FOREWORD

The research and development program reported herein was initiated by the Biomedical Laboratory of the 6570th Aerospace Medical Research Laboratories, Aerospace Medical Division, Wright-Patterson Air Force Base, Ohio. Work on this program was begun 19 February 1962 by the Mechanics Research Division of the American Machine and Foundry Company, under Contract AF 33 (657)-7922. On 1 September 1962 this Division was sold to the General American Transportation Corporation, and renamed the MRD Division. All customer contracts, including AF 33(657)-7922, were included in the sale. The MRD Division completed the work 15 May 1963.

Mr. S. J. Lis, Research Engineer, was the principal investigator at the MRD Division for the feasibility study phase of this program. Mr. P. P. Nuccio, Design Engineer, was the principal investigator for the design study, fabrication, and evaluation phases. Mr. G. W. Filson, Requirements and Evaluation Branch, Biotechnology Division, was contract monitor for the Biomedical Laboratory. The work was performed in support of Project 6373, "Equipment for Life Support in Aerospace," Task 637305, "Analysis and Integration of Life Support Equipment."

The authors acknowledge the invaluable assistance of Mr. G. Engholm, Supervisor of Thermal Processes, Mr. R. A. Landes, Supervisor of Design and Development and Mr. R. A. Bambenek, Group Leader of Applied Research, at the MRD Division; and thank Mr. J. D. Zeff, Supervisor of Chemical and Biological Processes, for his technical advice.

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ABSTRACT

A feasibility study of methods for heating foods during aerospace flight has shown that electrical resistance heating is the most effective technique. An internal heating probe is more efficient than external heating, but special food containers are required. A full-scale engineering model of an external heating food warmer, capable of heating available food containers, was designed, fabricated, and evaluated. This model has three separately controlled stations for mounting flexible heaters that are wrapped around the container to be heated. The system occupies a volume less than 288 cubic inches and weighs less than 4 pounds, when provided with six heater assemblies. Laboratory tests verified that the system meets the requirements specified, and it can heat a 6-ounce can of ham and eggs from 75°F to 160°F with less than 14 watt-hours of energy.

PUBLICATION REVIEW

This technical documentary report is approved.

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INTRODUCTION

The objective of this program was to determine the most effective method for heating foods during aerospace flight, and then to design, fabricate, and evaluate a full-scale engineering model of a food heating system based upon this technique. It was required that this system be capable of heating meat, vegetable, and drink items packaged in metal cans or plastic containers for a three-man crew on missions that will last for periods up to fourteen days.

Several systems for heating foods during aerospace flights were developed before this program was initiated. For examples, see Reference 10. All of these systems are classified as heating ovens; that is, the packaged food is placed in a cylindrical cavity whose walls are heated either by a circulating fluid, solar energy, or electricity. These systems are relatively ineffective because the food container does not make intimate contact with the heated walls. The wall temperature must be significantly higher than the desired food temperature if the food is to be heated in a short time period. Consequently, the systems developed were either inefficient, heavy, or slow in warming food. Also, with these systems it is difficult to control the maximum temperature of the food. MRD undertook this program with the principal goal of developing a food warmer that would efficiently heat packaged food and yet accurately limit the maximum food temperature. This restriction on maximum food temperature is especially important for heating food in plastic tubes during weightless conditions in crew compartments at pressures less than one atmosphere. If the container gets too hot, the plastic tube would burst or discharge part of its contents due to the excessive water vapor pressure.

The work on this program was divided into three phases, namely, a feasibility study, a design study, and finally the fabrication and evaluation of a full-scale engineering model. The feasibility study indicated that, to be practical, the system should use electrical power instead of solar energy or waste heat. The most efficient electrical heating method devised uses resistance heating elements or probes placed within the food containers - so that all of the heat is applied directly to the food at the center of the container, and the container itself is always at the lowest temperature and serves as insulation. Induction and dielectric heating also heat the food directly, but they require the use of relatively inefficient power conversion equipment.

It was decided not to develop the internal heating probe technique because special food containers would be required. Instead, the next best heating method was designed - namely, external resistance heating where a flexible heater is imbedded in an insulated wrap-on cover. Two three-heater models were fabricated and evaluated to meet the following system requirements:

1. Minimum volume, weight and power
2. Operable under weightless conditions
3. Rugged in design and construction
4. Operable at cabin pressure of 7.34 psia to 14.7 psia and temperatures of 60 to 75°F
5. Capacity to simultaneously heat two complete meals (up to 6 containers) of canned or plastic packaged meat and vegetable items in less than thirty minutes
6. Suitably controlled and monitored for temperature
7. Safe in operation and removal of heated containers
8. Operable, if required, by electrical power at 28 volts direct current,

or 115 volts alternating current, 400 cycles

9. Easily serviced and cleaned.
10. The average food temperature after 30 minutes of heating should be at least 160°F - because most pre-cooked, freeze-dried foods must be heated to this temperature for satisfactory reconstitution.
11. The maximum food temperature permissible is 180°F, the saturation temperature of steam at 7.51 psia - otherwise excessive internal pressures would be experienced when the system was used in a cabin at one-half atmosphere.

SECTION 2

FEASIBILITY STUDY

The initial task on this program was to conduct a comprehensive engineering evaluation of the feasibility of all applicable and practical techniques for heating foods to be consumed during aerospace missions. External resistance, induction, dielectric, and internal resistance heating techniques were studied in detail and compared for heating eight-ounce, cylindrical food containers. It was concluded that internal resistance heating is the best technique. However, the external resistance heating technique was recommended for development at this time because available food containers could be utilized.

Heating Techniques

External Resistance Heating

A food container, heated by an externally wound, helical, resistance heating element, is shown schematically in Figure 1. The power required for such an element is given by:

$$P = \frac{2.344 \rho r_2 N I^2 \eta}{d^2}$$

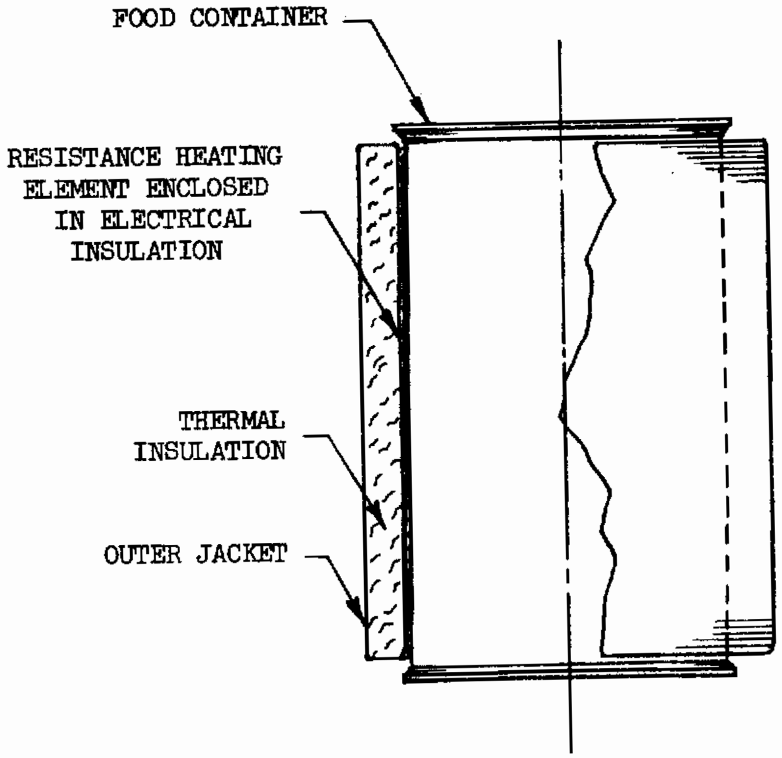

Figure 1 EXTERNAL RESISTANCE HEATING MODEL

where P = required power, in watts

r_2 = radius of the helical coil, in inches

N = number of turns

I = current, in amperes

η = efficiency, i.e., the effective energy over total energy for the system

d = heater wire diameter, in inches

ρ = resistivity of the heater, in ohm-in

The efficiency factor, η, is included to incorporate heat losses occurring to the surroundings.

To minimize the problem of nonuniform heating as well as to improve the linkage between heat source and container/food to be heated, a product manufactured by the Electrofilm Corporation was selected for study as a practical external resistance heating element. This product, known as electromesh heating elements, is made up of a fine resistance wire mesh embedded in a flexible electrical insulation. Close spacing of the wires comprising the mesh produces a fairly uniform temperature over the heating surface. Furthermore, a flexible thermal insulation is used over the heating element allowing the element to conform to the food container contour and reducing the effective space between heater and container.

Another advantage inherent to the externally wrapped resistance heating technique is that a thermostat may be easily located to sense the container outer surface temperature. While a thermostat so placed measures container-wall temperature rather than the more significant adjacent-to-the-inner-wall food temperature, a fixed relationship exists between these two temperatures. The thermal gradient through the container wall is fixed by the container properties and remains unchanged irrespective of the kind of food being heated. Further, the gradient is very small even at elevated temperatures due to the high thermal conductivity and thin cross-section of the container wall. The thermostat senses, then, a temperature which is truly representative of the conditions within the food container. It does so with repeatability and accuracy because the thermostat location is always the same - on the container wall. Adjustment for the thermal gradient can accurately be made by setting the thermostat to open at the maximum food temperature permissible, plus the fixed gradient upon heating, and to close again at the minimum food temperature minus the gradient.

Induction Heating

When an alternating electric current flows in a conductor, a magnetic field is established around the conductor. If the conductor is formed into a loop or coil the alternating magnetic field developed is intensified - the actual intensity being determined by the amount of current flowing through the coil, the number of turns in the coil, and the magnetic characteristics of the material being heated. The magnetic field is distorted and has a maximum density within the coil close to the turns.

Current will flow in any conductive material placed in this magnetic field, the amount of induced current being determined by the strength of the alternating magnetic field and the spacing between the material heated and the coil. The resistance offered by the material heated to the flow of the induced current produces heat in proportion to its electrical resistance and to the square of the current flowing. This phenomenon is similar to that which occurs in an electrical transformer. Thus, any metal part or other conductive material placed within a coil energized with alternating electric current heats very rapidly without physical contact between the part and the coil, i.e., it heats by induction.

A metallic food container placed within a coil carrying high frequency current will have induced currents passing through and heating the container walls and therefore the food within the container. The induction coil may be formed into any geometry corresponding to the part or container to be heated. However, a helical coil heating a cylindrical container lends itself to a solution of the complex analysis involved. Therefore, to facilitate comparison and evaluation it is assumed that the food container is cylindrical and its walls are metallic. Further, if the magnetic intensity is assumed uniform, it is given by:

$$H_o = \frac{0.4\pi NI}{L}$$

where N = number of turns or coils

I = current

L = length of coil

With these assumptions it is seen that the power absorbed in the hollow cylinder is proportional to the square of the ampere turns, i.e.,

$$P = K_1 (NI)^2$$

where the constant, K_1, (for a given system) is given by the function: (Ref. 2)

$$K_1 = \frac{1.28\pi^3}{\sigma L} \frac{2(r_2 - r_1)}{s} F$$

where r_2, r_1 = outer and inner radii of the container

L = length of the container

s = skin thickness

σ = electrical conductivity

F = complex function of r_2, r_1, and s (Reference 2)

With the foregoing relations it is possible to determine the power induced into any hollow conducting material placed within a helical induction coil.

Dielectric Heating

Dielectric heating is a method of generating or developing heat in a nonconductive material by molecular agitation caused by stresses resulting from a rapidly alternating electric field. The forces in a rapidly alternating electric field are such that the opposite charges are attracted and like charges are repelled.

Materials which are nonconductors of electricity do not contain electrons which are free to move independently of the molecule or atom. When a high voltage, high frequency force is applied to the electrode plates, the molecules tend to assume a polarity consistent with the charge on the plates.

If, at an instant of time a plate is positive and the other is negative, the negative charges in the molecules, that is the electrons, will have forces exerted upon them, causing them to be attracted or repelled. As the polarity of the plate is reversed, due to reversal of the current, the forces will be reversed accordingly. Thus, for dielectric heating a high frequency field will have a large number of reversals per second, resulting in rapid stresses of the molecules which, in turn, results in the development of heat due to interatomic or intermolecular friction. Since the field acts independently on each molecular particle throughout the material, the heat is generated uniformly in all parts of a homogeneous load. The amount of heat developed by this molecular vibration or friction is proportional to the frequency, to the square of the applied voltage, and to the loss factor of the particular material:

$$Q = P''' \times \tau = 1.41\, f \left(\frac{dV}{dx}\right)^2 (L.F.) \cdot \tau$$

where Q = energy (watt-seconds/inch^3)

P''' = power (watt/inch^3)

τ = time (seconds)

f = frequency (megacycles per second)

$\frac{dV}{dx}$ = voltage gradient (kilovolts/inch)

$L.F.$ = loss factor, physical constant of material
$L.F. = \epsilon \times \cos \phi$ (dielectric constant x power factor)

As the amount of heat is proportional to the three factors in the order shown, dielectric heating is accomplished most satisfactorily at extremely high frequencies. The second factor, the square of the applied voltage gradient, determines the amplitude of the vibrations or stresses. High voltages are dictated by the resistance to movement of the molecules. The third factor, i.e., the loss factor, is a physical constant of the material being heated. It is numerically equal to the product of the power factor and the dielectric constant, and expresses the fact that different materials have different heating rates. The higher the loss factor, the greater the molecular vibration and thus the higher the heating rate.

To apply the dielectric heating technique to food warming requires a food container made of a combination of metal and a nonconductor as shown in Figure 2. The metal electrode plates are the end plates of the food container, whereas the lateral sides cannot be metallic since they would cause a direct short of the high-frequency potential applied to the electrodes.

Internal Resistance Heating

Heat may be released within the food and container by means of a probe-type resistance heating element. This technique has numerous advantages. Heat is transferred entirely by conduction between solid and liquid, thereby eliminating any air gap in the linkage between heating source and the food or container to be heated. The external wall of the container would be at the lowest temperature in the entire system, thus reducing heat losses and increasing the efficiency of the food warmer without increasing its weight.

Internal-probe heating elements present some problems. The pressure within the container can correspond to the partial pressure of contained gases

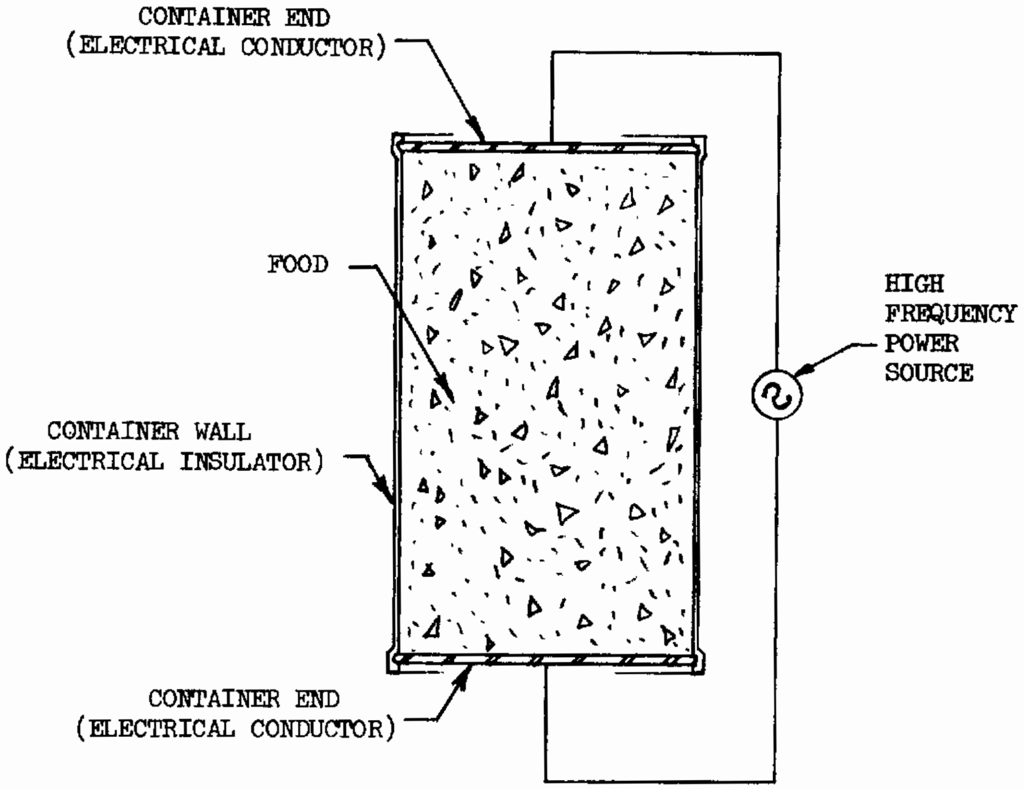

Figure 2 DIELECTRIC HEATING MODEL

plus that of water vapor at the surface temperature of the probe. Since the probe must pierce the container, the partial pressure of the contained gases will correspond to cabin pressure. At one-half atmosphere the boiling point of water would be approximately 180°F. Thus, probe surface temperatures higher than 180°F are not recommended.

Considering the probe heater as a continuous line source, the temperature excess over the initial temperature of the food at any radius, r, is given by: (Reference 3)

$$\theta = -\frac{q'}{4\pi k_f} E_i\left(-\frac{r^2}{4\alpha\tau}\right)$$

where θ = temperature excess

q' = heat transfer rate per unit length

α = thermal diffusivity of the food

k_f = thermal conductivity of the food

r = radius

τ = time

E_i = exponential integral defined by

$$-E_i(-x) = \int_x^\infty \frac{e^{-u}}{u}\, du$$

Using this relation it is possible to compute the temperature-time history of the surface of a probe. As an illustration, it was assumed that the food had the thermal properties of water, namely:

k_f = 0.386 thermal conductivity, Btu/hr ft°F at 167°F
ρ = 60.8 density, lb/ft^3 at 167°F
c_p = 1.0 specific heat, Btu/lb°F
α = 0.00635 thermal diffusivity, ft^2/hr

The resulting temperatures at the surface of a 1/2" diameter probe is as shown in Figure 3. As can be seen, the probe surface temperature rapidly approaches the boiling point for most of the constant power outputs considered.

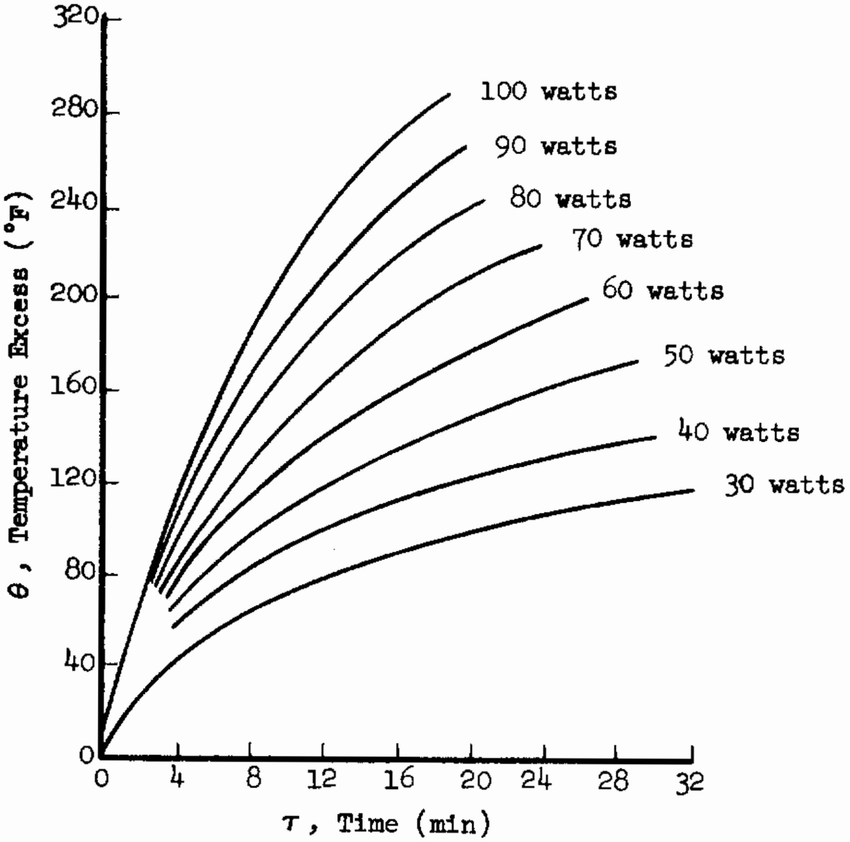

Figure 3 SURFACE TEMPERATURE HISTORY FOR A 0.5-INCH DIAMETER PROBE AT VARIOUS POWER LEVELS

Higher power inputs can be used if the power is controlled to limit surface temperature to 180°F; this requirement could be accomplished by supplying a variable voltage to the heating element. To illustrate this technique, the 1/2" probe was assumed to operate initially at 100 watts until such time that its surface reached 180°F. The power dissipated was assumed to raise the average temperature of a prescribed mass of food. At that point the voltage was dropped so as to operate at 90 watts and successively lower voltages as shown in Figure 4.

For these conditions it was found that an approximately cylindrical container of food 2 inches in diameter and 7 inches long could theoretically be heated from 70°F to 165°F within a period of 20 minutes with a total power

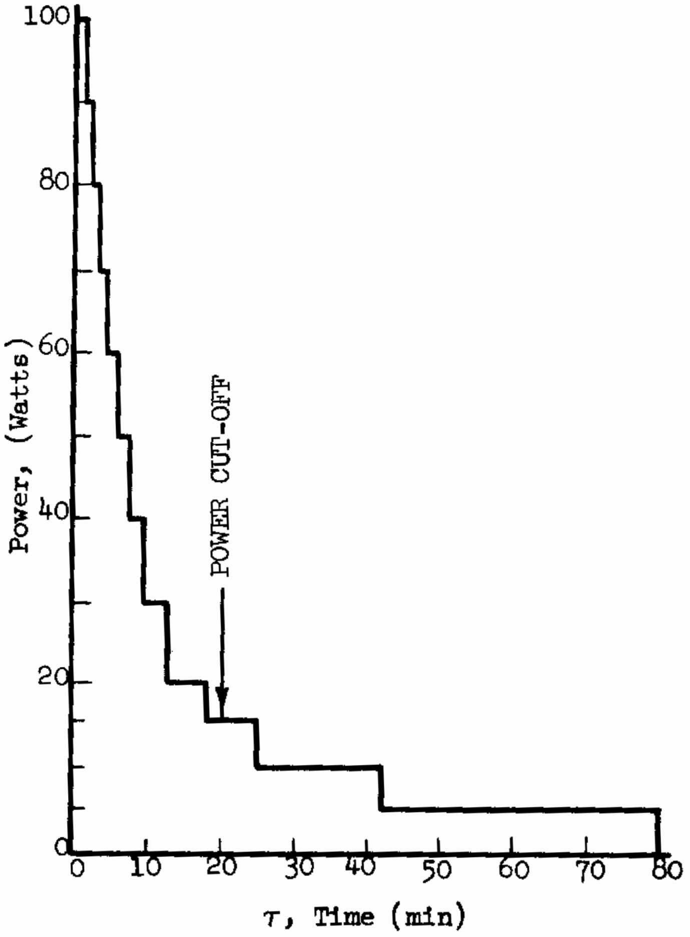

Figure 4 INCREMENTAL POWER LEVELS REQUIRED TO LIMIT 0.5-INCH DIAMETER PROBE SURFACE TEMPERATURE TO 180°F

consumption of 22 watt-hrs. However, if the timing circuit used a variable resistance potentiometer it would reflect a constant power of 100 watts for operation and an efficiency of 66 percent for the system.

Another approach to the internal probe heating technique is to utilize a flat or knife-like probe which provides more surface area per unit cross-sectional area, than a cylindrical probe. With more surface area it is possible to use constant power input without experiencing surface temperatures higher than 180°F. The temperature within a food container being heated by such a probe is defined as follows:

$$\theta = \frac{F_o \tau}{\rho c L} + \frac{F_o L}{K} \left[\frac{3x^2 - L^2}{6L^2} - \frac{2}{\pi^2} \sum_{n=1}^{\infty} \frac{(-1)^n}{n^2} e^{-\frac{\alpha n^2 \pi^2 \tau}{L^2}} \cos \frac{n\pi x}{L} \right]$$

where θ = temperature excess above initial temp.
F_o = constant heat flux supplied at $x = L$
τ = time
ρ = density of the food
c = specific heat of the food
L = distance from the probe surface to the outer surface
K = thermal conductivity of the food
x = variable distance from the outer surface $(0 \leq x \leq L)$
α = thermal diffusivity of the food

Other Methods

The Dithermal continuous process illustrated in Figure 5 presents a novel means of heating foods continuously (Ref. 4). This consists of two sections of nylon tubing connected by a solid copper coupling. A sheet of aluminum foil is wrapped around the connection between the two tubes and coupling and the current passes from the foil to the boundary copper electrodes. The copper ring electrodes are separated from each other by glass tubing. The path provided for the current leads from the generator to the first ring, through the food to the aluminum foil, again through the food to the second ring and finally to ground. The flow of food is maintained by the helical threads which are cut into the thick walled nylon tubing connected to the nylon shafts supporting the aluminum foil. When using a processing tube developed by the American Meat Institute Foundation, the technique heated 3.12 lbs per minute of ground pork using an industrial 15 kilowatt oscillator applying 9000 volts and operating at 9 megacycles.

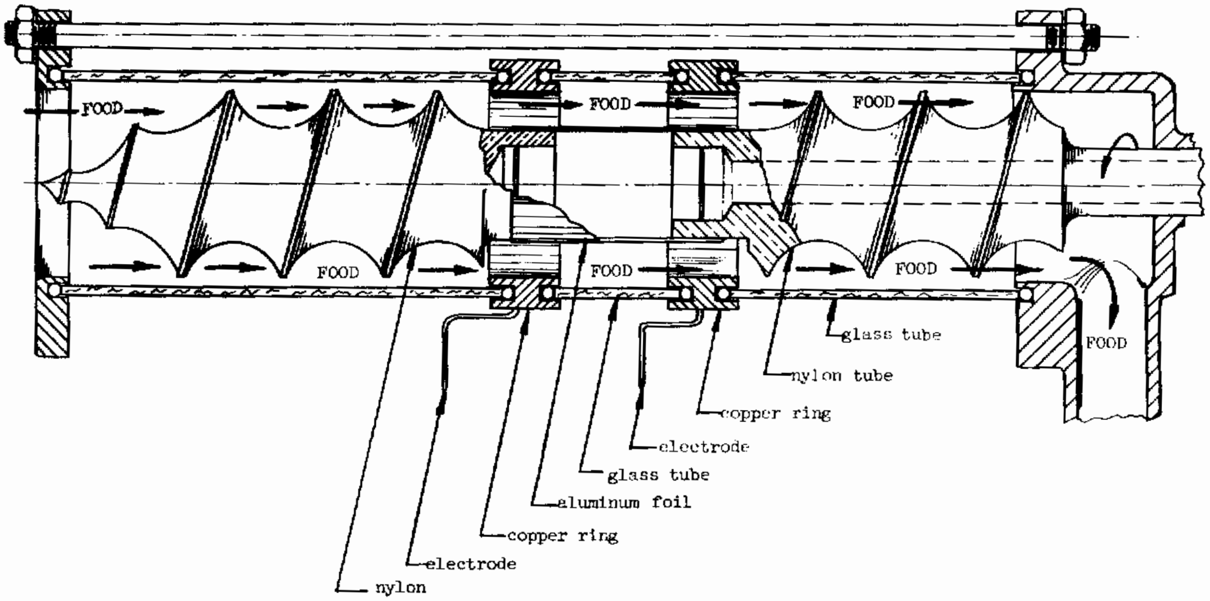

Figure 5 SCHEMATIC DRAWING OF DITHERMAL PROCESS

The novelty of warming food practically instantaneously is presented here only as an interesting alternate to the batch type, individual container food warming system considered in this program. The concept of food dispensing on a continuous basis is beyond the scope of the present study and consequently was not studied in more detail.

Nuclear systems for food warming were investigated (Reference 1) and were reported as expensive, requiring shielding, and presenting a potential radiation hazard along with other problems. To avoid duplication of effort, no further investigation into this technique was performed.

Chemical energy sources are unattractive due to the lack of reliable chemical compounds applicable to food-warmer designs. Heat pump and solar energy techniques are not considered here since they depend upon the cabin conditioning systems, and vehicle orientation and mission, respectively. These techniques are felt to be too restrictive for general application to all types of missions.

Application Study

It is necessary to formulate a typical daily menu to estimate the required number and type of food containers, and their weight and volume. Table 1 shows the generalized menu recommended as typical, and the appropriate calorie and water contents for the type of foods listed. Most of the data were obtained from the Quartermaster's Food and Container Institute.

The average portion size for the food items shown in Table 1 is normally 100 to 150 grams (except for candy bars and sugar cookies). If 100 grams of each item are consumed each day, the average daily caloric intake would be only 1050 kilocalories. With this menu the average portion size must be 200 grams to obtain a daily intake of 2100 kilocalories from food and beverage tubes. An additional 600 kilocalories can be supplied by one 60-gram candy bar and two 25-gram sugar cookies. This menu includes a daily water intake of 2570 grams, which is considered adequate.

To accommodate a 200-gram portion, each food tube should contain 7 to 8 ounces.

It was assumed that the foods to be heated are homogeneous, semi-solid to liquid in consistency, thus eliminating the necessity of special considerations for large chunks of foods, air voids, and other discontinuities.

Food containers could be plastic or metallic. To analyze these containers they were considered cylindrical in shape. As a result of this assumption it becomes possible to determine what the dimensions of the container must be to meet thermal requirements. Furthermore, the cylindrical geometry simplifies the analytical procedures performed to evaluate each of the techniques considered and offers a convenient comparative standard from which performance may be deduced. It is realized, however, that the actual container may be a squeeze-type configuration much like a toothpaste tube.

Properties of Foods

The thermal properties of foods were collected from the literature. A summary of these properties is given in Table 2. In addition to these data, a value of 145 was obtained for the dielectric constant (Reference 7). Also, the resistance value for meats was reported as ranging from 58.7 ohm/inch/in^2

TABLE 1

RECOMMENDED TYPICAL DAILY MENU AND ITS APPROXIMATE COMPOSITION

	Reconstituted?		Served?		Calories per 100 grams (approx.)	Grams of H_2O per 100 grams (approx.)
	Yes	No	Warm	Cold		
Breakfast						
Juice	X			X	50	90
Cereal	X		X		100	75
Meat		X	X		150	75
Beverage	X		X		25	95
Beverage	X		X	X	25	95
Lunch						
Soup	X		X		50	90
Meat food		X	X		150	75
Beverage	X		X		25	95
Sugar Cookies		X		X	400*	5*
Beverage	X		X	X	25	95
Dinner						
Fruit Cocktail		X		X	100	75
Meat & Gravy		X	X		150	75
Potatoes	X		X		100	75
Vegetable		X	X		50	85
Beverage	X			X	25	95
Beverage	X		X	X	25	95
Candy Bar		X		X	500*	5*

* Signifies dessert items available during normal flight

for D.C. and a value of 42.8 ohm/inch/in^2 at a frequency of 28 mc., both at 70°F (Reference 7).

The average thermal conductivity of different kinds of meat including fish and poultry is reported (Ref. 8) as 0.30 B/hr-ft°F at a temperature of approximately 60°F. The change of thermal conductivity of these foods rises slightly at higher temperature. These values and the data shown in Table 2 were sufficient to determine the heating requirements for the food heating systems evaluated.

Thermal Energy Requirements

For 8 ounces of food heated from an ambient temperature of 75°F to an average of 160°F within a period of 30 minutes the theoretically required minimum power level is:

$$Q = MC_p \frac{\Delta T}{\Delta \tau}$$

TABLE 2

THERMAL PROPERTIES OF FOODS

	Water Content %	Specific Heat (B/lb°F)	Reference	Thermal Conductivity (B/hr-ft°F)	Temp. (°F)	Reference
1. Vegetables						
Asparagus	93	0.94	1	0.22	47	11
Beans, green	88.9	0.91	1, 12			
Lima beans	66.5	0.73	1, 12			
Fresh	90	0.92	12			
String beans	88.9	0.91	9			
Dried beans	12.5	0.30	9			
Beets	87.6	0.90	1			
Broccoli	89.9	0.92	1	0.22	20	11
Carrots, boiled	88.2	0.90	1	0.72	18	11
Cauliflower	91.7	0.93	1			
Celery	93.7	0.95	1			
Corn, sweet	73.9	0.79	1			
Peas	74.3	0.79	1	0.18	50	11
Potatoes	77.8	0.82	1			
Sweet potatoes	68.5	0.75	1			
Spinach	92.7	0.94	1			
Tomatoes, ripe	94.1	0.95	1			
2. Fruits						
Apples, pulp	85	0.89	12			
Apricots	85.4	0.88	1			
Bananas	74.8	0.80	1			
Dates, dry	20	0.36	1			
fresh	78	0.82	1			
Figs, dry	24	0.39	1			
fresh	78	0.82	1			
Grapefruit	89	0.91	1			
Oranges	87	0.90	1			
Peaches, pitted	90	0.91	1			
Pears	82.7	0.86	1			
Pineapples, ripe	85.3	0.88	1			
Plums, fresh	85.7	0.88	1			
Tangerines	87.3	0.90	1			
3. Dairy Products						
Butter	16	0.33	1			
Cheeses	37-38	0.50	1			
Cream	73	0.85	1			
Ice cream	58-66	0.78	1			
Milk	87.5	0.93	1			
Eggs, dried, whole	5	0.25	1			
4. Meat & Poultry						
Bacon, cured	13-29	0.30-0.43	1			
Beef, fresh	62-67	0.70-0.84	1			
lean	70-76	0.76	1			
fat	50	0.60	5	0.12		5
Ham, cured	40-45	0.52-0.56	1			
Lamb, fresh	60-70	0.68-0.76	1			
Pork, fresh	57	0.73	6			
nonfat						
smoked	57	0.60	6			
Sausage, fresh	65	0.89	9			
franks	60	0.86	9			
Veal cutlet, fried	58	0.74	6			
Poultry, fresh	74	0.79	1			
5. Miscellaneous						
Bread, white	44-45	0.65-0.68	6			
Macaroni	13	0.44-0.45	6			
Rice		0.27-0.32	6			

where Q = thermal energy, B/hr

M = weight of food heated, 0.5 lb

C_p = specific heat of food, 0.8 B/lb°F

T = temperature difference, 160-75 = 85°F

τ = time, 0.5 hr

Thus

$$Q = 68 \text{ B/hr} = 19.9 \text{ watts}$$

Therefore, approximately 20 watts of power supplied for 30 minutes will be required per 8-ounce container of food. The minimum total energy requirement is thus 10 watt-hours or 34 Btu.

Container Shape

Considering the cylindrical food container, it is possible to determine what size it must be to absorb the energy necessary to externally heat the food within 30 minutes, without exceeding the surface temperature limit of 180°F. Consider a cylinder of radius, r_1, which is subjected to a constant flux F_o at the outside surface, ignoring the end surfaces. The temperature within and on the surface is given by: (Reference 3)

$$\theta = \frac{2F_o\alpha\tau}{kr_1} + \frac{F_o r_1}{k}\left\{\frac{r^2}{2r_1^2} - \frac{1}{4} - 2\sum_{n=1}^{\infty}\frac{\left(e^{-\alpha\beta_n^2\tau/r_1^2}\right) J_o\left(\frac{r\beta_n}{r_1}\right)}{\beta_n^2 J_o(\beta_n)}\right\}$$

where θ = temperature excess above initial temperature, °F

F_o = constant flux, B/hr ft^2

α = thermal diffusivity of the food, ft^2/hr

τ = time, hr

k = thermal conductivity of food, B/hr ft°F

r = variable of the cylinder, $0 \leq r \leq r_1$, ft

r_1 = outer radius of the cylinder, ft

e = base of the natural logarithm

and β_n = positive roots of:

$$J_1(\beta_n) = 0$$

where J_o, J_1 are the Bessel functions of zero and first order. Solving for the flux, F_o yields:

$$F_o = \frac{\theta}{\frac{2\alpha\tau}{kr_1} + \frac{r_1}{k}\left\{\frac{r^2}{2r_1^2} - \frac{1}{4} - 2\sum_{n=1}^{\infty}\frac{\left(e^{-\alpha\beta_n^2\tau/r_1}\right)\cdot J_o\left(\frac{r\beta_n}{r_1}\right)}{\beta_n^2 J_o(\beta_n)}\right\}}$$

Since this maximum temperature will be reached at the end of the 30-minute heating period, the flux becomes a function of the outside radius only. (See Figure 6). Furthermore, there is only one flux level for which the average temperature of the food is 160°F.

As was shown previously, the average power level must be 19.9 watts in order to reach an average food temperature of 160°F from an average of 75°F in a 30-minute period. Entering Figure 6 at 19.9 watts the radius of the food container is found to be 0.98 inches. Thus, it can be seen that for a theoretical power requirement of 19.9 watts there is a unique radius at which the power and surface temperature requirements can both be achieved.

Consistent with this radius and the total volume corresponding to eight ounces of food, the length of the cylinder becomes:

$$L = 4.786 \text{ inches.}$$

The cylinder size is therefore uniquely determined for the average temperature and theoretical power stipulated.

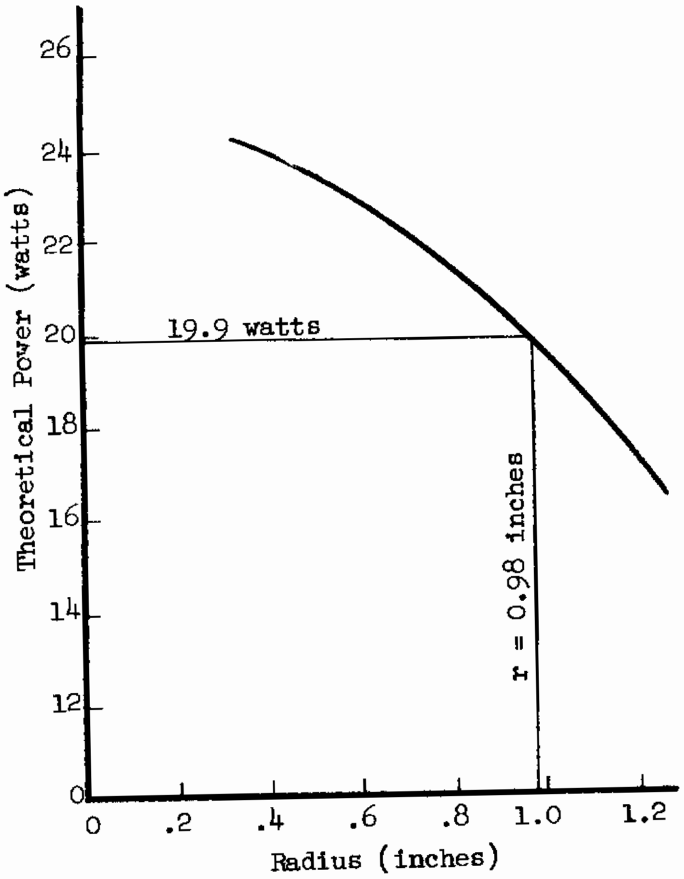

Figure 6 POWER LEVEL VERSUS CONTAINER RADIUS

Insulation

There exists an optimum insulation thickness for which losses are a minimum. This optimum is expressed by: (Reference 4)

$$r_{o,\ opt} = \frac{k}{h_o}$$

where

$r_{o,\ opt}$ = outer radius, ft

k = thermal conductivity of the insulation, B/hr ft°F

h_o = outer coefficient of heat transfer, B/hr ft^2°F

If it is assumed that asbestos insulation is used:

$$k = 0.111 \text{ B/hr ft°F}$$

and that the outer coefficient of heat transfer may be taken from the linearized approximation:

$$h_o = 40\epsilon T^3$$

where σ = Stefan-Boltzman constant = 1716.7×10^{-12} B/hr ft^2°R^4

ϵ = effective emittance = 0.9

T = absolute temperature of the outer surface - 560°R

the outer coefficient of heat transfer becomes:

$$h_o = 1.085 \text{ B/hr ft}^2\text{°F.}$$

The optimum outer radius of insulation becomes:

$$r_{o,\ opt} = 1.224 \text{ inches}$$

The total minimum heat loss, through the insulation becomes:

$$q_L = \frac{2\pi L(t_i - t_o)}{\frac{1}{k}\ \ell n \frac{r_o}{r_i} + \frac{1}{h_o r_o}}$$

where q = heat loss, B/hr

L = cylinder length, ft

t_i, t_o = inner and outer temperatures, respectively, °F

k = thermal conductivity, B/hr ft°F

r_i, r_o = inner and outer radii, respectively, ft

h_o = outer coefficient of heat transfer, B/hr ft^2°F

or

$$q_L = 24.2 \text{ B/hr} - 7.1 \text{ watts}$$

for a nominal inner wall temperature of 180°F and an assumed ambient temperature of 75°F. The heat loss here represents 26% of the total energy supplied. Should an air gap exist between the food container and the energy source, these losses would increase as shown in Figure 7. Thus, it can be seen that an energy source such as resistance elements and infra-red radiant glow-bars placed external to a food container will operate at a maximum efficiency of 74%, but can be as low as 63% for an air gap of 0.030 inches.

Weight Analysis

In order to evaluate the inherent qualities of each system discussed, total weight penalty of a six-container food warming system was selected as the criteria for comparison. Power weight penalty was estimated to be as follows:

For D.C.	0.05 lb/watt	(SNAP 8)
	0.10 lb/watt	(MRD design for space radiators)
	0.15 lb/watt	Total
For A.C.	0.18 lb/watt	Total (based on an efficiency of 85%)

The weight of control components and enclosures common to all systems was estimated to be as follows:

Enclosure	1.00 lb
6 circuit breakers	1.50
6 light switches	1.50
6 timers	4.00
2 connectors	2.00
Hardware and wire	3.00
Total	13.00 lbs

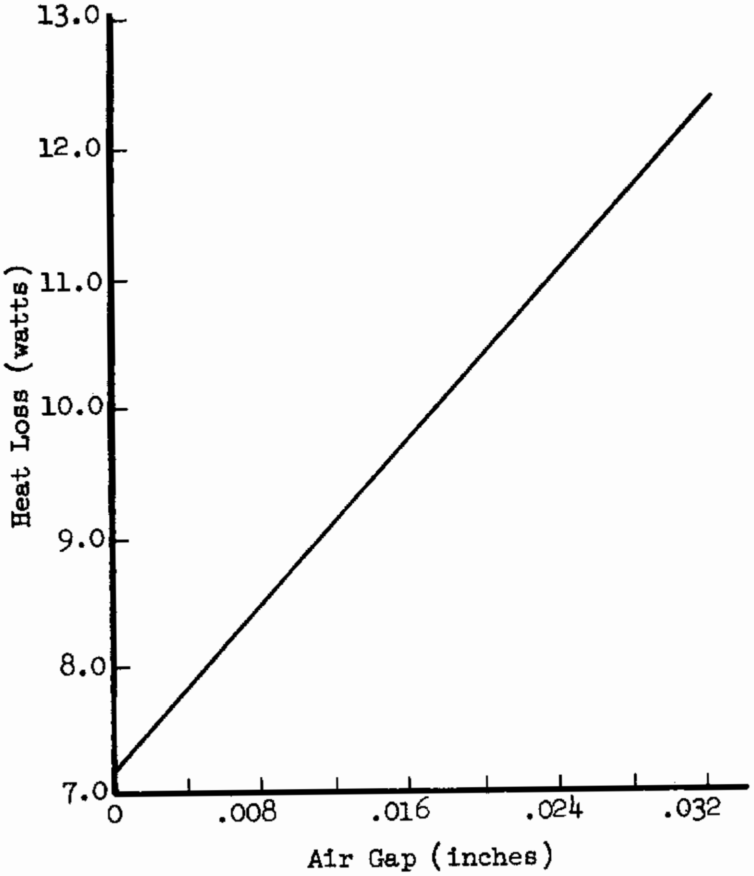

Figure 7 EFFECT OF AIR GAP ON HEAT LOSS

External Resistance Heating

The required heating element consistent with the thermal requirements and associated heat losses can be easily calculated from the power equation presented on page 3. If it is assumed that an air gap of 0.010" exists between the heating element and the container wall, then Figure 7 shows that a heat loss of 8.7 watts/container will occur with insulation of optimum thickness; this represents an overall efficiency of approximately 70%.

If "Electromesh" resistive heating elements are bonded to a cylindrical container the air gap would be zero and the system would operate at its maximum efficiency of 74%. The weight of such heating elements, based upon 0.0035 lbs/in^2 for a total surface area of 181 in^2, is 0.63 pounds. Total power required is:

$$P_T = \frac{19.9 \times 6}{0.74} = 161.3 \text{ watts}$$

Thus, the weight penalties for this system become:

Power weight penalty	= 0.15 lb/watt x 161.3 watts =	24.2 lbs
Weight of heating elements	=	0 63 lbs
Weight of basic controls		13.0 lbs
	Total weight penalty =	37.83 lbs

Induction Heating

Induction heating presupposes the use of metallic containers. If it is assumed that a wall thickness of 0.020" is required for an aluminum cylindrical container, the container required would have the following dimensions.

Outer radius = 1.00 inches
Inner radius = 0.98 inches
Length = 4.79 inches

With relationships developed on page 5, it is possible to compute a typical design curve for induction heating consistent with the required heat load and the physical size assumed; this curve is shown in Figure 8.

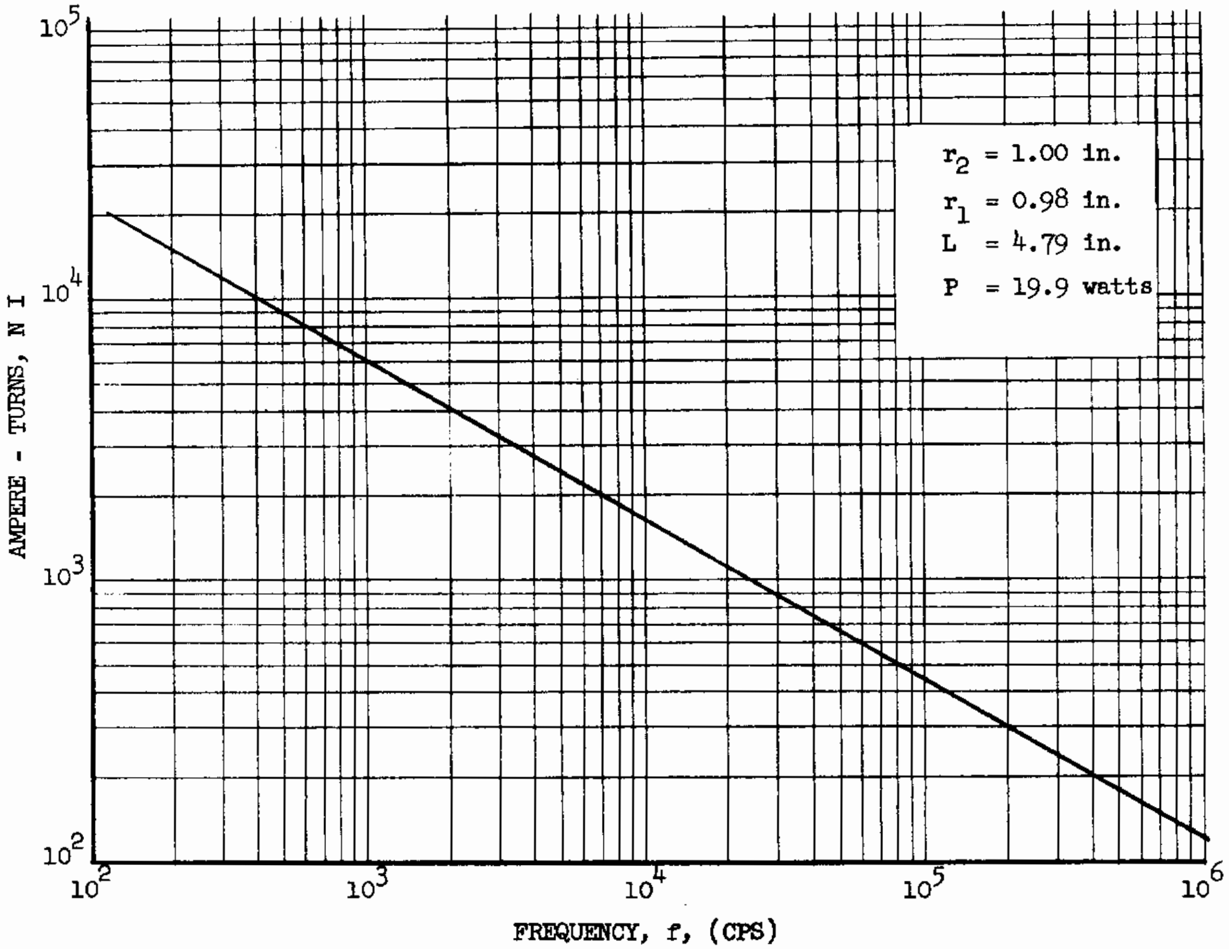

Figure 8 INDUCTION HEATING ALUMINUM CYLINDER

Power generators of the type required for the present application would have to be specially developed. However, to indicate the performance typical for presently available equipment, some analytical estimates are possible. Most high frequency generators operate at a conversion efficiency in the neighborhood of 46%. Such power supplies produce nominal frequencies of 450 KC. If it is assumed that a copper tubing coil is utilized at 450 KC it follows that for N = 10, a current of 20 amperes will be drawn per container. In this case 6.6% (1.42 watts per cavity) of the power will be generated as heat in the coil, which could be reclaimed by heating water if desired However, if this is not reclaimed, the overall efficiency of the system would be 43%.

Thus, on the basis of 6 cavities of containers being heated (2 meals) a total of 277.6 watts will be required while 119.4 watts are actually used. Thus, weight penalties for the system become:

Power weight penalty = 277.6 watt x 0.18 lb/watt	=	49.97 lbs
Weight of induction coil	=	2.14 lbs
Weight of power conversion equipment*	=	200.0 lbs
Weight of basic controls	=	13.0 lbs
Total weight penalty	=	265.11 lbs

Dielectric Heating

To heat food by dielectric heating would require a combination metal and plastic container. For the dielectric constant, and electrical resistivity of: (taken for meat, Reference 7)

$$\epsilon = 145$$

$$\rho = 50.7 \text{ ohm-in}$$

Typical voltage-frequency requirements are as shown in Figure 9. It can be seen that a power supply would have to be incorporated in the system to make the technique applicable. It is virtually impossible to operate at 400 cps since voltage requirements would be on the order of 10^7 volts. The efficiency of the system would be that of the power generator, which is about 45%.

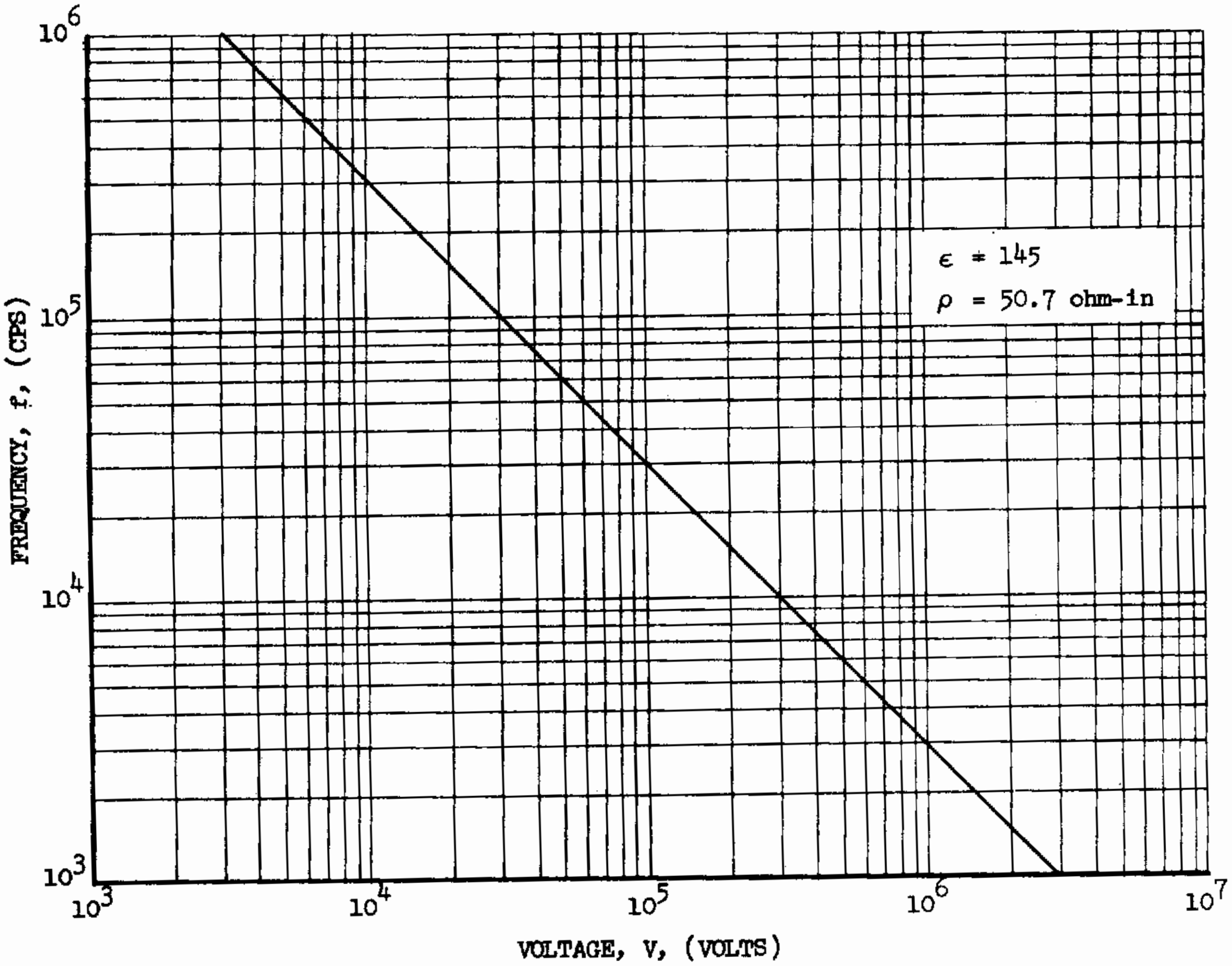

Figure 9 DIELECTRIC HEATING

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*R. W. Brisky, U. S. Controls, Inc., Private Communication, June 5, 1962

Thus, the total power requirement for the dielectric heating system becomes:

$$P_T = \frac{19.9 \times 6}{0.45} = 265.3 \text{ watts}$$

and it follows that the weight penalties for the system become:

Power weight penalty - 265.3 watts x 0.18 lb/watt = 47.75 lbs
Weight of power conversion equipment* = 200.0 lbs
Weight of basic controls = 13.0 lbs
Total weight penalty = 260.75 lbs

Internal Resistance Heating

It has been shown that for this application an internal resistance heater requires a relatively large heater surface area - like a knife blade, if constant power input is to be utilized. The equation presented on page 9 can be used to calculate the local temperatures developed by such a heater. The heater dimensions required, however, must be determined by trial and error. This was done for the case of an 8-ounce food container whose initial temperature is 75°F, and the average food temperature must be 160°F after heating for 30 minutes with a flat, probe-heater whose surface temperature never exceeds 180°F. Several probe sizes were selected and calculations made to determine the average food temperature at the end of 30 minutes of heating. Figure 10 illustrates the results. As can be seen the probe must have a width slightly less than two inches and a length less than seven inches.

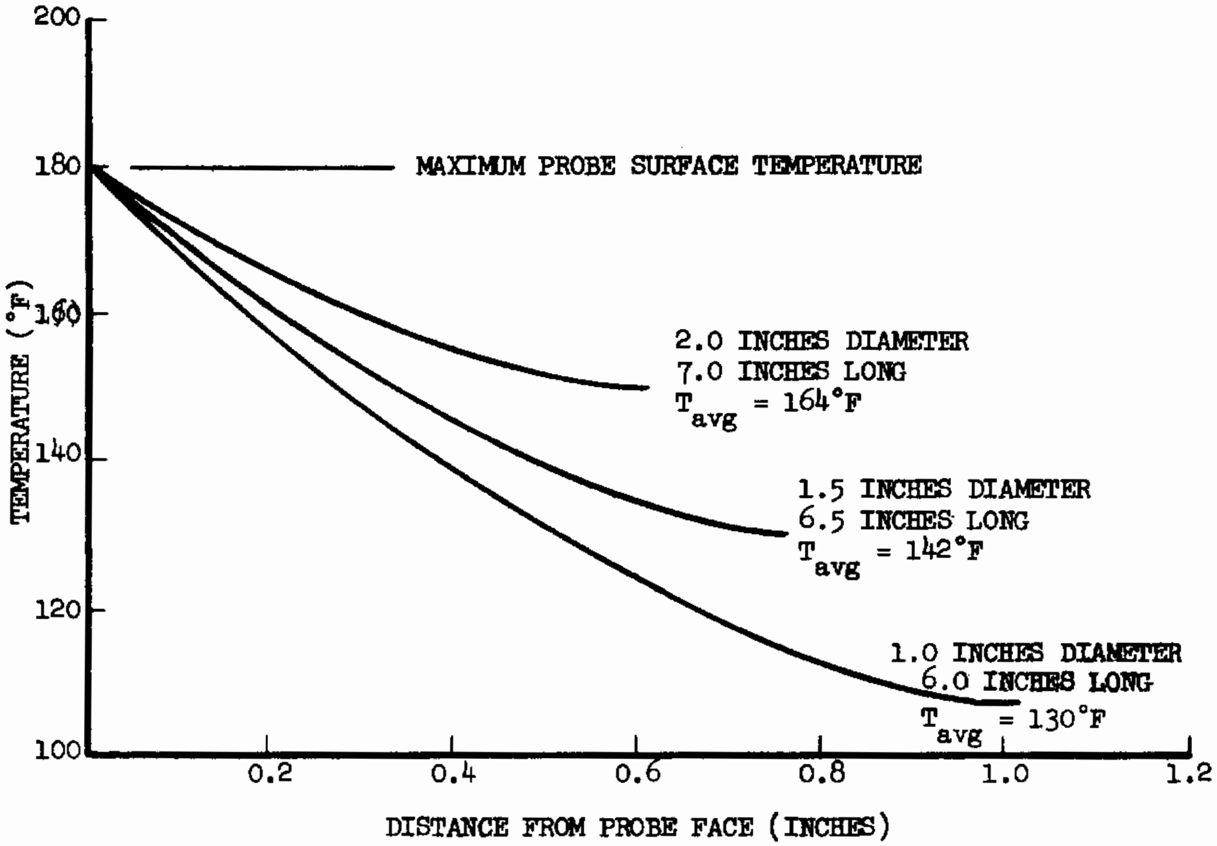

Figure 10 TEMPERATURE DISTRIBUTION FOR SEVERAL PROBE SIZES

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* R. W. Brisky, U. S. Controls, Inc., Private Communication, June 5, 1962

Some heat would be lost from the external surface of the container; these losses would be less than those experienced with external heating methods, and are estimated to be 20% of the total power supplied. Therefore total power required for the internal probe-type heating element is:

$$P_T = \frac{19.9 \times 6}{0.80} = 150 \text{ watts}$$

And the weight penalties become:

Power weight penalty = 150 watts x 0.15 lb/watt = 22.5 lbs
Weight of heating elements = 6 x 0.9 lb = 5.4 lbs
Weight of basic controls = 13.0 lbs
Total weight penalty = 40.9 lbs

Conclusions

The feasibility study established that the following design guidelines are typical for the foods and containers studied:

1. For a typical recommended menu, three containers of food should be heated per meal per man, and each container will contain either a portion of meat, a vegetable, or a liquid food item.
2. The following properties are typical for most of the foods considered:

   thermal conductivity, k = 0.30 B/hr ft°F
   specific heat, C = 0.8 B/lb°F
   density, δP = 62.4 lb/ft^3
   thermal diffusivity, α = 6.01 x 10^{-3}
   electrical resistivity, ρ = 50.7 ohm-in
   dielectric constant, ϵ = 145

3. Theoretically, the minimum energy required to raise a typical container of food from 75°F to an average of 160°F in a period of 30 minutes is approximately 10 watt-hrs.
4. For external heating techniques a unique cylindrical container is required to meet thermal requirements. The diameter of this container is approximately 2.0 inches.
5. Based on a cylindrical container, the insulation thickness which would be optimum is approximately 1/4 inch. This yields a maximum efficiency for all external heating techniques of 74%.

The results of computations based upon typical systems for each of the techniques studied are summarized in Table 3. The table shows that resistance heating, (either external or internal probe) is definitely superior on the basis of weight penalty. The probe-type resistance heater is slightly more efficient than the external resistance heater, but it is estimated that the probes would weigh more than heating blankets. Also, special containers would be required for the probe heating system. The external resistance heating technique was therefore recommended for development.

TABLE 3

SYSTEM CHARACTERISTICS

Technique	Advantages	Disadvantages	Efficiency	Power (watts)	Weight Penalty (Power) lbs	Weight (Heating Element) lbs	Weight (Auxiliary Power, Supply) lbs	Weight Basic Controls lbs	Total Weight Penalty lbs
1. External Resistive Heating - Bonded or Sprayed Element	1. Puts heater directly on container 2. High efficiency 3. No auxiliary power supply 4. Can be designed for all containers	1. Disposable heating element	74%	161.3	24.20	0.63	0	13.0	37.83
2. Induction Heating - Hollow Tubing Induction Coil	1. Generates heat at container wall 2. Can reclaim loss by heating water	1. Requires auxiliary power supply 2. Metallic containers only 3. Low efficiency 4. High weight penalty 5. Requires food mixing due to temperature gradient	43%	277.6	49.97	2.14	200	13.0	265.11
3. Dielectric Heating	1. Can heat food rapidly 2. Extremely flat temperature Distribution	1. Requires auxiliary power supply 2. Special food container	45%	265.3	47.75	0	200	13.0	260.75
4. Probe Type - Internal Resistance Heating	1. Puts heater directly in food 2. Less external heat loss 3. Easily applied to 28 V D.C. 4. High efficiency	1. Needs cleaning 2. Requires special container 3. Requires food mixing due to temperature gradients	80%	195	29.25	5.40	0	13.0	40.9

SECTION 3

SYSTEM DESIGN

General Description

One of the design requirements of the food warmer system was that it heat food in two types of containers -- a two-inch diameter metal can and a plastic beverage tube. Also, looking to the future, a wide variety of aerospace food containers might be developed, varying in size, shape and material. By applying heat with a detachable blanket, which is but a small portion of the whole system, new containers could be easily accommodated by fabricating only the heater blanket. This type of heater was therefore recommended, approved, designed, and fabricated.

Flexibility of another kind was achieved by designing the food warmer as a basic one-man-meal-module, as shown in Figure 11. The modules may be grouped vertically, horizontally, or in blocks, to accommodate any number of crewmembers eating simultaneously. Each module is a self-contained system composed of three warming station. The stations operate independently and each has the means to control the final temperature, time the warming cycle and indicate when the cycle is complete and the food is ready for consumption. Overall size of the module developed is eight (8) inches high by nine (9) inches wide by four (4) inches deep, displacing 288 cubic inches; its weight including six (6) heater blankets is 3.75 pounds.

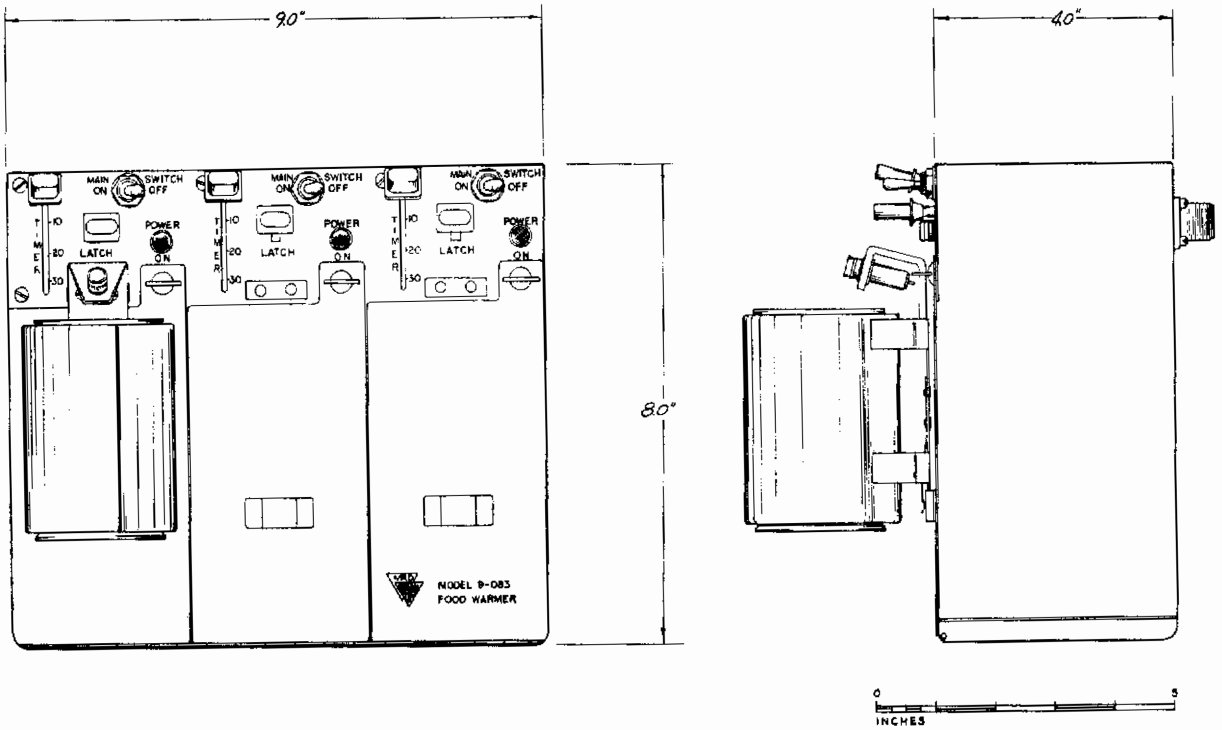


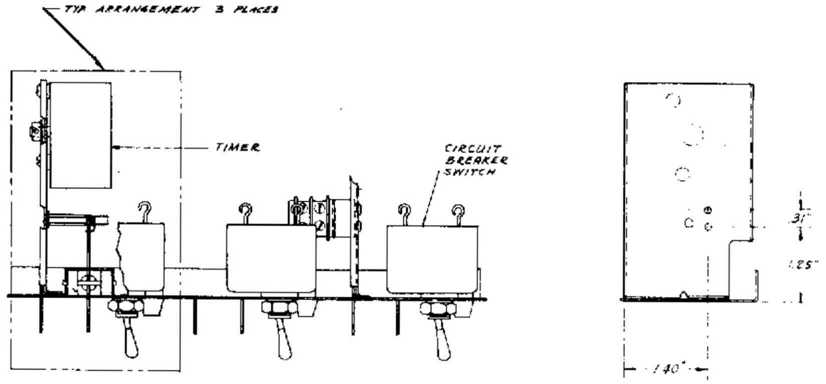
Figure 11 DRAWING OF FULL-SCALE ENGINEERING MODEL

Cabinet

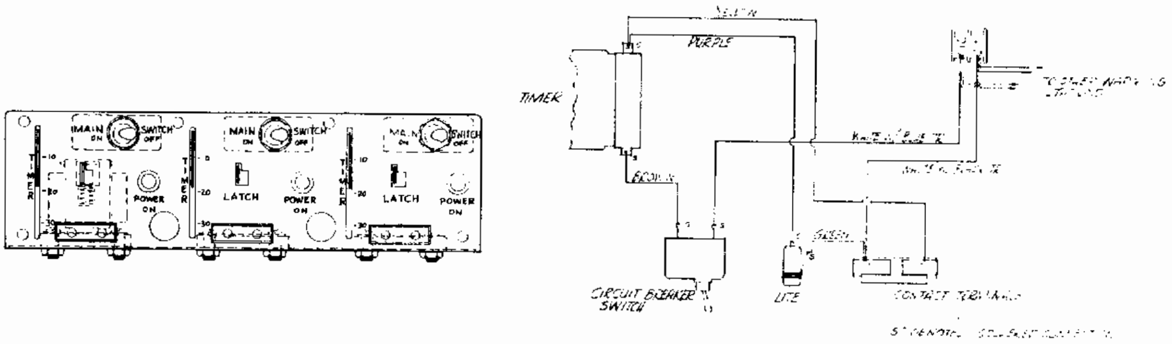
The modular cabinet is formed of 0.032 gage, 5052-H34 aluminum alloy, and is divided into two sections. The upper section contains the functional controls and the lower portion is allotted entirely to storage. Layout of the control section is in compliance with good human engineering principles. It induces easy identification of the controls and their function as well as the determination of which controls constitute a set and which warming station is controlled by each set. Cabinet styling is functional and direct; no trim or decoration is used. The cabinet, finished by color anodizing, presents a clean appearance.

Storage Compartment

An aluminum hinge along the bottom of the cabinet allows the storage compartment doors to swing open with very low friction drag. The doors are securely locked closed when the system is not in use, but each may be opened easily even during weightlessness. Inside, the same clean appearance and good human engineering practice is followed. There are no sharp projections to snag the operator's hands or his clothing. Further, to facilitate cleaning, the doors lie flat and the inside corners are formed in large radii. A bead is formed along the edges of the cabinet to stop the door upon closing; the bead also eliminates a potentially dangerous sharp edge when the door is open.



TIMER BRACKET



FACE PLATE

WIRING DIAGRAM
(ONE STATION SHOWN - OTHERS SIMILAR)

Figure 12 CONTROL SECTION ASSEMBLY

Control Section

The storage section of the cabinet is separated from the control section by a panel approximately 5-3/4 inches above the bottom of the cabinet. The panel serves many functions. In addition to separating the two compartments, it adds greatly to the cabinet's rigidity, and becomes a floor for the control section. It allows cleaning the storage compartment with a damp cloth without an electrical shock hazard by isolating the electrical components.

Figure 12 shows the assembly drawing for the control section which is removable for servicing or possible in-flight replacement. The fasteners holding the control section in place are easily distinguished from those holding the storage compartment doors closed.

Because the food warmer must function in weightlessness, its design must permit normal operation without floor-reacted forces. All forces applied to clamp a food container into a heater blanket, to operate switches and timers and to couple a heater blanket to a socket, can be applied by a squeeze between the fingers or a force between two hands.

Electrical System

The control section of each warming station is composed of: a main switch, a timer, an indicator light, an electrical socket, and a latch which secures any of the heater blankets into the socket. Each component is clearly identified on the control panel face, and is located to allow manipulation by an operator with gloved hands. By these controls the heating cycle may be manually initiated, regulated, interrupted, and re-started - or the cycle may be set and run to completion automatically.

The circuit elements are wired as shown in Figure 13. Power is supplied to each module through an "AN" connector mounted on the cabinet back surface. Inside, a coiled cord carries the power from the connector to a terminal strip on the control section frame. The coiled cord permits the cabinet and control section to be separated without disconnecting the power, and nests neatly into a cavity when the module is again assembled. From the terminal strip power is distributed to each of the three identical control circuits.

The main switch at each station is also a circuit breaker; it opens and protects the entire station if excessive current flows. An open breaker must be manually reset, affording an opportunity to locate a shorted circuit without further power consumption. The mechanically operated timer controls the heating cycle duration. Usually the period will be 30 minutes, although 10- and 20-minute markings are shown on the panel. Setting the timer, with the main switch on, will turn on the panel-mounted green indicator light and energize the electrical socket. If a heater blanket is latched into that socket, power is supplied to the blanket circuit. The socket remains energized and the green light remains on until the cycle is either completed, as determined by the timer, or interrupted by opening the main switch.

The latch, though purely mechanical, is considered a part of the electrical system because it applies a force within the socket which guarantees positive electrical contact. In conventional plug-socket sets, good contact is achieved upon coupling by overcoming a friction force caused by one or both members acting as a spring. That force is relatively large and often is great enough to support the plug and a considerable length of wire. In flight, however, where the operator may be weightless, and is unable to apply floor-reacted forces, conventional plug-socket sets are unsuitable. The socket and latching mechanism incorporated into the food warmer satisfies both of the normal requirements of a plug-socket set, positive contact and mechanical support, while overcoming the unique problem of weightlessness. Good electrical contact is guaranteed by lowering the spring-balanced latch on to the pins. The latch also serves to lock the pins in position eliminating the danger of dislodging the heater blanket assembly by an accidentally applied force. To set the latch the operator need only squeeze two knobs on the panel - a floor reacted force is not required Similarly, to remove a container, two knobs are squeezed together to release the latch, and the container may be taken from its socket. The withdrawal force is so light that in a gravity field the container will almost fall into the operator's hand, after the pins are unlatched.

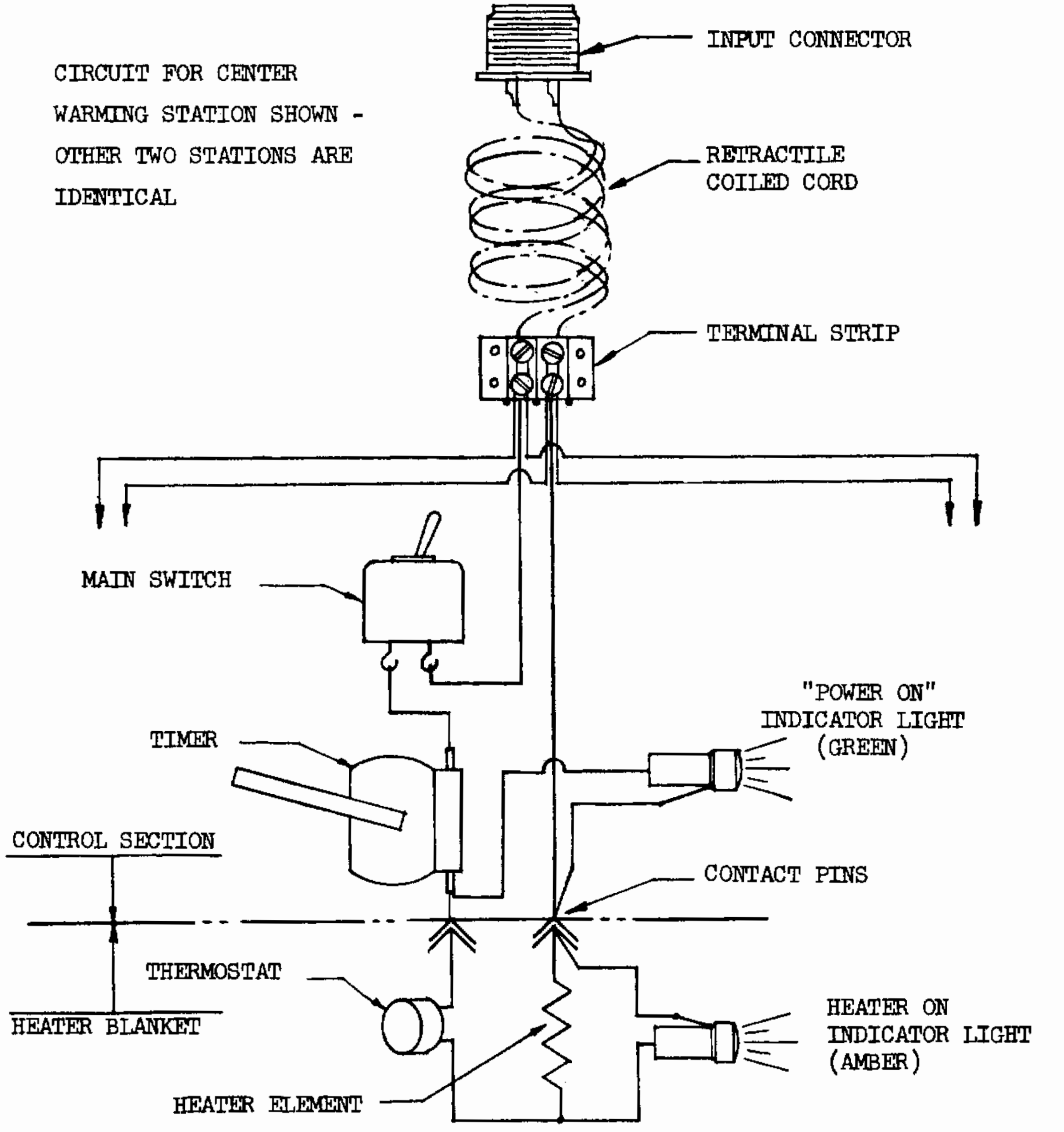


Figure 13 ELECTRICAL DIAGRAM

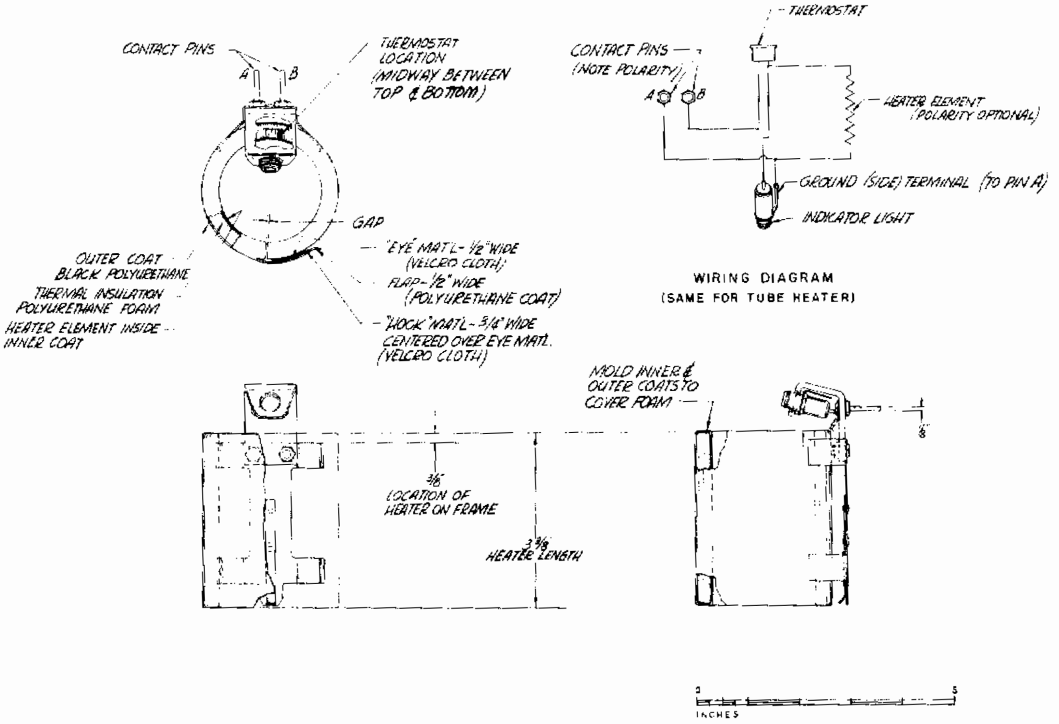


Figure 14 HEATER BLANKET FOR 2-INCH DIAMETER CANS

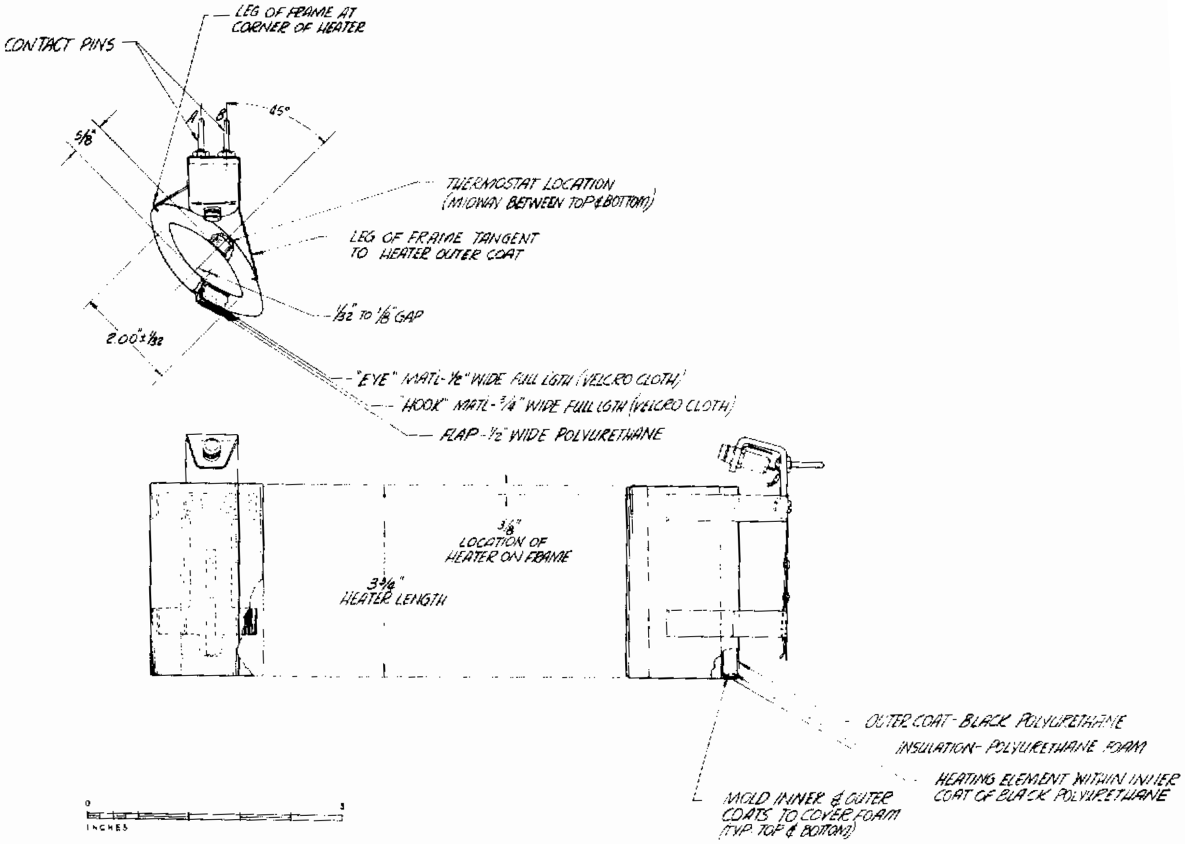


Figure 15 HEATER BLANKET FOR PLASTIC BEVERAGE TUBES

Heater Blankets

Supplied with the food warmer are two types of heater blankets - similar in construction, but each designed to hold and heat food containers with different characteristics. One type is sized for cylindrical cans approximately 2 inches in diameter, and operates at a power level of 50 watts. The other type holds flexible beverage tubes and dissipates 25 watts. The heaters shown in Figures 14 and 15, may be used interchangeably at any of the food warmer stations.

In each blanket the heating element is a fine resistance-wire mesh imbedded in Neoprene, which serves as both a mechanical support for the mesh and as an electrical insulation. A one-quarter-inch thick layer of polyurethane foam covers the element's outer surface and forms an effective thermal barrier between the heater element and the surrounding environment. Finally, an outer jacket of Neoprene-impregnated, tough cotton cloth is wrapped around the inner plies; the jacket is cemented to the Neoprene inner surface to seal the ends. The assembly is flexible and can be wrapped tightly around the food containers. The two ends of the outer jacket are fastened with hook and eye (Velcro) cloth, which holds tightly when the two faces are pressed together, but can be easily released by pulling the "hook" face away from the "eye" face. The heater blanket is light in weight but very strong; it allows easy mounting and removal of the food containers.

High versatility is inherent in this heater design. Because of its flexibility the heater can be wrapped around containers of slightly different contours and diameters. The Velcro fasteners, which can be coupled anywhere along their contacting surfaces, are able to adjust for variations in container perimeter. In addition, by leaving the blanket ends open the length of food containers which can be heated is not limited. Also, if food containers of greatly differing size and contour are to be accommodated in the future, the only redesign necessary will be minor and confined to the heater blanket configuration and power level.

Application of wire mesh heater elements insures very high reliability, because if an element is punctured and some of the resistance wires are severed, current is redistributed by wires running perpendicular to the flow of current to the remaining resistance wires. Thus the mesh all around a puncture is still effective in power conversion, and very nearly the same current flow will continue in the heater unless, of course, the heater is severely damaged. Watt density in both the can and tube heaters is held below two (2) watts per square inch - another factor which contributes to the heater's high reliability. The low watt density was achieved by operating the heaters at low power levels, and by locating the mesh evenly throughout the entire available area. Further, local hot spots on the heater surface are eliminated and uniform surface temperatures conducive to efficient heat transfer are insured.

Heater Thermostat

A thermostat is mounted within each heater blanket to control current flow through the element. The thermostat is held against the container wall and senses the container surface temperature. The configuration is compatible with the optimum externally-wrapped resistance heating technique, and senses temperatures more reliably and accurately than if the measurement were taken inside the food. Sensing container wall temperature rather than the more significant adjacent-to-the-inner-wall food temperature improves reliability because the thermostat is located on the surface which is at the highest temperature, precluding the possibility of overheating the food. Thermostats held against the container surface are more accurate because so placed they are not subjected to errors in location. Sensors placed inside the food can not be located with the same precision.

The entire problem of accurate thermostat location could be circumvented if the sensors were placed inside the container in contact with the inner wall. However, at that location the sensitive point can become enveloped in a localized area of film or neucleate boiling, and sense a temperature substantially different from that prevailing at other locations adjacent-to-the-inner-wall.

By placing the thermostat outside the container on the wall outer surface, a thermal gradient between the sensed temperature and the significant food temperature exists through the container wall. That gradient is fixed by the container properties alone, and is independent of the kind of food being heated. The gradient through the wall is very small due to high thermal conductivity and thin cross-section of the container material. Also, because of its high thermal conductivity, the wall acts as a buffer to thermally dampen the temperature variations which might be caused by any localized boiling in the food. The thermostat operating temperature can be easily adjusted to include the fixed gradient across the container wall. Moreover, internal probes introduce a sanitary problem and probably require a device to apply large piercing forces in weightless space. While these problems are minor relative to the probe's accuracy limitation, they are eliminated by the superior and lighter weight external-surface thermostat location.

Summary

Figure 16 shows the full-scale engineering model fabricated. Two of the basic three container modules were made to form this system. Each module occupies a volume of 288 cubic inches and weighs less than 3.75 pounds, with three can heaters and three tube heaters. The can heaters are rated at 50 watts, while the tube heaters are rated at 25 watts, when operated with 28-volt direct current.

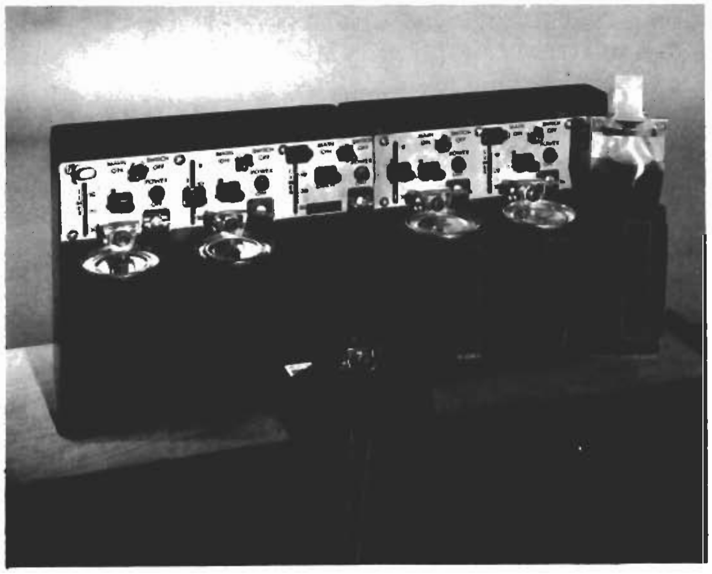


Figure 16 PHOTOGRAPH OF FULL-SCALE ENGINEERING MODEL

SECTION 4

LABORATORY EVALUATION

Described in this section are the various laboratory tests performed during the program. Two groups of food heating tests were run. First, early in the design phase, prototype externally-wrapped resistance heaters were operated at many different controlled conditions. Those tests determined the specific operating characteristics of the preferred heating technique, and established guidelines used in the design of final production heaters. Later, after the food warmer was fabricated, performance and evaluation tests were run on the finished system.

Other testing included functional check-out of system components; an evaluation of operating procedure, including attaching and removing a container of food, and the effects of emergency interruption of a heating cycle; and a study of the built-in safety measures protecting both the operator and the system.

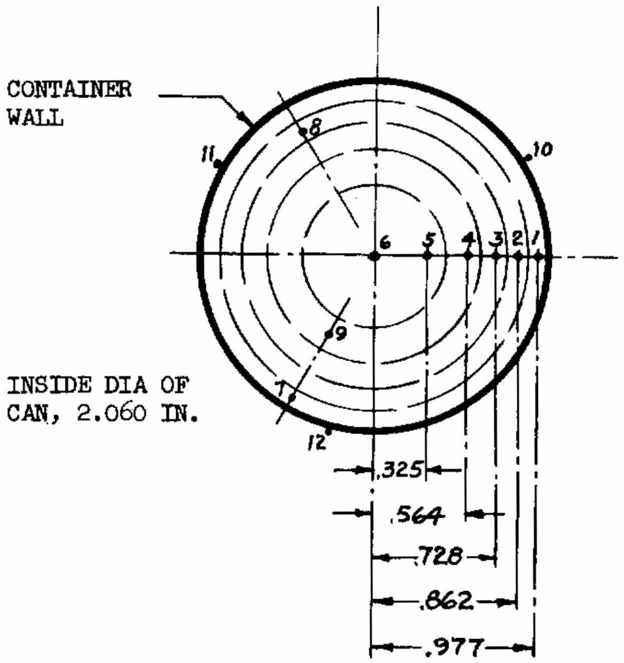
Development Tests

A comprehensive testing program was undertaken to:

1. Evaluate the externally-wrapped resistance heating technique in practical use
2. Determine the total energy which must be applied to containers of food to effect an 85°F average food temperature rise
3. Establish at what rate (power level) that energy must be applied to realize the required temperature rise in 30 minutes
4. Determine the necessary thermostat operating limits, and whether presently available thermostats could be used succesfully.

Special consideration was necessary in developing a conclusive laboratory test program because the food warmer was designed for operation in a weightless environment, and was tested in a gravity-influenced environment. During the tests therefore, several limiting factors were present, namely: (1) heat loss by free convection off the ends of the food containers existed in the laboratory - but would not occur in flight, (2) thermal motion of the food within the container will occur in the laboratory - but not in a space environment, (3) the tendency for container contents to settle to the bottom in the laboratory would not be present in weightlessness, and (4) reduced ambient pressures may affect operation of electrical components in an aerospace vehicle. While most of these factors tend to safely oversize the heaters when used in the cabin of an aerospace vehicle they were minimized in the test program by including the following:

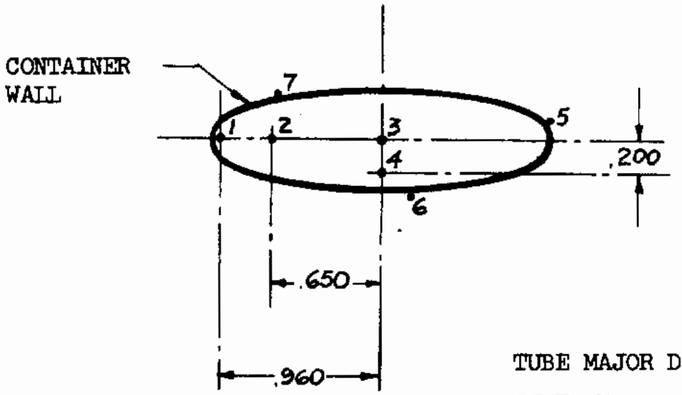
1. Insulated covers were placed on both ends of the cylindrical food containers to reduce convective heat losses off those surfaces.
2. Special food mixtures were chosen, of an oatmeal consistency or of gelatinous character, to reduce thermal motion of the food in the container.
3. Completely filled, air-free containers were used to insure a uniformity of heat-absorbing material inside the container surfaces. Whenever material had to be added, its quantity and specific heat were known so that its heat absorption could be deducted from the total energy input.
4. Final tests were conducted at 1/2 atmosphere ambient pressure to evaluate the effects of reduced pressure on the electrical system



• = THERMOCOUPLE LOCATION

THERMOCOUPLES NO. 1 THRU 5
LOCATED AT CENTERS OF EQUAL
AREA CONCENTRIC CIRCLES.
NO. 6 AT CENTER OF CAN
NO. 7 DUPLICATES NO. 1
NO. 8 DUPLICATES NO. 2
NO. 9 DUPLICATES NO. 4
NOS. 10, 11, & 12 LOCATED
ON CAN'S OUTER SURFACE

Figure 17a THERMOCOUPLE LOCATIONS, CAN



THERMOCOUPLES 1 THRU 4
LOCATED INSIDE TUBE,
MEASURING HIGHEST,
LOWEST, & INTERMEDIATE
TEMPERATURES
NUMBERS 5, 6, & 7
LOCATED ON TUBE
OUTER SURFACE

TUBE MAJOR DIAMETER 2.0 IN.
TUBE MINOR DIAMETER 0.6 IN.

Figure 17b THERMOCOUPLE LOCATIONS, BEVERAGE TUBE and energy loss rate.

During development testing, heat was applied to the food through the container wall by an externally-wrapped resistance heater similar in configuration and identical in operation to the production heaters. Container surface temperature was measured at three points by permanently attached thermocouples. Similarly, three thermocouples were held to the plastic beverage tube by small pieces of transparent tape. Measurements taken by those instruments represent the temperatures sensed by the thermostats. Food temperature in the containers was measured by nine (9) thermocouples immersed in the food and held in place by a rigid frame. Five of those were located at the center of equal area circles. Thus by averaging the five readings arithmetically, the average food temperature was determined. The remaining four thermocouples duplicated some measurements and served as a check on thermocouple location and accuracy. Figure 17 depicts the thermocouple locations. Each thermocouple was read periodically during each test by means of a recording potentiometer.

Power level was set before each run by adjusting the applied voltage to a value between 22 and 31 volts d.c. During each test, action of the thermostat was simulated by manually interrupting the power when the container surface temperature reached 180°F, and turning it on again when the surface cooled to a lower temperature. Runs were made at various cut-in temperatures to select the most suitable thermostat operating range.

Each test was terminated after 30 minutes, but thermocouple readings continued for at least five minutes after termination of each test to observe the rate at which the thermal gradient was reduced with time, and to note the reduction in average temperature as heat was lost through the insulation. The temperatures from which the results are taken, however, are those occurring at time 30 minutes. When heater power level and thermostat operating temperatures were adjusted to their best values - those which effected the required food temperature rise while showing the lowest energy consumption - temperature histories like those shown in Figure 18 were recorded.

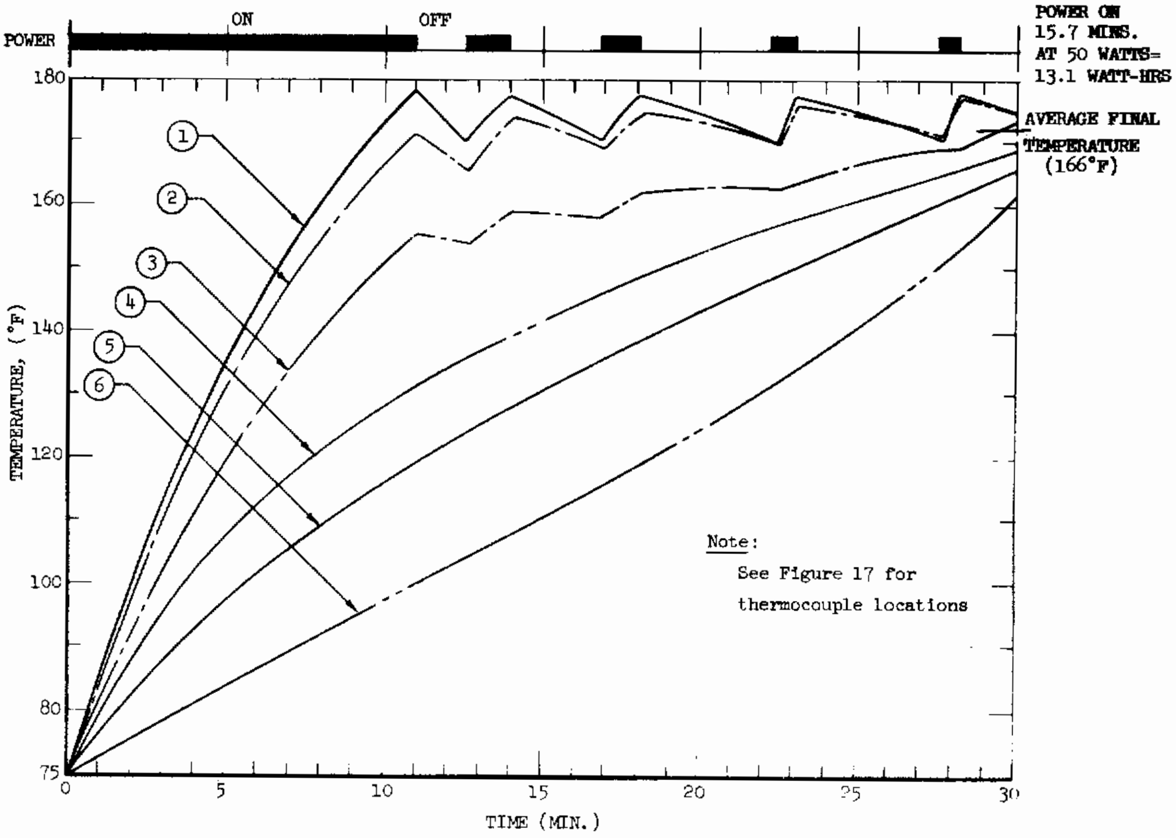
Performance Testing

A set of evaluation tests was performed on the finished model.

The mechanical latches were locked and opened many times to observe any binding or wear and to test the reliability of electrical contact upon each closing. The storage compartment doors were checked for alignment and smooth operation; and torsional loads were applied to the cabinet on all three axes to check its rigidity. Electrical continuity between the cabinet and both sides of the power-input line was measured. The automatic controls at each station were tested for cycle duration and overload protection. No malfunctions were detected.

The heater assemblies were tested for power level, thermostat operating limits, dimensional size and operation of the mechanical closure. Each heater was connected to all stations to insure perfect compatibility and was run at 28 volts d.c. with a container of food to check its outer surface temperature. Then the heaters were tested at 24 and 32 volts d.c. to prove their reliability at other than design voltage. The production heaters passed all tests.

The fully-instrumented containers used in earlier testing were placed into the production heaters and run through automatically controlled heating cycles. Temperature histories of the thermocouples were permanently taken by a recording potentiometer Results were as shown in Figure 18 - a typical run in which ham and eggs were heated from 75°F to 166°F The test was run with 28 volts d.c. applied, and energy consumption was 13.1 watt-hours.



Note:
See Figure 17 for thermocouple locations

Figure 18 TYPICAL TEMPERATURE HISTORIES AT SEVERAL THERMOCOUPLE LOCATIONS

Finally, the entire food warmer system was placed in a vacuum chamber and run through automatically-controlled cycles under ambient pressures of 5 psia and 15 mm Hg absolute. At these pressures heat losses were lower and therefore energy consumption decreased to below 13 watt-hours. No malfunction was detected in any of the performance testing.

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

A study of methods for heating foods during aerospace flight, and the design, fabrication, and evaluation of a full-scale food heating system has been performed. The following conclusions were determined from this study.

1. Electrical resistance heating is the most effective method of heating foods, if the heating element can be placed in close contact with the food or container.
2. Induction and dielectric heating require power conversion equipment that is relatively inefficient.
3. Solar, nuclear, and chemical energy methods of heating are impractical.
4. The most efficient method of heating foods is to use an internal probe that contains a resistance heating element. However, a special food container is required for this technique.
5. The most efficient method of heating food in available containers is to use a flexible resistance heater that can be wrapped-on the food container. An engineering model of a three-container system based on this technique was designed, and two full-scale engineering models fabricated. Each model occupies a volume less than 288 cubic inches and weighs less than 3.75 pounds when furnished with six heater assemblies.
6. Laboratory evaluation tests of each model showed that the system meets all of the requirements listed on pages 1 and 2. In addition, it was demonstrated that the system can heat a 6-ounce can of ham and eggs from 75°F to 166°F with an energy requirement of 13.1 watt-hours.

The external resistance heating technique developed under this program is the most effective method of heating foods in available containers. An internal resistance heating probe would be even more efficient, but special food containers would be required. It is recommended that the internal probe technique be developed next, along with the food container necessary. A three-container food warmer based upon this technique would weigh approximately four pounds, and have an overall efficiency greater than 75%. The food containers developed for this technique should contain an internal pocket for accommodating the internal heating probe.

SECTION 6

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