BACTERICIDAL EFFICIENCY OF A HELICALLY COILED TUBE TURBULENT FLOW PROCESSING SYSTEM

by

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Dissertation submitted to the Graduate Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Animal Science

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December, 1971

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ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation to his major professor, Dr. W. K. Stone, for his encouragement, guidance, and for his assistance during the preparation of the manuscript.

Special thanks and appreciation are given to Dr. N. R. Krieg and Dr. W. C. Thomas for their suggestions and encouragement throughout the project.

Appreciation is also extended to Dr. E. N. Boyd, Dr. S. J. Ritchey, and Dr. A. Lopez for their suggestions and evaluation of this research.

The author is thankful to Professor P. M. Large, Mr. L. E. Cassada, Mr. R. L. Johnson, and Mr. H. E. Cromer for their help with the processing operations. Thanks are also extended to Mr. J. Viles, graduate student in Mechanical Engineering, for his assistance in writing the computer program.

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INTRODUCTION

The recent advances in ultra-high temperature (UHT) processing have been focused on improving the quality and shelf life of fluid dairy products. This process could be used, however, to process other fluid foods if more technical information were available on flow properties, heat exchange characteristics, and on lethality of selected microorganisms.

The two general types of UHT processing equipment are the direct and indirect heat exchange systems. In the direct system, heating of the product involves direct contact with culinary steam, whereas in the indirect system, heating of the product is accomplished through a metal barrier. The direct heating system dilutes the product with the condensate, and after a short holding time it is concentrated to its original volume by a vacuum process. The disadvantages of this process are physical damage and possible contamination from the steam. Even with these disadvantages, several commercial applications have been made in Europe, the United States, and Canada.

Indirect systems do not subject the food to contamination or to chemical breakdown by dilution and are highly adaptable to aseptic processing systems. Present commercial units consist primarily of plate-type and tube-type indirect heat exchange systems. The plate exchangers are more widely used, because many units are already in operation for high temperature short time (HTST) processing of fluid foods. The principal disadvantage of plate-type systems for UHT processing is that they cannot withstand the extreme pressures that occur during heating and cooling.

Helically coiled tube UHT heat exchange systems can withstand extreme changes in pressure and can be operated up to 5000 lb/sq in. product pressure. This permits the use of high flow rates that are necessary to maintain turbulent flow during processing highly viscous foods. Many fluid food products, including concentrated foods such as cream and ice cream mix, can be processed by heat treatments in helically coiled tube exchange systems. Before wider commercial applications can be made, additional data are needed on factors affecting bactericidal efficiency of helically coiled tube heat exchange systems. More basic information is needed on flow properties, and on heat exchange characteristics of these systems. In addition to this, information on bacterial destruction is required in these types of systems involving rapid heating and cooling treatments with short holding times. Application of this information would increase processing efficiency, reduce "burn-on," and improve the quality of foods pasteurized or sterilized in helically coiled tube heat exchange systems.

OBJECTIVES

(1) To devise a helically coiled tube heat exchange system for processing menstruums of 1.4% to 40% solids under closely controlled turbulent flow conditions.

(2) To develop methods for comparing the bactericidal efficiency of turbulent flow heat treatments in helically coiled tube heat exchange systems under different conditions of velocity and Reynolds numbers.

(3) To determine the effects of nonfat milk solids on bactericidal efficiency, temperature distribution, and on lethality of *Escherichia coli* in rapid-flow heat transfer systems under thoroughly defined conditions.

REVIEW OF LITERATURE

In commercial processing, heat treatments range from pasteurization to commercial sterilization. Pasteurization is used to destroy potential disease producing microorganisms and to decrease total counts, while commercial sterilization is used to destroy both pathogenic and spoilage microorganisms. As new types of equipment become commercially available, reliable methods are needed to evaluate thermal processes. Bigelow *et al.* (1920), Olson and Stevens (1939), Ball and Olson (1957), and Stumbo (1965) presented procedures for evaluating the effectiveness of food sterilization. Their calculations were based upon an orderly destruction of microorganisms by moist heat in static systems.

Chick (1910) was among the first to show that the destruction of bacteria by moist heat in non-flow systems takes place in an orderly manner. The logarithm of the viable count was plotted against time at a constant temperature and a straight line survivor curve was obtained. Olsen and Scott (1950), Sugiyama (1951), and Webster and Esselen (1956) reported additional data to support this logarithmic order of destruction. Deviations from this order, however, were observed by Kaufmann and Andrews (1954), by El-Bisi and Ordal (1956a, b), and by Moats *et al.* (1971).

Slopes of survivor curves are influenced by several factors, such as types of suspension, heat resistance of the organism, number of cells, and the heating temperature (Foster *et al.*, 1957). The negative reciprocal of the slope represents 90% destruction and was designated as decimal reduction time (D). These values are used to compare the heat resistance of microorganisms.

Survival curves of *Bacillus subtilis* spores were plotted and used to evaluate direct steam injection type UHT treatments in a flow system by Edwards *et al.* (1965a,b). Deviations from a straight line function for the survival curves were observed, and complications were encountered in predicting population levels after certain heat treatments.

The comparison of the thermal resistance among microorganisms has always been an important phase of food processing. For many years relative heat resistance was determined mainly by the thermal death point (Associates of L. A. Rogers, 1935). This was defined as the lowest temperature at which a given bacterial suspension in a known environment was killed in ten minutes. Bigelow (1921), however, established the logarithmic relationship between destruction time and temperature of heating and plotted thermal death time (TDT) curves. Ball (1923, 1928) in developing mathematical methods for calculating process requirements for canned foods pointed out that TDT curves could be characterized by a thermal death point F, and a slope Z. The slope of the TDT curve currently is widely used as a basis of comparison of heat resistance of microorganisms. For calculating food processing requirements, TDT curves are used (The Canned Food Reference Manual, 1949). Standards for processing of fluid milk products that were established by the United States Department of Health, Education and Welfare (1965) required exact holding times at specific temperatures. Each holding requirement at the designated temperature is the thermal death time in the TDT curve (Foster *et. al.*, 1957).

Stumbo (1948), Stumbo *et al.* (1950), and Reynolds *et al.*(1952) reported that a linear relationship existed between the logarithm of D values and heating temperatures. Ball (1943) characterized this curve as a "Phantom" TDT curve. It was defined as a thermal destruction curve by Stumbo (1965) and called a decimal reduction time curve by Speck and Busta (1968).

Both Z and Z_D were used to represent the slope of this curve. In the range of 130°F to 160°F for vegetative cells and of 220°F to 270°F for spore suspensions, Schmidt (1957) noted that the slope of the "Phantom" TDT curve was the same as that of the TDT curve. Esselen and Pflug (1956) found a Z_D value of 15.8°F, and Segner *et al.* (1963) reported a Z_D value of 20.3°F for Putrefactive Anaerobe (P.A.) 3679.

Busta (1967) observed a Z_D value of 35°F for P.A. 3679 in a direct steam injection UHT processing system. Applications of such unusually high Z_D values as 35°F for calculating thermal processes would result in the use of severe heat treatments to obtain sterility. When processing at 300°F for 4 sec, Speck and Busta (1968) noted that a built-in safety factor was operative, and because of the unusual thermal inactivation characteristics as indicated by high Z_D values, separate testing of each UHT unit was recommended to assure public health safety.

Galesloot (1956) proposed an equation for measuring the sterilizing effect of UHT processing systems. The equation was defined as:

$$\text{Sterilizing Effect} = \log_{10} \left(\frac{\text{initial spore count}}{\text{surviving spore count}}\right)$$

In this method large quantities of spore suspensions were inoculated in the raw milk and processed at various temperatures, and the survivors were detected by conventional counting methods. The sterilizing effect was actually the reduction of the logarithm of the spore count as a result of the process. This method of assessing the sterilizing effect has been widely adopted in Europe.

Williams *et al.* (1957) developed methods of assessing the sporocidal efficiency of a commercial plate-type UHT milk sterilizing plant. A *Bacillus subtilis* spore suspension in water was processed at various temperatures and a membrane filter technique was used to determine survival. They observed that a processing temperature of 275°F for 2.5 sec was required to obtain 99.99999% destruction. With the same processing equipment, Franklin *et al.* (1958) determined the survival of *B. subtilis* spores in milk. They used a dilution technique to determine survival and found 99.99999% destruction at a processing temperature of 267°F. This lower UHT heat treatment requirement for destruction of *Bacillus subtilis* in milk than in water was attributed to unidentified inhibitory substances that prevented germination and growth of some surviving spores. Using UHT processed milk as the growth medium, Franklin *et al.* (1959) again demonstrated the presence of inhibitory substances and suggested that they were sulfhydryl groups.

Burton (1958a,b) recognized the need for measuring the bactericidal efficiency of UHT processing units, and developed a procedure for calculating the bactericidal effectiveness of a commercial UHT plate-type sterilizing unit. Sodium nitrite solution was used to determine the flow time distribution in the heating and holding sections. It was assumed that a similar pattern occurred for bacterial flow time distribution. The logarithm of the proportion of surviving organisms was plotted against time. The slope, K, was obtained from the resulting curve, and was specific for each heat treatment temperature and for each type of organism. The theoretical lethality for both the holding and the heating sections was computed for different values of K. The mean holding time was 2.56 sec and had little lethal effect when compared with the heat-up time. When the calculated logarithmic proportion of surviving organisms was plotted against time, the function was not linear. The curve consisted of a set of component straight lines. In the narrow temperature range of 267°F to 275°F, Burton *et al.* (1958), later concluded that the determined levels of survival of *B. subtilis* spores in milk were in close agreement with the calculated values.

Since higher bacterial destruction, better flavor, and higher nutritional quality were reported in products that were processed by HTST methods, investigations were directed toward further improvement of this process. Ball (1943) developed procedures for calculating the lethality of HTST plate-type pasteurizers and emphasized that the coming-up and cooling periods have been overlooked in prescribing standards. He further showed that the coming-up and cooling periods could be designed to achieve complete lethality and stated that they should be included in calculating the lethality of any process.

Read *et al.* (1956a) developed a straight-tube laboratory size high temperature heat exchange unit for milk pasteurization. The heating section consisted of five feet of 0.11 in. ID stainless steel tubing that was heated by electrical resistance. Milk was pre-heated to 135°F, heated in the heating section to a specific temperature, and then rapidly cooled by passing it over pre-cooled glass marbles or by inoculating it into a cold fluid. Air pressure was used to obtain velocities of 10 to 20 ft per sec. Although highly turbulent flow conditions were reported, as calculated by Reynolds number (Re), these flow indexes were not given. In this heat exchanger, Read *et al.* (1956b) heated milk that was inoculated with *Micrococcus* species, MS 102, and found 99.9 percent destruction at mean temperatures of 191.9 and 190.6°F for come-up times of 0.25 and 0.5 sec, respectively. The holding time for each process was 0.05 sec. An essentially linear relationship was observed between heating distance and temperature in the heating tube.

Later, Read *et al.* (1957) reported complete destruction of *E. coli*, suspended in autoclaved milk, at mean temperatures of 174.5°F and 172.3°F with come-up times of 0.25 and 0.50 sec, respectively. In raw milk complete destruction of *E. coli* took place at a mean temperature of 171.7°F with a come-up time of 0.50 sec and complete destruction of *Salmonella typhosa*, *Shigella paradysnteriae*, *Streptococcus pyogenes*, *Corynebacterium diptheriae* and *Escherichia coli* occurred at a mean temperature of 175.6°F with come-up time at 0.25 sec. Destruction of *E. coli* at 175.6°F and 171.7°F by the 0.25 and 0.50 sec come-up times was significantly different. Based on pasteurization at 143°F for 30 min and an assumed Z value of 9°F, they plotted a TDT curve for calculating lethality. A temperature of 181.5°F with a 0.50 sec come-up time and 0.05 sec holding time was comparable to heating in a non-flow system at 143°F for 30 min.

Tobias *et al.* (1955) introduced a method of measuring the bactericidal efficiency of UHT treatments in a Roswell, coiled-tube heat exchanger. The logarithm of survival in ice-cream mix inoculated with *Micrococcus* species MS 102 was linear with increases in UHT treatments from 180°F to 192°F with a holding time of 0.2 sec. The possible interferences from the natural flora of the ice-cream mixes were not taken into consideration and it was assumed that the heat treatment temperature of the product was maintained in the heating and cooling portions for 0.50 and 0.1 sec, respectively. This gave a total estimated holding time of 0.8 sec which was used to calculate a Z value of 9.8°F. It was concluded that a heat treatment of 194°F for 0.8 sec or 186°F for 3.8 sec gave the same lethality in terms of *Mycobacterium tuberculosis* as 175°F for 25 sec. Herreid and Tobias (1959) later recognized that the experiments could be better controlled in a laboratory size heat exchanger.

Brown *et al.* (1951) developed a combined direct steam injection heater and evaporator for processing fluid foods. Raw milk that had a total plate count of 2.5×10^4 per ml and a positive coliform test was processed at 185°F for 0.4 sec. At a 1:100 dilution no surviving organisms were indicated by the total plate count, and the coliform test was negative. They also sterilized orange juice by processing at 167°F for 1.8 sec and at 193°F for 0.8 sec.

Hedrick (1959) used a plate type heat exchanger along with direct steam injection and studied bacterial destruction in raw milk by heat treatments of 165°F through 300°F with a holding time of 43.8 sec. He found no advantages in processing raw milk above 260°F by this method. Using a plate type heat exchanger and a Vacu-therm, Glazier (1963) observed that UHT processing of raw milk at 193.5°F for one sec did not produce objectionable "cooked" flavors. The UHT milk had the same keeping quality at 36°F as milk pasteurized at 172°F for 16 sec.

Evans *et al.* (1963) processed raw milk in increments of 10°F between 160°F and 260°F in a plate-type UHT heat exchanger. Milk processed by UHT treatments of 220°F to 260°F for 0.6 sec had better bacteriological keeping quality than milk pasteurized by the conventional method of 161°F for 16 sec. Evans and Litsky (1968) reported that a temperature of 170°F for 0.6 sec was required for complete destruction of *E. coli* in milk. Evans *et al.* (1970), using the same plate-type system, investigated the heat resistance of some pathogenic microorganisms. D values were determined for each organism and were used to calculate theoretical lethality by the procedures of Stumbo (1965). An arbitrary standard of 15 times D was used as the equivalent to one unit of lethality. The temperature distribution in the heating, holding, and cooling sections was measured with thermocouples, but only the temperatures above 140°F were used for lethality calculations. Although the time required to heat to 180°F contributed more than one unit of lethality, processing at 180°F for 0.6 sec was recommended for pasteurization of milk. The lethality from the holding and cooling periods was considered an additional safety factor.

Burton (1969) reviewed UHT processing of milk and noted that definitions of these processes were not the same in Europe as in the United States and Canada. In Europe heat treatments between 266°F and 302°F with a holding time of at least one sec generally refer to UHT processing, but in the United States and Canada heat treatments higher than conventional pasteurization temperatures usually refer to UHT processing. The present trend in the United States, however, is toward adoption of the European definition. Since UHT processing in Europe has been widely adopted, very little work on HTST processing has been reported there.

Read *et al.* (1968) reported that the United States Public Health Service had received requests from the industry for minimum standards for UHT pasteurization of milk products. Based on the time-temperature relationship for HTST pasteurization of ice-cream mix at 155°F for 30 min or 175°F for 25 sec, extrapolations were made to predict equivalent time temperature requirements for UHT pasteurization. The following combinations were derived for plate-type systems:

191°F for 1.00 sec

194°F for 0.50 sec

201°F for 0.10 sec

204°F for 0.05 sec

212°F for 0.01 sec

Lindamood and Harper (1969) reported that the above standards were approved in the state of Ohio. Assuming laminar flow, they presented an equation for calculating the holding tube length for plate type pasteurizers of various capacities. The equation is as follows:

$$L = \frac{588\ Q\ t}{D^2}$$

where: L = Holding tube length (in.)

Q = Pumping rate (gal/sec)

t = Holding time standard (sec)

D = Inside diameter of the holding tube (in.)

It was also pointed out that the holding time standards have a built-in margin of safety that is about 65 times the minimum requirements. Since the flow conditions were assumed to be laminar, these new UHT pasteurization requirements would not apply to turbulent flow conditions or to processing of heat sensitive foods.

Farrall (1963) recommended turbulent flow conditions to minimize burn-on and heat damage of heat sensitive products. Burton (1969) pointed out that either natural or induced turbulence in a flow system would increase the rate of heat transfer. Hall and Trout (1968) reported higher heat transfer coefficients in turbulent flow systems than laminar flow systems. The advantages of high-pressure heat transfer systems were recognized by Mallory (1942), Roswell (1957), and Carlson (1963). There is no reported work, however, on thermal inactivation of microorganisms in well defined helically coiled tube, high pressure turbulent flow heat transfer systems.

Webb (1964) discussed applications of turbulent flow conditions to the processing of fluid foods and defined turbulent flow as the condition where the main bulk of the fluid food is sufficiently mixed so that it has uniform temperature distribution and physical characteristics. He also presented calculations for standardizing these processes. For pipes completely filled with liquids, this condition was defined by the Re number, a flow index which was calculated as follows:

$$Re = \frac{D\ V\rho}{\eta}$$

where: Re = Reynolds number

D = Diameter of the tube (ft or cm)

V = Velocity (ft/sec or cm/sec)

ρ = Density (lb/ft^3 or g/cc)

η = Dynamic viscosity (lb/sec ft or gm/cm sec)

Note: One centipoise = 6.72×10^{-4} (lb/sec ft)

The value of the Reynolds number at which the flow changes from laminar to turbulent is called the critical Re. For straight circular pipes, Webb (1964) noted that the Re should be greater than 2100, to obtain fully turbulent flow conditions and if this value was below 1500, the flow would be viscous or laminar. Ito (1959) found that the diameter of the tube and coil diameter in helically coiled tubes were essential in computing the critical Re. He reported that:

$$\text{Critical Re} = 2 \times 10^4 \ (D/D_H)^{0.32}$$

where: D = Diameter of the tube

D_H = Coil diameter

In order to be assured of turbulent flow conditions in such helically coiled tubes, the computed Re should be significantly larger than the critical Re values.

As shown in the Re formula, Re is inversely proportional to the viscosity coefficient. This coefficient depends on the physical properties, chemical composition, and temperature of the liquid and is defined by Kramer and Twigg (1962), Daniels and Alberty (1967), and Barrow (1966), as the resistance that a liquid offers to an applied shearing force. All these authors presented procedures for determining the viscosity coefficient of liquids.

Kramer and Twigg (1962) recommended the term viscosity for Newtonian liquids and consistency for non-Newtonian liquids. Differences between these liquids were explained on the basis that the viscosity of Newtonian liquids remains constant with changes in shearing rate and that a linear relationship exists between the rate of shear and shearing forces. Conversely, the viscosity of non-Newtonian liquids changes with changes in shearing rate and a non-linear relationship exists between rate of shear and shearing forces.

Webb and Johnson (1965) reported that skim milk and whole milk do not appreciably deviate from Newtonian behavior and that cream and concentrated milks have varying degrees of non-Newtonian behavior. The Newtonian behavior of skim milk and whole milk may be attributed to their low levels of solids in suspension. They noted that the three types of viscometers that have been used to measure viscosity of fluid dairy products are: the coaxial cylinders (e.g., Brookfield, Couette, and MacMichael), the falling spheres (e.g., Hoeppler) and the capillary tubes (e.g., Ostwald).

McKennell (1960) discussed the limitations of falling sphere and capillary tube type viscometers for measuring the viscosity of non-Newtonian fluids, and pointed out that large correction factors were required. Hence, coaxial cylinder type viscometers were recommended for measuring the viscosity of non-Newtonian fluids. Dinsdale and Moore (1962) listed the advantages of using coaxial cylinder viscometers for studying the flow properties of non-Newtonian fluids and noted that these viscometers were often less accurate than the other types for Newtonian fluids. The Brookfield and MacMichael viscometers are designed to measure viscosity of both Newtonian and non-Newtonian fluids at different temperatures (Brookfield Engineering Brochure, 1964, and Fisher Scientific Manual, 1970). The MacMichael viscometer has a built-in temperature control that permits consecutive viscosity measurements on the same sample at different temperatures.

There are no published data on the effect of temperatures on viscosity of concentrated skim milk products. Whitaker *et al.* (1927)

determined the viscosity of skim milk with an Ostwald Viscometer in the temperature range of 41°F to 141°F and observed lower viscosity values at higher temperatures. Eilers *et al.* (1947), using a U-Tube viscometer, found that the viscosity of skim milk decreased with temperature between 41°F and 176°F and that the casein fraction contributed to these decreases more than any other fraction. They also measured the viscosity of concentrated skim milk products at 78°F and found a curvilinear relationship between increases in total solids and viscosity.

The density of fluid foods generally decreases with increases in temperature above 39.2°F and thereby affects the flow properties of these products. Specific gravity or relative density has long been used for estimating the comparison of fluid milks. If specific gravity of a liquid is known, the density can then be easily calculated. Procedures for measuring specific gravity with lactometers and the Westphal balance were published in detail by the Milk Industry Foundation (1949). Specific gravity was measured by lactometers in the range of 50°F to 70°F and corrected to 60°F. Measurements were made by the Westphal balance at 60°F with no provisions for making determinations at higher temperatures.

The Baumé hydrometer was widely used for composition control in commercial processing of evaporated and sweetened condensed milks (Hunziker, 1949). Baumé readings, made at temperatures up to 130°F, were converted to the Baumé value at 60°F by a formula. From this value the estimated specific gravity at 60°F was obtained from a table.

Shortley and Williams (1960) and Schaum (1968) described procedures for determining densities of liquids at any desired temperature. Their calculations were based on evaluating the cubical expansion coefficient of liquids (β) as follows:

$$\beta = \frac{\Delta V + 3\alpha V_1 \Delta T}{V_1 \Delta T}$$

where: β = Cubical expansion coefficient of liquid

ΔV = Loss in volume due to expansion

V_1 = Original volume of liquid

α = Linear expansion of container

ΔT = Difference in temperature

If β and density at one temperature were known, the density at any desired temperature was calculated as follows:

$$\rho_x = \frac{\rho_r}{1 + \beta \Delta T}$$

where: ρ_x = Density at temperature x

ρ_r = Density at temperature r

β = Coefficient of cubical expansion of liquid

ΔT = Difference in temperature, i.e., (x-r)

The flow velocity of fluid foods affects both heat transfer and rate of bacterial destruction in continuous flow systems. Hall and Trout (1968) noted that the Re value was increased by increasing the velocity of flow in a given tube or by decreasing the diameter of the tube for a particular flow rate, thus increasing the velocity. Evans *et al.* (1970) found that lethality values were decreased when the mass flow rate in a plate-type exchanger was increased and emphasized the importance of specifying flow rates when evaluating flow-type processing systems.

Charm (1963) presented procedures for calculating the lethality for turbulent flow in a tubular heat exchanger. Temperature distribution and velocity were calculated and used to establish the time-temperature distribution. Using the principles of Ball and Olson (1957) to compute lethality, he calculated the thermal requirements of the process.

Sugar, fat, and other food solids in fluid products protect microorganisms against destruction by heat (Hersom and Hulland, 1964). There are no reported data, however, on the effect of concentration of various food solids on the thermal destruction of bacteria in high pressure turbulent flow heat transfer systems. Much of the reported work on processes with short holding times is on fluid milk (Glazier, 1963; and Brown *et al.*, 1951). Even in these cases the holding times represented the entire heat treatment without accounting for the heat-up and cool-down times.

Also, recent outbreaks of salmonellosis from dried milk have threatened the entire dry milk industry and resulted in enforcement of strict sanitation procedures (United States Department of Health, Education and Welfare, 1971). Adoption of the procedures in the proposed Grade "A" pasteurized, condensed dry milk products sanitation ordinance was urged for manufacture of dried milk products. In addition, re-pasteurization of the concentrated products just prior to drying was suggested (United States Department of Health, Education and Welfare, 1966). An in-line continuous flow indirect heat exchanger, that will not cause heat damage, is needed to meet this requirement.

MATERIALS AND METHODS

I. Materials

A. Heating Menstruums

Flow properties, thermal characteristics, and thermal inactivation of *Escherichia coli* ATCC strain No. 9723 were determined in various menstruums that varied from 1.4% to 40% solids.

Bigger and Nelson (1941) found that distilled water was frequently bactericidal for *E. coli*; moreover, Starka and Stokes (1957) reported that distilled water *per se* was lethal to bacterial populations, although these authors did not work specifically with *E. coli*. Distilled water was therefore not considered to be a satisfactory menstruum for *E. coli* in the present investigation. Minimal broth (Davis *et al.*, 1968) was selected as a satisfactory test menstruum, because it supported growth of the test organism and had flow properties comparable to water. This medium contains 1.36% solids, and is prepared with ACS certified chemicals. Its composition is:

K_2HPO_4	0.70%
KH_2PO_4	0.30%
$Na_3Citrate \cdot 2H_2O$	0.05%
$MgSO_4 \cdot 7H_2O$	0.01%
$(NH_4)_2SO_4$	0.10%
Glucose	0.20%
Distilled water	98.64%
Total	100.00%

Menstruums containing 10%, 20%, 30%, and 40% solids were prepared by rehydrating low-heat Grade "A" nonfat dry milk (NDM), as defined by the United States Department of Health, Education, and Welfare (1966). After mixing thoroughly, the percentage of total solids was determined by the Mojonnier method (Milk Industry Foundation, 1949). Prior to use, each menstruum was heated at 160°F for thirty min to destroy any test organism species that might have been present but not to impair the physical properties of the menstruum. Bacteriological analyses were made to determine whether any test organisms survived.

B. Bacterial Suspensions

The test organism, *E. coli* ATCC strain No. 9723, was cultured in trypticase soy broth for 24 hr at 89.6°F. Ten ml of culture was transferred into 800 ml of the broth, incubated for 24 hr, and centrifuged aseptically at 44.6°F for 10 min at 16,300 x g in a Sorvall-Superspeed RC 2-B automatic refrigerated centrifuge (Ivan Sorvall Co.). The supernatant was discarded and the pellet resuspended in 0.85% sterile saline solution and centrifuged again. The saline supernatant was discarded and the pellet resuspended in sterile saline solution. Turbidity of the suspension was measured using a Bausch and Lomb "Spectronic 20" colorimeter with a one in. cuvette, at a wave-length of 450 nm; sterile saline solution was added to obtain a standard absorbance of 1.0. The standardized *E. coli* suspension contained from 1.25×10^8 to 1.50×10^8 viable cells per ml.

II. Equipment

Heat Exchange System

A laboratory, helically coiled tube heat exchange system was designed and assembled for this study. Commercially available parts were purchased and others were fabricated. The system provided accurate temperature control and permitted processing the menstruums over a wide range of flow characteristics under closely controlled conditions. The system consisted of the following major units:

(a) pumps and mixing vats;

(b) heat exchange sections, including special units for heating by steam or water; and

(c) recording instruments and temperature controller.

The heat exchange sections were assembled into a compact unit as shown in Fig. 1. A flow diagram illustrating the steps in each heat treatment process is shown in Fig. 2.

Pumps with adjustable flow rates ranging from 25 to 140 gal/hr were included in the system. A variable speed drive, positive displacement sanitary pump (Fig. 3 G) that had a maximum rated capacity of 70 gal/hr was used to pump the menstruums containing 1.4 to 10% solids. The inoculated menstruum was placed in one of the five-gallon vats (Fig. 3 A) and the uninoculated menstruum was placed in the other vat (Fig. 3 B). These vats were joined with a 1/4 in. ID stainless steel pipe. Valves were fitted in this pipe so that flow could be directed from either vat into the heat exchange system. A reduced pressure of 15 in. of Hg was maintained in each vat by a

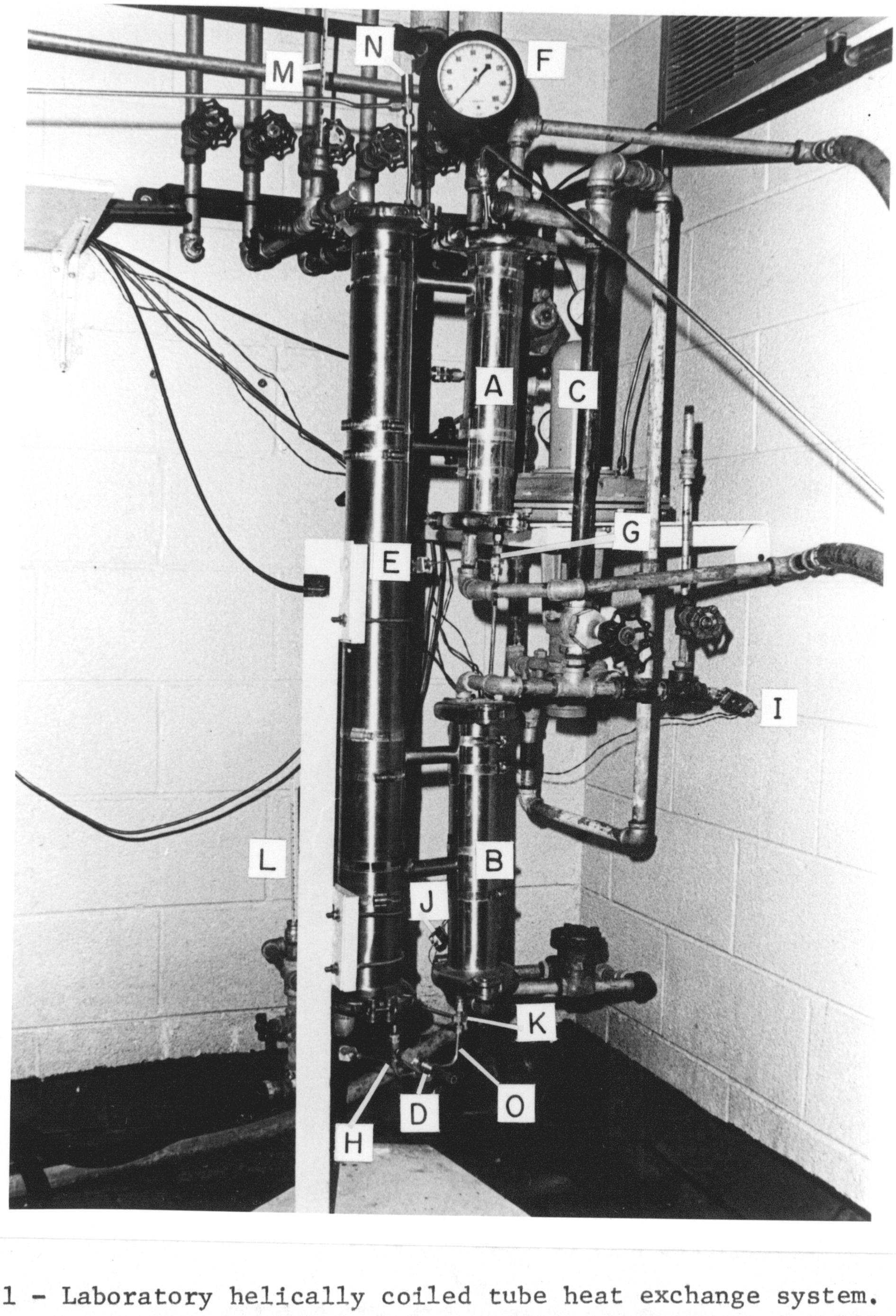
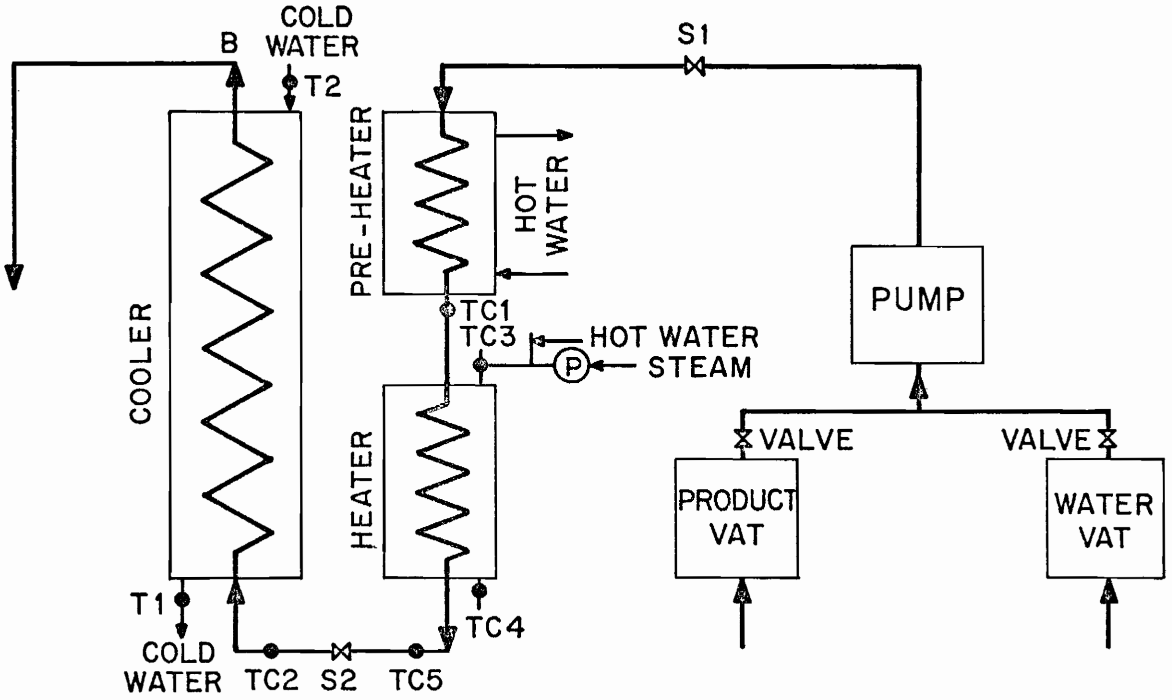


Fig. 1 - Laboratory helically coiled tube heat exchange system. A, preheater; B, heater; C, pneumatic valve; D, sampling valve No. 2; E, cooler; F, product pressure gauge; G, H, I, J, and K, thermocouples TC1, TC2, TC3, TC4, and TC5; L and M, thermometers T1 and T2, N, back pressure valve; O, holding tube.



TC1, TC2, TC3, TC4, TC5: Copper-Constantan Thermocouples

T1, T2: Thermometers

S1, S2: Sampling Valves

B: Back Pressure Valve

P: Pneumatic Valve

Fig. 2-Schematic flow diagram of helically coiled tube heat exchange system

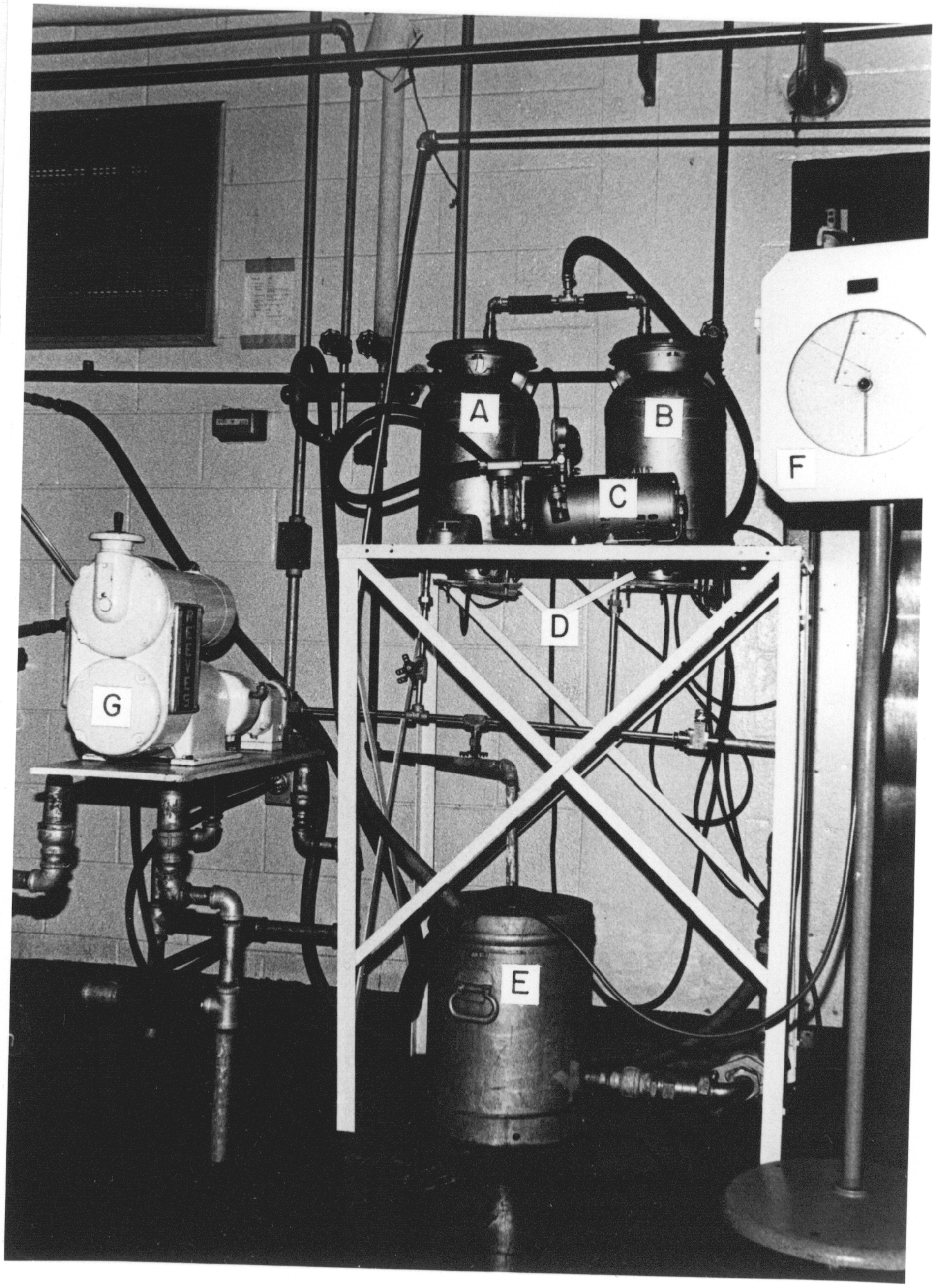


Fig. 3 - Hot water reservoir, mixing vats and sanitary pump for low-solids menstruums. A and B, mixing vats; C, vacuum pump; D, magnetic stirrers; E, hot water reservoir; F, temperature recorder; G, variable speed drive pump.

vacuum pump (Fig. 3 C) to keep foaming at a minimum. The inoculated menstruum was stirred continuously by a magnetic stirrer (Fig. 3 D) located at the bottom of the vat to maintain an even distribution of the microbial population.

Larger amounts of the menstruums containing 20%, 30%, and 40% solids were required to maintain turbulent flow conditions. Moreover, in case of high flow rates, large amounts of the menstruums containing 1.4% and 10% solids were also needed. Hence the two five-gallon vats were replaced by two fifty-gallon vats. One was used to hold the inoculated menstruum (Fig. 4 B) and the other to hold the water (Fig. 4 C) for prestandardizing the heat treatment procedures. A mechanical stirrer (Fig. 4 D) and an air-space heater for suppressing foaming were installed in the vat holding the inoculated menstruums. The variable speed drive pump was replaced by a high-pressure piston pump (Fig. 4 A) with a rated maximum capacity of 200 gal/hr. Sampling valve No. 1 (Fig. 4 E) was installed in the line between the high pressure pump and the product pressure gauge.

Since rapid continuous flow through the entire heat exchange system was required, the pre-heating (Fig. 1 A), heating (Fig. 1 B), and cooling (Fig. 1 E) units were assembled compactly in this order. Both the pre-heating and heating units were made from 27.11 ft of 1/4-in. OD (0.18 in. ID) stainless steel tubing and consisted of 40 coils of 2.5 in. mean diameter. Each coil was fitted into an 18 in. x 3 in., 316 type stainless steel shell. Pre-heating was achieved in the range of 125°F to 135°F by recirculating thermostatically controlled hot

Fig. 4 - High pressure pump and mixing vats for high-solids products. A, high pressure pump; B, product vat; C, water vat; D, mechanical stirrer; E, sampling valve No. 1.

water (Fig. 3 E) through the shell. The flow of hot water was countercurrent to the flow of the menstruum. The pre-heated menstruums were heated in the unit by either steam or hot water under pressure that flowed parallel with the flow of the menstruum.

Two thermocouples, TC2 (Fig. 1 H) and TC5 (Fig. 1 K), and sampling valve No. 2 (Fig. 1 D) were installed in the holding tube (Fig. 1 O) that joined the heating and cooling sections. The length of this tube was one ft and the flow time from the heating to the cooling section varied from 0.25 sec to 0.05 sec depending on the velocity.

The heat-treated menstruums were rapidly cooled in the cooling section by refrigerated water at 36°F, circulating counter-current to the flow of the menstruum. The cooling shell contained 46 coils of 0.18 in. ID stainless steel tubing. The mean diameter of the coil was three in. and a solid metal core was tightly fitted inside the coils to minimize vibrations. The length of the tubing in the shell was 38 ft, as calculated by measuring the internal volume of the coiled tube.

The outlet temperature of the heat treated menstruums depended on the flow rate and ranged from 40°F to 80°F. The temperature of the circulating cold water was measured at the inlet and outlet of the cooling section by thermometers T2 (Fig. 1 M) and T1 (Fig. 1 L). A back pressure valve (Fig. 1 N) was installed at the outlet of cooler to prevent vaporization. Samples were taken at this outlet, immediately immersed in ice water, and stored at 38°F. The temperatures measured by copper-constantan in-line thermocouples were recorded by a multiple-point recorder (Fig. 5 A). The inlet temperature and the outlet temperature of the heating medium, either hot water or steam, were measured by thermocouples TC3 (Fig. 1 I) and TC4 (Fig. 1 J). The pre-heat temperature was measured by a thermocouple, TC1 (Fig. 1 G), and the heat treatment temperature was measured by another thermocouple, TC2 (Fig. 1 H).

The heat treatment temperature was controlled by a Solid State Electromax Signaling Controller (Leeds and Northrup, 1968) when steam was used (Fig. 5 B). The impulse to the controller was a voltage signal from the thermocouple, TC5 (Fig. 1 K). This signal regulated the input of steam by means of a pneumatic valve (Fig. 1 C). For each test the desired temperature was set on the Electromax and deviations from the set point were shown. Deviations were also measured by a Taylor recorder (Fig. 5 C).

III. Procedures

A. Calculation of Flow Properties of Menstruums

The velocity, density, viscosity and Re values were calculated for each set of processing conditions. Velocity was calculated by the following formula (Charm, 1963):

$$V = \frac{Q}{900\Pi D^2}$$

Where: V = Velocity (ft/sec)

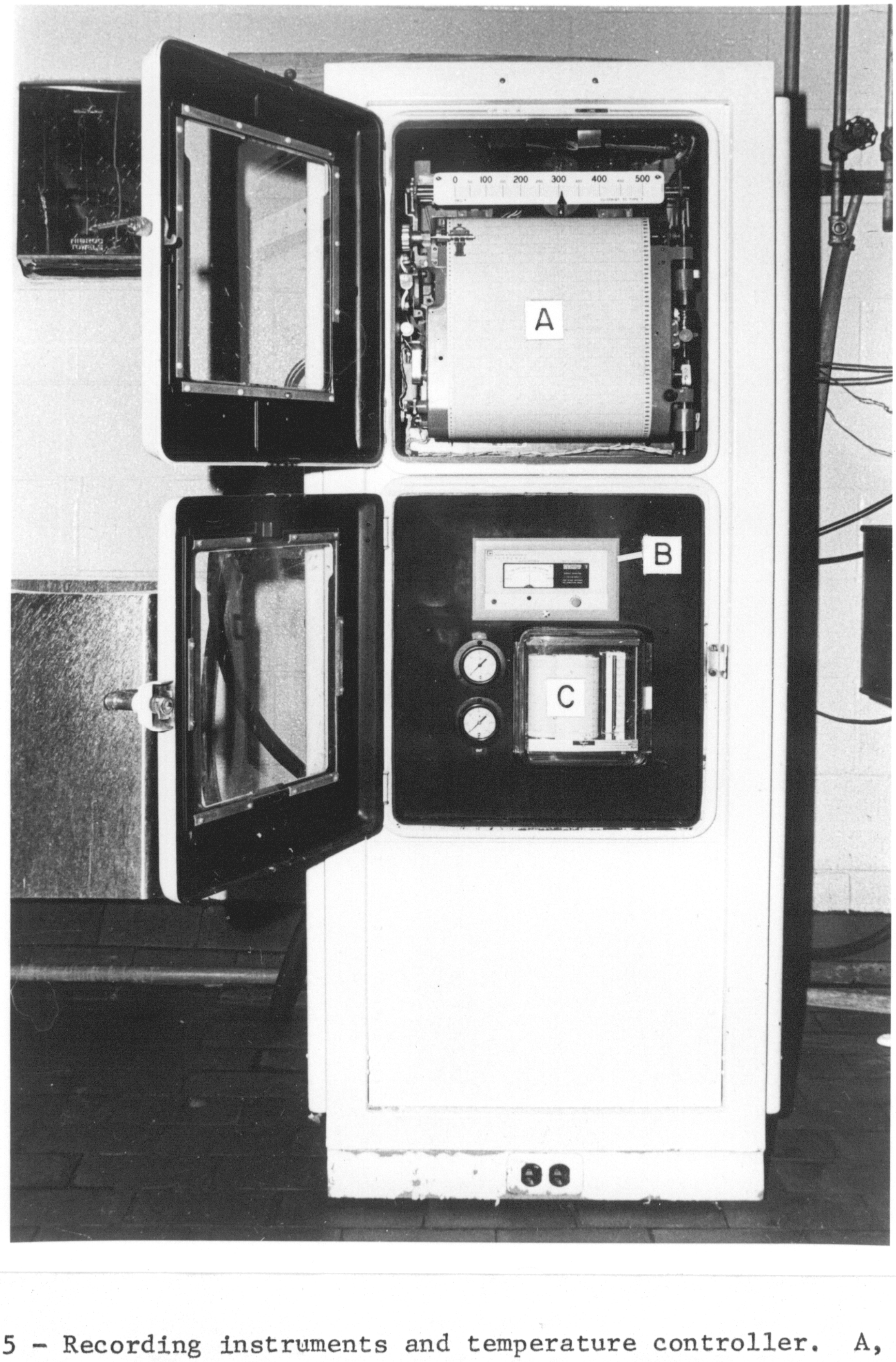


Fig. 5 - Recording instruments and temperature controller. A, multiple-point recorder; B, solid state Electromax signaling controller; C, Taylor recorder.

Q = Flow rate (gal/hr)

D = Internal diameter (ft)

Densities of the menstruums were determined at 69.8°F ± 1.8°F in 50 ml or 100 ml pycnometers. Then the pycnometers containing the menstruums were placed in a thermostatically controlled water bath and held at 149°F until no further expansion was observed. The pycnometers were removed from the water bath, allowed to cool to 69.8°F ± 1.8°F, and loss of weight due to cubical expansion was calculated.

After taking into consideration the cubical expansion of the pycnometer, the cubical expansion coefficients of the test menstruums were determined. From these values, densities at the heat treatment temperatures were calculated (Shortley and Williams, 1960; Schaum, 1968). All tests were run in duplicate and mean values were used in calculating results.

Viscosity of the test menstruums was determined between 68°F and 158°F with an improved MacMichael viscometer (Fisher Scientific Manual, 1970). Using glycerine or sucrose solutions of known viscosity, the constant K for each wire was calculated as follows:

$$K = \frac{\eta HN}{M}$$

where: K = Constant

η = Viscosity in centipoises

H = Depth of immersion of the plunger

N = Number of revolutions per min

M = Dial deflection in degrees MacMichael.

Viscosity in centipoises of the test menstruums was then calculated by the formula:

$$\eta = KM/HN$$

where M, H, and N were measured separately for each test menstruum.

B. Heat Treatment Procedures

The test menstruum was placed in the product vat and inoculated with 2% (v/v) standard bacterial suspension. Specific heat treatments were used to determine the inactivation temperature and establish the order of destruction. Each run consisted of two series of heat treatments. The first series was in increments of 10°F and determined the temperature for complete destruction. The second series of heat treatments were run in decrements of about 5°F between the complete destruction temperature and the pre-heat temperature.

One phase of the study included a set of tests made at a constant Re value and varying velocities. The other phase included tests made at a constant velocity and varying Re values. Flow conditions were first standardized for each heat treatment either with water or with uninoculated menstruum. The inoculated menstruum was introduced into the system and allowed to flow for two min to adjust to the predetermined heat treatment conditions.

C. Temperature Distribution in the Coils

The inlet and the outlet temperatures of the heating medium, hot water or steam, and of the inoculated menstruum were measured with thermocouples (Fig. 1). From these data, the temperature distribution of the menstruum in the heating coil was calculated with an IBM 360 Computer by the equation given by Thomas (1970) and confirmed by Aldrich (1971). The equation is:

$$\mathrm{Tm}_X = \frac{(\mathrm{Th}_1\ \mathrm{Tm}_2 - \mathrm{Tm}_1\ \mathrm{Th}_2 - (\mathrm{Tm}_2-\mathrm{Tm}_1)(\mathrm{Th}_1-\mathrm{Tm}_1)(\frac{\mathrm{Th}_2-\mathrm{Tm}_2}{\mathrm{Th}_1-\mathrm{Tm}_1})^{X/L})}{(\mathrm{Th}_1 - \mathrm{Tm}_1 - (\mathrm{Th}_2 - \mathrm{Tm}_2))}$$

where: Th_1 = Inlet temperature of the heating medium

Th_2 = Outlet temperature of the heating medium

Tm_1 = Inlet temperature of the menstruum

Tm_2 = Outlet temperature of the menstruum

Tm_X = Temperature of menstruum at distance X

X = Distance from the inlet

L = Total length of tubing in heating coil.

The above equation also was used to calculate the temperature distribution in the cooling section. The outlet temperature Tm_2 of the menstruum from the heating section will become Tm_1 in the cooling section. The outlet temperatures of the menstruums at the cooling section and inlet and outlet temperatures of cold water were measured and used in the above equation.

D. Lethalities of Heat Treatments

Heating and cooling curves were used to calculate lethalities. Based on the distance-temperature (Tm_X) relationship in the above formula, the temperature-time (X/V, where V = velocity) relationships were established. From these relationships and using the Z value of Olson *et al.* (1952) for *E. coli*, the lethality values for the heating-holding-cooling process were calculated by the procedures of Ball and Olson (1957), as applied by Charm (1963) to straight tube turbulent flow systems.

E. Survival Curves

Samples were taken from the inoculated vat and from the outlet of the cooling section after each specific heat treatment. All samples were held at 38°F for no longer than two hr. Using desoxycholate agar, all viable counts were run in triplicate by the procedures of the American Public Health Association (1967). Desoxycholate agar was used to distinguish the test organism from other types of bacteria, such as spore formers, that may have survived the initial pasteurization treatment of the menstruum. From the average of these counts, per cent survival was calculated and plotted against the heat treatment temperatures.

F. Statistical Analysis of the Data

The regression and correlation coefficients were calculated by the procedures of Steel and Torie (1960) and prediction equations were derived to estimate percentage survival of the test organism at different processing temperatures. IBM system 360 computers were used for these calculations. The slopes of the regression lines were used as indexes to bactericidal efficiency.

G. Sterilizing Effect

Based on the initial count and on the viable survival count of each heat treatment, the Sterilizing Effect was calculated by the procedures of Galesloot (1956).

RESULTS AND DISCUSSION

Flow Properties

To resolve the objectives of this study, it was necessary to determine the flow properties of the menstruums over a wide range of flow rates. These flow properties were governed essentially by the Reynolds number (Re).

The critical Re value is an important parameter. It determines the point of transition from laminar to turbulent flow. There was no published information on the critical Re value for processing fluid foods in helically coiled tube systems. A value greater than 2,100 as recommended by Webb (1964) for straight tube systems has been generally used by processors. As explained by Ito (1959), however, the critical Re value should be calculated for each helically coiled tube system. The critical Re for this helically coiled tube heat transfer system (Fig. 1) was 8,617, as calculated by Ito's (1959) formula:

$$\text{Critical Re} = 2 \times 10^4 \, (D/D_H)^{0.32}$$

The inside diameter (ID) of the product tube, D, was 0.18 in. and the mean diameter, D_H, of the coils was 2.5 in. The ratio of D to D_H determines the magnitude of the critical Re value and shows the necessity for calculating this value for each helically coiled tube system.

To attain turbulent flow conditions during heat treatment of each menstruum, the Re value must be higher than the critical value.

Therefore, it was necessary to determine the Re value for each menstruum during each heat treatment.

The variables affecting the Re values were tube ID, density, velocity, and viscosity. The product tubes had an ID of 0.18 in. The density and the cubical expansion coefficient for each menstruum are presented in Table 1. The density of the test menstruum increased as percentage of NDM solids increased.

There are no published data on density of concentrated milks prepared from NDM solids. In connection with measuring the required density values at different temperatures, a procedure was developed by using the cubical expansion coefficient method for calculating the density of concentrated milks at any desired temperature.

The densities of the 10% and 30% NDM menstruums were adjusted to 71.6°F by the cubical expansion procedure. The relationship between density at 71.6°F and the percentage of NDM solids was found to be linear as shown in Fig. 6. The equation for the straight line is as follows:

$$y = 0.0043\,x + 0.9978\ \text{(g/cc)}$$

or

$$y = 0.2703\,x + 62.24\ (\text{lb/ft}^3)$$

These formulas have industrial applications in connection with concentrating and drying of skim milk and in UHT treatment of concentrated NDM products.

The cubical expansion coefficient method permitted calculation of density in the UHT range. For concentrated products containing 10%, 20%, and 30% NDM solids, the density at room temperature was 6.4%, 6.4%, and 6.0% higher, respectively, than at 320°F.

Density at the heat treatment temperature for the test menstruums is shown in Tables 3 and 4. The heat treatment temperature was measured at the inlet of the cooler by the thermocouple, TC2, Fig. 1.

The density values in Table 1, as compared to those in Tables 3 and 4, show that the density of the menstruums was influenced more by composition than by difference in temperature. Hence, the Re values were not affected as much by changes in temperature as by changes in composition of menstruums.

The Re value is inversely proportional to the viscosity coefficient and hence viscosity is an important factor in establishing flow conditions. Viscosity affects flow conditions both through changes in concentration and temperature. The viscosity measurements at different temperatures are presented in Table 2. At 80.6°F, the viscosity values of the menstruums containing 10%, 20%, 30%, and 40% NDM were higher, respectively, than the viscosity of water at the same temperature by factors of 1.4, 5.9, 10.8, and 21.1.

A nonlinear relationship was observed between viscosity and percentage concentration of rehydrated NDM solids. Eilers *et al.* (1947) reported a similar nonlinear relationship at 79°F between viscosity and percentage concentration of nonfat milk solids in the range of 10% to 30%.

There was no published information on the effect of temperature on viscosity of the menstruums. As shown in Table 2, the viscosity values of minimal broth, 10% NDM, 20% NDM, 30% NDM, and 40% NDM were decreased 6.3%, 10.2%, 17.3%, 11.8%, and 5.6%, respectively, by increasing the temperature from 80.6°F to 86.0°F. The decreases in viscosity due to heating were nonlinear. This was expected due to the non-Newtonian properties of the menstruums. Whitaker *et al.* (1927) and Eilers *et al.* (1947) also observed that heating skim milk and whey resulted in nonlinear decreases in viscosity.

In the helically coiled tube heat transfer system (Fig. 1), the temperature increases progressively, as shown in Fig. 12. Accordingly, the viscosity values would decrease. The viscosity values were calculated at the arithmetic mean of the entrance and exit temperatures as recommended by Charm (1963) and are presented in Table 2. These values were used to calculate the Re values.

The turbulent flow conditions for the test menstruums that were processed with nearly constant Re values are shown in Table 3. These Re values ranged from 11,407 to 15,492. To attain these values during processing of the high-solid menstruums, it was necessary to increase the velocity. The velocity varied from 5.2 ft/sec for the 10% NDM to 27.0 ft/sec for the 30% NDM. Although the velocity of the 40% NDM menstruum was 29.6 ft/sec, the Re value was only 3,908 and the flow conditions were not turbulent.

The heat treatment temperatures necessary to obtain complete destruction of *E. coli* under the flow conditions listed in Table 3 were: 150°F, for minimal broth; 160°F, for the 10% NDM; 170°F, for the 20% NDM; 180°F, for the 30% NDM; and 190°F, for the 40% NDM. As defined earlier, each total heat treatment was represented by the temperature of the respective menstruum at the inlet of the cooler.

The thermal inactivation temperatures varied from 150°F to 190°F when the Re values were nearly constant and were directly related to percentage solids (Table 3). As viscosity increased the Re values decreased, and to obtain the same Re value for each menstruum it was necessary to increase the velocity.

Increasing velocity reduced processing time (Figs. 12, 13). The velocity and processing times were: for minimal broth, 5.5 ft/sec and 13.12 sec; for 10% NDM, 5.2 ft/sec and 13.79 sec; for 20% NDM, 10.1 ft/sec and 6.98 sec; for 30% NDM, 27.0 ft/sec and 2.63 sec; and for 40% NDM, 29.6 ft/sec and 2.38 sec. The higher temperatures for inactivation of *E. coli* were attributed to the protective effect of the solids and to the shorter processing times.

The turbulent flow conditions for the test menstruums that were processed at a constant velocity and varying Re values are shown in Table 4. The menstruums in Table 4 were processed at a velocity of 27 ft/sec and the processing time was 2.38 sec. The Re values varied from 14,579 for the 30% menstruum to 88,638 for the minimal broth. *E. coli* was inactivated at 174°F, 176°F, 178°F, and 180°F, respectively, for minimal broth, 10%, 20%, and 30% NDM. These increases in thermal inactivation temperatures were attributed to the differences in solids content of the menstruums and were statistically significant at the 10% level of probability ($P < 0.1$).

The higher thermal inactivation temperatures of *E. coli* in minimal broth, 10% NDM, and 20% NDM in Table 4 as compared to Table 3 were explained by differences in velocity at each heat treament. Tobias *et al.* (1955) also noted that temperatures of 181.3°F and 187°F were required for complete destruction of *Micrococcus* sp. MS 102 in ice cream mix with effective holding times of 3.8 sec and 0.8 sec. Although velocity was not defined, it was assumed that it was taken into consideration in computing the holding times. Read *et al.* (1957) observed that the velocity had a direct influence on the thermal inactivation temperatures. They processed milk inoculated with *E. coli* at velocities of 10 ft/sec and 20 ft/sec and noted that mean temperatures of 172.3°F and 174.5°F were needed for complete destruction. Evans *et al.* (1970) predicted a higher rate of microbial destruction when the mass flow rates of milk were decreased. The relationship between mass flow rate and velocity may explain their prediction.

Process Lethality in Helically Coiled Tubes

Laboratory determination of Z and F values in nonflow systems is the basis for characterizing thermal destruction and calculating lethality. The thermal death time (TDT) of an organism is the time required for complete destruction at a given temperature under specific conditions. The plot of the log of TDT against temperature characterizes the heat resistance of the test organism under the conditions of its exposure. The symbol Z, the negative reciprocal of the slope of the TDT curve, is the degrees Fahrenheit necessary to reduce the time ten-fold. The time on this curve is represented by the symbol F at a specific temperature.

Lethality is the ratio of heating time at a constant temperature to the TDT for that temperature.

$$L = \frac{t_1}{t_2}$$

where: L = Lethality

t_1 = Time of heating at specific temperature

t_2 = TDT at the specific temperature

At the temperature at which sterility is achieved, one unit of lethality is obtained and t_1 becomes equal to t_2. Rate of lethality is as follows:

$$\text{Lethal rate} = \frac{1}{F \text{ antilog } (150-T)/Z}$$

where: F = Number of minutes required for complete destruction of the test organism at 150°F

T = Temperature of heating

Z = Negative reciprocal of the slope of the TDT curve

A computer program was written that simultaneously calculated temperature as a function of time, rate of lethality, and accumulated lethality (Appendix pages 102 to 107). These operations were carried out in 0.1 sec intervals. This approach is of considerable importance to industrial operations as it can be used to evaluate all helically coiled tube processes. In addition, the mathematical analysis provided a basis for comparing the turbulent flow processes with other processes.

A Z value of 11.4°F and an F_{150} value of 6.1 min that were determined in a nonflow system (Olson *et al.*, 1952) were used to calculate lethality in the 10% menstruum. Lethal rate and accumulated lethality values at flow velocities from 5.2 ft/sec to 29.6 ft/sec are presented in the Appendix (pages 108 to 131). The relationship between lethal rate and time is shown in Fig. 15 at a flow velocity of 5.2 ft/sec and in Fig. 16 at a flow velocity of 27.0 ft/sec in the 10% NDM menstruum. The unit lethal area is also defined in these figures.

Lethality is the integrated area under the lethal rate curve (Figs. 15, 16). At the temperature of complete destruction of *E. coli* in the 10% NDM menstruum the theoretical lethality is defined as one unit. The lethalities calculated from the experimental data, however, were 0.0385 and 0.1202 units, respectively, at flow velocities of 5.2 ft/sec and 27.0 ft/sec (Table 14). The calculated lethalities obtained in this study are comparable to those reported by Read *et al.* (1957) in a straight tube turbulent flow system. Read *et al.* (1957) offered no explanation for these low calculated lethality values.

When calculated lethality values were used to evaluate the helically coiled tube process, the bactericidal efficiency at a flow velocity of 5.2 ft/sec would have been 30 times greater than in a nonflow system at 150°F for 6.1 min. At a flow velocity of 27.0 ft/sec, the bactericidal efficiency would have been 10 times greater than in the nonflow system. This indicates that lethality, calculated from Z and F values that were determined in a nonflow system, cannot be directly used to evaluate helically coiled tube processes. These low calculated lethality values in relation to the nonflow system were attributed primarily to the high degree of mixing and rapid heating properties that are characteristics of turbulent flow.

The three stages of the turbulent flow process were evaluated by the percentage of lethality in each section in relationship to the determined lethality. Diagrammatic representations are shown in Figs. 15 and 16. The percentage of lethality was significantly lower in the holding period than in the heat-up time. At a flow velocity of 5.2 ft/sec, 86.49%, 10.13%, and 3.38% of the lethality occurred during the heat-up time, holding time, and cool-down time, respectively. At a flow velocity of 27.0 ft/sec,80.03%, 15.64%, and 4.33% occurred in the heat-up time, holding time, and the cool-down time. These figures show that the major portion of the lethality of the process occurred in the heat-up time.

There are no reports in the literature on the importance of lethality during cooling for evaluating rapid flow systems. Read *et al.* (1957) did not take into account the lethality of cooling in a straight tube turbulent flow system. The heat treated samples were collected directly in precooled medium. Burton *et al.* (1958) claimed that the lethality in the cool-down period was insignificant in plate type systems, but no calculations or measurements were presented to support this statement.

For a critical evaluation, it was found necessary to compute the lethality during cooling in the helically coiled tube heat transfer system.

The lethality calculated for the cooling section increased as the heat treatment temperature increased. For example, when 10% NDM menstruum was processed at a flow velocity of 27.0 ft/sec with heat treatment temperatures of 176°F and 180°F, the lethality for the cooling section increased from 0.0052 unit to 0.0102 unit (Appendix pages 127 and 131). This increase in lethality clearly demonstrates that the lethal effect of cooling must be taken into consideration when evaluating UHT turbulent flow processes, especially when high heat treatment temperatures are required.

The calculated lethality of these turbulent flow processes could be increased to one unit at the inactivation temperature by increasing the length of the holding tube. For example, at flow velocities of 5.2 ft/sec and 27.0 ft/sec (Figs. 15, 16), the holding tube length would need to be 243 ft and 46 ft, respectively.

In commercial UHT processing, the lethal effects of the heat-up and cool-down periods are not taken into account when prescribing equivalent heat treatments (Hsu, 1970). This procedure appears impracticable for turbulent flow processes because extreme overheating of the product would result. For example, at the inactivation temperature of 160°F and 176°F (Figs. 12, 13), if the lethal effects of heating and cooling were not considered, 252 ft and 54 ft, respectively, of holding tube would be required to obtain one unit of lethality. When processing at 27.0 ft/sec, the holding tube length would be equal to the combined length of the pre-heater and the heater, and would give a much higher heat treatment than required.

The information obtained in this study indicates that the recent UHT pasteurization standards promulgated by Read *et al.* (1968) would be too high if applied to this turbulent flow process. These standards were determined by extrapolating the pasteurization curve for ice cream mix. This curve was based on a minimum heat treatment of 175°F for 25 sec.

The low calculated lethality values that were obtained in the turbulent flow process were attributed to the use of Z and F values in the calculations that were determined in a nonflow system. If the Z and F values had been determined in the turbulent flow process, one unit of lethality would have been expected at the inactivation temperature.

The data on thermal inactivation in turbulent flowwere made more applicable to industrial processes by the work of Viles (1971). He developed procedures for calculating the thermal lethality in variable temperature flow systems by using a digital computer. He analyzed the data of Read *et al.* (1957) and calculated a Z value of 13°F and an F_{150} value of 6.5 sec for *E. coli* in a straight tube turbulent flow system.

The data for survival of *E. coli* in the 10% NDM menstruum (Tables 6 and 11) also were analyzed by Viles (1971). He obtained a Z value of ca. 19°F and F_{150} value of ca. 9 sec using equivalent holding times for the process. This unusually high Z value in the helically coiled tube system possibly was due to the flow characteristics and to the extreme sensitivity of calculating Z values from experimental data. A five percent error in viable count caused the Z values to vary from 14°F to 27°F. Similarly, an error of 1.5°F in measuring the holding temperature caused the Z values to vary from 11°F to 27°F. The Z values were sensitive to experimental accuracy primarily because Z is an exponential term in the calculations. The F value in the helically coiled tube system was much lower than for the nonflow system. No conclusive explanation was proposed for these differences.

The results obtained by Viles (1971) show that Z and F values of microorganisms that were determined in static systems cannot be used to evaluate rapid flow systems. If used, the prescribed thermal processing requirements would be higher than needed to inactivate the test organism. In addition, his work showed that the bactericidal efficiency of the turbulent flow system was 40 times that of the nonflow system when calculations were made by using an F_{150} of 9 sec in turbulent flow and an F_{150} of 6.1 min in the nonflow system. This higher bactericidal efficiency indicates that the turbulent flow process would have many industrial applications if more basic information in engineering and food processing were known.

Time-Temperature Distribution in the Coils

Indirect continuous flow heat transfer systems use a metal barrier to transmit heat into the flowing product or out of the product through the metal barrier for cooling. The product is heated progressively in the heating section, held for a specific time in the holding section, and cooled progressively in the cooling section. These time-temperature treatments are the total heat treatments for a process.

The temperature as a function of time was calculated for each menstruum at 0.1 sec intervals, using the equation given by Thomas (1970), and is presented in the Appendix, pages 108 to 131. Time-temperature distribution curves for the 10% NDM menstruum are shown in Figs. 12 and 13. At a velocity of 5.2 ft/sec, the heating time was 5.12 sec, the holding time was 0.19 sec, and the cooling time was 0.80 sec. At a velocity of 27.0 ft/sec, the heating time was 0.98 sec, the holding time was 0.03 sec, and the cooling time was 0.40 sec.

The rate of heating depended on the coil length, flow velocity, inlet temperature of the menstruum in the heating section and on the inlet temperature of the heating medium. The time and temperature relationship in Figs. 12 and 13 clearly show that rate of heating at a flow velocity of 27.0 ft/sec is five times greater than at a flow velocity of 5.2 ft/sec.

A nonlinear relationship existed between time and temperature when steam or steam mixed with water was used as a heating medium. Charm (1963) also reported a nonlinear relationship in a straight tube system that was steam heated.

The type of heating medium influences the rate of heating. Read *et al.* (1956b) observed a linear relationship between temperature and distance in a straight tube turbulent flow system. Since uniform heating by electrical resistance was used, a linear relationship was expected.

In static systems, the time-temperature standards are based on the region of greatest temperature lag, where the rate of heating is quite slow. The heating and cooling curves are generally nonlinear. The center line temperature is more commonly used as the point of maximum temperature lag. The heating occurs at a faster rate in turbulent flow than in stream line flow or in a static system.

In most indirectly heated UHT processing equipment, deposit formation or "burn-on" constitutes a serious problem. The relative scarcity of information on the composition of these deposits and conditions favoring their formation may be partly due to the difficulties of the experimental work. These time-temperature relationships provide a basis for studying factors affecting "burn-on" in turbulent and stream line flow processes. The time-temperature relationship in Fig. 13 shows processing conditions that would prevent the accumulation of deposits that cause "burn-on." The heating time was less than one sec, the Re value was 66,506, the velocity was 27.0 ft/sec, the menstruum was under a pressure of ca. 1300 lb/sq in. and cooling was very rapid. After five hr of continuous operation there was no indication of "burn-on." On the other hand, the time-temperature relationship in Fig. 14 indicates processing conditions that would be less favorable in preventing deposit accumulation and "burn-on." Although the velocity was 29.6 ft/sec for the 40% NDM menstruum, the flow conditions were non-turbulent (Table 3). This was essentially due to the high viscosity of this menstruum.

These results indicate that the helically coiled tube processing system has industrial applications for processing most dairy products and many non-dairy fluid products such as fruit drinks and baby formulas. It can also be used for sterilizing pharmaceutical products like saline solutions and would fit into automated aseptic operations.

Temperature-Survivor Curves

A basic concept in microbiology is that in static systems, the order of destruction of vegetative cells and spores by moist heat is logarithmic. A straight line survivor curve generally is obtained when the log of survivors is plotted against time at a specific temperature. The cell distribution in turbulent flow and the long heat-up and cool-down periods as compared to the holding time make it more difficult to establish the order of bacterial destruction based on the holding time alone. In this heat exchange system, Fig. 1, the heat-up and cool-down periods were, respectively, 27 and 38 times longer than the holding time (Fig. 13). The technique of plotting survival against heat treatment temperatures has been used as an alternate means of evaluating continuous rapid flow systems (Tobias *et al.*, 1955; Burton *et al.*, 1958; Edwards *et al.*, 1965a).

To study the effect of velocity on bactericidal efficiency under turbulent flow conditions, the menstruums were processed at nearly constant Re values in the range of 11,407 to 15,492 (Table 3). To attain these Re values for all the menstruums, the velocities were varied from 5.2 ft/sec to 27.0 ft/sec. Results are presented in Tables 5 to 8. To show the influence of NDM solids on bactericidal efficiency under turbulent flow conditions, the velocity was held constant at 27.0 ft/sec and Re values were varied from 14,579 to 88,639. Results are presented in Tables 10 to 12.

The percentage survival at 5.5 ft/sec in the minimal broth menstruum at each heat treatment temperature of the process is shown in Table 5. The regression of percentage survival (y) on the heat treatment temperature (x) was y = 625.16 - 4.27 x. This linear relationship is shown in Fig. 7 when the total processing time for each heat treatment was 13.12 sec.

At a flow velocity of 27.0 ft/sec, the percentage survival in minimal broth at the corresponding heat treatment temperatures is shown in Table 10. The regression of percentage survival (y) on the heat treatment temperature (x) was y = 390.41 - 2.22 x. This linear relationship is shown in Fig. 7. The total processing time was 2.59 sec for each heat treatment.

The different slopes of the curves in Fig. 7 is explained primarily by the differences in processing time which at 5.5 ft/sec was five times longer than at 27.0 ft/sec. At a specific temperature, the percentage of viable organisms is less at the lower velocity than at the higher velocity. The results clearly show that flow velocity must be defined when evaluating a process by this method.

The percentage survival in the 10% NDM menstruum at the various heat treatment temperatures at a flow velocity of 5.2 ft/sec is shown in Table 6. The regression for calculating the percentage survival was $y = 449.69 - 2.84\ x$. This linear relationship is shown in Fig. 8. The total processing time for each heat treatment was 13.79 sec.

At a flow velocity of 27.0 ft/sec, the percentage survival in the 10% NDM menstruum and the corresponding heat treatment temperature are shown in Table 11. The regression equation for calculating the percentage survival was $y = 379.93 - 2.17\ x$. This linear relationship is also shown in Fig. 8. The total processing time at this flow velocity was 2.61 sec for each heat treatment. The differences between the slopes of the curves in Fig. 8 are explained by the different flow velocities. The higher flow velocity resulted in a shorter processing condition.

The flow velocities for processing the 10% NDM menstruum were comparable to those for minimal broth. Therefore, the slopes of the temperature-survivor curves were a measure of the effect of the NDM solids on the bactericidal efficiency. The results show that the protective effect of the solids was more pronounced at the lower velocity of 5.2 ft/sec. At this velocity bacterial destruction was 33 times higher in minimal broth than in the 10% NDM menstruum when calculated from the slopes.

At the higher velocity, the protective effect of solids was less evident. Bacterial destruction was only 2.2% higher in the minimal broth than in the 10% NDM menstruum. This was attributed primarily to the high degree of mixing at a velocity of 27.0 ft/sec.

There are no reports in the literature on the relationship between flow velocity in turbulent flow and rate of bacterial destruction.

The percentage survival in the 20% NDM menstruum at the various heat treatment temperatures is shown in Table 7. The flow velocity was 10.1 ft/sec and the Re value was 12,013. The regression equation for calculating percentage survival was $y = 483.18 - 2.87\ x$. This linear relationship is shown in Fig. 9. The total processing time was 6.55 sec. Since none of the other menstruums were processed at this velocity, the slope of this line was not compared with the other slopes.

At a flow velocity of 27.3 ft/sec and a Re value of 37,976, the percentage survival in the 20% NDM menstruum and the corresponding heat treatment temperature are shown in Table 12. The regression equation for calculating the percentage survival was $y = 375.38 - 2.16\ x$. This linear relationship is also shown in Fig. 9. The total processing time at this flow velocity was 2.59 sec for each heat treatment.

When the flow velocity was increased from 10.1 ft/sec to 27.3 ft/sec, the slope of the temperature-survivor curve decreased. At a flow velocity of 27.3 ft/sec, the slope of the temperature-survivor curve for the 20% NDM menstruum was 2.8% lower than the slope of the minimal broth survivor curve at the same velocity. The slope of the curve for the 10% NDM menstruum, however, was not significantly different from the slope of the curve for the 20% NDM menstruum.

The percentage survival at a velocity of 27.0 ft/sec in the 30%

NDM menstruum at the various heat treatment temperatures is shown in Table 8. The regression equation for calculating percentage survival was $y = 379.55 - 2.12\ x$. This linear relationship is shown in Fig. 10. The total processing time for each heat treatment was 2.63 sec.

The protective effect of solids on microbial destruction in static systems is well known. In contrast, at a flow velocity of 27.0 ft/sec, the concentration of NDM solids had no measurable effect on destruction of *E. coli* as indicated by the slopes of the temperature-survivor curves. The slopes were: for minimal broth, the 10% NDM menstruum, the 20% menstruum, and the 30% NDM menstruum, respectively, 2.22, 2.17, 2.16, and 2.12. This lack of protection of the solids to the bacterial cells was attributed to the high degree of mixing and rapid heating.

Since the Re value of minimal broth was 88,638 and the Re value of the 30% NDM menstruum was 14,579, the results further show that attaining a Re value higher than the critical Re did not improve bactericidal efficiency. This information appears to have industrial applications, because processing of the optimum velocity would save considerable costs in operation.

At a flow velocity of 29.6 ft/sec, the percentage survival in the 40% NDM menstruum and the corresponding heat treatment temperature are shown in Table 9. The regression equation for calculating the percentage survival was $y = 364.05 - 1.96\ x$. This linear relationship is also shown in Fig. 11. The total processing time at this flow velocity was 2.50 sec for each heat treatment. The higher standard deviation, the lower correlation coefficient (Table 13), and the lower slope were attributed to the non-turbulent flow conditions during processing of the 40% NDM menstruum. As high velocity was required, the high pressure pump did not have sufficient capacity to attain the required velocity to obtain turbulent flow conditions, since the viscosity of this menstruum was higher.

During the past decade considerable research has been directed toward development and improvement of the UHT processes. Most of the published information, however, is on direct steam injection heating units or plate-type heat exchange systems. Research studies on helically coiled tube flow process are sparse. These data are the first that have been reported on bacterial destruction in a helically coiled tube heat transfer system under well defined flow conditions.

The slopes of temperature-survivor curves were a good index to the bactericidal efficiency of the processes using different menstruums and velocities. Five menstruums were used to make 21 runs, Six runs were at a flow velocity of 5.2 ft/sec, three at 10.1 ft/sec, nine at 27.0 ft/sec and three were at 29.6 ft/sec. For each run, the plot of percent survival of *E. coli* (y) on heat treatment temperature (x) was linear under the test conditions.

Equivalent holding times for the helically coiled tube processes are needed to make comparisons with currently used commercial processing equipment. Most of the research workers (Tobias *et al.*, 1955; Read *et al.*, 1956b; Edwards *et al.*, 1965a) were unable to determine equivalent holding times because of the intricacies involved. Tobias *et al.* (1955) plotted log of survival against heat treatment temperatures, but did not obtain data on temperature distribution in the heating and cooling sections. Their data would have been more meaningful if the log survival had been plotted against time. Read *et al.* (1956b) did not calculate equivalent holding times although the temperature distribution data were available. Edwards *et al.* (1965a) processed at different holding times, and plotted the log survival against these holding times. The equivalent holding time in the heat-up and cool-down periods was not taken into consideration.

The temperature distribution in the heating and cooling coils is needed to calculate equivalent holding times for a reference temperature. From this information, an equivalent classical survivor curve can be plotted. Viles (1971) developed a procedure for calculating equivalent holding times for this system.

The survival of heated bacteria is influenced by many factors such as type and concentration of the organism, incubation temperature of the culture, of the poured plates and by the plating and suspending medium. Olson *et al.* (1952) demonstrated that the incubation temperature and concentration of the organisms significantly affected the recovery of heated bacteria. Prolonged incubation of poured plates can influence the recovery of heated bacteria (Dabbah *et al.*, 1969). Moats *et al.* (1971) found higher viable counts by using trypticase soy agar as compared to MacConkey's agar in the detection of survival of *Salmonella sentfenberg* that was heated at 140°F in the range of 0 to 50 min. These results are pertinent to the present investigation where desoxycholate agar was used throughout for viable counts of *E. coli*, an organism related to *Salmonellae*. Desoxycholate agar was chosen because viable organisms were present after pasteurization of the menstruums containing NDM solids. High heat treatments were not applied because it was necessary to minimize physical and chemical changes. Swanson *et al.* (1964) reported that concentrated milks coagulated in the vat during heating at 190°F for 10 min. High heat treatment of milk denatures the serum proteins and increases viscosity (Jenness and Patton, 1959).

If trypticase soy agar or standard plate count agar had been employed as a plating medium, it would not have been possible to distinguish the colonies of other organisms that were present in the pasteurized menstruums from those of *E. coli*. Desoxycholate agar, on the other hand, was both a selective and a differential plating medium. It was selective for gram negative organisms, and differentiated lactose fermenting bacteria (i.e., *E. coli*) from non-lactose fermenters. Although minimal broth was sterile, desoxycholate agar was still employed, in order to provide a valid basis for making a comparison throughout the study. In view of the work of Moats *et al.* (1971), the possibility certainly exists that different estimations of bacterial survival might have been found if other plating media had been employed. Moreover, physical conditions might also influence the viable counts obtained. Unpublished data from the VPI & SU Anaerobe Laboratory have indicated that *E. coli* may yield higher viable counts under anaerobic conditions as compared to aerobic conditions. Such considerations would play an important role in establishing UHT treatments by governmental or public health agencies. The present investigation was not designed to establish such standards, but to devise a helically coiled tube turbulent flow system, to define its flow properties and time-temperature distribution, and to determine the effect of flow rate, turbulence, and temperature on bactericidal efficiency under thoroughly defined conditions. Indeed, the test organism employed would not be used as a basis for public health standards, since it is not comparable to the most heat resistant non-spore forming pathogen found in raw milk, *Coxiella burnetti*. The results of the present investigation are valid only for the present conditions and test agent employed. The possibility of recovery from heat treatment under conditions other than those employed here would be of considerable importance in establishing public health standards for UHT processing. Additional work, however, should be done on this problem. Perhaps a type of thermal injury different from that indicated by Moats *et al.* (1971) may occur in processing, because of the short total processing time (3 sec to 14 sec) under the conditions of rapid heating and cooling. Consequently, it is possible that the type of medium used for plating may have little effect. No increase in colony counts have resulted from prolonged incubation of desoxycholate agar plates in the present study. A definite conclusion must await direct experimental evidence. It would seem mandatory that such evidence would be obtainable only by the use of sterile menstruums and a variety of plating media. As noted above, however, sterilization of the NDM menstruums and reprocessing them would alter the physical and chemical properties and possibly produce inhibitory substances. In addition, the flow characteristics would no longer be comparable to commercial products. The possible resolution of this problem is to resort to the use of the chemical sterilizing agent, ethylene oxide. This method would involve cooling the menstruum 10-50°F and then adding liquid ethylene oxide. The vessel containing the menstruum would be closed and not sealed. The menstruum would be allowed to stand in this state for an hour or so and then transferred to a warm place and left there for a few hours, until all the ethylene oxide has been volatilized and removed. This method has been recommended by Judge and Pelczar (1955) for sterilizing bacteriological culture media and it has been used to sterilize milk and serum. In the experience of Sykes (1969), however, media treated in this way were rather less capable of supporting bacterial growth. Moreover, ethylene oxide gas is extremely hazardous, and also expensive. Two chief advantages are the ability to kill bacterial spores as easily as vegetative cells, and keeping the viscosity changes to a minimum.

Sterilization Effect

The sterilization effect (SE) is widely used in Europe for evaluating UHT processes. This method is based on the existence of a linear relationship between the log of survival of spores and time of heating at a specific temperature. Galesloot (1956) reported SE values greater than 6.0 after heat treatments of spore suspensions at 275°F in a tubular heater. The SE values increased with time of holding.

There are no reports in the literature on the use of this method when non-sporing bacteria were used as test organisms. Calculations of SE values were made at the inactivation temperatures for *E. coli* under the processing conditions in Tables 3 and 4. For a survival of one organism per ml, the SE values ranged from 6.4 to 6.8; but for one organism per 10 ml, the SE values ranged from 7.4 to 7.8. Based on the recommendations of Galesloot (1956), these heat treatments were highly effective for all menstruums.

Determination of SE values is relatively simple, but the initial numbers and final survivor count influence the numerical value. Indexes to the bactericidal efficiency of processes can be obtained if the same organism at a designated initial concentration is used in the same menstruum.

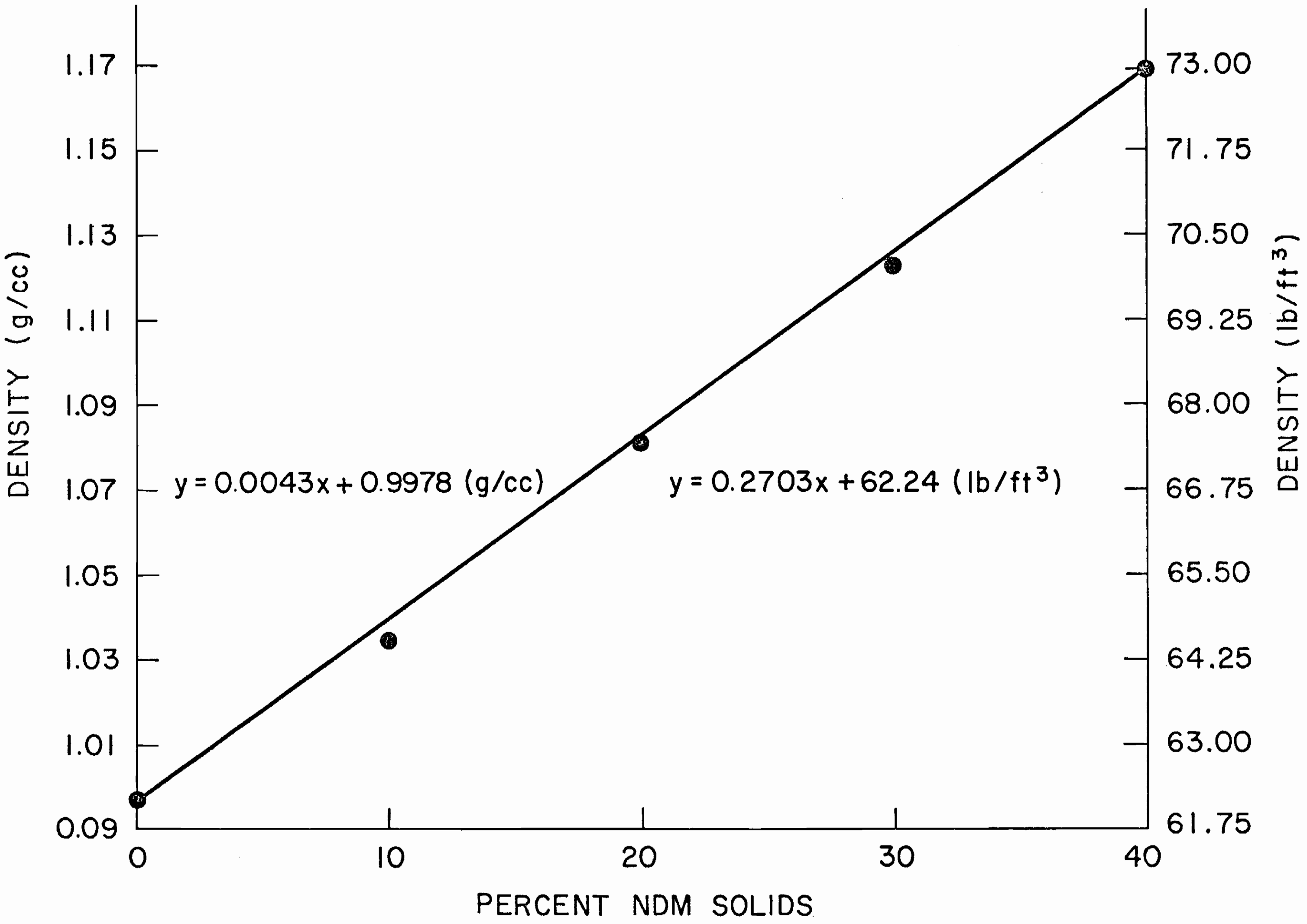


FIG. 6 - RELATIONSHIP BETWEEN DENSITY AND PERCENT NONFAT DRY MILK SOLIDS AT 71.6 °F (22 °C).

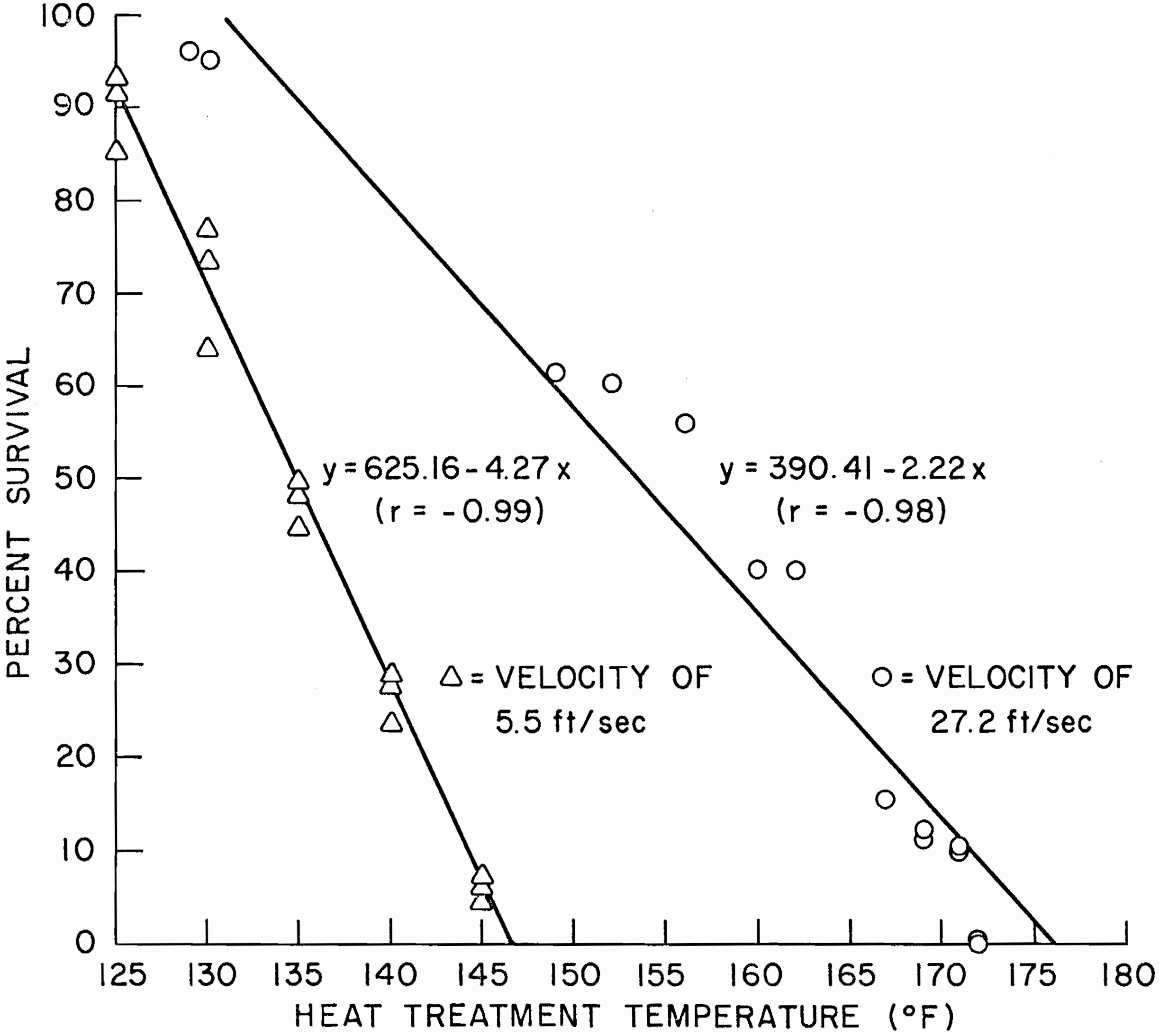


FIG. 7 - PERCENT SURVIVAL IN THE MINIMAL BROTH.

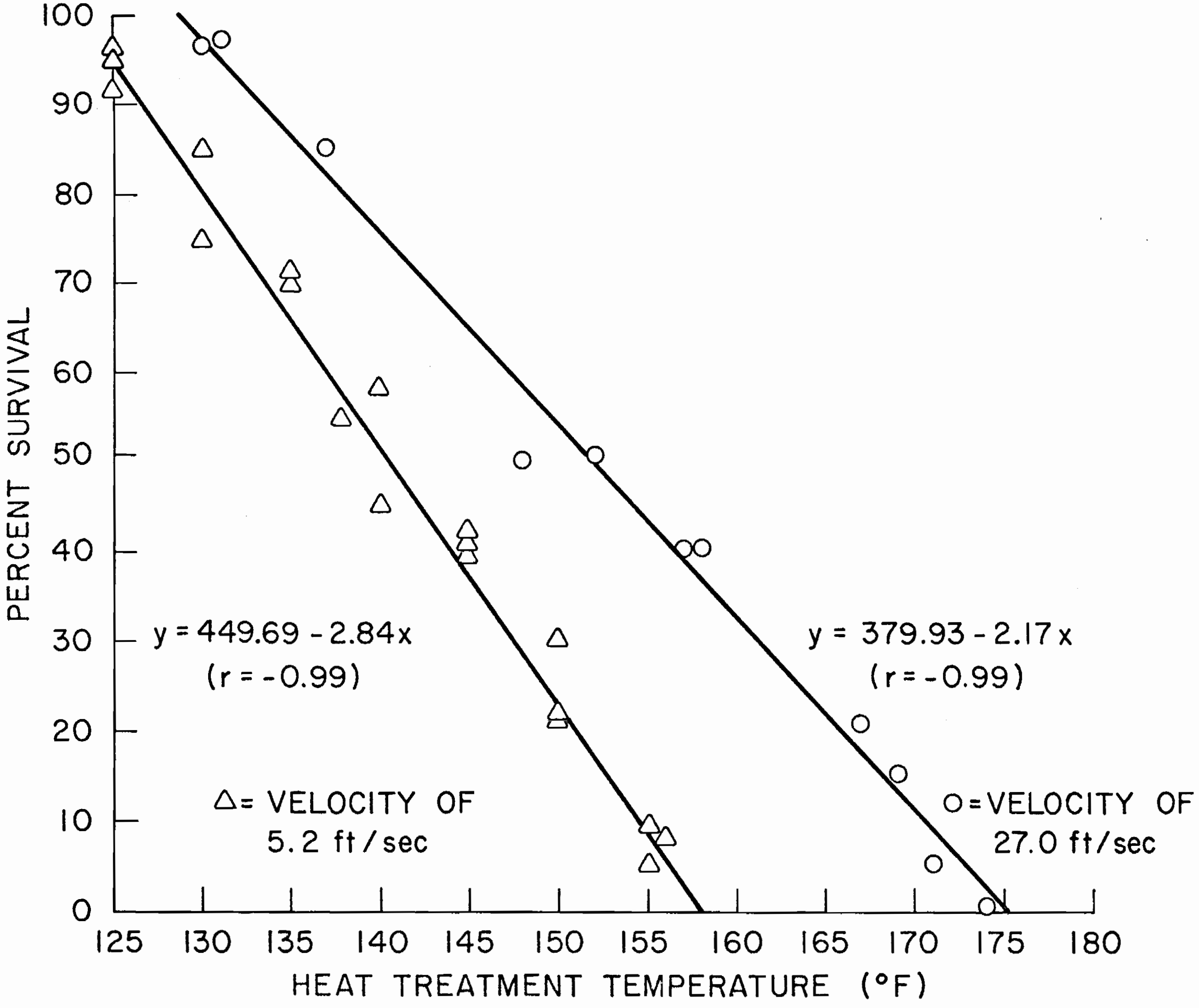


FIG. 8 - PERCENT SURVIVAL IN 10% NDM MENSTRUUM.

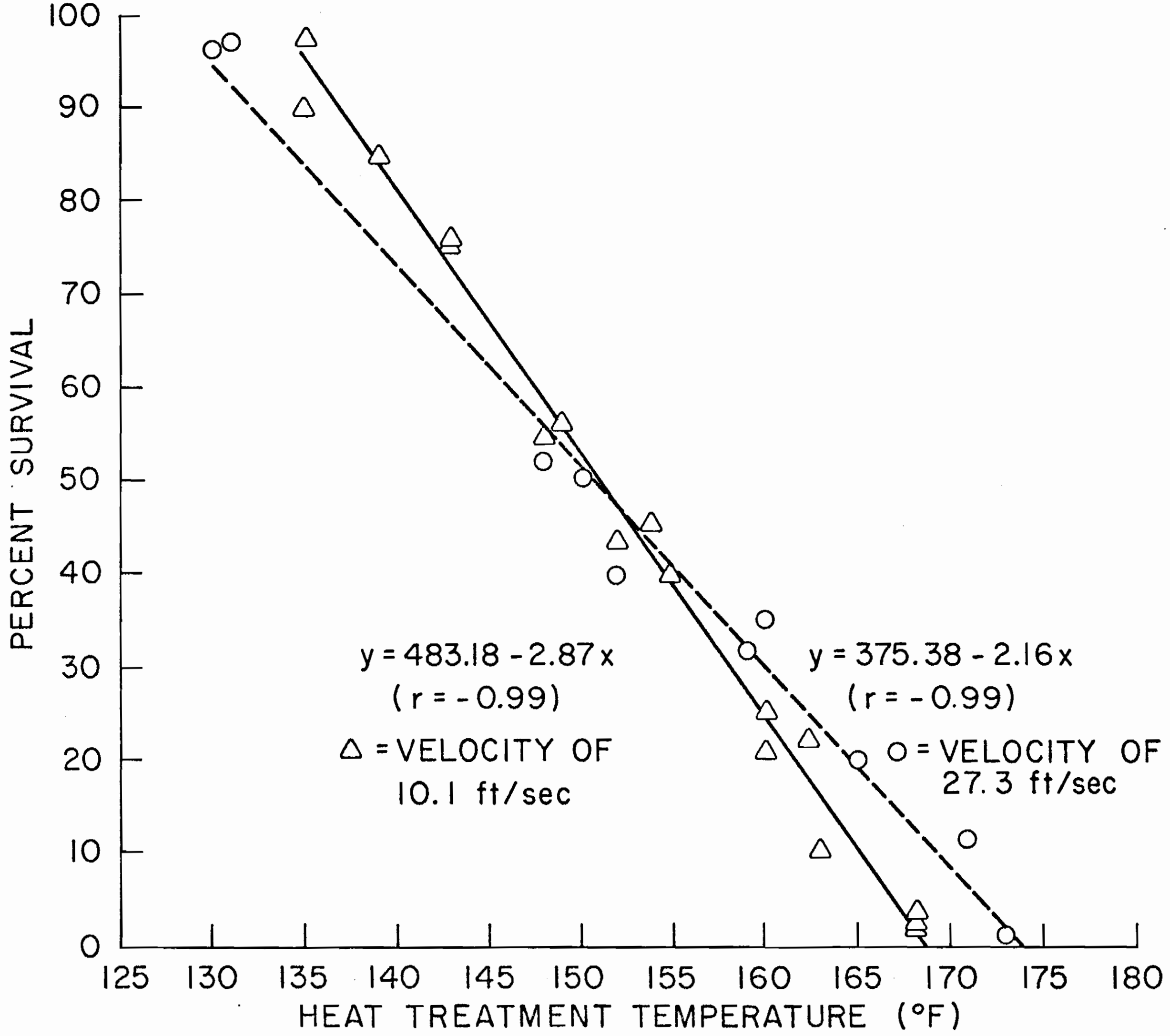


FIG. 9 - PERCENT SURVIVAL IN 20% NDM MENSTRUUM.

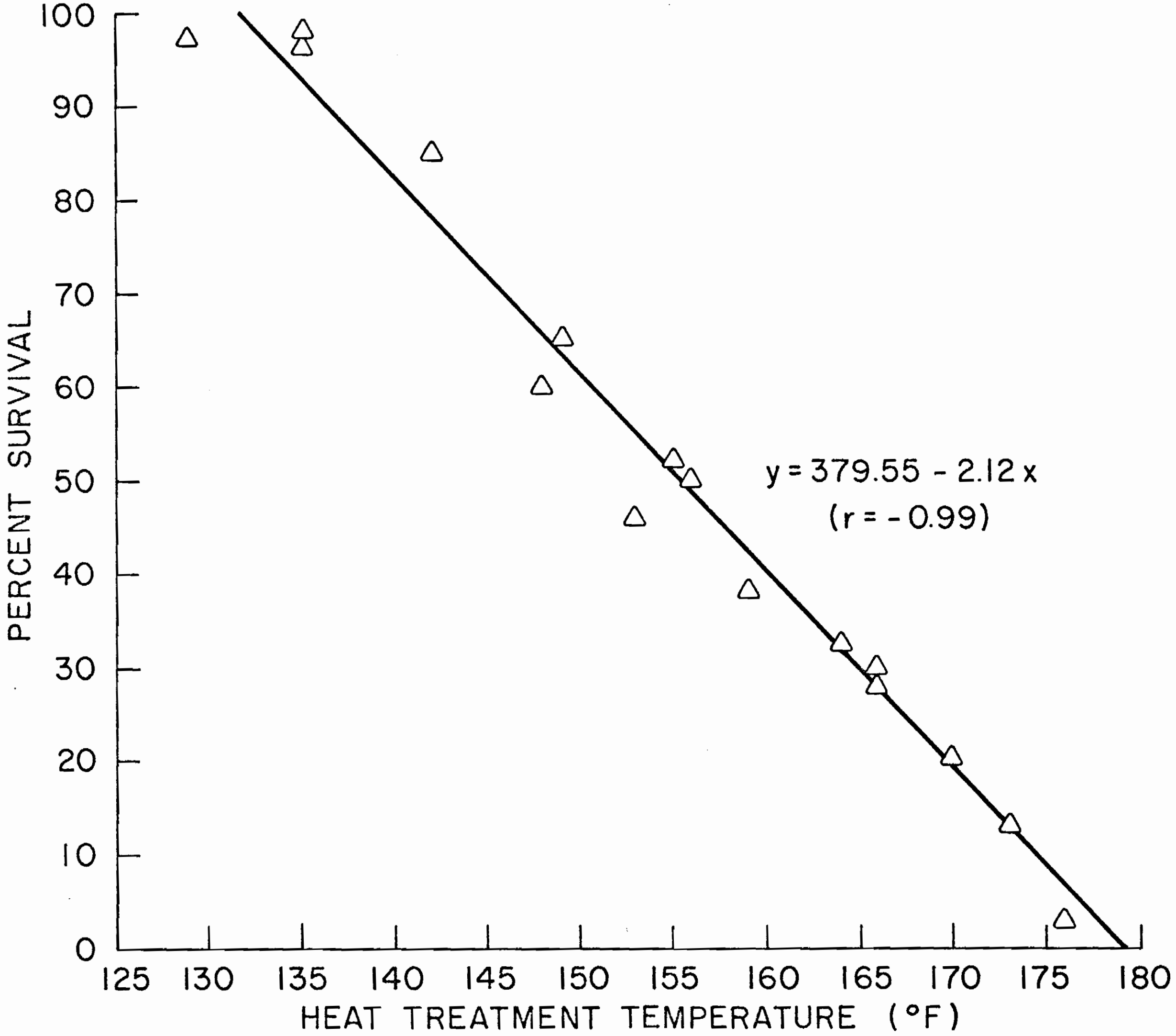


FIG. 10 - PERCENT SURVIVAL IN 30% NDM MENSTRUUM AT A VELOCITY OF 27.0 ft/sec.

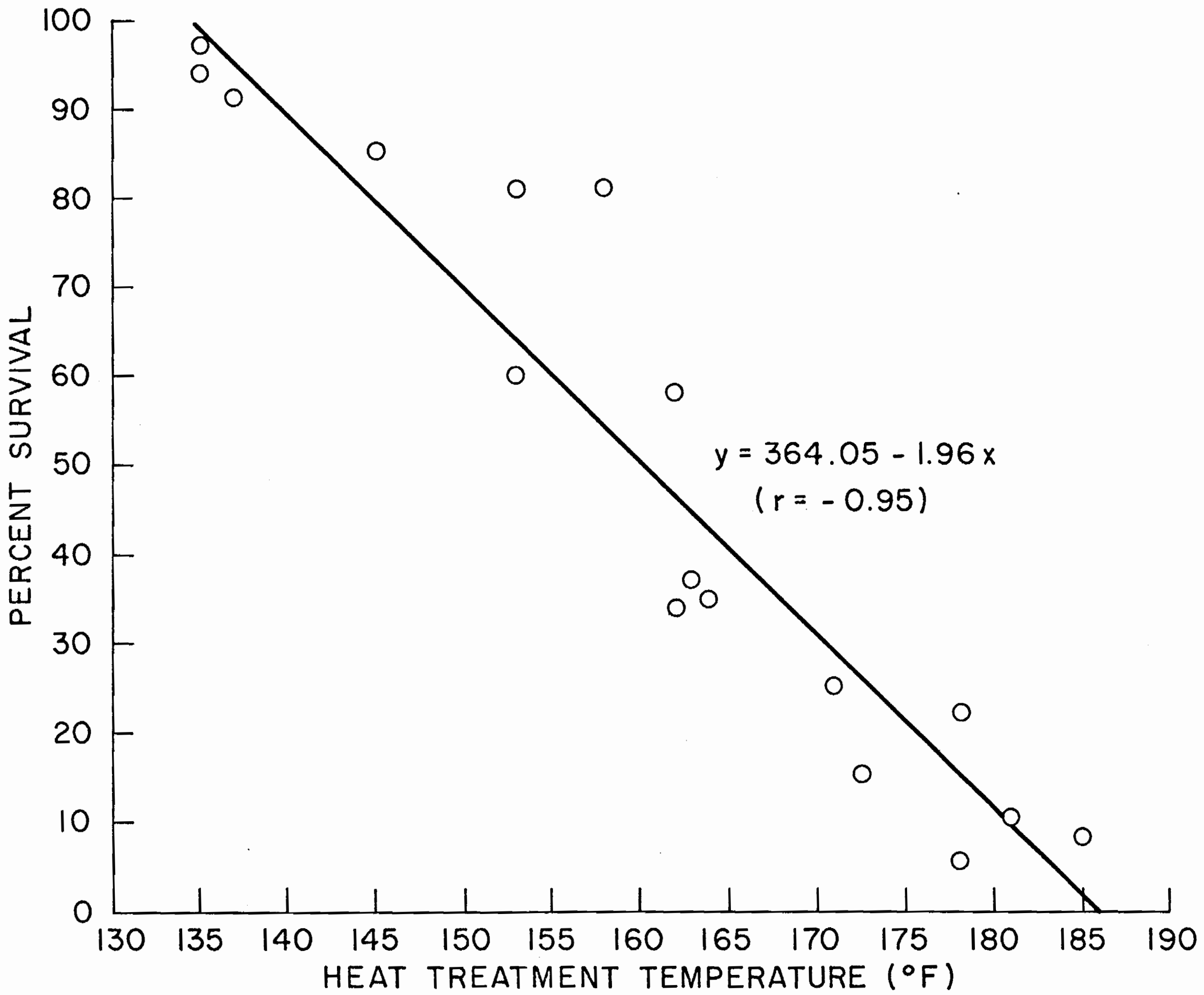


FIG. 11 - PERCENT SURVIVAL IN 40% NDM MENSTRUUM AT A VELOCITY OF 29.6 ft/sec.

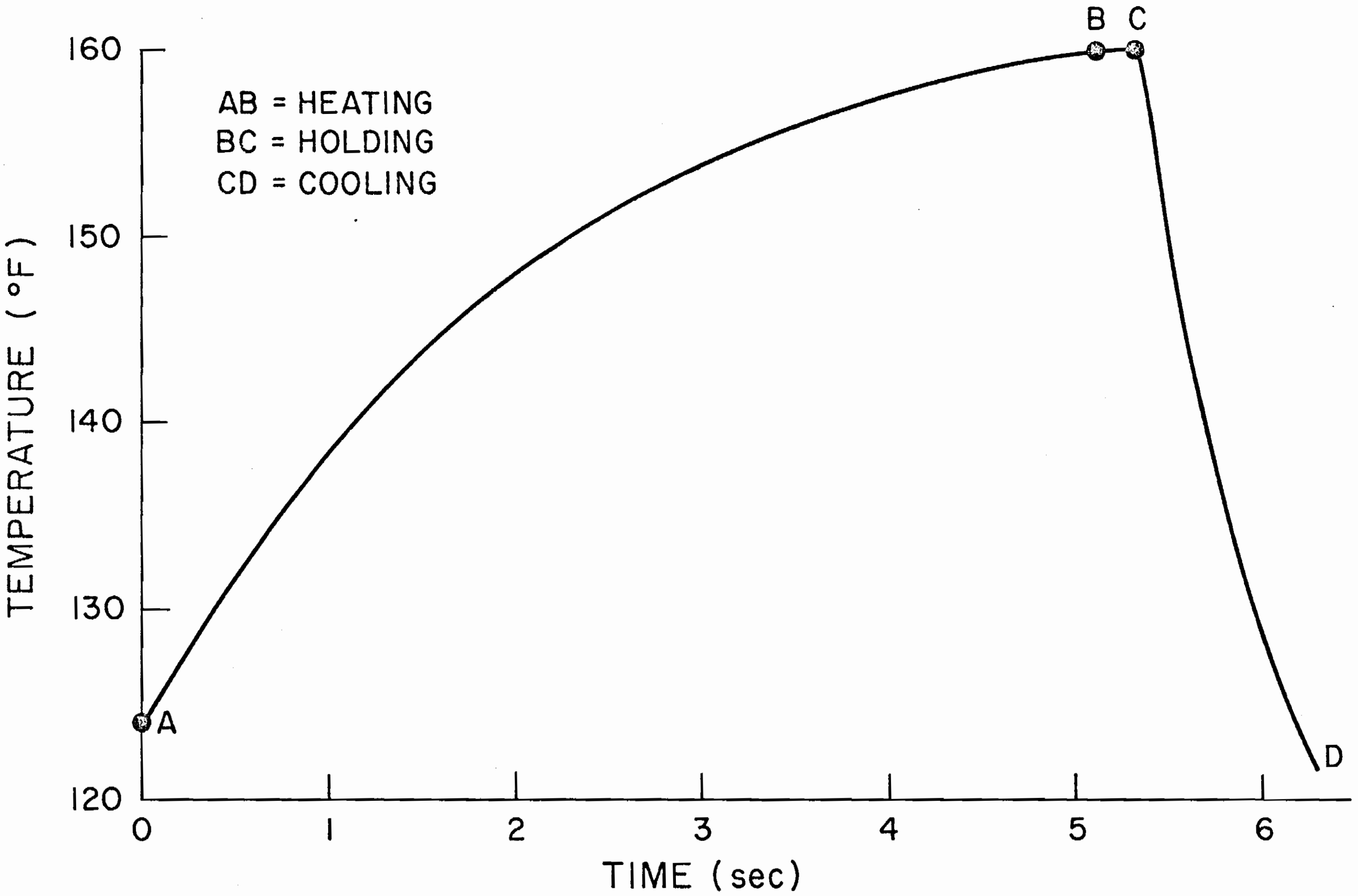


FIG. 12 - TIME - TEMPERATURE CURVE FOR 10% NDM MENSTRUUM
AT A VELOCITY OF 5.2 ft/sec.

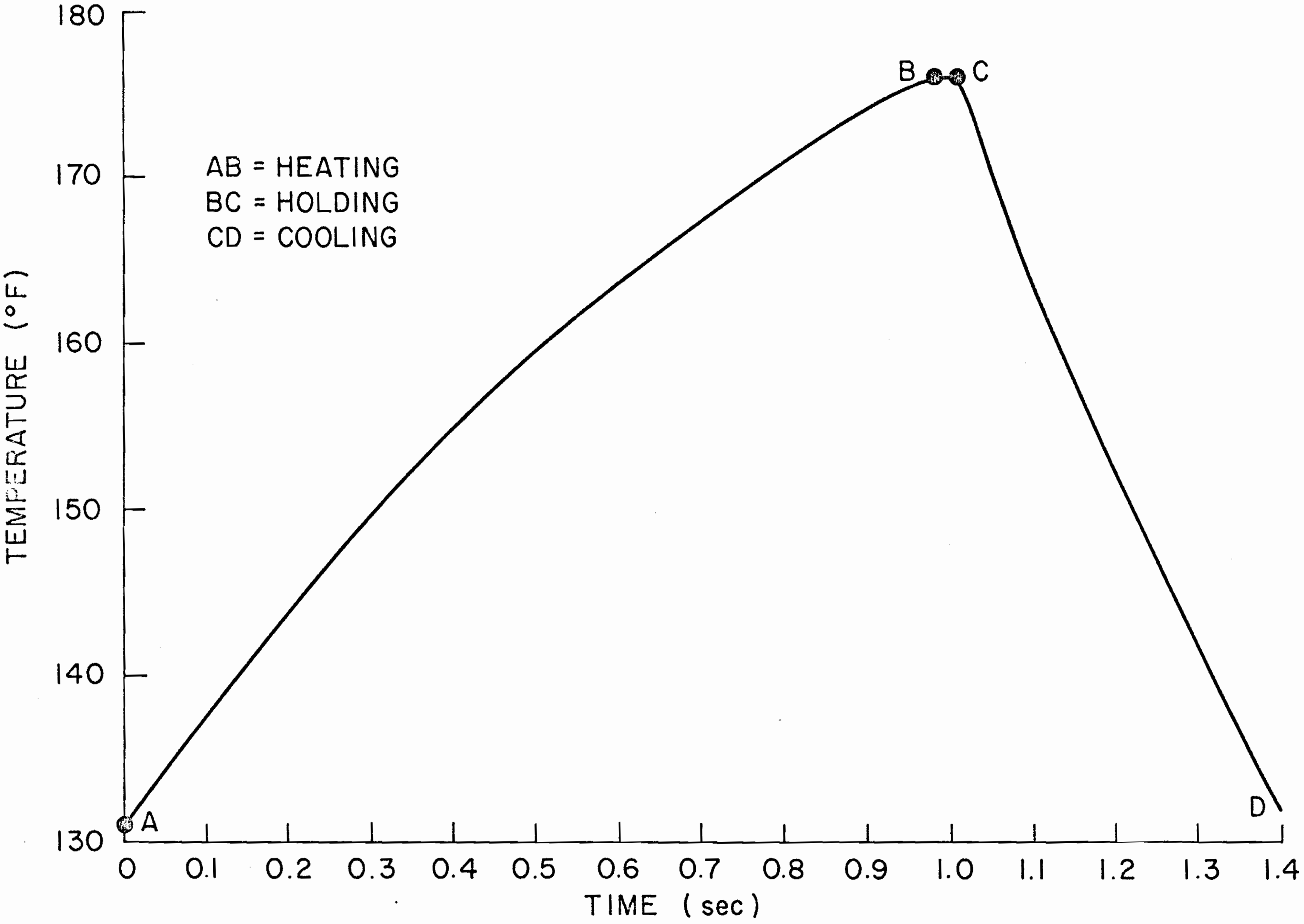


FIG. 13 - TIME - TEMPERATURE CURVE FOR 10 % NDM MENSTRUUM AT A VELOCITY OF 27.0 ft/sec.

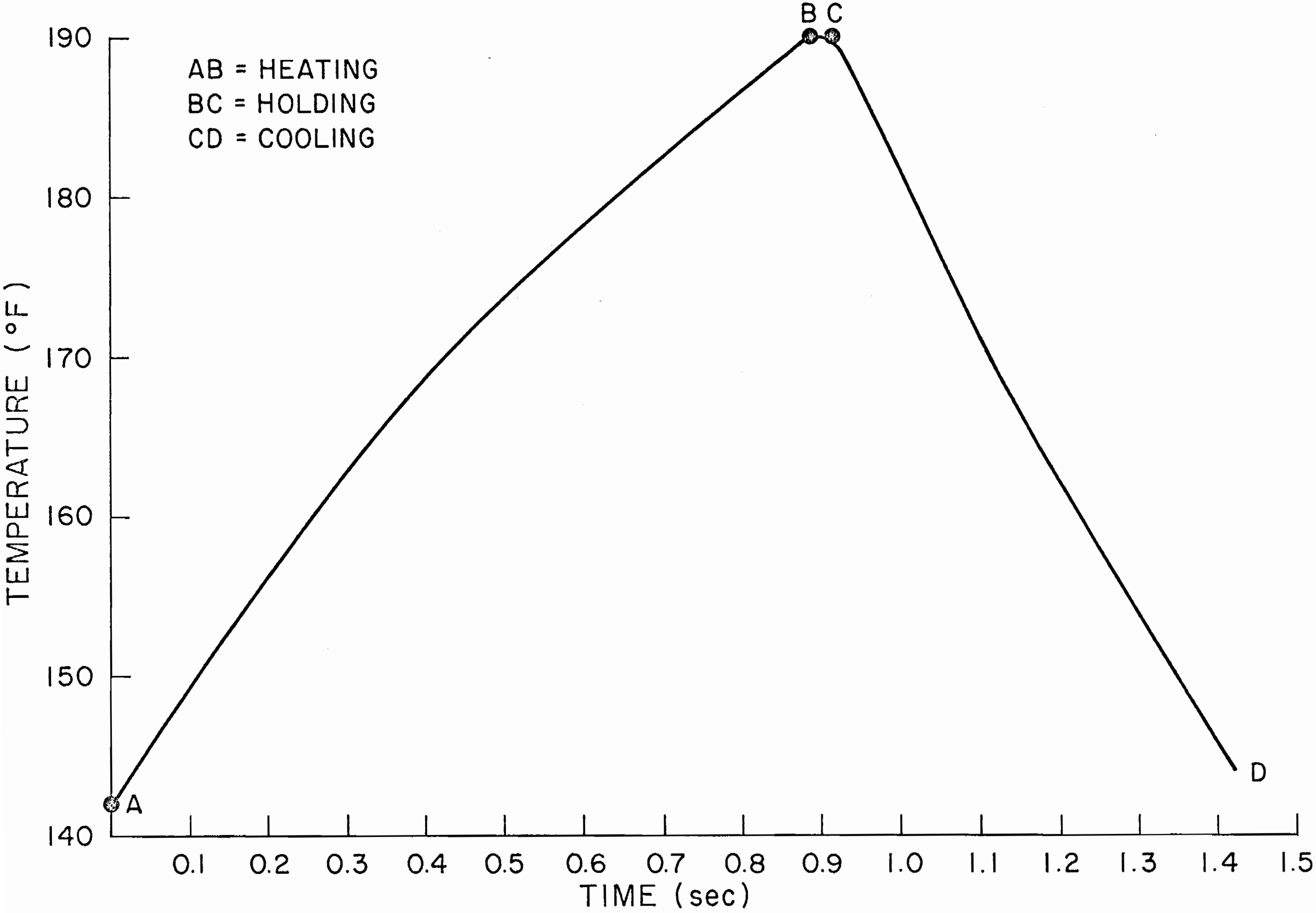


FIG. 14 - TIME - TEMPERATURE CURVE FOR 40% NDM MENSTRUUM AT A VELOCITY OF 29.6 ft/sec.

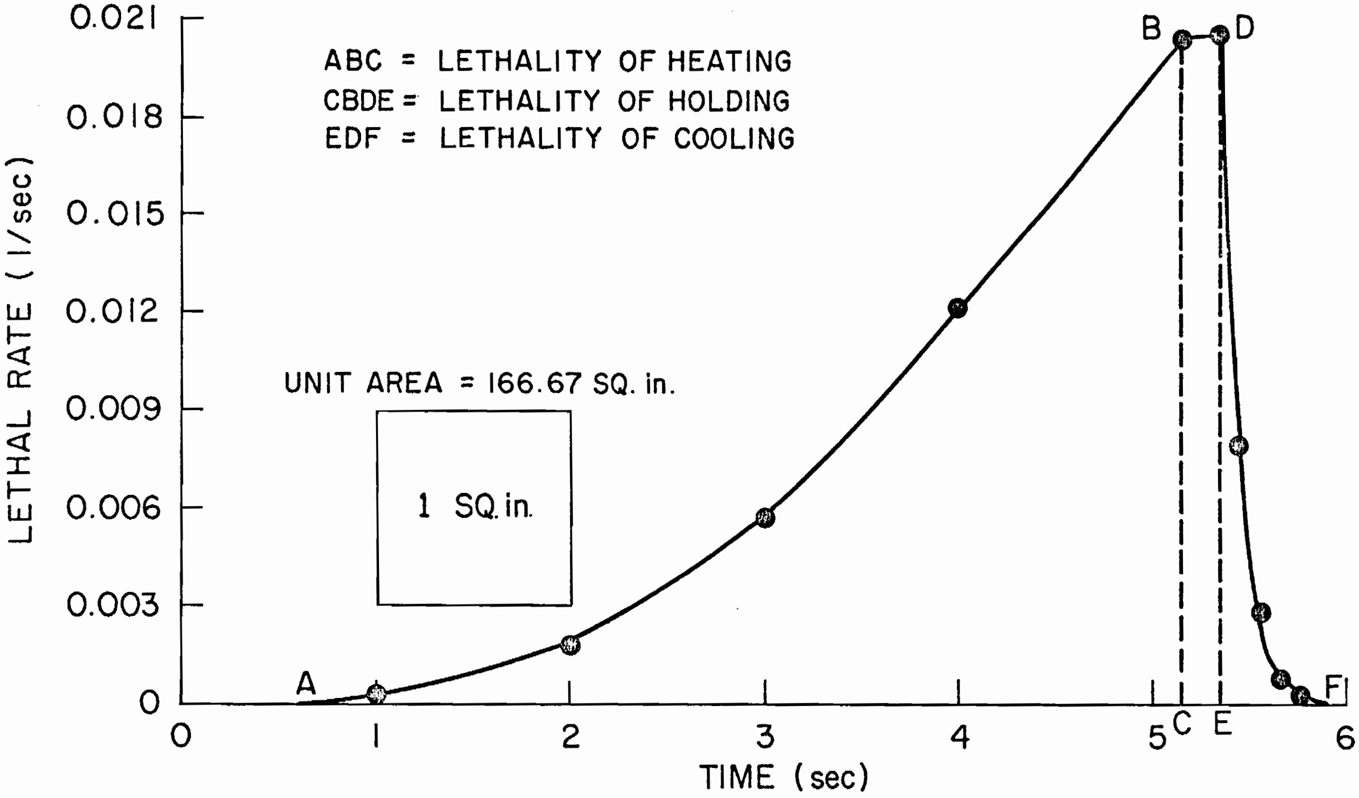


FIG. 15 - LETHAL RATE CURVE IN 10% NDM MENSTRUUM AT A VELOCITY OF 5.2 ft/sec.

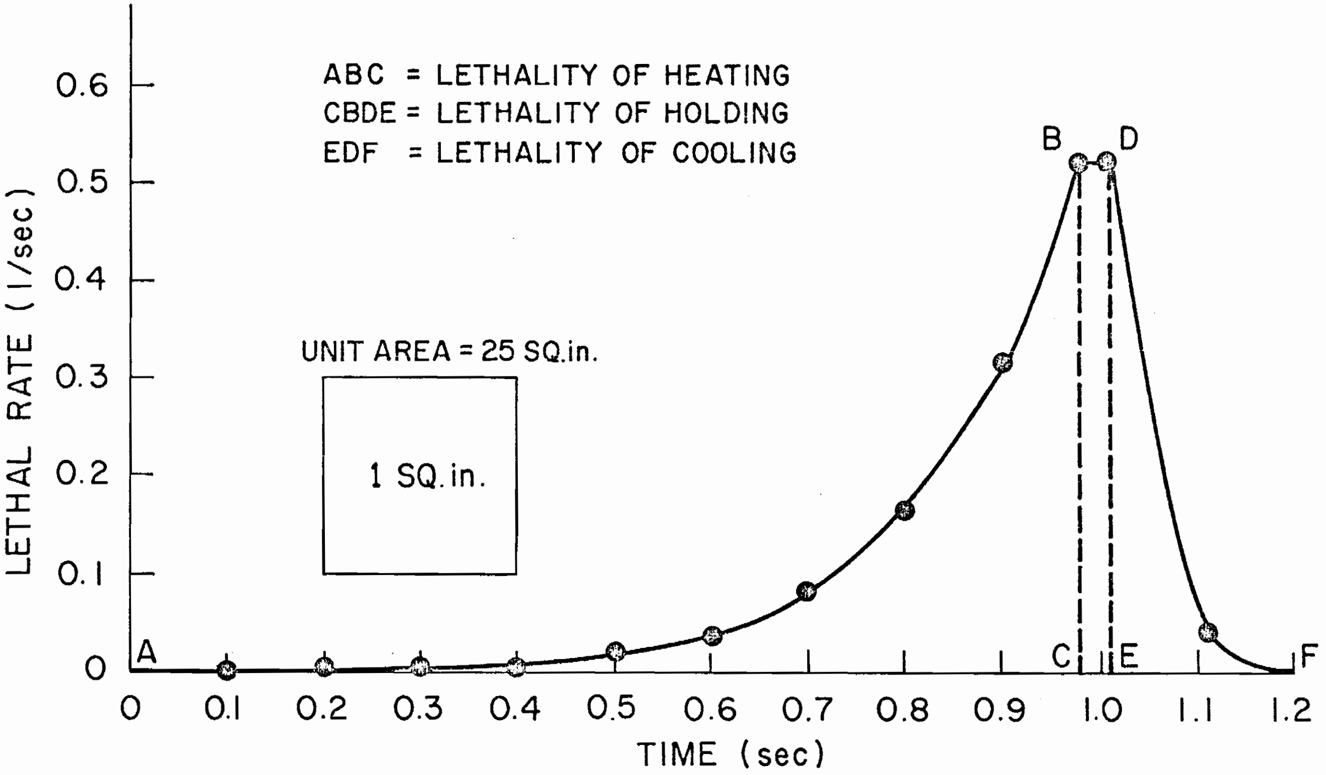


FIG. 16 - LETHAL RATE CURVE IN 10% NDM MENSTRUUM AT A VELOCITY OF 27.0 ft/sec.

Table 1 - Density and cubical expansion coefficients of menstruums.

	Temperature		Density		Cubical expansion coefficient	
Menstruum	(°C)	(°F)	(g/cc)	(lb/ft^3)	(per °C)	(per °F)
Minimal broth[a]	22	71.6	0.9978[b]	62.24[b]	-	-
10% NDM[c]	20	68.0	1.0356	64.65	4.5×10^{-4}	2.50×10^{-4}
20% NDM	22	71.6	1.0815	67.52	4.6×10^{-4}	2.56×10^{-4}
30% NDM	21	69.8	1.1230	70.05	4.3×10^{-4}	2.37×10^{-4}
40% NDM	22	71.6	1.1701	73.05	4.3×10^{-4}	2.38×10^{-4}

[a] contained 1.36% solids.

[b] value for water.

[c] NDM = non-fat dry milk solids.

Table 2 - Viscosity of menstruums at various temperatures.

Menstruum	Temperature (°F)	Viscosity[a] (cp)
Minimal broth	80.6	0.8513
	86.0	0.7975
	137.5[b]	0.4846
	154.5[b]	0.4155
10% NDM	80.6	1.2183
	86.0	1.0945
	142.0[b]	0.6483
	153.5[b]	0.5700
20% NDM	80.6	5.0350
	86.0	4.1658
	149.0[b]	1.2350
	154.0[b]	1.1470
30% NDM	80.6	9.1667
	86.0	8.0834
	157.0[b]	2.8218
40% NDM	80.6	18.0
	86.0	17.0
	166.0[b]	12.0

[a] cp = 6.72×10^{-4} (lb/ft sec).

[b] mean temperature.

Table 3 - Effect of composition of menstruums on flow properties at different velocities.

Menstruum	Temperature			Density	Flow rate	Velocity	Reynolds number
	Preheat (°F)	Heat treatment[a] (°F)	Mean (°F)	(lb/ft^3)	(gal/hr)	(ft/sec)	(Re)
Minimal broth	125	150	137.5	61.37	25.9	5.5	15,492
10% NDM	124	160	142.0	63.71	24.7	5.2	11,407
20% NDM	128	170	149.0	65.81	48.2	10.1	12,013
30% NDM	134	180	157.0	68.26	128.2	27.0	14,579
40% NDM	142	190	166.0	70.98	140.8	29.6	3,908

[a] Inactivation temperature measured at inlet of cooling section.

Table 4 - Effect of composition of menstruums on flow properties at a constant velocity.

	Temperature						
Menstruum	Preheat (°F)	Heat treatment[a] (°F)	Mean (°F)	Density (lb/ft^3)	Flow rate (gal/hr)	Velocity (ft/sec)	Reynolds number (Re)
Minimal broth	135	174	154.5	60.66	129.6	27.2	88,638
10% NDM	131	176	153.5	62.90	128.4	27.0	66,506
20% NDM	130	178	154.0	65.64	129.8	27.3	37,976
30% NDM	134	180	157.0	68.26	128.2	27.0	14,579

[a] Inactivation temperature at inlet of cooling section.

Table 5 - Effect of heat treatments on survival in the minimal broth menstruum at a velocity of 5.5 ft/sec.[a]

Trial (No.)	Initial viable count (No./ml)	Heat treatment temperature (°F)	Survival[b] (%)
1	2.62×10^6	125	85.11
		130	74.05
		135	48.09
		140	28.63
		145	6.79
		150	0.00
2	2.50×10^6	125	92.00
		130	77.20
		135	49.20
		140	24.00
		145	5.00
		150	0.00
3	2.54×10^6	125	93.70
		130	64.96
		135	45.28
		140	28.35
		145	6.30
		150	0.00

[a] Reynolds number = 15,492

[b] Based on mean of triplicate counts.

Table 6 - Effect of heat treatments on survival in the 10% NDM menstruum at a velocity of 5.2 ft/sec.[a]

Trial (No.)	Initial viable count (No./ml)	Heat treatment temperature (°F)	Survival[b] (%)
1	2.89×10^6	125	96.19
		130	85.12
		135	70.24
		140	58.13
		145	42.41
		150	21.45
		155	5.02
		160	0.00
2	2.64×10^6	125	91.29
		130	75.00
		135	71.59
		140	45.08
		145	40.15
		150	30.30
		155	9.81
		160	0.00
3	2.50×10^6	125	95.20
		138	55.20
		145	40.00
		150	22.00
		156	8.00
		160	0.00

[a] Reynolds number = 11,407

[b] Based on mean of triplicate counts.

Table 7 - Effect of heat treatments on survival in the 20% NDM menstruum at a velocity of 10.1 ft/sec.[a]

Trial (No.)	Initial viable count (No./ml)	Heat treatment temperature (°F)	Survival[b] (%)
1	2.86×10^6	143	75.87
		154	45.10
		160	21.67
		163	10.17
		168	1.95
		170	0.00
2	2.60×10^6	135	95.00
		143	75.00
		148	54.61
		155	40.00
		162	23.84
		168	3.00
		170	0.00
3	2.74×10^6	135	97.44
		139	85.03
		149	56.20
		152	43.79
		160	25.18
		168	2.99
		170	0.00

[a] Reynolds number = 12,013.

[b] Based on mean of triplicate counts.

Table 8 - Effect of heat treatments on survival in the 30% NDM menstruum at a velocity of 27.0 ft/sec.[a]

Trial (No.)	Initial viable count (No./ml)	Heat treatment temperature (°F)	Survival[b] (%)
1	2.91×10^6	135	96.21
		149	65.86
		155	52.57
		156	50.17
		164	32.98
		166	28.17
		176	2.98
		180	0.00
2	2.78×10^6	135	98.20
		142	85.25
		148	60.43
		153	46.04
		159	38.84
		170	20.14
		173	13.30
		180	0.00
3	2.88×10^6	129	97.91
		166	30.20
		180	0.00

[a] Reynolds number = 14,579.

[b] Based on mean of triplicate counts.

Table 9 - Effect of heat treatments on survival in the 40% NDM menstruum at a velocity of 29.6 ft/sec.[a]

Trial (No.)	Initial viable count (No./ml)	Heat treatment temperature (°F)	Survival[b] (%)
1	2.87×10^6	135	94.07
		162	34.14
		163	37.11
		172	15.68
		182	10.80
		185	8.01
		190	0.00
2	2.91×10^6	137	91.75
		153	81.09
		158	81.79
		164	35.05
		178	6.91
		190	0.00
3	2.85×10^6	135	97.19
		145	85.96
		153	60.35
		162	58.25
		171	25.61
		178	22.11
		190	0.00

[a] Reynolds number = 3,908.

[b] Based on mean of triplicate counts.

Table 10 - Effect of heat treatments on survival in the minimal broth menstruum at a velocity of 27.2 ft/sec.[a]

Trial (No.)	Initial viable count (No./ml)	Heat treatment temperature (°F)	Survival[b] (%)
1	2.43×10^6	129	96.70
		152	60.43
		162	40.29
		169	12.08
		171	10.51
		171	10.36
		172	0.74
		174	0.00
2	2.89×10^6	130	95.15
		140	80.96
		149	61.59
		156	56.05
		160	40.13
		167	15.57
		169	11.76
		172	0.50
		174	0.00

[a] Reynolds number = 88,638.

[b] Based on mean of triplicate counts.

Table 11 - Effect of heat treatments on survival in the 10% NDM menstruum at a velocity of 27.0 ft/sec.[a]

Trial (No.)	Initial viable count (No./ml)	Heat treatment temperature (°F)	Survival[b] (%)
1	2.88×10^6	131	94.22
		152	51.38
		158	40.62
		167	21.18
		171	5.08
		176	0.00
2	2.67×10^6	130	96.25
		137	85.01
		148	50.93
		157	40.07
		169	15.35
		174	0.50
		176	0.00

[a] Reynolds number = 66,506.

[b] Based on mean of triplicate counts.

Table 12 - Effect of heat treatments on survival in the 20% NDM menstruum at a velocity of 27.3 ft/sec.[a]

Trial (No.)	Initial viable count (No./ml)	Heat treatment temperature (°F)	Survival[b] (%)
1	2.94×10^6	130	96.25
		150	50.34
		160	35.37
		171	11.22
		178	0.00
2	2.65×10^6	131	97.35
		148	52.07
		152	40.00
		159	32.07
		165	20.00
		173	1.00
		178	0.00

[a] Reynolds number = 37,976.

[b] Based on mean of triplicate counts.

Table 13 - Regression equations for survival of *E. coli* in the test menstruums at constant and variable velocities.

Menstruum	Velocity	Predicted equation	Degrees of freedom (df)	Correlation coefficient r**	Standard deviation (s)
Minimal broth	5.5	Y=625.16-4.27X	13	-0.99	3.58
	27.2	Y=390.41-2.22X	13	-0.98	6.69
10% NDM	5.2	Y=449.69-2.84X	17	-0.99	4.17
	27.0	Y=379.93-2.17X	9	-0.99	3.70
20% NDM	10.1	Y=483.18-2.87X	15	-0.99	2.93
	27.3	Y=375.38-2.16X	8	-0.99	4.30
30% NDM	27.0	Y=379.55-2.12X	14	-0.99	4.62
40% NDM	29.6	Y=364.05-1.96X	15	-0.95	11.07

**A significant difference at the 1% level between percent survival and heat treatment temperature.

Table 14 - Calculated lethality values in different sections of the process.

Section		Lethal units	
		1[a]	2[b]
Heating		0.0333	0.0962
Holding		0.0039	0.0188
Cooling		0.0013	0.0052
	Total units	0.0385	0.1202

[a] At a velocity of 5.2 ft/sec and 160°F heat treatment temperature.

[b] At a velocity of 27.0 ft/sec and 176°F heat treatment temperature.

SUMMARY AND CONCLUSIONS

At present, there is a definite trend in the food industry toward the use of higher temperatures and shorter times for processing fluid products. This trend is based on the desirability of achieving destruction of microorganisms while at the same time minimizing detrimental effects on flavor and other properties. Helically coiled tube systems offer great promise in this regard, but much basic information is required before wide applications can be made.

This dissertation represents an investigation of the relation of flow properties and temperature distribution to bacterial destruction in a helically coiled tube turbulent flow system. It differs from all previous studies in that all conditions employed have been thoroughly defined and the type of helically coiled tube turbulent flow system employed has never before reportedly been used for such studies. This system was especially designed to provide measurement and control of the temperatures and of the flow rates and flow characteristics that were required for this study. The system was able to operate over a wide range of flow rates, under turbulent or non-turbulent flow conditions, and was equipped with automatic temperature control and recording units. The test menstruums were minimal broth that contained 1.4% solids and rehydrated NDM products that ranged from 10% to 40% solids. The bacterial species *E. coli* (ATCC strain No. 9723) was used as the test microorganism. Defined inocula and conditions for determination of survival were also employed with desoxycholate agar used as the plating medium.

Turbulent flow conditions for this system were determined by the critical Reynolds number which was calculated to be 8,617. Reynolds numbers up to 88,000 were needed to maintain a constant flow velocity of 27 ft/sec for processing the test menstruums under turbulent flow conditions. Density, velocity, viscosity, and tube ID determined the magnitude of Reynolds numbers which in turn were the indexes to the flow properties.

Density of the menstruums influenced flow properties to a greater extent by increasing the solids than by increasing the temperature. A linear relationship was found between density (y) and concentration of NDM solids (x) as shown by the following formulas: $y\ (g/cc) = 0.0043\ x + 0.9978$ or $y\ (lb/ft^3) = 0.2703\ x + 62.24$. These formulas have commercial applications, especially for determining the flow properties of concentrated milks in connection with the manufacture of NDM products. From the percentage solids in concentrated milks, density at 71.6°F can be calculated and then converted to the density at higher temperatures by using the cubical expansion coefficient method.

The Reynolds number is inversely proportional to the viscosity coefficient, making viscosity a significant factor in establishing flow properties. Viscosity was found to increase as the percentage concentration of NDM solids in the menstruums was increased and to decrease as the temperature of the menstruums was increased. Nonlinear relationships were found between viscosity and percentage NDM solids and between viscosity and temperature. These nonlinear functions were attributed to the non-Newtonian nature of the menstruums.

The helically coiled tube system employed was evaluated for the destruction of *E. coli* by the lethality method. A computer program was written that simultaneously calculated temperature as a function of time, rate of lethality, and accumulated lethality. These calculations were made in 0.1 sec intervals during heating and cooling of the menstruums. The mathematical analysis provided a basis for comparing turbulent flow processes with other processes.

The low calculated lethality values that were obtained in the turbulent flow process were attributed to the use of reported Z and F values of *E. coli* in the calculation that were determined in a nonflow system.

The three stages of the turbulent flow system were evaluated by calculating the percentage of lethality in each section. More than 80% of lethality occurred during the heat-up time, 10 to 15% during the short holding time, and 3 to 4% during the cool-down period.

The lethality during cooling progressively increased with increases in processing temperatures. Hence, the lethality in the cooling section of helically coiled tube systems must be taken into account when making an accurate evaluation for UHT treatments.

The bactericidal efficiency of the turbulent flow system was 40 times that of the nonflow system when calculations were made by using F values in turbulent flow and nonflow systems. This higher bactericidal efficiency indicates that the turbulent flow process would have many industrial applications if more basic information in engineering and food processing were available.

The temperature-time distribution in the heating and cooling coils was calculated at 0.1 sec intervals. These are the first data that have been reported on this distribution for processing concentrated milk products. A nonlinear relationship was observed between time and product temperature. Menstruums were processed with heat-up times of less than one sec and holding times of less than 0.04 sec.

During the past decade considerable research has been directed toward bacterial destruction in UHT processes. Most of the published information, however, is on inactivation in direct steam injection heating units or plate-type heat exchange systems. These data are the first that have been reported on bacterial destruction in a helically coiled tube heat transfer system under thoroughly defined flow conditions.

Five kinds of menstruums were used in a total of 21 experiments for determining survival of *E. coli* by different heat treatments. Six experiments were at a flow velocity of 5.2 ft/sec, three at 10.1 ft/sec, nine at 27.0 ft/sec and three were at 29.6 ft/sec. For each menstruum, the plot of percent survival of *E. coli* (y) on the heat treatment temperature (x) appeared to be linear under these test conditions. Regression equations were used to determine the straight lines that best fitted the data. The slopes of the temperature-survivor curves were used to compare the bactericidal efficiency of the process under different conditions of velocity and concentration of NDM solids.

The slopes of the temperature-survivor curves were significantly different when a menstruum was processed at different velocities.

These differences in slopes were due to changes in processing times and heat treatment temperatures. Therefore, velocity must be defined when evaluating bacterial survival in such a helically coiled tube system.

Under turbulent flow conditions, the protective effect of NDM solids was greater at a velocity of 5.2 ft/sec than at 27.0 ft/sec. At this lower velocity, a 10% increase in NDM solids reduced the bactericidal efficiency 33% (as calculated from the slopes of the curves for minimal broth and for the 10% NDM menstruum). This is essentially in agreement with the results reported for nonflow systems. At the faster velocity of 27.0 ft/sec, however, the protective effect of the solids was less evident. An increase in 10% NDM solids reduced the bactericidal efficiency by only 2.2% as calculated from the slopes. This was attributed to the high degree of mixing and rapid heating at the faster velocity. There are no previous reports in the literature on the relationship between velocity in thoroughly defined turbulent flow conditions and rate of bacterial destruction as influenced by the concentration of NDM solids.

To process at a constant Reynolds number, it was necessary to increase velocity as the concentration of NDM solids was increased. Increasing the velocity, however, reduced the processing time and thereby increased the thermal inactivation temperatures.

At the rapid flow velocity of 27.0 ft/sec, the Reynolds number varied from 14,579 to 88,638, depending on the type of menstruum. At this velocity, the thermal inactivation temperatures were only slightly different, and the Reynolds number was not closely related to the inactivation temperature when turbulent flow conditions existed. In other words, provided the Reynolds number exceeded the critical Reynolds number, its absolute value appeared to make little difference at a high flow velocity. This dissertation provides the first evidence reported for such a relationship.

There are no previous reports in the literature on the use of the recently developed sterilization effect method for evaluating helically coiled tube turbulent flow processes, when non-spore forming bacteria were used as test organisms. Calculations of sterilziation effect values were made at the inactivation temperatures for *E. coli*. If it were assumed that there was a survival of one bacterial cell per ml, the sterilization effect values ranged from 6.4 to 6.8. On the other hand, with an assumption of survival of one bacterial cell per 10 ml, the sterilization effect values ranged from 7.4 to 7.8. These heat treatments were highly effective for all menstruums and indicated that this method could be used to compare different heat exchange systems if a specific organism at a specific initial concentration was used in the same menstruum.

These findings suggest that the helically coiled tube processing system might be applicable to industrial processing of most dairy products and many non-dairy fluid products such as fruit drinks and baby formulas. It could possibly be used also for sterilizing pharmaceutical products like saline solutions and could easily fit into automated aseptic operations.

The basic information obtained in this study on flow properties, temperature distribution and destruction of *E. coli* under thoroughly defined conditions will be useful as a preliminary study leading to further work with different types of microorganisms, especially pathogens. Investigations of the type and extent of thermal injury of bacterial cells exposed to high temperatures for very short times should also be made using different types of media and physical conditions for estimation of survival. Standards for industrial or public health purposes cannot be proposed until such additional investigations are made.

LITERATURE CITED

Aldrich, S. G. 1971. Private communication. Department of Mechanical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Va. 24061.

American Public Health Association. 1967. "Standard Methods for the Examination of Dairy Products." 12th ed. Am. Public Health Assoc., Inc., New York, N. Y.

Associates of L. A. Rogers. 1935. "Fundamentals of Dairy Science." American Chemical Society Monograph Series, Reinhold Publishing Corporation, New York, N. Y.

Ball, C. O. 1923. Thermal processes for canned foods. Natl. Research Council Bull., Part I, No. 37.

Ball, C. O. 1928. Mathematical solution of problems on thermal processing of canned food. Univ. Calif. (Berkeley) Publications, Public Health 1: 15.

Ball, C. O. 1943. Short-time pasteurization of milk. Indust. and Eng. Chem. 35: 71.

Ball, C. O. and Olson, F. C. W. 1957. "Sterilization in Food Technology." McGraw-Hill, New York, N. Y.

Barrow, G. M. 1966. "Physical Chemistry." McGraw-Hill, New York, N. Y.

Bigelow, W. D., Bohart, G. S., Richardson, A. C. and Ball, C. O. 1920. Heat penetration in processing canned foods. Natl. Canners Assoc. Bull. 16L.

Bigelow, W. D. 1921. The logarithmic nature of thermal death time curves. J. Infect. Dis. 29: 528.

Bigger, J. W. and Nelson, J. H. 1941. Growth of coliform bacilli in distilled water. J. Pathol. and Bacteriol. 53: 189.

Brookfield Engineering Brochure. 1964. Brookfield Engineering Laboratories, Stoughton, Mass.

Brown, A. H., Lazer, M. E., Wasserman, T. and Cole, M. W. 1951. Rapid heat processing of fluid foods by steam injection. Ind. Eng. Chem. 43: 2949.

Burton, H. 1958a. An analysis of the performance of an ultra-high-temperature milk sterilizing plant. I. Introduction and physical measurements. J. Dairy Res. 25: 75.

Burton, H. 1958b. An analysis of the performance of an ultra-high-temperature milk sterilizing plant. II. Calculation of the bactericidal effectiveness. J. Dairy Res. 25: 324.

Burton, H., Franklin, J. G., Williams, D. J., Chapman, H. R., Harrison, A. J. W. and Clegg, L. F. L. 1958. An analysis of the performance of an ultra-high-temperature milk sterilizing plant. III. Comparison of experimental and calculated sporicidal effects for a strain of *Bacillus subtilis*. J. Dairy Res. 25: 338.

Burton, H. 1969. Ultra-high-temperature processed milk. Dairy Sci. Abstr. 31: 287.

Busta, F. F. 1967. Thermal inactivation characteristics of bacterial spores at ultra-high temperatures. Appl. Microbiol. 15: 640.

Carlson, V. R. 1963. HTST - Aseptic processing systems and equipment. Paper to Dairy Industry Conference, University of Nebraska, April, 1963.

Charm, S. E. 1963. "The Fundamentals of Food Engineering." The AVI Publishing Company, Inc., Westport, Conn.

Chick, H. 1910. The process of disinfection by chemical agencies and hot water. J. Hyg. 10: 237.

Dabbah, R., Moats, W. A. and Mattick, J. F. 1969. Factors affecting resistance to heat and recovery of heat-injured bacteria. J. Dairy Sci. 52: 608.

Daniels, F. and Alberty, R. A. 1967. "Physical Chemistry." 3rd ed. John Wiley & Sons, Inc., New York, N. Y.

Davis, B. D., Dulbecco, R., Eisen, H. N., Ginsberg, H. S. and Wood, W. B. Jr. 1968. "Microbiology." Hoeber Medical Division, Harper & Row, Publishers, New York, N. Y.

Dinsdale, A. and Moore, F. 1962. "Viscosity and its Measurement." Reinhold Publishing Corporation, New York, N. Y.

Edwards, J. L. Jr., Busta, F. F. and Speck, M. L. 1965a. Thermal inactivation characteristics of *Bacillus subtilis* spores at ultra-high temperatures. Appl. Microbiol. 13: 851.

Edwards, J. L. Jr., Busta, F. F. and Speck, M. L. 1965b. Heat injury of *Bacillus subtilis* spores at ultra-high temperatures. Appl. Microbiol. 13: 858.

Eilers, H., Saal, R. N. J. and Van Der Waarden, M. 1947. "Chemical and Physical Investigations on Dairy Products." Elsevier Publishing Company, Inc., New York, N. Y.

El-Bisi, H. M. and Ordal, Z. J. 1956a. The effect of certain sporulation conditions on the thermal death rate of *Bacillus coagulans* var. *thermoacidurans*. J. Bacteriol. 71: 1.

El-Bisi, H. M. and Ordal, Z. J. 1956b. The effect of sporulation temperature on the thermal resistance of *Bacillus coagulans* var. *thermoacidurans*. J. Bacteriol. 71: 10.

Esselen, W. B. and Pflug, I. J. 1956. Thermal resistance of Putrefactive Anaerobe No. 3679 spores in vegetables in the temperature range of 250-290°F. Food Technol. 10: 557.

Evans, D. A., Lachman, E. L. and Litsky, W. 1963. Some observations on the bacteriological keeping quality of milk processed by high temperatures with a 0.6 second holding time. J. Milk and Food Technol. 26: 332.

Evans, D. A. and Litsky, W. 1968. Thermal inactivation studies on certain pathogenic organisms in milk. Bact. Proceedings. 68th Annual Meeting Abstracts. Agriculture and Industrial Microbiology Section, p. 10.

Evans, D. A., Hankinson, D. J. and Litsky, W. 1970. Heat resistance of certain pathogenic bacteria in milk using a commercial plate heat exchanger. J. Dairy Sci. 53: 1659.

Farrall, A. W. 1963. "Engineering for Dairy and Food Products." John Wiley & Sons, Inc., New York, N. Y.

Fisher Scientific Manual. 1970. Fisher Scientific Company, New York, N. Y.

Foster, E. M., Nelson, F. E., Speck, M. L., Doetsch, R. N. and Olson, J. C. Jr. 1957. "Dairy Microbiology." Prentice-Hall, Inc., Englewood Cliffs, N. J.

Franklin, J. G., Williams, D. J., Chapman, H. R. and Clegg, L. F. L. 1958. Methods of assessing the sporicidal efficiency of an ultra-high-temperature milk sterilizing plant. II. Experiments with suspensions of spores in milk. J. Appl. Bacteriol. 21: 47.

Franklin, J. G., Williams, D. J., Burton, H., Chapman, H. R. and Clegg, L. F. L. 1959. The sporicidal efficiency of an ultra-high temperature sterilizing plant against thermophilic spores in milk. 15th International Dairy Congr., London. 1: 410.

Galesloot, Th. E. 1956. A simple method of estimating the bacteriological effect of sterilizing processes in milk, applied to the sterilization of milk in ultra-high temperature-short time (U.H.T.S.T.) - and "in bottle" sterilizers. Neth. Milk and Dairy J. 10(2): 79.

Glazier, L. R. 1963. Quality comparisons of high-temperature, short-time and ultra-high-temperature pasteurized milk. J. Milk and Food Technol. 26: 347.

Hall, C. W. and Trout, G. M. 1968. "Milk Pasteurization." The AVI Publishing Company, Inc., Westport, Conn.

Hedrick, T. I. 1959. Further developments in ultra-high-temperature pasteurization. Milk Ind. Found. 52nd Ann. Confer., Proc. Lab. Soc. p. 29.

Herreid, E. O. and Tobias, J. 1959. Ultra-high temperature short-time experimental studies on fluid milk products - experimental equipment. J. Dairy Sci. 42: 1486.

Hersom, A. C. and Hulland, E. D. 1964. "Canned Foods." Chemical Publishing Company, Inc., New York, N. Y.

Hsu, D. S. 1970. "Ultra High Temperature Processing and Aseptic Packaging of Dairy Products." Damana Tech Inc., New York, N. Y.

Hunziker, O. F. 1949. "Condensed Milk and Milk Powder." 7th ed. O. F. Hunziker, La Grange, Ill.

Ito, H. 1959. Friction factors for turbulent flow in curved pipes. J. Basic. Eng. Trans. A.S.M.E. Section D., 81: 123.

Jenness, R. and Patton, S. 1959. "Principles of Dairy Chemistry." John Wiley & Sons, Inc., New York, N. Y.

Judge, L. F. Jr. and Pelczar, M. P. Jr. 1955. The sterilization of carbohydrates with liquid ethylene oxide for microbiological fermentation test. Appl. Microbiol. 3: 292.

Kaufmann, O. W. and Andrews, R. H. 1954. The destruction rate of psychrophilic bacteria in skim milk. J. Dairy Sci. 37: 317.

Kramer, A. and Twigg, B. A. 1962. "Fundamentals of Quality Control for the Food Industry." The AVI Publishing Company, Inc., Westport, Conn.

Leeds and Northrup Brochure. 1968. Leeds and Northrup Company, Philadelphia, Pa.

Lindamood, J. B. and Harper, W. J. 1969. Ultra-high-temperature pasteurization. Cooperative Extension Work in Agriculture and Home Economics, Ohio State University, Columbus, Ohio, March, 1969 Bulletin.

Mallory, W. E. 1942. Process of treating liquids. U. S. Pat. 2,270,540.

McKennell, R. 1960. The influence of viscometer design on non-Newtonian measurements. Anal. Chem. 32: 1459.

Milk Industry Foundation. 1949. Laboratory Manual. M. I. F. Washington, D. C.

Moats, W. A., Dabbah, R. and Edwards, V. M. 1971. Interpretation of nonlogarithmic survivor curves of heated bacteria. J. Food Sci. 36: 523.

Olsen, A. M. and Scott, W. J. 1950. The enumeration of heated bacterial spores. I. Experiments with *Clostridium botulinum* and other species of *Clostridium*. Australian J. Sci. Res. 3: 219.

Olson, F. C. W. and Stevens, H. P. 1939. Thermal processing of canned foods in tin containers. II. Nomograms for graphic calculation of thermal processes for non-acid canned foods exhibiting straight-line semi-logarithmic heating curves. Food Res. 4: 1.

Olson, J. C. Jr., Marcy, H. and Halvorson, H. O. 1952. Thermal death-time studies of coliform bacteria in milk. Minn. Agric. Expt. Sta. Tech. Bull. 202.

Read, R. B. Jr., Boyd, T. C., Litsky, W. and Hankinson, D. J. 1956a. Come-up time method of milk pasteurization. I. Description of laboratory instrument. J. Milk and Food Technol. 19: 39.

Read, R. B. Jr., Norcross, N. L., Hankinson, D. J. and Litsky, W. 1956b. Come-up time method of milk pasteurization. II. Investigation of milk properties and some preliminary bacteriological studies. J. Milk and Food Technol. 19: 45.

Read, R. B. Jr., Norcross, N. L., Hankinson, D. J. and Litsky, W. 1957. Come-up time method of milk pasteurization. III. Bacteriological studies. J. Dairy Sci. 40: 28.

Read, R. B. Jr., Dickerson, R. W. Jr. and Thompson, H. E. Jr. 1968. Time-temperature standards for the ultra-high temperature pasteurization of grade A milk and milk products by plate heat exchange. J. Milk and Food Technol. 31: 72.

Reynolds, H., Kaplan, A. M., Spencer, F. B. and Lichtenstein, H. 1952. Thermal destruction of Cameron's Putrefactive Anaerobe 3679 in food substrates. Food Res. 17: 153.

Roswell, C. N. 1957. Engineering principles "No-hold" pasteurization. Proceedings of Fifth Annual National Dairy Engineering Conference, Michigan State University, p. 2.

Schaum, D. 1968. "Theory and Problems of College Physics." 6th ed. Schaum's Outline Series, McGraw-Hill, New York, N. Y.

Schmidt, C. F. 1957. Thermal resistance of microorganisms. In "Antiseptics, Disinfectants, Fungicides, and Chemical and Physical Sterilization," ed. Reddish, G. F., 2nd ed. p. 831. Lea and Febiger, Philadelphia, Pa.

Segner, W. P., Frazier, W. C. and Calbert, H. E. 1963. Thermal inactivation of heat-resistant bacterial spores in milk concentrate at ultra-high temperatures. J. Dairy Sci. 46: 891.

Shortley, G. and Williams, D. 1960. "Principles of College Physics." Prentice-Hall, Inc., Englewood Cliffs, N. J.

Speck, M. L. and Busta, F. F. 1968. Sterilization and aseptic packaging of milk products - Microbiological trends. J. Dairy Sci. 51: 1146.

Starka, R. P. and Stokes, J. L. 1957. Rapid destruction of bacteria in commonly used diluents and its elimination. Appl. Microbiol. 5: 21.

Steel, R. G. D. and Torrie, J. H. 1960. "Principles and Procedures of Statistics." McGraw-Hill, New York, N. Y.

Stumbo, C. R. 1948. A technique for studying resistance of bacterial spores to temperatures in the higher range. Food Technol. 2: 228.

Stumbo, C. R., Murphy, J. R. and Cochran, J. 1950. Nature of thermal death time curves of PA 3679 and *Clostridium botulinum*. Food Technol. 4: 321.

Stumbo, C. R. 1965. "Thermobacteriology in Food Processing." Academic Press, New York, N. Y.

Sugiyama, H. 1951. Studies on factors affecting the heat resistance of spores of *Clostridium botulinum*. J. Bacteriol. 62: 81.

Swanson, A. M., Sanderson, W. B. and Grindrod, J. 1964. The effects of heat treatments given to skim milk and skim milk concentrate before drying. Cereal Sci. Today 9: 292

Sykes, G. 1969. Methods and equipment for sterilization of laboratory apparatus and media. In "Methods in Microbiology," eds. Norris, J. R. and Ribbons, D. W., Vol. 1, p. 77. Academic Press, New York, N. Y.

The Canned Food Reference Manual. 1949. American Can Company, New York, N. Y.

Thomas, W. C. 1970. Private communication. Department of Mechanical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Va. 24061.

Tobias, J., Kaufmann, O. W. and Tracy, P. H. 1955. Pasteurization equivalents of high-temperature short-time heating with ice-cream mix. J. Dairy Sci. 38: 959.

United States Department of Health, Education, and Welfare. 1965. Grade "A" pasteurized milk ordinance. Public Health Service Publication No. 229. U. S. Government Printing Office, Washington, D. C.

United States Department of Health, Education, and Welfare. 1966. Recommendations of the United States Public Health Service, second draft. Public Health Service, Bureau of State Services (Environmental Health), Division of Environmental Engineering and Food Protection, Washington, D. C.

United States Department of Health, Education, and Welfare. 1971. Salmonella Surveillance Report No. 105, April 5, 1971. Public Health Service, Communicable Disease Center, Atlanta, Ga.

Viles, J. M. 1971. Private communication. Department of Mechanical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Va. 24061.

Webb, F. C. 1964. "Biochemical Engineering." D. Van Nostrand Company Ltd., New York, N. Y.

Webb, B. H. and Johnson, A. H. 1965. "Fundamentals of Dairy Chemistry." The AVI Publishing Company, Inc., Westport, Conn.

Webster, R. C. and Esselen, W. B. 1956. Thermal resistance of food poisoning organisms in poultry stuffing. J. Milk and Food Technol. 19: 209.

Whitaker, R., Sherman, J. M. and Sharp, P. F. 1927. Effect of temperature on the viscosity of skim milk. J. Dairy Sci. 10: 361.

Williams, D. J., Franklin, J. G., Chapman, H. R. and Clegg, L. F. L. 1957. Methods of assessing the sporicidal efficiency of an ultra-high-temperature milk sterilizing plant. I. Experiments with suspensions of spores in water. J. App. Bacteriol. 20: 43.

APPENDIX

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C                  COMPUTER PROGRAM
C
C  K. K. REDDY, FOOD SCIENCE AND TECHNOLOGY DEPT.
C   TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS
C  TH1=INLET TEMP. OF THE HEATING MEDIUM
C  TH2=OUTLET TEMP. OF THE HEATING MEDIUM
C  TC1=TM1= INLET TEMP. OF THE MENSTRUUM
C  TC2=TM2=OUTLET TEMP. OF THE MENSTRUUM
C  TC =TMX=TEMP. OF THE MENSTRUUM AT A DISTANCE X
C  X  = DISTANCE FROM THE INLET
C  L  =TOTAL LENGTH OF TUBING IN HEATING COIL
      DIMENSION Y(1,100),DC(2)
      H(X) = (TH1*TC2 -TC1*TH2- (TC2-TC1)*(TH1-TC1)*((TH2-TC2)/(TH1-
     1TC1))**X)/(TH1-TC1-TH2 + TC2)
      CH(X)=(TC2*TH1-TH2*TC1-(TH2-TH1)*(TH1-TC1)*((TC2-TH2)/(TC1-TH1))*
     1*X)/(TC2-TH2-TC1+TH1)
      G(BETA) = EXP(BETA)/F
      READ(5,11)(DC(I),I=1,2)
      N=1
    1 READ(5,200) TC1, TC2,TH1,TH2,RHO,XMD,Z,F,XMU
      IF(TC1.LE.0.0) STOP
      RE = 4.0*XMD/(3.1416*0.18/12.0*XMU*3600.0)
      IF(N.EQ.1)WRITE(6,900)
      IF(N.EQ.2)WRITE(6,902)
      WRITE (6, 10) TC1, TC2, TH1, TH2, RHO, XMU, XMD, RE, Z, F
      WRITE (6, 20)
      DO 100 M=1,50
  100 Y(1,M) = 0.00
      XL = 0.0
      R = 0.0
      DT=0.1
      T = 0.0
```

```
      TC = TC1
      XZ = 0.0
      WRITE (6, 30) XZ, T, TC, R, XL
      TM = 3.1416*RHO*(0.18/12.0)**2*DC(N)/4.0/XMD*3600.0
       T=0.1
      DO 2 I = 2, 50
      XZ = T/TM
      YZ = (T - 0.1*DT)/TM
      TCM = H(YZ)
      BETA = 2.303*(TCM - 150.0)/Z
      R = G(BETA)/60.0
      XL = XL + R*DT
      TC = H(XZ)
      LL = I
       Y(1,LL) = TC
      WRITE (6, 30) XZ, T, TC, R, XL
       AI = I
      IF(AI.EQ.25.)WRITE(6,903)
      IF(AI.EQ.25.)WRITE(6,900)
      IF(AI.EQ.25.)WRITE(6,10)TC1,TC2,TH1,TH2,RHO,XMU,XMD,RE,Z,F
      IF(AI.EQ.25.)WRITE(6,20)
      T = T + 0.1
      IF(T - TM) 2, 3, 3
    2 CONTINUE
  904 FORMAT(////)
    3 T = T -DT
      YZ = (T + TM)/(2.0*TM)
      TCM = H(YZ)
      BETA = 2.303*(TCM - 150.0)/Z
      R = G(BETA)/60.0
      XL = XL + R*(TM - T)
      T = TM
```

```
      XZ = 1.0
      TC = TC2
      LL =  LL + 1
       Y(1,LL) = TC
      WRITE (6, 30) XZ, T, TC, R, XL
      IF(XZ.EQ.1.)WRITE(6,901)
      TH = TM/DC(N)
      IF(N.GT.1) GO TO 51
      GO TO 52
51     TH=TH*6.5
52    BETA = 2.303*(TC-150.)/Z
      R = G(BETA)/60.0
      XL = XL + R*TH
      T = T+ TH
      XZ = T/TM
      LL =  LL + 1
       Y(1,LL) = TC
      WRITE (6, 30) XZ, T, TC, R, XL
  903 FORMAT(1H1)
      WRITE(6,903)
       N=2
      READ(5,200) TH1, TH2,TC1,TC2,RHO,XMD,Z,F,XMU
      IF(TC1.LE.0.0) STOP
      RE = 4.0*XMD/(3.1416*0.18/12.0*XMU*3600.0)
      IF(N.EQ.2)WRITE(6,902)
      WRITE (6, 10) TC1, TC2, TH1, TH2, RHO, XMU, XMD, RE, Z, F
      WRITE (6, 20)
      DO 101 M=1,50
  101 Y(1,M) = 0.00
      XL = 0.0
      R = 0.0
      DT=0.1
```

```
      T = 0.0
      TC = TH1
      XZ = 0.0
      WRITE (6, 30) XZ, T, TC, R, XL
      TM = 3.1416*RHO*(0.18/12.0)**2*DC(N)/4.0/XMD*3600.0
       T=0.1
      DO 22 I = 2, 50
      XZ = T/TM
      YZ = (T - 0.1*DT)/TM
      TCM =CH(YZ)
      BETA = 2.303*(TCM - 150.0)/Z
      R = G(BETA)/60.0
      XL = XL + R*DT
      TC = CH(XZ)
      LL = I
       Y(1,LL) = TC
      WRITE (6, 30) XZ, T, TC, R, XL
       AI = I
      IF(AI.EQ.25.)WRITE(6,903)
      IF(AI.EQ.25.)WRITE(6,902)
      IF(AI.EQ.25.)WRITE(6,10)TC1,TC2,TH1,TH2,RHO,XMU,XMD,RE,Z,F
      IF(AI.EQ.25.)WRITE(6,20)
      T = T + 0.1
      IF(T - TM) 22,33,33
   22 CONTINUE
   33 T = T -DT
      YZ = (T + TM)/(2.0*TM)
      TCM = CH(YZ)
      BETA = 2.303*(TCM - 150.0)/Z
      R = G(BETA)/60.0
      XL = XL + R*(TM - T)
      T = TM
```

```
      XZ = 1.0
      TC = TH2
      LL =  LL + 1
       Y(1,LL) = TC
      WRITE (6, 30) XZ, T, TC, R, XL
      TH = TM/DC(N)
       TH=TH*6.5
      BETA = 2.303*(TC-150.)/Z
      R = G(BETA)/60.0
      XL = XL + R*TH
      T = T+ TH
      XZ = T/TM
      LL =  LL + 1
       Y(1,LL) = TC
      IF(XZ.EQ.1.)GO TO 1
      WRITE (6, 30) XZ, T, TC, R, XL
      GO TO 1
   10 FORMAT(15X,'TC1   TC2   TH1   TH2  DENSITY VISCOSITY',//,13X,4F6.1
     1,F7.2,2X,E9.3,//,19X,'MASS-FLOW    RE. NO.    Z      F',//,19X,
     2F8.2,F12.2,2F7.2,//)
   20 FORMAT(14X,'X/L  TIME  PROD TEMP   RATE     LETHALITY',/)
   30 FORMAT(12X,F5.2,F6.2,F9.2,F10.4,F11.4,F8.2)
  200 FORMAT(8F8.2,F10.8)
11    FORMAT(1X,2(F4.2,3X))
  900 FORMAT(////,9X,'TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATION
     1S',//, 6X,'IN 10% NDM MENSTRUUM AT A VELOCITY OF  5.2 FT/SEC (HEAT
     2ING)',//)
  901 FORMAT(//,9X,'TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS'
     1  ,//, 6X,'IN 10% NDM MENSTRUUM AT A VELOCITY OF  5.2 FT/SEC (HOLD
     2ING)',//)
  902 FORMAT(////,9X,'TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATION
     1S',//, 6X,'IN 10% NDM MENSTRUUM AT A VELOCITY OF  5.2 FT/SEC (COOL
```

```
     2ING)',//)
      END
```

```
   TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS

IN    MINIMAL   BROTH   AT A VELOCITY OF   5.5 FT/SEC (HEATING)

           TC1    TC2    TH1    TH2   DENSITY VISCOSITY

          125.0 150.0 156.0 154.0   61.37   0.326E-03

               MASS-FLOW     RE. NO.     Z        F

                 216.00     15622.56  11.40    6.10

          X/L   TIME   PROD TEMP   RATE      LETHALITY

         0.0    0.0     125.00     0.0          0.0
         0.02   0.10    126.18     0.0000       0.0000
         0.04   0.20    127.30     0.0000       0.0000
         0.06   0.30    128.38     0.0000       0.0000
         0.08   0.40    129.42     0.0000       0.0000
         0.10   0.50    130.41     0.0001       0.0000
         0.12   0.60    131.37     0.0001       0.0000
         0.14   0.70    132.28     0.0001       0.0000
         0.16   0.80    133.16     0.0001       0.0000
         0.18   0.90    134.00     0.0001       0.0001
         0.20   1.00    134.81     0.0001       0.0001
         0.22   1.10    135.58     0.0001       0.0001
         0.24   1.20    136.32     0.0002       0.0001
         0.27   1.30    137.03     0.0002       0.0001
         0.29   1.40    137.72     0.0002       0.0001
         0.31   1.50    138.37     0.0003       0.0002
         0.33   1.60    139.00     0.0003       0.0002
         0.35   1.70    139.60     0.0003       0.0002
         0.37   1.80    140.18     0.0004       0.0003
         0.39   1.90    140.73     0.0004       0.0003
         0.41   2.00    141.26     0.0005       0.0004
         0.43   2.10    141.77     0.0005       0.0004
         0.45   2.20    142.26     0.0006       0.0005
         0.47   2.30    142.73     0.0006       0.0005
         0.49   2.40    143.18     0.0007       0.0006
```

```
   TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS

IN   MINIMAL  BROTH  AT A VELOCITY OF  5.5 FT/SEC (HEATING)

         TC1   TC2   TH1   TH2  DENSITY VISCOSITY

        125.0 150.0 156.0 154.0  61.37  0.326E-03

             MASS-FLOW    RE. NO.    Z      F

               216.00    15622.56  11.40   6.10

        X/L  TIME  PROD TEMP   RATE     LETHALITY

       0.51  2.50   143.61    0.0007     0.0007
       0.53  2.60   144.02    0.0008     0.0007
       0.55  2.70   144.42    0.0009     0.0008
       0.57  2.80   144.80    0.0009     0.0009
       0.59  2.90   145.16    0.0010     0.0010
       0.61  3.00   145.51    0.0011     0.0011
       0.63  3.10   145.85    0.0012     0.0013
       0.65  3.20   146.17    0.0013     0.0014
       0.67  3.30   146.48    0.0013     0.0015
       0.69  3.40   146.77    0.0014     0.0017
       0.71  3.50   147.06    0.0015     0.0018
       0.73  3.60   147.33    0.0016     0.0020
       0.76  3.70   147.59    0.0017     0.0021
       0.78  3.80   147.84    0.0018     0.0023
       0.80  3.90   148.08    0.0018     0.0025
       0.82  4.00   148.31    0.0019     0.0027
       0.84  4.10   148.53    0.0020     0.0029
       0.86  4.20   148.74    0.0021     0.0031
       0.88  4.30   148.95    0.0022     0.0033
       0.90  4.40   149.14    0.0023     0.0035
       0.92  4.50   149.33    0.0024     0.0038
       0.94  4.60   149.51    0.0025     0.0040
       0.96  4.70   149.68    0.0026     0.0043
       0.98  4.80   149.84    0.0026     0.0046
       1.00  4.90   150.00    0.0027     0.0048

   TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS

IN  MINIMAL BROTH    AT A VELOCITY OF  5.5 FT/SEC (HOLDING)


       1.04  5.08   150.00    0.0027     0.0053
```

```
   TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS

 IN  MINIMAL BROTH    AT A VELOCITY OF  5.5 FT/SEC (COOLING)

          TC1    TC2   TH1    TH2  DENSITY VISCOSITY

          39.0   36.0 150.0   40.0  61.37  0.326E-03

             MASS-FLOW     RE. NO.    Z       F

               216.00     15622.56  11.40   6.10

        X/L   TIME  PROD TEMP   RATE     LETHALITY

       0.0    0.0     150.00    0.0        0.0
       0.01   0.10    144.61    0.0010     0.0001
       0.03   0.20    139.48    0.0004     0.0001
       0.04   0.30    134.58    0.0001     0.0002
       0.06   0.40    129.92    0.0001     0.0002
       0.07   0.50    125.48    0.0000     0.0002
       0.09   0.60    121.25    0.0000     0.0002
       0.10   0.70    117.22    0.0000     0.0002
       0.12   0.80    113.37    0.0000     0.0002
       0.13   0.90    109.72    0.0000     0.0002
       0.15   1.00    106.23    0.0000     0.0002
       0.16   1.10    102.91    0.0000     0.0002
       0.17   1.20     99.74    0.0000     0.0002
       0.19   1.30     96.72    0.0000     0.0002
       0.20   1.40     93.85    0.0000     0.0002
       0.22   1.50     91.11    0.0000     0.0002
       0.23   1.60     88.51    0.0000     0.0002
       0.25   1.70     86.02    0.0000     0.0002
       0.26   1.80     83.65    0.0000     0.0002
       0.28   1.90     81.40    0.0000     0.0002
       0.29   2.00     79.25    0.0000     0.0002
       0.31   2.10     77.20    0.0000     0.0002
       0.32   2.20     75.25    0.0000     0.0002
       0.33   2.30     73.39    0.0000     0.0002
       0.35   2.40     71.62    0.0000     0.0002
```

```
   TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS
IN  MINIMAL BROTH    AT A VELOCITY OF  5.5 FT/SEC (COOLING)

          TC1   TC2   TH1   TH2  DENSITY VISCOSITY
          39.0  36.0 150.0  40.0  61.37  0.326E-03
              MASS-FLOW    RE. NO.    Z      F
                216.00    15622.56  11.40   6.10

         X/L   TIME  PROD TEMP   RATE     LETHALITY

        0.36   2.50    69.93    0.0000     0.0002
        0.38   2.60    68.32    0.0000     0.0002
        0.39   2.70    66.79    0.0000     0.0002
        0.41   2.80    65.33    0.0000     0.0002
        0.42   2.90    63.94    0.0000     0.0002
        0.44   3.00    62.61    0.0000     0.0002
        0.45   3.10    61.35    0.0000     0.0002
        0.47   3.20    60.15    0.0000     0.0002
        0.48   3.30    59.00    0.0000     0.0002
        0.50   3.40    57.91    0.0000     0.0002
        0.51   3.50    56.87    0.0000     0.0002
        0.52   3.60    55.88    0.0000     0.0002
        0.54   3.70    54.94    0.0000     0.0002
        0.55   3.80    54.04    0.0000     0.0002
        0.57   3.90    53.18    0.0000     0.0002
        0.58   4.00    52.36    0.0000     0.0002
        0.60   4.10    51.58    0.0000     0.0002
        0.61   4.20    50.84    0.0000     0.0002
        0.63   4.30    50.14    0.0000     0.0002
        0.64   4.40    49.46    0.0000     0.0002
        0.66   4.50    48.82    0.0000     0.0002
        0.67   4.60    48.21    0.0000     0.0002
        0.68   4.70    47.63    0.0000     0.0002
        0.70   4.80    47.08    0.0000     0.0002
        0.71   4.90    46.55    0.0000     0.0002
        1.00   6.87    40.00    0.0000     0.0002
        1.17   8.04    40.00    0.0000     0.0002
```

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   TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS

 IN 10% NDM MENSTRUUM AT A VELOCITY OF  5.2 FT/SEC (HEATING)

         TC1    TC2    TH1    TH2   DENSITY VISCOSITY

        124.0 160.0 168.0 164.0   63.71   0.436E-03

              MASS-FLOW     RE. NO.     Z        F

                213.33     11536.69  11.40    6.10


        X/L   TIME   PROD TEMP   RATE      LETHALITY

       0.0    0.0     124.00     0.0         0.0
       0.02   0.10    125.80     0.0000      0.0000
       0.04   0.20    127.52     0.0000      0.0000
       0.06   0.30    129.16     0.0000      0.0000
       0.08   0.40    130.73     0.0001      0.0000
       0.10   0.50    132.23     0.0001      0.0000
       0.12   0.60    133.65     0.0001      0.0000
       0.14   0.70    135.02     0.0001      0.0000
       0.16   0.80    136.32     0.0002      0.0001
       0.17   0.90    137.56     0.0002      0.0001
       0.19   1.00    138.74     0.0003      0.0001
       0.21   1.10    139.87     0.0003      0.0001
       0.23   1.20    140.95     0.0004      0.0002
       0.25   1.30    141.98     0.0005      0.0002
       0.27   1.40    142.97     0.0006      0.0003
       0.29   1.50    143.91     0.0008      0.0004
       0.31   1.60    144.80     0.0009      0.0005
       0.33   1.70    145.66     0.0011      0.0006
       0.35   1.80    146.48     0.0013      0.0007
       0.37   1.90    147.25     0.0015      0.0009
       0.39   2.00    148.00     0.0018      0.0011
       0.41   2.10    148.71     0.0021      0.0013
       0.43   2.20    149.39     0.0024      0.0015
       0.45   2.30    150.03     0.0027      0.0018
       0.47   2.40    150.65     0.0031      0.0021
```

```
   TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS

IN 10% NDM MENSTRUUM AT A VELOCITY OF  5.2 FT/SEC (HEATING)

          TC1    TC2    TH1    TH2   DENSITY VISCOSITY

         124.0  160.0  168.0  164.0   63.71   0.436E-03

                MASS-FLOW     RE. NO.     Z       F

                  213.33     11536.69  11.40    6.10


         X/L   TIME   PROD TEMP    RATE      LETHALITY

        0.49   2.50    151.24     0.0035      0.0024
        0.50   2.60    151.80     0.0039      0.0028
        0.52   2.70    152.34     0.0043      0.0032
        0.54   2.80    152.85     0.0048      0.0037
        0.56   2.90    153.34     0.0053      0.0043
        0.58   3.00    153.81     0.0058      0.0048
        0.60   3.10    154.25     0.0064      0.0055
        0.62   3.20    154.68     0.0070      0.0062
        0.64   3.30    155.08     0.0076      0.0069
        0.66   3.40    155.47     0.0082      0.0078
        0.68   3.50    155.84     0.0088      0.0086
        0.70   3.60    156.19     0.0095      0.0096
        0.72   3.70    156.53     0.0102      0.0106
        0.74   3.80    156.85     0.0108      0.0117
        0.76   3.90    157.16     0.0115      0.0128
        0.78   4.00    157.45     0.0122      0.0141
        0.80   4.10    157.73     0.0130      0.0154
        0.82   4.20    158.00     0.0137      0.0167
        0.84   4.30    158.25     0.0144      0.0182
        0.85   4.40    158.50     0.0151      0.0197
        0.87   4.50    158.73     0.0159      0.0213
        0.89   4.60    158.95     0.0166      0.0229
        0.91   4.70    159.16     0.0173      0.0247
        0.93   4.80    159.37     0.0180      0.0265
        0.95   4.90    159.56     0.0188      0.0283
        1.00   5.15    160.00     0.0197      0.0333

   TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS

IN 10% NDM MENSTRUUM AT A VELOCITY OF  5.2 FT/SEC (HOLDING)


        1.04   5.34    160.00     0.0206      0.0372
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      TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS

    IN 10% NDM MENSTRUUM AT A VELOCITY OF  5.2 FT/SEC (COOLING)

              TC1    TC2    TH1    TH2   DENSITY VISCOSITY

              41.0   36.0 160.0   41.5   63.71   0.436E-03

                  MASS-FLOW     RE. NO.     Z       F

                    213.33    11536.69  11.40    6.10


             X/L   TIME   PROD TEMP   RATE      LETHALITY

            0.0    0.0     160.00     0.0        0.0
            0.01   0.10    154.82     0.0080     0.0008
            0.03   0.20    149.86     0.0029     0.0011
            0.04   0.30    145.10     0.0011     0.0012
            0.06   0.40    140.54     0.0004     0.0013
            0.07   0.50    136.17     0.0002     0.0013
            0.08   0.60    131.99     0.0001     0.0013
            0.10   0.70    127.98     0.0000     0.0013
            0.11   0.80    124.13     0.0000     0.0013
            0.12   0.90    120.45     0.0000     0.0013
            0.14   1.00    116.92     0.0000     0.0013
            0.15   1.10    113.53     0.0000     0.0013
            0.17   1.20    110.29     0.0000     0.0013
            0.18   1.30    107.18     0.0000     0.0013
            0.19   1.40    104.21     0.0000     0.0013
            0.21   1.50    101.35     0.0000     0.0013
            0.22   1.60     98.62     0.0000     0.0013
            0.24   1.70     96.00     0.0000     0.0013
            0.25   1.80     93.49     0.0000     0.0013
            0.26   1.90     91.08     0.0000     0.0013
            0.28   2.00     88.77     0.0000     0.0013
            0.29   2.10     86.56     0.0000     0.0013
            0.30   2.20     84.44     0.0000     0.0013
            0.32   2.30     82.41     0.0000     0.0013
            0.33   2.40     80.47     0.0000     0.0013
```

```
    TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS

IN 10% NDM MENSTRUUM AT A VELOCITY OF  5.2 FT/SEC (COOLING)

          TC1    TC2    TH1    TH2   DENSITY VISCOSITY

          41.0   36.0 160.0   41.5   63.71   0.436E-03

                MASS-FLOW     RE. NO.     Z       F

                  213.33     11536.69  11.40    6.10


         X/L   TIME   PROD TEMP    RATE      LETHALITY

        0.35   2.50     78.61     0.0000      0.0013
        0.36   2.60     76.82     0.0000      0.0013
        0.37   2.70     75.11     0.0000      0.0013
        0.39   2.80     73.47     0.0000      0.0013
        0.40   2.90     71.89     0.0000      0.0013
        0.42   3.00     70.39     0.0000      0.0013
        0.43   3.10     68.94     0.0000      0.0013
        0.44   3.20     67.56     0.0000      0.0013
        0.46   3.30     66.23     0.0000      0.0013
        0.47   3.40     64.96     0.0000      0.0013
        0.48   3.50     63.75     0.0000      0.0013
        0.50   3.60     62.58     0.0000      0.0013
        0.51   3.70     61.46     0.0000      0.0013
        0.53   3.80     60.39     0.0000      0.0013
        0.54   3.90     59.36     0.0000      0.0013
        0.55   4.00     58.38     0.0000      0.0013
        0.57   4.10     57.44     0.0000      0.0013
        0.58   4.20     56.53     0.0000      0.0013
        0.60   4.30     55.67     0.0000      0.0013
        0.61   4.40     54.84     0.0000      0.0013
        0.62   4.50     54.04     0.0000      0.0013
        0.64   4.60     53.28     0.0000      0.0013
        0.65   4.70     52.55     0.0000      0.0013
        0.66   4.80     51.85     0.0000      0.0013
        0.68   4.90     51.18     0.0000      0.0013
        1.00   7.22     41.50     0.0000      0.0013
        1.17   8.45     41.50     0.0000      0.0013
```

```
   TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS

IN 20% NDM MENSTRUUM AT A VELOCITY OF 10.1 FT/SEC (HEATING)

             TC1    TC2    TH1    TH2   DENSITY VISCOSITY

            128.0 170.0 214.0 201.0   65.81   0.830E-03

                  MASS-FLOW     RE. NO.    Z       F

                    435.00    12357.39  11.40    6.10


             X/L   TIME   PROD TEMP   RATE      LETHALITY

            0.0    0.0     128.00    0.0          0.0
            0.04   0.10    130.52    0.0001       0.0000
            0.08   0.20    132.94    0.0001       0.0000
            0.12   0.30    135.27    0.0001       0.0000
            0.15   0.40    137.51    0.0002       0.0000
            0.19   0.50    139.67    0.0003       0.0001
            0.23   0.60    141.74    0.0005       0.0001
            0.27   0.70    143.73    0.0007       0.0002
            0.31   0.80    145.65    0.0011       0.0003
            0.35   0.90    147.49    0.0016       0.0005
            0.38   1.00    149.26    0.0023       0.0007
            0.42   1.10    150.97    0.0032       0.0010
            0.46   1.20    152.60    0.0045       0.0015
            0.50   1.30    154.18    0.0062       0.0021
            0.54   1.40    155.70    0.0084       0.0029
            0.58   1.50    157.15    0.0113       0.0040
            0.61   1.60    158.55    0.0150       0.0055
            0.65   1.70    159.90    0.0197       0.0075
            0.69   1.80    161.20    0.0256       0.0101
            0.73   1.90    162.44    0.0329       0.0134
            0.77   2.00    163.64    0.0420       0.0176
            0.81   2.10    164.79    0.0530       0.0229
            0.84   2.20    165.90    0.0664       0.0295
            0.88   2.30    166.97    0.0824       0.0377
            0.92   2.40    167.99    0.1014       0.0479
```

```
 TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS

IN 20% NDM MENSTRUUM AT A VELOCITY OF 10.1 FT/SEC (HEATING)

        TC1    TC2    TH1    TH2   DENSITY VISCOSITY

       128.0 170.0 214.0 201.0   65.81   0.830E-03

           MASS-FLOW     RE. NO.     Z       F

             435.00     12357.39  11.40   6.10

       X/L   TIME   PROD TEMP    RATE      LETHALITY

      0.96   2.50    168.98     0.1238      0.0603
      1.00   2.60    169.92     0.1501      0.0753
      1.00   2.61    170.00     0.1541      0.0765

 TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS

IN 20% NDM MENSTRUUM AT A VELOCITY OF 10.1 FT/SEC (HOLDING)

      1.04   2.70    170.00     0.1553      0.0915
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     TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS
IN 20% NDM MENSTRUUM AT A VELOCITY OF 10.1 FT/SEC (COOLING)

         TC1    TC2    TH1    TH2   DENSITY VISCOSITY

         62.6   35.6 170.0   66.2   65.81   0.830E-03

              MASS-FLOW     RE. NO.     Z        F

                435.00     12357.39  11.40    6.10


        X/L   TIME   PROD TEMP    RATE       LETHALITY

       0.0    0.0     170.00     0.0          0.0
       0.03   0.10    165.10     0.0636       0.0064
       0.05   0.20    160.37     0.0244       0.0088
       0.08   0.30    155.79     0.0096       0.0098
       0.11   0.40    151.37     0.0039       0.0102
       0.14   0.50    147.10     0.0017       0.0103
       0.16   0.60    142.98     0.0007       0.0104
       0.19   0.70    138.99     0.0003       0.0104
       0.22   0.80    135.14     0.0001       0.0104
       0.25   0.90    131.42     0.0001       0.0105
       0.27   1.00    127.82     0.0000       0.0105
       0.30   1.10    124.35     0.0000       0.0105
       0.33   1.20    120.99     0.0000       0.0105
       0.36   1.30    117.74     0.0000       0.0105
       0.38   1.40    114.61     0.0000       0.0105
       0.41   1.50    111.58     0.0000       0.0105
       0.44   1.60    108.65     0.0000       0.0105
       0.46   1.70    105.82     0.0000       0.0105
       0.49   1.80    103.09     0.0000       0.0105
       0.52   1.90    100.45     0.0000       0.0105
       0.55   2.00     97.90     0.0000       0.0105
       0.57   2.10     95.43     0.0000       0.0105
       0.60   2.20     93.05     0.0000       0.0105
       0.63   2.30     90.75     0.0000       0.0105
       0.66   2.40     88.52     0.0000       0.0105
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   TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS

IN 20% NDM MENSTRUUM AT A VELOCITY OF 10.1 FT/SEC (COOLING)

          TC1    TC2    TH1    TH2   DENSITY VISCOSITY

          62.6   35.6 170.0   66.2   65.81   0.830E-03

               MASS-FLOW     RE. NO.     Z        F

                  435.00     12357.39  11.40    6.10

         X/L   TIME   PROD TEMP    RATE      LETHALITY

        0.68   2.50     86.37     0.0000      0.0105
        0.71   2.60     84.30     0.0000      0.0105
        0.74   2.70     82.29     0.0000      0.0105
        0.77   2.80     80.35     0.0000      0.0105
        0.79   2.90     78.48     0.0000      0.0105
        0.82   3.00     76.67     0.0000      0.0105
        0.85   3.10     74.92     0.0000      0.0105
        0.87   3.20     73.23     0.0000      0.0105
        0.90   3.30     71.60     0.0000      0.0105
        0.93   3.40     70.02     0.0000      0.0105
        0.96   3.50     68.50     0.0000      0.0105
        0.98   3.60     67.02     0.0000      0.0105
        1.00   3.66     66.20     0.0000      0.0105
        1.17   4.28     66.20     0.0000      0.0105
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      TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS

IN 30% NDM MENSTRUUM AT A VELOCITY OF 27.0 FT/SEC (HEATING)

         TC1    TC2    TH1    TH2   DENSITY VISCOSITY

        134.0 180.0 220.0 202.0   68.26   0.1906E-02

             MASS-FLOW     RE. NO.     Z        F

              1200.00     14891.66  11.40    6.10


        X/L   TIME   PROD TEMP    RATE      LETHALITY

       0.0    0.0     134.00     0.0         0.0
       0.10   0.10    142.02     0.0005      0.0000
       0.20   0.20    149.00     0.0020      0.0002
       0.31   0.30    155.08     0.0068      0.0009
       0.41   0.40    160.37     0.0201      0.0029
       0.51   0.50    164.97     0.0515      0.0081
       0.61   0.60    168.97     0.1169      0.0198
       0.71   0.70    172.45     0.2386      0.0436
       0.82   0.80    175.48     0.4441      0.0880
       0.92   0.90    178.12     0.7624      0.1643
       1.00   0.98    180.00     0.9740      0.2429

      TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS

IN 30% NDM MENSTRUUM AT A VELOCITY OF 27.0 FT/SEC (HOLDING)


       1.04   1.02    180.00     1.1710      0.2852
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   TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS

IN 30% NDM MENSTRUUM AT A VELOCITY OF 27.0 FT/SEC (COOLING)

          TC1    TC2    TH1    TH2   DENSITY VISCOSITY

          64.0   36.0  180.0   80.0   68.26   0.190E-02

              MASS-FLOW     RE. NO.      Z        F

               1200.00     14891.66   11.40     6.10


         X/L   TIME   PROD TEMP    RATE      LETHALITY

        0.0    0.0     180.00      0.0         0.0
        0.07   0.10    169.03      0.1583      0.0158
        0.15   0.20    158.81      0.0198      0.0178
        0.22   0.30    149.29      0.0029      0.0181
        0.29   0.40    140.41      0.0005      0.0181
        0.36   0.50    132.14      0.0001      0.0182
        0.44   0.60    124.43      0.0000      0.0182
        0.51   0.70    117.25      0.0000      0.0182
        0.58   0.80    110.55      0.0000      0.0182
        0.65   0.90    104.31      0.0000      0.0182
        0.73   1.00     98.50      0.0000      0.0182
        0.80   1.10     93.08      0.0000      0.0182
        0.87   1.20     88.03      0.0000      0.0182
        0.95   1.30     83.32      0.0000      0.0182
        1.00   1.38     80.00      0.0000      0.0182
        1.17   1.61     80.00      0.0000      0.0182
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        TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS
IN 40% NDM MENSTRUUM AT A VELOCITY OF 29.6 FT/SEC (HEATING)

            TC1    TC2    TH1    TH2   DENSITY VISCOSITY
           142.0 190.0 254.0 238.0   70.98   0.806E-02
                MASS-FLOW     RE. NO.     Z       F
                 1380.00      4037.01  11.40    6.10

           X/L   TIME   PROD TEMP    RATE      LETHALITY

          0.0    0.0     142.00     0.0          0.0
          0.11   0.10    149.65     0.0022       0.0002
          0.23   0.20    156.61     0.0091       0.0011
          0.34   0.30    162.94     0.0330       0.0044
          0.45   0.40    168.68     0.1065       0.0151
          0.56   0.50    173.91     0.3090       0.0460
          0.68   0.60    178.65     0.8137       0.1273
          0.79   0.70    182.97     1.9618       0.3235
          0.90   0.80    186.89     4.3653       0.7601
          1.00   0.89    190.00     6.4904       1.3231

        TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS
IN 40% NDM MENSTRUUM AT A VELOCITY OF 29.6 FT/SEC (HOLDING)

          1.04   0.92    190.00     8.8292       1.6120
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      TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS
  IN 40% NDM MENSTRUUM AT A VELOCITY OF 29.6 FT/SEC (COOLING)

              TC1    TC2    TH1    TH2   DENSITY VISCOSITY

              62.0   36.0  190.0   96.8   70.98   0.806E-02

                   MASS-FLOW     RE. NO.     Z        F

                    1380.00      4037.01   11.40    6.10


             X/L   TIME   PROD TEMP    RATE       LETHALITY

            0.0    0.0     190.00     0.0          0.0
            0.08   0.10    179.68     1.3455       0.1346
            0.16   0.20    169.97     0.1867       0.1532
            0.24   0.30    160.81     0.0291       0.1561
            0.32   0.40    152.19     0.0050       0.1566
            0.40   0.50    144.07     0.0010       0.1567
            0.48   0.60    136.43     0.0002       0.1568
            0.56   0.70    129.22     0.0000       0.1568
            0.64   0.80    122.44     0.0000       0.1568
            0.72   0.90    116.05     0.0000       0.1568
            0.80   1.00    110.03     0.0000       0.1568
            0.88   1.10    104.36     0.0000       0.1568
            0.97   1.20     99.02     0.0000       0.1568
            1.00   1.24     96.80     0.0000       0.1568
            1.17   1.46     96.80     0.0000       0.1568
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     TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS
IN   MINIMAL  BROTH  AT A VELOCITY OF 27.0 FT/SEC (HEATING)

             TC1   TC2   TH1   TH2  DENSITY VISCOSITY

            135.0 174.0 210.0 199.0  60.66  0.279E-03

                  MASS-FLOW    RE. NO.    Z      F

                   1080.00    91271.56  11.40   6.10

            X/L   TIME  PROD TEMP   RATE      LETHALITY

           0.0    0.0    135.00     0.0        0.0
           0.10   0.10   141.27     0.0004     0.0000
           0.21   0.20   146.88     0.0013     0.0002
           0.31   0.30   151.88     0.0036     0.0005
           0.41   0.40   156.34     0.0090     0.0014
           0.52   0.50   160.33     0.0204     0.0035
           0.62   0.60   163.88     0.0422     0.0077
           0.72   0.70   167.06     0.0807     0.0158
           0.83   0.80   169.90     0.1441     0.0302
           0.93   0.90   172.43     0.2416     0.0543
           1.00   0.97   174.00     0.2982     0.0747

     TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS
IN  MINIMAL BROTH    AT A VELOCITY OF 27.0 FT/SEC (HOLDING)

           1.04   1.00   174.00     0.3485     0.0872
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   TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS

IN  MINIMAL BROTH     AT A VELOCITY OF 27.0 FT/SEC (COOLING)

            TC1    TC2    TH1    TH2   DENSITY VISCOSITY

            64.4   35.6 174.0   66.0   60.66   0.279E-03

                MASS-FLOW     RE. NO.     Z        F

                 1080.00     91271.56  11.40    6.10


          X/L   TIME   PROD TEMP    RATE       LETHALITY

         0.0    0.0     174.00     0.0          0.0
         0.07   0.10    160.53     0.0298       0.0030
         0.15   0.20    148.28     0.0024       0.0032
         0.22   0.30    137.12     0.0003       0.0032
         0.29   0.40    126.98     0.0000       0.0032
         0.37   0.50    117.75     0.0000       0.0032
         0.44   0.60    109.35     0.0000       0.0032
         0.52   0.70    101.70     0.0000       0.0032
         0.59   0.80     94.75     0.0000       0.0032
         0.66   0.90     88.42     0.0000       0.0032
         0.74   1.00     82.67     0.0000       0.0032
         0.81   1.10     77.43     0.0000       0.0032
         0.88   1.20     72.66     0.0000       0.0032
         0.96   1.30     68.33     0.0000       0.0032
         1.00   1.36     66.00     0.0000       0.0032
         1.17   1.59     66.00     0.0000       0.0032
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   TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS

IN 10% NDM MENSTRUUM AT A VELOCITY OF 27.0 FT/SEC (HEATING)

         TC1    TC2    TH1    TH2   DENSITY VISCOSITY

        131.0 176.0 222.0 210.0   62.90  0.383E-03

            MASS-FLOW     RE. NO.     Z       F

             1110.00    68334.56  11.40    6.10


        X/L   TIME  PROD TEMP   RATE     LETHALITY

       0.0    0.0     131.00    0.0        0.0
       0.10   0.10    137.89    0.0002     0.0000
       0.20   0.20    144.11    0.0007     0.0001
       0.31   0.30    149.74    0.0023     0.0003
       0.41   0.40    154.83    0.0066     0.0010
       0.51   0.50    159.44    0.0168     0.0027
       0.61   0.60    163.60    0.0393     0.0066
       0.72   0.70    167.36    0.0847     0.0151
       0.82   0.80    170.76    0.1696     0.0320
       0.92   0.90    173.84    0.3177     0.0638
       1.00   0.98    176.00    0.4212     0.0962

   TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS

IN 10% NDM MENSTRUUM AT A VELOCITY OF 27.0 FT/SEC (HOLDING)


       1.04   1.01    176.00    0.5220     0.1150
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   TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS

IN 10% NDM MENSTRUUM AT A VELOCITY OF 27.0 FT/SEC (COOLING)

          TC1   TC2   TH1   TH2  DENSITY VISCOSITY

          64.4  35.6 176.0  68.0  62.90  0.383E-03

              MASS-FLOW    RE. NO.    Z      F

               1110.00    68334.56  11.40   6.10

         X/L   TIME  PROD TEMP   RATE     LETHALITY

        0.0    0.0    176.00    0.0         0.0
        0.07   0.10   162.86    0.0474      0.0047
        0.15   0.20   150.86    0.0041      0.0051
        0.22   0.30   139.89    0.0004      0.0052
        0.29   0.40   129.87    0.0001      0.0052
        0.36   0.50   120.72    0.0000      0.0052
        0.44   0.60   112.35    0.0000      0.0052
        0.51   0.70   104.71    0.0000      0.0052
        0.58   0.80    97.73    0.0000      0.0052
        0.66   0.90    91.35    0.0000      0.0052
        0.73   1.00    85.52    0.0000      0.0052
        0.80   1.10    80.19    0.0000      0.0052
        0.88   1.20    75.32    0.0000      0.0052
        0.95   1.30    70.88    0.0000      0.0052
        1.00   1.37    68.00    0.0000      0.0052
        1.17   1.60    68.00    0.0000      0.0052
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      TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS

   IN 20% NDM MENSTRUUM AT A VELOCITY OF 27.0 FT/SEC (HEATING)

            TC1    TC2    TH1    TH2   DENSITY VISCOSITY

           130.0 178.0 226.0 214.0   65.64   0.708E-03

                 MASS-FLOW     RE. NO.     Z       F

                  1170.00     38964.45  11.40    6.10


           X/L   TIME   PROD TEMP   RATE      LETHALITY

          0.0    0.0     130.00     0.0         0.0
          0.10   0.10    137.41     0.0002      0.0000
          0.21   0.20    144.10     0.0007      0.0001
          0.31   0.30    150.14     0.0025      0.0003
          0.41   0.40    155.61     0.0076      0.0011
          0.52   0.50    160.54     0.0209      0.0032
          0.62   0.60    165.01     0.0523      0.0084
          0.72   0.70    169.04     0.1183      0.0202
          0.83   0.80    172.68     0.2487      0.0451
          0.93   0.90    175.97     0.4867      0.0938
          1.00   0.97    178.00     0.6390      0.1367

      TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS

   IN 20% NDM MENSTRUUM AT A VELOCITY OF 27.0 FT/SEC (HOLDING)


          1.04   1.00    178.00     0.7818      0.1646
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    TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS

IN 20% NDM MENSTRUUM AT A VELOCITY OF 27.0 FT/SEC (COOLING)

           TC1    TC2    TH1    TH2   DENSITY VISCOSITY

           62.6   36.0 178.0   68.0   65.64   0.708E-03

                MASS-FLOW     RE. NO.     Z       F

                 1170.00     38964.45  11.40    6.10


          X/L   TIME  PROD TEMP    RATE      LETHALITY

         0.0    0.0     178.00    0.0          0.0
         0.07   0.10    164.26    0.0636       0.0064
         0.15   0.20    151.77    0.0050       0.0069
         0.22   0.30    140.40    0.0005       0.0069
         0.29   0.40    130.06    0.0001       0.0069
         0.37   0.50    120.65    0.0000       0.0069
         0.44   0.60    112.09    0.0000       0.0069
         0.52   0.70    104.30    0.0000       0.0069
         0.59   0.80     97.22    0.0000       0.0069
         0.66   0.90     90.77    0.0000       0.0069
         0.74   1.00     84.91    0.0000       0.0069
         0.81   1.10     79.57    0.0000       0.0069
         0.88   1.20     74.72    0.0000       0.0069
         0.96   1.30     70.31    0.0000       0.0069
         1.00   1.36     68.00    0.0000       0.0069
         1.17   1.59     68.00    0.0000       0.0069
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      TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS

   IN 10% NDM MENSTRUUM AT A VELOCITY OF 27.0 FT/SEC (HEATING)

                TC1    TC2    TH1    TH2   DENSITY VISCOSITY

               131.0 180.0 222.0 210.0   62.90   0.383E-03

                    MASS-FLOW     RE. NO.     Z        F

                     1110.00     68334.56  11.40    6.10


               X/L   TIME   PROD TEMP    RATE       LETHALITY

              0.0    0.0     131.00     0.0          0.0
              0.10   0.10    138.85     0.0002       0.0000
              0.20   0.20    145.85     0.0010       0.0001
              0.31   0.30    152.11     0.0037       0.0005
              0.41   0.40    157.69     0.0116       0.0017
              0.51   0.50    162.67     0.0321       0.0049
              0.61   0.60    167.12     0.0797       0.0128
              0.72   0.70    171.09     0.1794       0.0308
              0.82   0.80    174.64     0.3702       0.0678
              0.92   0.90    177.80     0.7065       0.1385
              1.00   0.98    180.00     0.9422       0.2109

      TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS

   IN 10% NDM MENSTRUUM AT A VELOCITY OF 27.0 FT/SEC (HOLDING)


              1.04   1.01    180.00     1.1710       0.2532
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      TEMPERATURE DISTRIBUTION AND LETHALITY CALCULATIONS

IN 10% NDM MENSTRUUM AT A VELOCITY OF 27.0 FT/SEC (COOLING)

               TC1    TC2    TH1    TH2   DENSITY VISCOSITY

               64.4   35.6 180.0   68.0   62.90   0.383E-03

                   MASS-FLOW     RE. NO.     Z       F

                    1110.00     68334.56  11.40    6.10

             X/L   TIME   PROD TEMP   RATE       LETHALITY

            0.0    0.0     180.00    0.0         0.0
            0.07   0.10    166.20    0.0942      0.0094
            0.15   0.20    153.63    0.0073      0.0101
            0.22   0.30    142.17    0.0007      0.0102
            0.29   0.40    131.72    0.0001      0.0102
            0.36   0.50    122.20    0.0000      0.0102
            0.44   0.60    113.53    0.0000      0.0102
            0.51   0.70    105.63    0.0000      0.0102
            0.58   0.80     98.42    0.0000      0.0102
            0.66   0.90     91.86    0.0000      0.0102
            0.73   1.00     85.87    0.0000      0.0102
            0.80   1.10     80.42    0.0000      0.0102
            0.88   1.20     75.45    0.0000      0.0102
            0.95   1.30     70.92    0.0000      0.0102
            1.00   1.37     68.00    0.0000      0.0102
            1.17   1.60     68.00    0.0000      0.0102
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VITA

Karimireddy Krishna Reddy, son of Mr. and Mrs. K. Rama Krishna Reddy, was born on June 4, 1933, in Gundlacheruvu, Andhra Pradesh, India. He received his primary education in Gundlacheruvu, his high school education in Cuddapah, and attended Besant Theosophical College, Madanapalle. He received his Intermediate in Arts and Science in September, 1953, and his B.V.Sc., (D.V.M.) degree in July, 1958, from Madras University. He was the recipient of a State Scholarship at the School of Veterinary Medicine of Madras University.

After graduation, Reddy worked in the State of Andhra Pradesh as a Veterinary Surgeon from August, 1958, to May 1959. He imparted instruction in Animal Husbandry in the College of Agriculture from June, 1959, to May, 1961. He joined the College of Veterinary Science, Andhra Pradesh, Agricultural University, Hyderabad, as Instructor from June,1961, to August, 1965.

The author entered the Graduate School of Auburn University, Auburn, Alabama, in September, 1965, and completed the requirements for his M.S. degree in Dairy Manufacturing in August, 1967. He received a graduate research assistantship and entered the Graduate School of Virginia Polytechnic Institute and State University in September, 1967, to work toward his Ph.D. degree in Food Science and Technology.

He was married to Uma Saraswathi of Hyderabad. They have one son, Hari Hara Reddy.

The sterilizing effect showed that turbulent flow heat treatments were highly effective in destruction of the test organism. This method appeared applicable for evaluating helically coiled tube processes provided that the same test conditions are used.