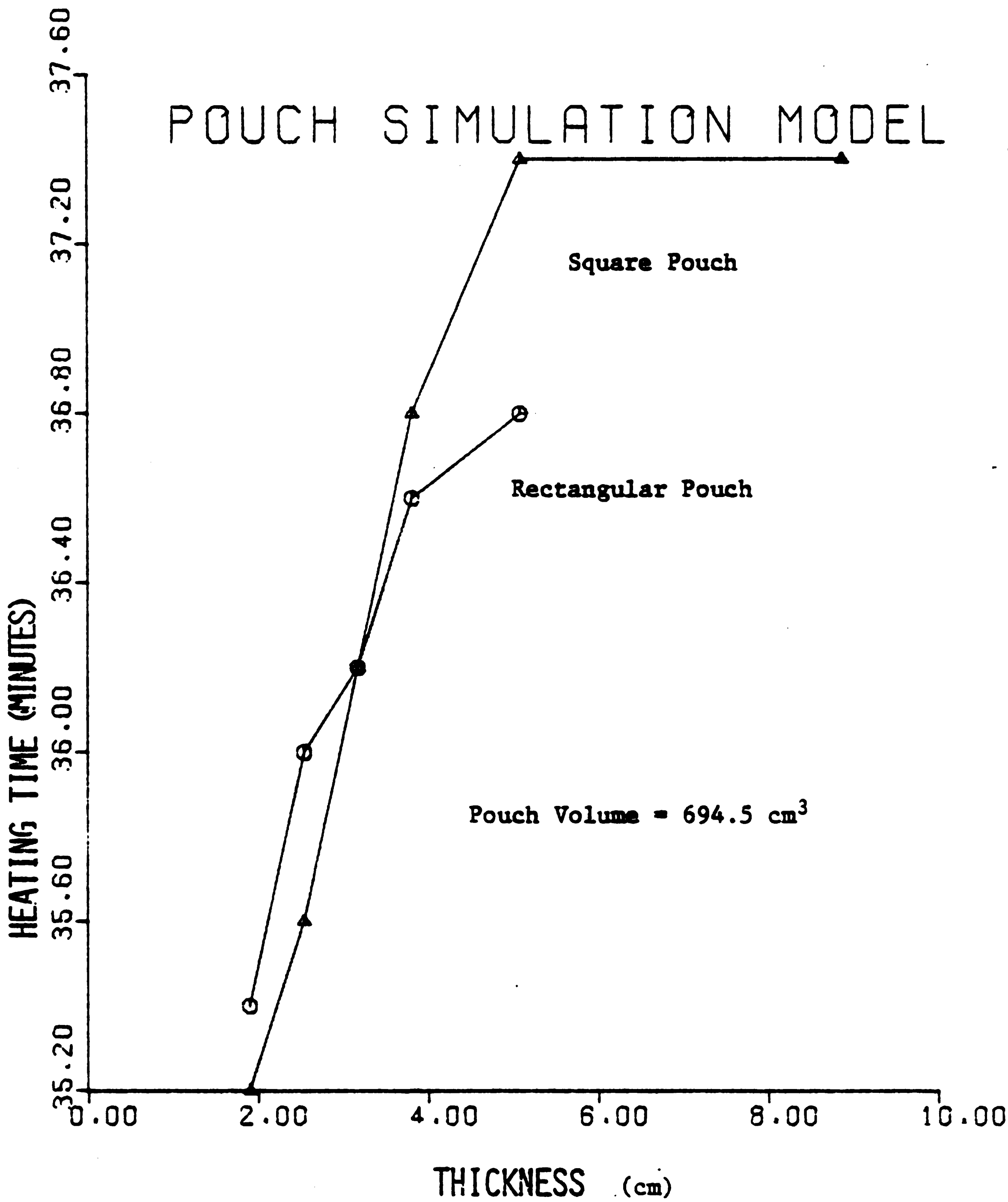

FIGURE 5.1 Variation in heating time with thickness for a conduction heating food in square and rectangular pouches.

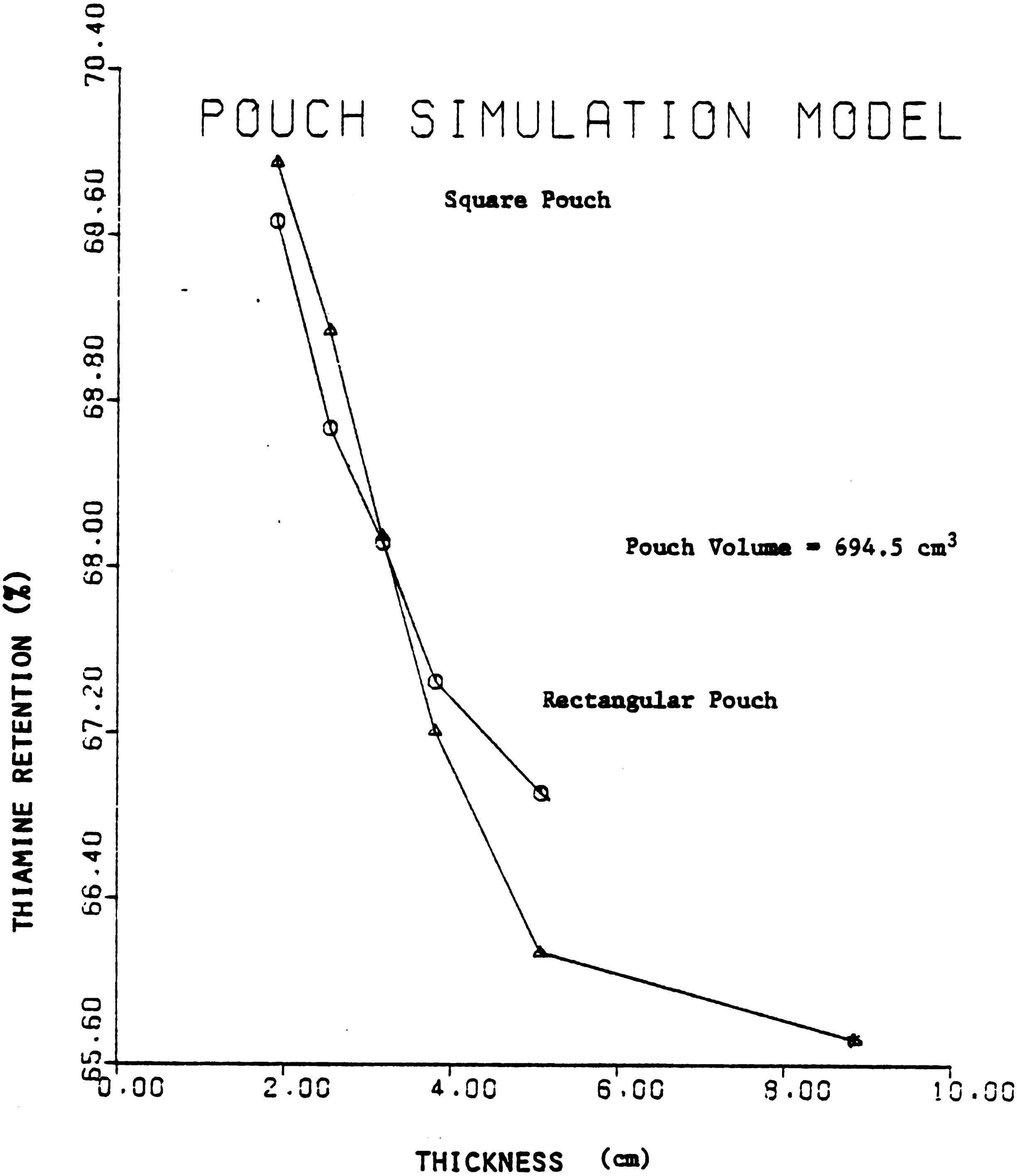

FIGURE 5.2 Variation in the percent retention of Thiamine with thickness for a conduction heating food in square and rectangular pouches.

TABLE 5.1 Results of Simulating the thermal processing of conduction heating food contained in a pouch.

Thickness	Type*	Number of Survivors per container x 10^5	Percent Thiamine Retention	FS Value	Heating** Time (minutes)	Total*** Time (minutes)
1.90	S	1.223	69.95	9.91	35.20	40.40
1.90	R	1.159	69.67	9.94	35.40	40.60
2.54	S	1.053	69.14	9.98	35.60	40.80
2.54	R	0.821	68.67	10.09	36.00	41.20
3.17	S	0.869	68.15	10.06	36.20	41.40
3.17	R	0.946	68.12	10.02	36.20	41.40
3.81	S	0.714	67.21	10.15	36.80	42.80
3.81	R	0.536	67.45	10.27	36.60	42.60
5.08	S	0.449	66.14	10.35	37.40	43.80
5.08	R	0.335	66.91	10.48	36.80	43.60
8.86	CUBE	0.105	65.72	10.98	37.40	45.80
26.9	SHAFT	0.327	67.49	10.48	36.40	43.20
1.32	+S	1.022	70.37	9.84	35.00	40.20
1.32	+R	1.182	70.31	9.77	35.00	40.20
1.78	+S	1.296	70.90	9.73	35.00	40.20
1.78	+R	1.274	69.81	9.74	35.20	40.40
2.22	+S	1.017	69.37	9.84	35.40	40.60
2.22	+R	1.125	69.08	9.79	35.60	41.00
2.67	+S	0.948	68.65	9.87	35.80	41.20
2.67	+R	0.856	68.40	9.91	36.00	41.60
3.56	+S	0.862	67.31	9.91	36.60	42.40
3.56	+R	0.533	67.58	10.12	36.60	42.40
7.88	+CUBE	0.105	65.98	10.82	37.20	45.60

* S and R refer to square and rectangular pouches

** Time interval with steam on

*** Entire Process Time (including cooling)

\+ Pouches with 486.2 cm^3 volume (otherwise the volume is 694.5 cm^3)

with the same thickness and constant volume was small. For example when the pouch thickness is 3.17 cm the heating time is the same (36.20 minutes) for both a rectangular and a square pouch (Figure 5.1). A square pouch can be processed slightly faster than a rectangular pouch when thickness is less than 3.17 cm. The reverse is true for thicknesses greater than 3.17 cm. A 5.08 cm thick rectangular pouch requires 0.6 minutes less heating time than the corresponding pouch. Similar results were obtained with respect to nutrient retention.

5.3 Can Simulation Results

The can model indicates (Table 5.2) the least process time (46.63 minutes) and the best nutrient retention (68.65 percent) occurs with a 2.54 cm radius and 34.26 cm height can, which is the limiting height. The greatest bacterial kill (FS value of 10.42), longest process time (49.63 minutes), and the least nutrient retention (66.53 percent) occur with the 5.08 cm radius and 8.57 cm height can. The relationship of the heating time required for cans based on the radius is shown by Figure 5.3. Changing the diameter with constant volume has a greater effect than changing the height. The geometry of a 2.54 cm radius can has 360° of heat transfer surface 2.54 cm from the cold spot. A 5.08 cm tall can has only 2 surface points that are 2.54 cm from the slowest heating point. By comparison the 5.08 cm diameter can has a heating time 0.9 minutes less than the 5.08 cm tall can. Changes in the can radius have little effect on the nutrient retention (Figure 5.4), only a 2.5 percent change over the simulated range.

5.4 Comparison Between the Pouch and Can Simulation Studies

The energy difference between heating cans and pouches of the same

TABLE 5.2 The results of simulating the thermal processing of conduction heating food contained in cans.

Radius	Height	Number of Survivors per container x 10^5	Percent Thiamine Retention	FS Value	Heating** time (minutes)	Total*** time (minutes)
2.54	34.24	1.068	68.65	9.97	36.50	46.43
2.94	25.38	1.142	68.30	9.94	36.75	46.88
3.17	21.90	0.965	67.92	10.02	36.88	47.25
3.50	18.12	0.984	67.48	10.01	37.13	47.75
3.81	15.23	0.873	67.07	10.06	37.38	48.38
4.37	11.57	0.505	66.61	10.30	37.63	49.38
5.08	8.55	0.378	66.53	10.42	37.63	49.63
5.38	7.61	0.506	66.55	10.30	37.63	49.50
5.89	6.35	0.987	66.65	10.01	37.63	49.13
6.35	5.48	1.768	66.91	9.75	37.45	48.38
6.60	5.08	2.330	67.13	9.63	37.38	47.88
7.61	3.81	UNSTABLE				

** Time interval with the steam on.

*** Entire process time (including cooling)

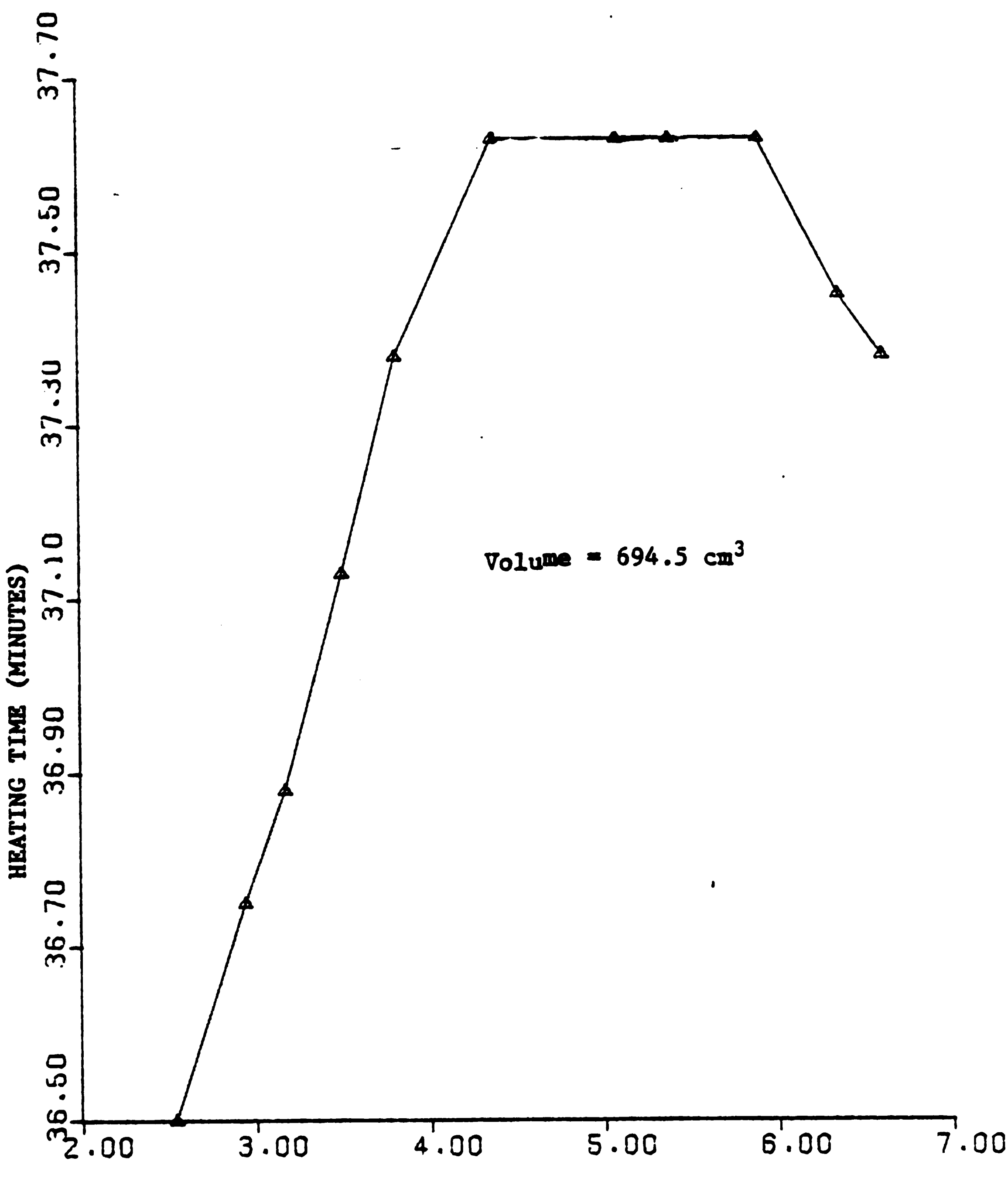

FIGURE 5.3 The variation in heating time (total time with steam on) with changes in can radius.

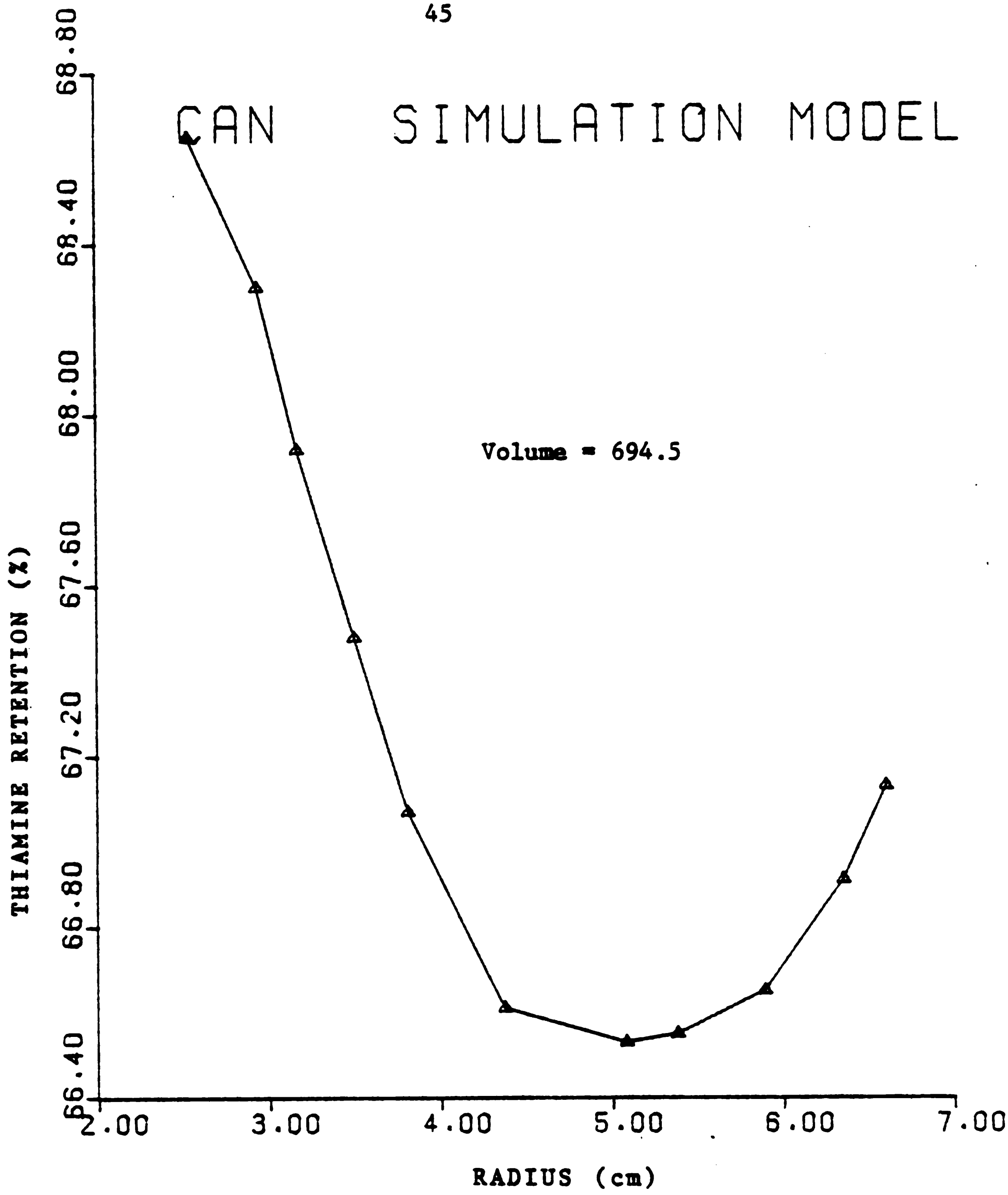

FIGURE 5.4 The variation in percent retention of thiamine with changes in can radius.

volume was small. The most efficient to the least efficient is 0.137 (588 kJ) to 0.139 (59.4 kJ) cents per pouch, respectively. The corresponding differences for cans are 0.138 (591 kJ) to 0.139 (594 kJ) cents per can, respectively. The energy analysis is based on an actual operation, which includes heating the product, bringing the retort up to the desired temperature, and venting the retort before the processing begins. Appendix D contains the necessary equations to obtain the energy required at current cost. Although, the cans require more energy for processing than the pouches the difference is minor compared to the material cost. The energy difference for processing conduction heated foods in pouches as opposed to cans is much smaller than the published information would indicate (Table 2.2). In fact the energy required for processing pouches and cans overlap for the range of containers simulated. The difference in steam consumption between processing a regular pouch and a can is shown in figure 5.5.

The material cost provides the largest cost variation and savings because the raw pouch material is much cheaper than the raw products required for cans (Tables 5.3 and 5.4). The price of each container was supplied by producers using their respective containers (Donley, 1979; Foster, 1979). It is assumed that the container cost is a function of the amount and type of material used to manufacture it. The pouch cost varied from 8.11 to 4.26 cents for a 1.90 cm thick rectangular pouch to the cube, respectively. The cost per can varied from 20.08 to 14.89 cents for the 2.54 cm radius to a 5.08 cm radius can. Hence, material cost for a can is two or three times the cost of pouch material when considering constant volume containers.

Quality differences are very important. The nutrient retention for pouch processing varied by 5 percent while processing the can varied only 2 percent (Figures 5.2 and 5.4). Quality is not an economic factor in the sense of material or energy and improved quality will not guaranty a higher price. The analysis to account for quality differences was done by considering a ratio of cost to nutrient retention. The cube, which had the lowest material cost and poorest thiamine retention, was used as the base cost and nutrient level for the pouches. The basis for comparison was

$$\frac{(\text{cost of arbitrary container})-(\text{cost of cube})}{(\text{percent thiamine retention of arbitrary container})-(\text{percent thiamine retention of cube})} = \frac{(\text{difference in cost})}{(\text{improved thiamine retention})} \qquad [34]$$

The 5.08 cm radius and 8.55 cm height can was used as the basis for comparing the cans because it had the poorest nutrient retention and smallest surface area of all the cans (Table 5.3 and 5.4). Based on equation (34) the 3.17 cm thick square pouch has the least cost per improved nutrient retention ratio. The 4.37 cm radius and 11.57 cm height can is the least cost for improved retention for the cans. The 3.17 cm thick square pouch is recommended for the least cost for improved nutrient retention. The cost is 0.57 cents per improved retention. The most expensive pouch is the 1.90 cm thick rectangular pouch, with a cost of 0.97 cents per improved retention. All the values for pouches were below 1.0 cent for improved retention. In contrast, all of the can sizes cost more than pouches. The variation is 7.50 to 1.00 cents per improved retention for the 7.38 cm radius and 7.64 cm height and the 4.37 cm radius and 11.58 cm height cans, respectively. The cost for improved nutrient retention in cans is nearly double that of the least cost pouch. The 4.37 cm radius can provides the least cost

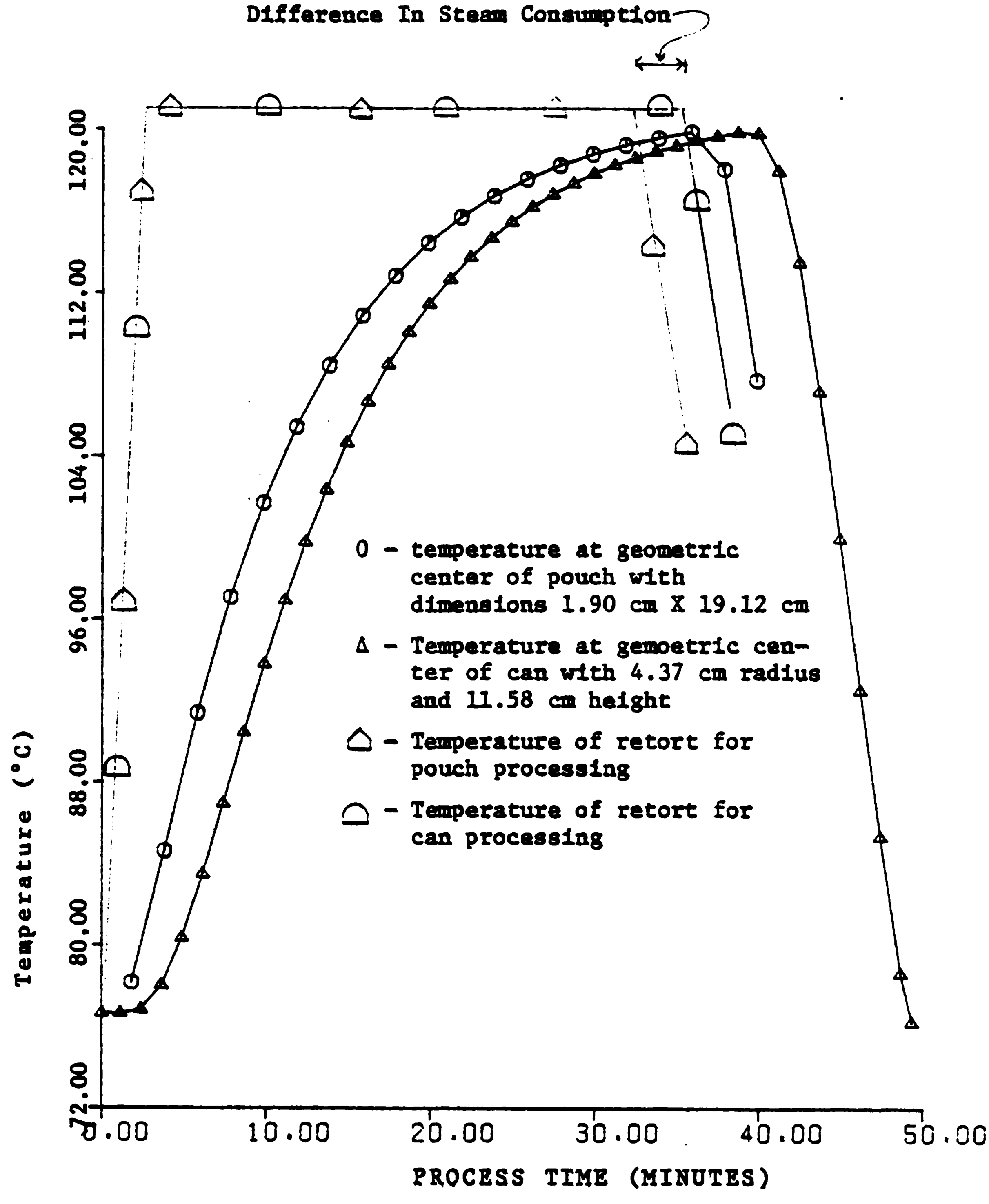

FIGURE 5.5 Retort temperature and center temperatures of a can and pouch of equal volume as a function of process time.

TABLE 5.3 Energy and cost comparison calculated by simulating the thermal processing of pouches of various sizes.

Thickness** (cm)	Type	Area (cm^2)	Material cost (¢)	Energy required per container (RJ)	Energy cost (¢)	Cost of improved nutrient retention (¢)
1.90	S	875.2	7.91	588.	0.137	.863
1.90	R	897.1	8.11	588.	0.137	.974
2.54	S	714.8	6.46	589.	0.137	.643
2.54	R	741.3	6.70	590.	0.138	.827
3.17	S	624.8	5.64	590.	0.138	.570
3.17	R	654.4	5.91	590.	0.138	.689
3.81	S	571.1	5.16	592.	0.138	.605
3.81	R	602.5	5.44	591.	0.138	.685
5.08	S	510.5	4.61	594.	0.138	.838
5.08	R	547.9	4.95	592.	0.138	.581
8.86	CUBE	471.5	4.46	594.	0.138	----
26.90	ROD	598.7	5.41	591.	0.138	.650

* All containers have the same volume (694.5 cm^3)

** Remaining pouch dimensions may be found on Table 4.4

TABLE 5.4 Energy and cost comparison calculated by simulating the thermal processing of various can sizes.

Radius (cm)	Area (cm^2)	Material cost (¢)	Energy required per container (KJ)	Energy cost (¢)	Cost of improved nutrient retention (¢)
2.54	587.4	20.1	591.	0.138	2.448
2.94	524.8	17.9	592.	0.138	1.723
3.17	500.6	17.1	592.	0.138	1.604
4.50	476.6	16.3	593.	0.138	1.484
3.81	456.0	15.6	594.	0.138	1.296
4.37	437.9	15.0	594.	0.139	1.000
5.08	435.4	14.9	594.	0.139	-----
5.38	440.0	15.0	594.	0.139	7.500
5.89	453.3	15.5	594.	0.139	5.083
6.35	472.3	16.1	594.	0.138	3.316
6.60	484.8	16.6	594.	0.138	2.817
7.61	547.2	18.7	594.	-----	-----

* All containers have the same volume (694.5 cm^3)

for improved thiamine retention of all cans considered.

A comparison of pouch thickness and quality changes shows that the cube is the worst pouch shape. It is one percent lower than any of the can shapes simulated. According to the results, for each 0.63 cm increase in pouch thickness the nutrient retention is decreased by nearly one percent. Thicker pouches will have reduced quality.

5.5 Small Pouches Compared with the 4.37 cm Radius and 11.58 cm Height Can

As previously mentioned (Section 2.2), cans may contain more fill water than pouches. Although both models dealt with conduction heat transfer, pouches with 70 percent of the regular volume (small pouches) were also simulated. The comparison was made in order to compare the most favorable pouch condition to cans. The results are on Table 5.1. These results are compared with the 4.37 cm radius can which gave the least cost for improved retention with the cans considered. The small pouches have rapid heating and cooling, with a heating time of 35.0 to 36.6 minutes and a cooling time of 5.0 to 5.8 minutes for the 1.32 and 3.56 cm thick small square pouches, respectively. The 4.37 cm radius can requires 37.6 minutes of heating time and 11.8 minutes of cooling time which results in a 22.8 percent longer process time than found with the 1.32 cm thick small pouch. The energy cost per unit for the small pouches is about 0.096 (411 kJ) cents per pouch while the 4.37 cm radius can costs 0.139 cents per can (Table 5.5). The small pouches can lower energy costs by 30.9 percent. This savings is mainly due to the reduced volume of food being cooked. The reduced steam consumption from processing a can and a small pouch is shown in Figure 5.6.

The container cost for the small pouches varies from 3.37 to 7.64 cents for the cube to the 1.32 cm thick rectangular pouch, respectively.

TABLE 5.5 Energy and cost comparison calculated by simulating the thermal processing of small pouches of various sizes.*

Thickness	Type	Area (cm)	Material cost (¢)	Energy required per container (RJ)	Energy cost (¢)	cost of improved nutrient retention (¢)
1.32	S	829.5	7.50	411.	0.096	0.941
1.32	R	845.3	7.64	411.	0.096	0.986
1.78	S	663.4	6.00	411.	0.096	0.640
1.78	R	683.2	6.12	412.	0.096	0.718
2.22	S	567.5	5.13	412.	0.096	0.519
2.22	R	588.5	5.32	412.	0.096	0.629
2.67	S	508.9	4.60	413.	0.096	0.461
2.67	R	530.7	4.80	413.	0.096	0.591
3.56	S	439.2	3.97	414.	0.097	0.451
3.56	R	417.1	3.77	414.	0.097	0.250
7.88	CUBE	372.6	3.37	416.	0.097	------

* All containers have the same volume (486.2 cm^3)

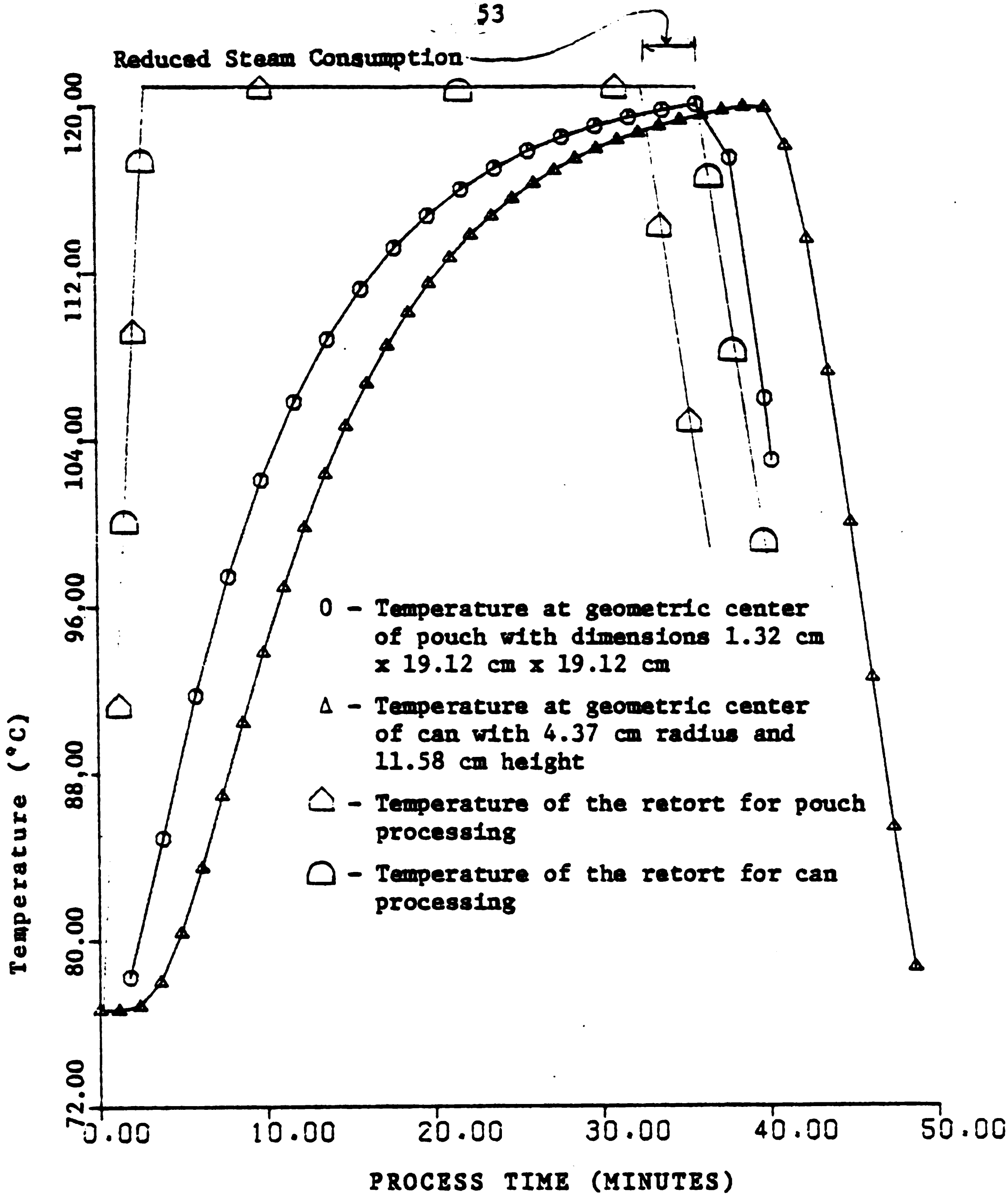

FIGURE 5.6 Retort temperature and center temperature of a can and pouch of unequal volume as a function of process time.

The 4.37 cm radius can cost 15.0 cents per container. The range of small pouch nutrient retention is 70.37 to 65.98, with the cube being the worst case. The percent retention for the 4.37 cm radius can is 66.61 percent. The 1.78 cm thick small pouch has three percent better retention than the can. Using the cost comparison described earlier, the 3.56 cm thick rectangular small pouch will cost 0.250 cents per improved retention. The 4.37 cm radius can is four times this amount. However, the cost approach requires other comparisons which would be consistent with the expectations of retort pouch foods. The retortable pouch products are expected to be higher in quality than cans, and each of the small pouches are higher in quality than the 4.37 cm radius can. The small pouches should also be higher in quality than the regular size pouch. This would eliminate the 3.56 cm rectangular small pouch. The small pouch should not have a higher cost for improved nutrient content or cost per container. Table 5.6 shows that by using a 2.22 cm square small pouch the nutrient content can be improved by 1.2 percent and a cost savings of 0.5 cents per container. It is possible to improve the quality by 0.5 percent and save 1.0 cent per container using the 2.67 cm square small pouch. The individual circumstances would determine whether the company reduced cost by 1.0 cent or 0.5 cents.

With thirty percent less water, less leaching of water soluable vitamins would occur and there would be a higher nutrient retention in some food items. The small pouches allow more control over the degree of processing. The 4.37 cm radius can has an FS value 0.5 greater than the small pouches. A significant portion of the 4.37 cm radius can is overprocessed, this is not true with the small pouches. Although, thiamine is predicted only 3.48 percent higher other factors may allow for a much greater quality difference.

TABLE 5.6 The optimum container size for pouches and cans based on material cost and percent thiamine retention.

DIMENSIONS	TYPE	Cents per Improved Retention	Percent Retention	Cents per Container
4.37 cm radius	Can*	1.00	66.61	15.0
3.17 cm thick	Regular pouch* (square)	0.57	68.15	5.7
3.56 cm thick	Small pouch** (rectangular)	0.25	67.58	3.8
2.22 cm thick	Small pouch** (square)	0.52	69.37	5.1
2.67 cm thick	Small pouch** (square)	0.46	68.65	4.6

* 694.5 cm^3 volume

** 486.2 cm^3 volume

IV CONCLUSIONS

1. Several scientific articles have been written dealing with the pouch material and methods at measuring heat transfer within the pouch. The majority of the available information is from Nadic Laboratories of U.S. Army and trade journals. Labor and machinery costs are currently two of the important factors, which limit wide scale adoption of retort pouch processing.

2. Computer simulation studies based on the sufficient lethal kill method determined the energy and quality changes (thiamine) in constant volume (694.5 cm^3) can and pouch shaped containers. The energy difference required in processing these two containers was insignificant. The nutrient retention, based on thiamine, which is one of the more heat stable vitamins, was between 69.95 and 65.72 percent for the 1.90 cm thick square regular pouch and cube, respectively. The results for cylindrical shapes varied from 68.65 to 66.53 percent retention for the thin rod (2.54 cm radius and 45.26 cm height) to the squat can (5.08 cm radius and 8.55 cm height).

3. The reduced energy consumption (for processing) based on an equal drained weight of food and thirty percent less fill water was found to be 30.9 percent when comparing the small square pouch (1.32 cm x 19.12 cm x 19.13) and the 4.37 cm radius and 11.57 cm height can. The total process time can be reduced by 22.8 percent using a 1.32 cm thick small pouch compared with a 4.37 cm radius can. The percent nutrient retention for the

small pouches was higher than the retention for pouches containing larger volumes of food.

4. The optimum size pouch with 694.5 cm^3 volume is 3.77 cm x 14.80 cm x 14.80 cm based on the nutrient retention and material cost. The recommended small pouches (486.2 cm^3) have a higher nutrient retention than the larger pouches and a lower cost. The recommended sizes are 2.22 cm x 14.80 cm x 14.80 cm and 2.67 cm x 13.50 cm x 13.50 cm.

Appendices

```
      PROGRAM RCANS (INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C THIS PROGRAM IS DESIGNED TO SOLVE CONDUCTION HEATING
C PROBLEMS IN RECTANGULAR SHAPED CONTAINERS USING
C THE SUFFICIENT LETHAL KILL METHOD
C THIS PROGRAM CAN BE USED TO SOLVE CONVENTICNAL CONDUCTION
C HEATING PROBLEMS BY MAKING THE DESIRED NUMBER OF
C BACTERIA  MUCH LARGER THAN THE LIKELY RESULT
C  A=INITIAL SPORE LOAD IN CONTAINER
C AL=THERMAL DIFFUSIVITY
C BE= TOTAL NUMBER OF LIVE SPORES AFTER PROCESS
C AN= CONCENTRATION AT ANY POINT (SPORES PER CUBIC INCH)
C CO= INITIAL CONCENTRATION
C D= DEATH RATE AT ANY TIME AT ANY POINT
C DO- THE DEATH RATE FOR ANY ORGANISM
C DU- TIME INCREMENT  MINUTES
C FH- SLOPE OF THE HEATING RATE CURVE
C AO BO CO - ARE THE LENGTH WIDTH AND HEIGHT
C I J K  ARE THE INCREMENTS OF THE LENGTH , WIDTH, AND HEIGHT
C NA NB NC ARE THE NUMBER OF INCREMENTS IN EACH DIRECTION
C SUM IS THE NUMBER OF LIVE SPORES IN THE 1/8 PART OF THE CAN
C RCUT IS THE TIME FOR THE RETORT TO COME UP TO TEMP
C RCDT IS THE TIME FOR THE RETORT TO COOL TO EFFECT WATER TEMP.
C JCH IS THE HEATING J-VALUE
C JCC IS THE COOLING J-VALUE
C PT IS THE PROCESSS TIME FROM WHEN RETORT REACHES PROCESSING TEMP.
C DR= TIME TO DESTROY 90 OF AN ORGANISM AT 250F
C TA IS THE OLD TEMPERATURE AT EACH POINT
C T IS THE AVERAGE TEMPERATURE AT EACH POINT
C TB IS THE NEW TEMPERATURE AT EACH POINT
C TI IS THE INITIAL TEMPERATURE AT EACH POINT
C TR IS THE RETORT TEMPERATURE
C TO CORRESONDS TO THE THERMAL DEATH RATE
C U PROCESS TIME
C UT THE TIME AT ANY POINT DURING THE PROCESS
C Z THE THERMAL DEATH CONSTANT FOR THE ORGANISM
      DIMENSION TA(7,8,11),TB(7,8,11),T(7,8,11),CA(7,8,11),CN(7,8,11)
      READ*,A,DO,TO,Z,AN,DN,TN,ZN
      READ*,U,TR,TI,TC,TV,FH,RCUT,RCDT
      READ*,AO,BO,CO,NA,NB,NC,DU
      READ*,DESIRED
C *TO* IS NOT USED IN THIS PROGRAM 250 IS THE BASE TEMP.
C SET FI= TO THE NUMBER OF INCREMENTS
      PRINT(6,390) A,DO,TO,Z
      PRINT(6,391) AN,DN,TN,ZN
      PRINT(6,392) U,TR,TI,TC,TV
      PRINT(6,393) FH,RCUT,RCDT
      PRINT(6,394) AO,BO,CO
      PRINT(6,395) NA,NB,NC,DU
      PRINT(6,998) DESIRED
      FI=NA
      FJ=NB
      FK=NC
C UT IS THE TIME AT ANY POINT IN THE PROCESS
      UT=0.
      ICOUNT=0
      IKNOW=0
C IKNOW AND ICOUNT ARE USED AS COUNTERS
      NA1=NA+1
      NA2=NA+2
      NB1=NB+1
      NB2=NB+2
      NC1=NC+1
      NC2=NC+2
C TCF IS THE FIRST LETHAL TEMPERATURE
      TCF=TR-2.*Z
C AT A LOCATION YOU FIX THE INITIAL CONTENT PER VOLUME BOTH
C QUALITY AND BACTERIA
      DO 100 I=1,NA
      DO 100 J=1,NB
      DO 100 K=1,NC
      CN(I,J,K)=AN/(AO*BO*CO)
      CA(I,J,K)=A/(AO*BO*CO)
100   CONTINUE
C INITIALIZES TEMPERATURE OF EACH POINT
      DO 120 I=2,NA2
      DO 120 J=2,NB2
      DO 120 K=2,NC2
      TA(I,J,K)=TI
```

```
120   CONTINUE
C WE ARE DEALING WITH 1/8 OF THE VOLUME
      AL=.933/((((1./(AO/2.)**2.)+1./(BO/2.)**2.)+1./(CO/2.)**2.)*FH)
      P=AL*DU/(.5*AO/FI)**2.
      Q=AL*DU/(.5*BO/FJ)**2.
      S=AL*DU/(.5*CO/FK)**2.
      STABLE=1.-2.*P-2.*Q-2.*S
      IF(STABLE.GT.0.) GO TO 180
            PRINT*,STABLE,P,Q,S
            PRINT(6,160)
      GO TO 399
  180 TRS=TR-(TR-TV)*10**(-UT/(RCUT/10.))
C 180 IS THE EQUATION DESCRIBING RETORT COME-UP TIME
C THIS EQUATION ALLOWS SYSTEM TO BE USED DURING HEATING AND
C AND COOLING OF THE PRODUCT
      IF(TRS.LE.TI) TRS=TI
      DO 199 K=1,NC2
      DO 199 J=1,NB2
      DO 199 I=1,NA2
      TA(I,J,1)=TRS
      T(I,J,1)=TRS
      TA(I,1,K)=TRS
      T(I,1,K)=TRS
      TA(1,J,K)=TRS
      T(1,J,K)=TRS
199   CONTINUE
200    DO 220 K=2,NC1
      DO 220 J=2,NB1
      DO 220 I=2,NA1
      TB(I,J,K)=TA(I,J,K)+P*(TA(I-1,J,K)-2.*TA(I,J,K)+TA(I+1,J,K))
     ++Q*(TA(I,J-1,K)-2.*TA(I,J,K)+TA(I,J+1,K))
     ++S*(TA(I,J,K-1)-2.*TA(I,J,K)+TA(I,J,K+1))
      TB(I,J,NC2)=TB(I,J,NC)
      TB(NA2,J,K)=TB(NA,J,K)
      TB(I,NB2,K)=TB(I,NB,K)
220   CONTINUE
C THIS AVERAGES THE TEMPERATURE BEFORE AND AFTER THE CYCLE
      DO 245 I=2,NA1
      DO 245 J=2,NB1
      DO 245 K=2,NC1
      T(I,J,K)=(TB(I,J,K)+TA(I,J,K))/2.
245   CONTINUE
C CHANGES NEW TO OLD TEMP.
      DO 255 I=2,NA2
      DO 255 J=2,NB2
      DO 255 K=2,NC2
      TA(I,J,K)=TB(I,J,K)
255   CONTINUE
C GENERATES THE NEW TEMPERATURES
      DO 270 I=1,NA
      DO 270 J=1,NB
      DO 270 K=1,NC
      TB(I,J,K)=(T(I,J,K)+T(I+1,J,K)+T(I,J+1,K)+T(I,J,K+1)
     ++T(I+1,J+1,K)+T(I+1,J,K+1)+T(I+1,J+1,K+1)+T(I,J+1,K+1))/8.
270   CONTINUE
      DO 292 K=1,NC
      DO 292 J=1,NB
      DO 292 I=1,NA
      CN(I,J,K)=CN(I,J,K)*10**(-DU/((DN/1.0)*
     + 10**((TN-TB(I,J,K))/(ZN/1.0))))
      CA(I,J,K)=CA(I,J,K)*10**(-DU/((DO/1.0)*
     + 10**((TO-TB(I,J,K))/(Z/1.0))))
292   CONTINUE
C ONCE THE DESIRED LEVEL IS REACHED THIS SECTION IS NO
C LONGER NEEDED AND WILL THEREFORE BE SKIPPED
      IF(UT.GE.U)IKNOW=1
      IF(IKNOW.NE.0) GO TO 86
      SUM=0.
      DO 999 K=1,NC
      DO 999 J=1,NB
      DO 999 I=1,NA
      SUM=SUM+CA(I,J,K)*.125*AO*BO*CO/(FI*FJ*FK)
999   CONTINUE
      BE=SUM*8.
      IF(BE.LE.DESIRED) U=UT
      IF(U.EQ.UT)IKNOW=1
86    CONTINUE
C THIS ALLOWS FOR THE COLD SPOT AND TIME TO BE PRINTED OUT
C EVERY 10 REPETITIONS
      ICOUNT=ICOUNT+1
      IF(ICOUNT.NE.10)GO TO 85
```

```
      PRINT(6,84)TB(NA,NB,NC),UT
      ICOUNT=0
85    CONTINUE
      IF(UT.LT.U) GO TO 310
      IF(T(NA1,NB1,NC1)-TCF) 350,350,310
310   UT=UT+DU
      IF(UT.LE.RCUT) GO TO 180
      IF(UT.GT.(U+RCDT)) GO TO 200
      IF(UT.LE.(U+0.5*DU)) GO TO 200
C NEXT STATEMENT IS THE EQUATION FOR COOLING PHASE
      TCS=TR-(TR-TC)*(UT-U)/RCDT
      DO 340 K=1,NC2
      DO 340 J=1,NB2
      DO 340 I=1,NA2
      TA(I,1,K)=TCS
C START THE COOLING PROCESS
      T(I,J,1)= TCS
      TA(I,J,1)=TCS
      T(I,1,K)=TCS
      TA(1,J,K)=TCS
      T(1,J,K)=TCS
340   CONTINUE
      GO TO 200
350   SUM=0.
      SUMN=0.
      DO 370 K=1,NC
C SUM IS THE BACTERIA NUMBER
      DO 370 J=1,NB
      DO 370 I=1,NA
      SUMN=SUMN+CN(I,J,K)*.125*AO*BO *CO/(FI*FJ*FK)
      SUM=SUM+CA(I,J,K)*.125*AO*BO*CO/(FI*FJ*FK)
370   CONTINUE
      BN=8.*SUMN
      BE=SUM*8.
       F=(DO/1.0)*(ALOG10(A)-ALOG10(BE))
      PRINT(6,84)TB(NA,NB,NC),UT
              PRINT(6,380) BE
              PRINT(6,381) BN
              PRINT(6,382) F
      PRINT(6,392) U,TR,TI,TC,TV
390   FORMAT(* A=*F9.0* DO=*F6.2* TO=*F6.2* Z=*F6.2)
391   FORMAT(* AN=*F6.2* DN=*F6.2* TN=*F6.2* ZN=*F6.2)
392   FORMAT(* U=*F6.2* TR=*F6.2* TI=*F6.2* TC=*F6.2* TV=*F6.2)
393   FORMAT(* FH=*F6.2* RCUT=*F6.2* RCDT=*F6.2)
394   FORMAT(* AO=*F6.2* BO=*F6.2* CO=*F6.2)
395   FORMAT(* NA=*I3* NB=*I3* NC=*I3* INCREMENT* F6.3)
998   FORMAT(* THE DESIRED NUMBER OF BACTERIA IS *F12.10)
160   FORMAT(*STABILITY CRITERIA NOT MET*)
 376   FORMAT(F8.2,6I3,2F8.2)
401   FORMAT(*  K=*I4*   J=*I4* TB(I,J,K) *10F9.2)
84    FORMAT(* THE TEMPERATURE AT THE COLD POINT IS *F8.2
     +* THE TIME IS *F6.2* MINUTES*)
380   FORMAT(*NUMBER OF SURVIVORS=* F12.8)
381   FORMAT(*PERCENT RETENTION=* F6.2)
375   FORMAT(* I HAVE BEEN HERE*F6.2)
382   FORMAT(* FS VALUE=*F6.2)
399   END
70000. 1. 250. 14. 100. 188.7 246. 45.
45. 250. 170. 79. 220. 21. 9. 3.
 3.10  3.10  3.10
 5 6 9 .2
  .0008
```

APPENDIX B

Computer Program to Simulate the Thermal Processing of a Canned Product

```
      PROGRAM CYCL(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C THIS PROGRAM IS DESIGNED TO SOLVE CONDUCTION HEATING
C PROBLEMS IN CYLINDRICAL CONTAINERS USING THE
C SUFFICIENT LETHAL KILL METHOD
C THE PROGRAM HAS BEEN MODIFIED TO SOLVE BOTH
C BACTERIA AND QUALITY FACTORS AT THE SAME
C TIME   IN OPDER TO USE THIS PROGRAM IS THE
C COVENTIONAL MANNER IT IS NECESSARY TO
C INCREASE TE DESIRED NUMBER OF BACTERIA TO A
C SUFFICIENTLY LARGE NUMBER.
C THIS PROGRAM IS MODIFIED FROM TEIXEIRA 1969
C LETHALITY CALCULATIONS
C INPUT TO THIS PROGRAM CONSISTS OF FOUR CARDS
C ON THE FIRST CARD, INITIAL SPORE LOAD, DEATH RATE
C TEMPERATURE CORRESPONDING TO THE DEATH RATE
C AND THE Z VALUE
C SECOND CARD RADIUS, HEIGHT, PROCESS TIME
C THIRD CARD  INITIAL TEMP. RETORT TEMP. COOLING,TEMP.
C SLOPE OF HEATING CURVE /FH/, FINAL CUT-OFF TEMP.
C FOURTH CARD THE NUMBER A RADIAL INCREMENTS,
C NUMBER OF VERTICAL INCREMENTS, AND SIZE OF TIME INCRE.
C OUTPUT CONSISTS OF FINAL NUMBER OF SURVIVORS,
C TOTAL TIME FOR PROCESS INCLUDING COOLING AND
C FINAL TEMP. AT THE CENTER OF THE CAN
C ***************************************
C A-INITIAL SPORE LOAD IN CONTAINER
C AL- THERMAL DIFFUSIVITY
C AN- THE INITIAL CONCENTRATION OF THE QUALITY FACTOR
C BE- TOTAL NUMBER OF LIVE SPORES AFTER PROCESS
C CA- CONCENTRATION AT ANY POINT(SPORES PER CUBIC INCH)
C D - DEATH RATE AT ANY TIME AT ANY POINT
C DHO- VERTICAL INCREMENT SIZE
C DO- DEATH RATE CONSTANT FOR ORGANISM(MINUTES)
C DN- THE DESTRUCTION RATE CONSTANT FOR THE QUALITY FACTOR
C DU-TIME INCREMENT MINUTES
C DRO-RADIAL INCREMENT SIZE
C FH- SLOPE OF HEATING CURVE
C HO- HEIGHT OF THE CONTAINER
C I- SEQUENCE OF RADIAL INCREMENTS
C J- SEQUENCE OF VERTICAL INCREMENTS
C NH-NUMBER OF VERTICAL INCREMENTS
C NR-NUMBER OF RADIAL INCREMENTS
C PR- THE NUMBER OF SURVIVORS IN EACH VOLUME ELEMENT
C RO- RADIUS OF CONTAINER
C R- RADIUS AT ANY POINT
C SUM= NUMBER OF LIVE SPORES IN UPPER HALF CONTAINER AT ANY
C TIME
C T- AVERAGE OF TEMPERATURES BEFORE AND AFTER THE TIME
C INTERVAL, DU, AT ANY POINT IN CONTAINER
C TA- OLD TEMP AT EACH POINT
C TB= NEW TEMP. AT EACH POINT
C TC=EFFECTIVE MEAN COOLING WATER TEMPERATURE
C TCF= CUT OFF TEMP.
C TI = INITAL TEMPERATURE
C TN CORRES. TO THE QUALITY FACTOR  CONSTANT, DN
C TO= TEMP. CORRES. TO DEATH RATE CONSTANT,DO.
C TR= RETORT TEMP.
C TV= AVERAGE OF THE FOUR TEMP. AT THE CORNERS OF
C EACH VOLUME ELEMENT
C U=PROCESS TIME
C UT= TIME AT ANY POINT IN PROCESS
C Z= THERMAL DEATH CONSTANT FOR ORGANISM
C ZN= THERMAL CONSTANT FOR THE QUALITY FACTOR
C ***************************************
      DIMENSION TA(25,25),TB(25,25),T(25,25),CA(25,25)
      DIMENSION CNN(25,25),DD(25,25)
      DIMENSION PR(25,25)
      DIMENSION TV(25,25),PRN(25,25),D(25,25)
C READ IN DATA
      READ*,A,DO, TO, Z
      READ*,RO,HO,U
      READ*,TI,TR,TC,FH,TCF
      READ*,NR,NH,DU
      READ*,AN,DN,TN,ZN
      READ*,DESIRED
      PRINT(6,2) A,DO, TO,Z,RO
      PRINT(6,3) HO,U,TI,TR,TC
      PRINT(6,4) AN,DN,TN,ZN
```

```
      PRINT(6,5) FH,TCF,NR,NH,DU
      PRINT(6,111) DESIRED
C EVALUATE CONSTANTS
      FI= NR
      FJ= NH
      DRO=RO/FI
      DHO=HO/(2.*FJ)
      UT=0.0
      IKNOW=0
      ICOUNT=0
      CO= A/(HO*3.14*RO**2)
      CN=AN/(HO*3.14*RO**2)
      NR1=NR +1
      NR2= NR+2
      NH1= NH+1
      NH2= NH +2
C PRESET ALL POINTS TO INITIAL CONCENTRATION
      DO 40 I=1,NR
      DO 40 J= 1,NH
      CNN(I,J)= CN
40    CA(I,J)= CO
C PRESET BOUNDARY AND INTERIOR TEMPERATURE
      DO 10 I=2,NR2
      DO 10 J=2,NH2
10    TA(I,J)=TI
      DO 12 I=1,NR2
      T(I,1)=TR
12    TA(I,1)=TR
      DO 11 J=1,NH2
      T(1,J)=TR
11    TA(1,J)=TR
C AL IS COMPUTED FROM SLOPE OF THE HEATING CURVE GIVEN BY
C STUMBO
      AL= .398/(((1./RO**2)+.427/(HO/2.)**2)*FH)
      P= AL*DU/DRO**2
      Q=AL*DU/(2.*DRO)
      S= AL*DU/DHO**2
      PRINT(6,16)AL,P,Q,S
      IF(P.LT.1.0)GO TO 13
      PRINT(6,7)P
      GO TO 110
C CALCULATE TEMPERATURE DISTRIBUTION FOR THIS TIME INTERVAL
13    CONTINUE
      DO 15 J=2,NH1
C RESET INITIAL R FOR EACH NEW J
      R=RO
      DO 14 I=2,NR
      R = R-DRO
14    TB(I,J)=TA(I,J)+P*(TA(I-1,J)-2.*TA(I,J)+TA(I+1,J))
     ++Q/R*(TA(I-1,J)-TA(I+1,J))+S*(TA(I,J-1)-2.*TA(I,J)+TA(I,J+1))
C CENTERLINE TEMP MUST BE CALCULATED SEPERATELY SINCE R=0
      TB(NR1,J)= TA(NR1,J)+2.*P*(TA(NR,J)-2.*TA(NR1,J)+TA(NR2,J))
     ++S*(TA(NR1,J-1)-2.*TA(NR1,J)+TA(NR1,J+1))
C CALCULATE TEMP.AT FIRST INCREMENT OPPOSITE CENTERLINE
      TB(NR2,J)=TB(NR,J)
15    CONTINUE
C CALCULATE TEMP. IN ROW BENEATH CENTER
      DO 46 I=2,NR1
46    TB(I,NH2)=TB(I,NH)
C AVE TEMPERATURE OVER TIME, DU AT EACH POINT
      DO 20 I=2,NR1
      DO 20 J=2,NH1
20    T(I,J)= (TB(I,J)+TA(I,J))/2.
      DO 22 I=1,NR
      DO 22 J=1,NH
22    TV(I,J)=(T(I,J)+T(I+1,J)+T(I,J+1)+T(I+1,J+1))/4.0
C REPEAT, LET NEW TEMP. BECOME OLD TEMP.
      DO 52 I=2,NR2
      DO 52 J=2,NH2
52    TA(I,J)=TB(I,J)
C CALCULATE CONCENTRATION AT EACH POINT OVER TIME
      DO 75 J=1,NH
      DO 74 I=1,NR
      D(I,J)=DO*10**((TO-TV(I,J))/Z)
      DD(I,J)=DN*10**((TN-TV(I,J))/ZN)
      CNN(I,J)=CNN(I,J)*10**(-DU/DD(I,J))
74    CA(I,J)=CA(I,J)*10**(-DU/D(I,J))
75    CONTINUE
      IF(UT.GE.U)IKNOW=1
      IF(IKNOW.NE.0)GO TO 86
      SUM=0.0
```

```
      DO 999 J=1,NH
      R=RO
      DO 999 I=1,NR
      R=R-DRO
999   SUM= SUM + CA(I,J)*3.14* DHO*(2.*DRO*R+ DRO**2)
      BE=2.*SUM
      IF(BE.LE.DESIRED)U=UT
      IF(U.EQ.UT)IKNOW=1
86    CONTINUE
      ICOUNT=ICOUNT+1
      IF(ICOUNT.NE.10)GO TO 85
      PRINT(6,84)TB(NR,NH),UT
      ICOUNT=0
85    CONTINUE
     +*  THE TIME IS *F6.2* MINUTES*)
      IF(UT.LT.U)GO TO 103
      IF(T(NR1,NH1)-TCF) 100,100,103
C CALCULATE ELAPSED TIME
103   UT= UT+DU
C IF PROCESS TIME IS REACHED, SET BOUNDARY EQUAL TO TC
8     IF(UT-U) 13,9,9
9     IF(UT-U-DU) 100,130,13
130   DO 29 I=1,NR2
29    TA(I,1)=TC
      DO 28 J=1,NH2
28    TA(1,J)=TC
      DO 27 I=1,NR2
27    T(I,1)=TC
      DO 26 J=1,NH2
26    T(1,J)= TC
      GO TO 13
C CALCULATE LETHALITY
C MULTIPLY CONCENTRATION AT EACH POINT BY CORRESPONDING
C INCREMENT VOLUME, AND ADD TOGETHER.
100   SUM=0.0
      SUMN=0.0
      DO 32 J=1,NH
      R=RO
      DO 32 I=1,NR
      R=R-DRO
      PR(I,J)=CA(I,J)*3.14*DHO*(2.*R*DRO+DRO**2)
      PRN(I,J)=CNN(I,J)*3.14*DHO*(2.*R*DRO+DRO**2)
      SUMN=SUMN+PRN(I,J)
32    SUM=SUM +PR(I,J)
      BE= 2.*SUM
      BN=2.*SUMN
      PRINT(6,62) BE,UT,T(NR1,NH1)
      PRINT(6,63) BN,U,DN,TN,ZN
      PRINT(6,112) BE
      PRINT(6,113) BN
      F=DO*(ALOG10(A)-ALOG10(BE))
      PRINT(6,114)F
2     FORMAT(* A=*F9.1* DO=*F6.2* TO=*F6.2* Z=*F6.2* RO=*F6.2)
3     FORMAT(* HO=*F6.2* U=*F6.2* TI=*F6.2* TR=*F6.2* TC=*F6.2)
4     FORMAT(* AN=*F6.2* DN=*F6.2* TN=*F6.2* ZN=*F6.2)
5     FORMAT(* FH=*F6.2* TCF=*F6.2* NR=*I3* NH=*I3* DU=*F6.2)
6     FORMAT(*  *10(2X,F6.2))
7     FORMAT(* STABILITY CRITERIA NOT MET P= * F6.2)
16    FORMAT(* AL=*F8.2*  P=*F6.3* Q=*F6.3* S=*F6.3)
62    FORMAT(* BE=*F15.8* UT=*F6.2* T(NR1,NH1)=* F6.2)
63    FORMAT(* BN=*F15.8* U=*F8.2* DN=*F7.2* TN=*F5.1* ZN=*F5.1)
84    FORMAT(* THE TEMPERATURE AT THE COLD POINT IS *F8.2
111   FORMAT(* THE DESIRED NUMBER OF BACTERIA IS *F12.9)
112   FORMAT(* NUMBER OF SURVIVORS = *F12.9)
113   FORMAT(* PERCENT RETENTION = *F6.2)
114   FORMAT(* FS VALUE =*F6.2)
444   FORMAT(* I HAVE BEEN HERE*I4)
      IF(T(NR1,NH1)-TCF)110,110,13
110   CONTINUE
      STOP
      END
 100000. 1.0 250. 14.
  2.0  3.37
  45.
 170.0 250. 79. 21. 170.0
 10 10 .125
100. 188.7  246. 45.
.0008
```

APPENDIX C

Computer Results
of Selected
Computer Outputs

C1 Results From Thin Regular Rectangular Pouch

```
A= 100000. DO=  1.00 TO=250.00 Z= 14.00
AN=100.00 DN=188.70 TN=246.00 ZN= 45.00
U= 45.00 TR=250.00 TI=170.00 TC= 79.00 TV=220.00
FH= 21.00 RCUT=   9.00 RCDT=   3.00
AO=   3.49 BO=   3.49 CO=   3.49
NA=  5 NB=  6 NC=  9 INCREMENT  .200
THE DESIRED NUMBER OF BACTERIA IS  .0000000000
THE TEMPERATURE AT THE COLD POINT IS   170.14 THE TIME IS    1.00 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   172.75 THE TIME IS    3.00 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   179.91 THE TIME IS    5.00 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   189.61 THE TIME IS    7.00 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   199.57 THE TIME IS    9.00 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   208.64 THE TIME IS   11.00 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   216.41 THE TIME IS   13.00 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   222.87 THE TIME IS   15.00 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   228.15 THE TIME IS   17.00 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   232.44 THE TIME IS   19.00 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   235.90 THE TIME IS   21.00 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   238.68 THE TIME IS   23.00 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   240.92 THE TIME IS   25.00 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   242.71 THE TIME IS   27.00 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   244.15 THE TIME IS   29.00 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   245.31 THE TIME IS   31.00 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   246.24 THE TIME IS   33.00 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   246.98 THE TIME IS   35.00 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   247.58 THE TIME IS   37.00 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   247.90 THE TIME IS   39.00 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   245.20 THE TIME IS   41.00 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   234.17 THE TIME IS   43.00 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   215.65 THE TIME IS   45.00 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   215.65 THE TIME IS   45.00 MINUTES
UMBER OF SURVIVORS=   .00000105
ERCENT RETENTION= 65.72
FS VALUE= 10.98
U= 37.40 TR=250.00 TI=170.00 TC= 79.00 TV=220.00
```

C2 Results From Regular Cube

```
A=   100000.  DO=   1.00  TO=250.00  Z=  14.00
AN=100.00  DN=188.70  TN=246.00  ZN=  45.00
U= 45.00  TR=250.00  TI=170.00  TC=  79.00  TV=220.00
FH= 21.00  RCUT=   9.00  RCDT=   3.00
AO=   .75  BO=   4.34  CO=  13.02
NA=   5  NB=   6  NC=   9  INCREMENT   .200
THE  DESIRED  NUMBER  OF  BACTERIA  IS   .0008000000
THE  TEMPERATURE  AT  THE  COLD  POINT  IS    172.69  THE  TIME  IS    1.80  MINUTES
THE  TEMPERATURE  AT  THE  COLD  POINT  IS    184.28  THE  TIME  IS    3.80  MINUTES
THE  TEMPERATURE  AT  THE  COLD  POINT  IS    196.39  THE  TIME  IS    5.80  MINUTES
THE  TEMPERATURE  AT  THE  COLD  POINT  IS    206.59  THE  TIME  IS    7.80  MINUTES
THE  TEMPERATURE  AT  THE  COLD  POINT  IS    214.90  THE  TIME  IS    9.80  MINUTES
THE  TEMPERATURE  AT  THE  COLD  POINT  IS    221.63  THE  TIME  IS   11.80  MINUTES
THE  TEMPERATURE  AT  THE  COLD  POINT  IS    227.07  THE  TIME  IS   13.80  MINUTES
THE  TEMPERATURE  AT  THE  COLD  POINT  IS    231.46  THE  TIME  IS   15.80  MINUTES


THE  TEMPERATURE  AT  THE  COLD  POINT  IS    235.02  THE  TIME  IS   17.80  MINUTES
THE  TEMPERATURE  AT  THE  COLD  POINT  IS    237.89  THE  TIME  IS   19.80  MINUTES
THE  TEMPERATURE  AT  THE  COLD  POINT  IS    240.22  THE  TIME  IS   21.80  MINUTES
THE  TEMPERATURE  AT  THE  COLD  POINT  IS    242.10  THE  TIME  IS   23.80  MINUTES
THE  TEMPERATURE  AT  THE  COLD  POINT  IS    243.61  THE  TIME  IS   25.80  MINUTES
THE  TEMPERATURE  AT  THE  COLD  POINT  IS    244.84  THE  TIME  IS   27.80  MINUTES
THE  TEMPERATURE  AT  THE  COLD  POINT  IS    245.83  THE  TIME  IS   29.80  MINUTES
THE  TEMPERATURE  AT  THE  COLD  POINT  IS    246.64  THE  TIME  IS   31.80  MINUTES
THE  TEMPERATURE  AT  THE  COLD  POINT  IS    247.28  THE  TIME  IS   33.80  MINUTES
THE  TEMPERATURE  AT  THE  COLD  POINT  IS    247.81  THE  TIME  IS   35.80  MINUTES
THE  TEMPERATURE  AT  THE  COLD  POINT  IS    245.51  THE  TIME  IS   37.80  MINUTES
THE  TEMPERATURE  AT  THE  COLD  POINT  IS    228.60  THE  TIME  IS   39.80  MINUTES
THE  TEMPERATURE  AT  THE  COLD  POINT  IS    218.40  THE  TIME  IS   40.60  MINUTES
NUMBER  OF  SURVIVORS=    .00001159
PERCENT  RETENTION= 69.67
FS  VALUE=   9.94
U=  35.40  TR=250.00  TI=170.00  TC=  79.00  TV=220.00
```

C3 Results From Thin Small Square Pouch

```
A=    70000. CC=  1.00 TO=250.00 Z= 14.00
AN=100.00 DN=188.70 TN=246.00 ZN= 45.00
U= 45.00 TR=250.00 TI=170.00 TC= 79.00 TV=220.00
FH= 21.00 RCLT=  9.00 RCDT=  3.00
AO=   .52 BO=  7.52 CO=  7.52
NA=  5 NB=  6 NC=  9 INCREMENT  .200
THE DESIRED NUMBER OF BACTERIA IS  .0008000000
THE TEMPERATURE AT THE COLD POINT IS   172.86 THE TIME IS   1.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   184.83 THE TIME IS   3.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   197.14 THE TIME IS   5.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   207.42 THE TIME IS   7.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   215.75 THE TIME IS   9.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   222.45 THE TIME IS  11.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   227.84 THE TIME IS  13.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   232.17 THE TIME IS  15.80 MINUTES


THE TEMPERATURE AT THE COLD POINT IS   235.66 THE TIME IS  17.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   238.47 THE TIME IS  19.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   240.72 THE TIME IS  21.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   242.54 THE TIME IS  23.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   244.00 THE TIME IS  25.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   245.17 THE TIME IS  27.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   246.12 THE TIME IS  29.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   246.88 THE TIME IS  31.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   247.49 THE TIME IS  33.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   247.97 THE TIME IS  35.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   243.32 THE TIME IS  37.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   222.64 THE TIME IS  39.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   217.31 THE TIME IS  40.20 MINUTES
NUMBER OF SURVIVORS=   .00001022
PERCENT RETENTION= 70.37
FS VALUE=  9.84
U= 35.00 TR=250.00 TI=170.00 TC= 79.00 TV=220.00
```

C4 Results From Small Cube

```
A=    70000. DO=   1.00 TO=250.00 Z= 14.00
AN=100.00 DN=188.70 TN=246.00 ZN= 45.00
U= 45.00 TR=250.00 TI=170.00 TC= 79.00 TV=220.00
FH= 21.30 RCUT=   9.00 RCDT=   3.00
AO=  3.10 BO=   3.10 CO=   3.10
NA=  5 NB=   6 NC=   9 INCREMENT   .200
THE DESIRED NUMBER OF BACTERIA IS   .0008000000
THE TEMPERATURE AT THE COLD POINT IS    170.15 THE TIME IS    1.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    172.75 THE TIME IS    3.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    179.91 THE TIME IS    5.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    189.61 THE TIME IS    7.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    199.57 THE TIME IS    9.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    208.64 THE TIME IS   11.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    216.41 THE TIME IS   13.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    222.87 THE TIME IS   15.80 MINUTES

THE TEMPERATURE AT THE COLD POINT IS    228.15 THE TIME IS   17.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    232.44 THE TIME IS   19.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    235.90 THE TIME IS   21.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    238.68 THE TIME IS   23.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    240.92 THE TIME IS   25.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    242.71 THE TIME IS   27.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    244.15 THE TIME IS   29.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    245.31 THE TIME IS   31.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    246.24 THE TIME IS   33.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    246.99 THE TIME IS   35.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    247.58 THE TIME IS   37.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    247.82 THE TIME IS   39.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    244.49 THE TIME IS   41.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    232.55 THE TIME IS   43.80 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    215.63 THE TIME IS   45.80 MINUTES
UMBER OF SURVIVORS=    .0000115
ERCENT RETENTION= 65.92
FS VALUE= 10.82
U= 37.20 TR=250.00 TI=170.00 TC= 79.00 TV=220.00
```

C5 Results From A Cylindrical Rod

```
A= 100000.0 DO=   1.00 TO=250.00 Z= 14.00 RO=   1.00
HO= 13.49 U= 45.00 TI=170.00 TR=250.00 TC= 79.00
AN=100.00 DN=188.70 TN=246.00 ZN= 45.00
FH= 21.00 TCF=170.00 NR= 10 NH= 10 DU=     .13
THE DESIRED NUMBER OF BACTERIA IS    .000800000
AL=     .02  F=   .235 Q=   .012  S=   .005
THE TEMPERATURE AT THE COLD POINT IS    170.00  THE TIME IS   1.13 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    170.96  THE TIME IS   2.38 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    175.00  THE TIME IS   3.63 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    181.30  THE TIME IS   4.88 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    188.41  THE TIME IS   6.13 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    195.44  THE TIME IS   7.38 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    201.99  THE TIME IS   8.63 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    207.90  THE TIME IS   9.88 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    213.16  THE TIME IS  11.13 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    217.80  THE TIME IS  12.38 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    221.87  THE TIME IS  13.63 MINUTES

THE TEMPERATURE AT THE COLD POINT IS    243.68  THE TIME IS  27.38 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    244.49  THE TIME IS  28.63 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    245.19  THE TIME IS  29.88 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    245.80  THE TIME IS  31.13 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    246.33  THE TIME IS  32.38 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    246.80  THE TIME IS  33.63 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    247.20  THE TIME IS  34.88 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    247.56  THE TIME IS  36.13 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    247.87  THE TIME IS  37.38 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    247.29  THE TIME IS  38.63 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    240.96  THE TIME IS  39.88 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    228.77  THE TIME IS  41.13 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    214.01  THE TIME IS  42.38 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    198.96  THE TIME IS  43.63 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    184.74  THE TIME IS  44.88 MINUTES
THE TEMPERATURE AT THE COLD POINT IS    171.81  THE TIME IS  46.13 MINUTES
BE=      .00001068 UT= 46.63 T(NR1,NH1)=168.87
BN=    68.65220193 U=  76.50 DN= 188.70 TN=246.0 ZN= 45.0
NUMBER OF SURVIVORS =   .000010680
PERCENT RETENTION =  68.65
FS VALUE =  9.97
```

66 Results From A Squat Can

```
A= 100000.0 DO=  1.00 TO=250.00 Z= 14.00 RO=  2.60
HO=  2.00 U= 45.00 TI=170.00 TR=250.00 TC= 79.00
AN=100.00 DN=188.70 TN=246.00 ZN= 45.00
FH= 21.00 TCF=170.00 NR= 10 NH= 10 DU=    .13
THE DESIRED NUMBER OF BACTERIA IS   .000800000
AL=.    .03  P=   .061 Q=   .008 S=   .412
THE TEMPERATURE AT THE COLD POINT IS   170.07  THE TIME IS   1.13 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   172.59  THE TIME IS   2.38 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   177.83  THE TIME IS   3.63 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   183.95  THE TIME IS   4.88 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   190.09  THE TIME IS   6.13 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   195.93  THE TIME IS   7.38 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   201.38  THE TIME IS   8.63 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   206.43  THE TIME IS   9.88 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   211.08  THE TIME IS  11.13 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   215.33  THE TIME IS  12.38 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   219.20  THE TIME IS  13.63 MINUTES

THE TEMPERATURE AT THE COLD POINT IS   244.28  THE TIME IS  29.88 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   245.00  THE TIME IS  31.13 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   245.64  THE TIME IS  32.38 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   246.19  THE TIME IS  33.63 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   246.67  THE TIME IS  34.88 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   247.10  THE TIME IS  36.13 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   247.47  THE TIME IS  37.38 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   247.64  THE TIME IS  38.63 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   242.53  THE TIME IS  39.88 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   231.59  THE TIME IS  41.13 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   218.71  THE TIME IS  42.38 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   205.78  THE TIME IS  43.63 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   193.46  THE TIME IS  44.88 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   181.95  THE TIME IS  46.13 MINUTES
THE TEMPERATURE AT THE COLD POINT IS   171.28  THE TIME IS  47.38 MINUTES
BE=      .00002330 UT= 47.88 T(NR1,NH1)=169.19
BN=    67.12521666 U=    37.38 DN= 188.70 TN=246.0 ZN= 45.0
NUMBER OF SURVIVORS =   .000023301
PERCENT RETENTION =  67.13
FS VALUE =   9.63
```

APPENDIX D

Energy Cost Equations

ENERGY COST EQUATIONS

Natural Gas .25135¢/ft^3 gas (Consumer's Power Michigan September 1979)

Efficiencies 0.92 of heat exchanger (Holman, 1976)

995.4 BTU/ ft^3 gas (Henderson and Perry, 1976)

1087.9 BTU/ lbm steam (Reynolds and Perkins, 1977)

1 BTU = 1.055 kJ

42 cases of 24 number two cans require 420 lbm steam for the first 15 minutes, after 15 minutes 125 lbm steam per hour of heating time (Lopez, 1975).

Energy Required for 30 minutes
(420 lbs steam/retort) + (125 lb steam / hr retort)*(15 min) =
450.0 lbs steam/retort

for each additional minute
(125 lb steam/60 min retort) = 2.08 lb steam/min retort

example a 1.90 cm x 19.09 cm x 19.09 cm pouch has a heating time of
35.2 minutes

$$\frac{\left(\frac{1.055\text{kJ}}{1\text{ BTU}}\right)\left(\frac{1087.9\text{ BTU}}{\text{lb steam}}\right)\left(\frac{450\text{ lbs steam}}{\text{retort}} + \frac{2.08\text{ lb steam}}{\text{additional minute-retort}} \times 5.2\text{ min}\right)}{(42\text{ case/retort}) \times (24\text{ pouches/case}) \times (.92\text{ efficiencies})} =$$

$$= 588\ \frac{\text{kJ}}{\text{pouch}}$$

cost per pouch

$$\left(588\ \frac{\text{kJ}}{\text{pouch}}\right)\left(\frac{1\text{ BTU}}{1.055\text{ kJ}}\right)\left(\frac{\text{ft}^3}{995.4\text{ BTU}}\right)\left(\frac{.25135¢}{\text{ft}^3}\right) = \frac{0.137¢}{\text{pouch}}$$

cost for small pouch (70% of the volume of the regular pouches)

1.32 cm x 19.09 cm x 19.09 cm with heat time of 35.00 minutes

$$\frac{\left(\frac{.7\ \text{regular pouch}}{\text{small pouch}}\right)\left(\frac{1.055\ \text{kJ}}{\text{BTU}}\right)\left(\frac{1087.9\ \text{BTU}}{\text{lb steam}}\right)\left(450 + 2.08 \times 5.0\ \frac{\text{lbs steam}}{\text{retort}}\right)}{(42\ \text{case/retort}) \times (24\ \text{pouches/case}) \times (.92\ \text{efficiencies})} =$$

$$= 411.\frac{\text{kJ}}{\text{small pouch}}$$

cost per small pouch

$$\left(411.\ \frac{\text{kJ}}{\text{small pouch}}\right)\left(\frac{1\ \text{BTU}}{1.055\ \text{kJ}}\right)\left(\frac{\text{ft}^3}{995.4\ \text{BTU}}\right)\left(\frac{.25135¢}{\text{ft}^3}\right) = \frac{0.096¢}{\text{small pouch}}$$

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LIST OF REFERENCES

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