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THERMAL DESIGN OPTIMIZATION OF FOOD PACKAGES WITH INTEGRAL HEAT SOURCE

By

Il Young Kim

June 1996

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U.S. ARMY SOLDIER SYSTEMS COMMAND
NATICK RESEARCH, DEVELOPMENT AND ENGINEERING CENTER
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A mathematical heat transfer model developed in ANSYS, a commercial finite element analysis program, is used to improve the thermal performance of the Self-Heating Individual Meal Module (SHIMM). Design parameters such as size and arrangement of the Flameless Ration Heater (FRH) and container materials are optimized with the Finite Element Analysis (FEA) model. Evaluation factors include heating rate and uniformity during the self-heating process. Results from the analysis showed that the use of two one-third-size heaters with a different tub materials is the most thermal efficient SHIMM. An alternative design concept for the SHIMM is also discussed.

14. SUBJECT TERMS

THERMAL DESIGN	COMPUTER MODEL	NUMERICAL METHODS AND PROCEDURES
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Table of Contents

List of Figures

Figure | Page

Figures (cont'd)

List of Tables

Preface

This study was conducted from October 1992 to September 1993 to improve the transient thermal performance of the Self-Heating Individual Meal Module (SHIMM). The SHIMM contains an integral exothermic chemical heater known as the Flameless Ration Heater (FRH). The primary effort in this study was the development of two-dimensional models in ANSYS® (a commercial finite element code). This report covers the first part of the Thermal Analysis and Design Optimization project. The second part of the project dealt with the Self-Heating Group Ration (SHGR).

Acknowledgements

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OF
FOOD PACKAGES WITH INTEGRAL HEAT SOURCE

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United States Army Natick
Research, Development and Engineering Center

May 1996

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OBJECTIVE

The purpose of this study is to improve the thermal performance of current self-heating individual food packages by using heat transfer modeling and numerical methods. A mathematical heat transfer model will be developed and simulated by a commercial finite element analysis code to optimize design parameters such as heater size and container material. The result of this study will provide valuable information that could be directly applicable to any other self-heating food packages. The objectives of this study are:

1. Develop a computer model to estimate time-temperature profiles in a self-heating individual food container while evaluating the heating rate and uniformity during self-heating process.

2. Develop an optimization method to determine the optimum size and arrangement of the heater and container materials. Then evaluate the influence of these design parameters on rate and mode of heat transfer into the packaged food.

3. Recommend a new design concept based on the results of the model simulation.

BACKGROUND

The success of the Flameless Ration Heater (FRH) has accelerated the development of other self-heating food package concepts such as the Self-Heating Individual Meal Module (SHIMM) and Self-Heating Group Ration (SHGR). These alternate methods use a chemical heating pad as an integral part of a ration packaging system (see Figure 1). The pads generate heat from an exothermic chemical reaction in which metallic compounds react with an activating solution. During the reaction, the heater temperature surpasses 200°F (93.3°C) and boils the activator, which is water for this model. The boiling water fills the heater space between the upper (food) and lower (heater and activator) tubs and functions as a medium for heat convection inside the gap. Understanding principles of chemical heat generation and heat transfer inside a food package is critical to the development of a successful design of the food package. Appendix A covers all heat transfer phenomena observed in the container and their influence on the mathematical simulation.

There were some efforts at Natick to observe and model the heat transfer mechanisms of the heater and food. Dr. Satish Kandlikar developed a one-dimensional heat transfer model and

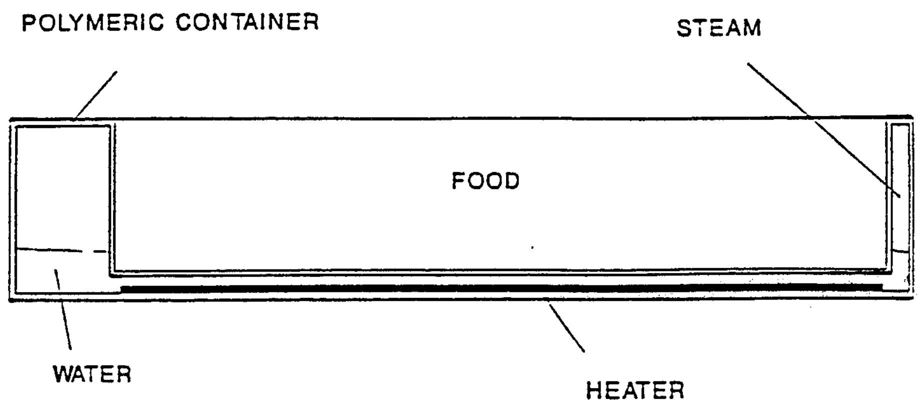


Figure 1. A Schematic of Self-heating Package Model

conducted experiments on chemical heaters to find their temperature profiles during h is summer facility program at Natick. The chemistry of the chemical heater was studied by Mr. Sebastian LaGambina, who determined the effect that activators have on the rate of heat generation.

Some experiments have been done to measure temperature profiles at various locations on the current SHIMM package to predict heat transfer inside. However, the experiments were limited to the current SHIMM, the only package available at this time. The preliminary experiments were used only to evaluate the function or performance of the SHIMM package.

To improve the current package design, at least several candidate prototypes, with different combinations of thermal design parameters, should be fabricated. The same previous experiment where temperature profiles were found could be done on the prototypes to select the best one. However, this is usually a very time-consuming and costly process based on trial and error. Conversely, mathematical modeling and finite element analysis can be done on a computer, saving time and money.

Mathematical Modeling

A mathematical model is a representation of a physical process or system that uses symbols which can be manipulated by the laws of mathematics. Mathematical modeling is distinguished from conventional computations by this purpose. Modeling is used to understand physical processes and form an agreement between a postulated model and the system it represents.

To construct a mathematical model, the important phenomena are identified and the most general form of the appropriate equation is formulated. The equation is then examined critically and any simplifications that are appropriate are made and a solution procedure developed. This almost always involves digital computations and numerical analysis. Finally, the model solution is compared with known solutions or experimental data to validate the model.

The following assumptions were made for the mathematical model of the SHIMM:

1. Heat transfer in the container is limited to conduction (See Appendix A, heat transfer modes in the container).

2. The thermal properties of the materials are constant over the temperature range of the heating process period.

3. The thermal properties of the materials for the heater space are modified to simulate heat convection in the boiling water.

4. The thermal properties of food are the same as those of water.

5. Heat contact resistance between different materials is negligible.

6. The initial temperature throughout the model is 50°F (10°C).

7. Both side walls of the container are adiabatic.

Based on the above assumptions, a mathematical model was developed for a self-heating individual food container (Figure 2). The final model is a two-dimensional transient heat conduction model with heat generation and heat convection around the container.

The time-temperature profile for different materials in a rectangular container can be expressed by the following equations:

For the heater and the gap for the heater with the activator:

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\dot{q}}{k} \quad (1)$$

For the food inside the container and the container wall with different values of thermal diffusivity:

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \quad (2)$$

and the boundary conditions at the wall can be represented by

$$\frac{\partial Tw}{\partial y} = \frac{h}{k}(Tw - Tamb) \quad (3)$$

The initial condition is given by

$$T = 50°F \qquad t = 0 \quad (4)$$

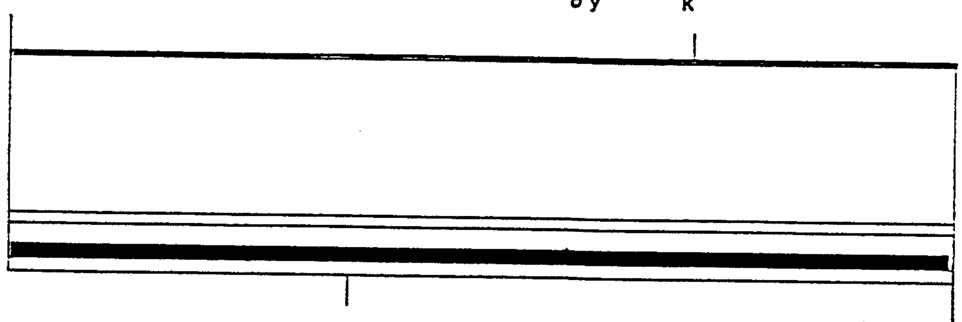
where T = temperature in the container wall or food as a function of x,y, t = time, Tw = outer wall temperature, Tamb = ambient temperature, h = heat transfer coefficient at the wall, k = thermal conductivity of the wall material, and α = thermal diffusivity. Except for heat convection

2-DIMENSIONAL TRANSIENT HEAT CONDUCTION
WITH HEAT GENERATION

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\dot{q}}{k}$$

$$\left.\frac{\partial T}{\partial x}\right|_{x=0} = 0$$

$$\frac{\partial T}{\partial y} = \frac{h}{k}\,(T - T_{amb})$$



$$\frac{\partial T}{\partial y} = \frac{h}{k}\,(T - T_{amb})$$

$$\left.\frac{\partial T}{\partial x}\right|_{x=L} = 0$$

Figure 2. A Mathematical Model for Heat Transfer
In A Self-heating Food Container

food and container materials. The calculations in Appendix A support the assumption that heat convection and heat radiation inside the container are negligible.

These equations will be solved simultaneously using numerical techniques. The advantages of using numerical modeling techniques to complement experimental testing are: the ability to investigate implications of design changes within relatively short time spans; the capability of providing detailed information on all primitive variables; the ability to simulate severe operating conditions; the reduction of time and material costs.

Thermal Design Variables

A good model can replace experiments which may be difficult to perform. A model can show how different design parameters affect heat transfer rate and mode in a container, whereas performing the work on real prototypes is a time-and money-consuming task. To appreciate this advantage, design parameters need only be defined and compared against each other to determine the number of prototypes that must be built and tested.

For this model, two major design parameters (heater design and container material) were considered. The size and arrangement of the heaters are the largest concerns for energy utilization of the limited chemical heater. The selection of container materials is another major thermal design parameter that can be controlled efficiently.

1. Size and location of the heater

Figure 3 shows three different size heaters and their locations. There is one full-size heater, one half size- heater, and two one-third size heaters.

One full-size heater covers the whole bottom surface area of food tub. The half-size heater is located in the middle of bottom surface area of food tub. And the two one-third heaters are two pieces of heater that cover two-thirds of the bottom surface area of the food tub symmetrically, as shown in Figure 4.

Therefore, the total amount of heat source mass varied. The half-size heater has one-half and the two one-third size heaters have two-thirds the mass of the full size heater. It is expected that the total amount of heat generated is proportional to the mass of the heater.

The heater size and locations were established to evaluate heater sizes smaller than the full-size heater in terms of cost savings and performance optimizations of the heater. The best choice will be the minimum size heater with the maximum heating capability.

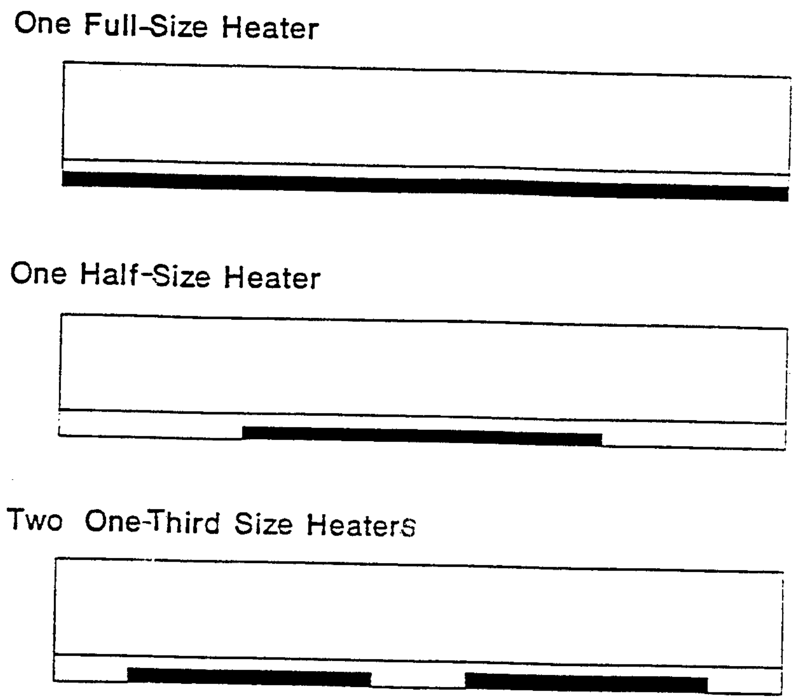


Figure 3. Three Different Sizes of the Heater

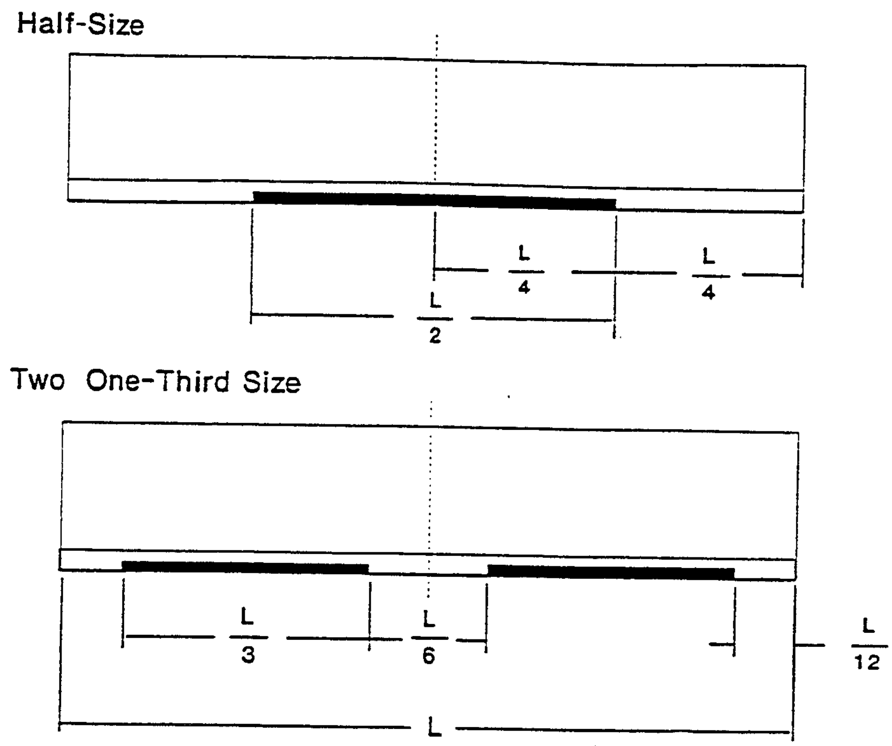


Figure 4. Optimal Arrangement of Two Partial Heaters

2. Container materials

Current prototypes of the SHIMM use polypropylene as the container material. The same material is used for both pieces of the tub, which consists of an upper tub for food and a lower tub for the heater and activator. Unfortunately, the two pieces of tub for this prototype have exactly opposite functions, one for heat transfer and the other for insulation. No single material is good for both functions. The thermophysical properties of polypropylene show that it is more thermally insulating than heat conducting. Its low thermal conductivity prevents heat loss from the lower tub, but also prevents heat transfer into food at the same time. A material that has low thermal conductivity is good for the bottom tub while a material that has high thermal conductivity is good for the top food tub. For this model, polypropylene was used as the material for the lower tub because of its low thermal conductivity. For the upper tub four materials including polypropylene were selected. The thermophysical properties of the four different candidate materials are as follows:

Table 1. - Thermophysical Properties Table for Container Materials

Thermophysical Properties	Polypropylene	Polyethylene	Tin (Sn 100)	Aluminum Foil
Density				
lb/ft³	56.18	57.39	358.97	168.68
(kg/m³)	(910)	(919)	(5,750)	(2,702)
Thermal Conductivity				
Btu/hr·ft·°F	0.08	0.19	38.71	136.33
(W/m·°K)	(.14)	(.33)	(67)	(235.99)
Specific Heat				
Btu/lb°F	0.46	0.55	0.0542	0.1513
(J/kg·°K)	(1,926)	(2,303)	(227)	(633.5)
Thermal Diffusivity				
ft²/hr	0.003	0.006	1.9896	5.388
(m²/hr)	(0.000028)	(0.000056)	(0.0185)	(0.0501)

These materials have different ranges for the three major thermal properties. The thermal conductivity of polyethylene is twice that of polypropylene, and Tin is 187 times higher than the thermal conductivity of polyethylene. The thermal diffusivity of Tin is 650 times higher than that of the current lower tub material, polypropylene.

Numerical Modeling using ANSYS Thermal Analysis

Because of the recent improvements in speed and efficiency of the personal computer, commercial finite element software codes have been used more frequently and successfully for thermal analysis and design optimization. ANSYS™ is a Finite Element pack°±²³age that was introduced in 1970 by Dr. John Swanson of Swanson Analysis Systems, Inc. The ANSYS program is a general purpose finite element program which includes a variety of analysis capabilities for linear and nonlinear structures. These capabilities include static, transient dynamics and harmonic response analysis. The program is graphics oriented, depending largely on graphic displays for verifying user supplied information, and for retrieving ANSYS calculated results in the post-processors.

The principles of ANSYS thermal analysis are derived from proven numerical techniques. In the finite element process a differential equation is reformulated into a matrix equation that is suitable for the computer analysis. The matrix equation for heat steady state transfer is

$$[C]\{\dot{T}\} + [K]\{T\} = \{Q\} \tag{5}$$

where [C] specific heat matrix

[K] effective thermal conductivity matrix
-conduction, convection, and radiation

{Q} effective heat flow rate vector
-internal heat generation

{T} nodal temperature vector

$\{\dot{T}\}$ time derivative of temperature

For transient thermal analyses, the governing equation must be integrated with respect to time. This is accomplished through the Crank-Nicolson/Euler theta integration method in which the equation is solved at discrete time points within the transient analysis. The difference between any two time points is known as the integration time step, which is specified by the user.

ANSYS consists of Preprocessing, Solving, and Post-processing stages. The geometrical model is created in the Preprocessing stages as shown in Figure 5. The element type and material properties were also specified in this stage. Figure 6 shows the nodes created for the container using x-y coordinates. The input cross-section of the container was divided into parametric

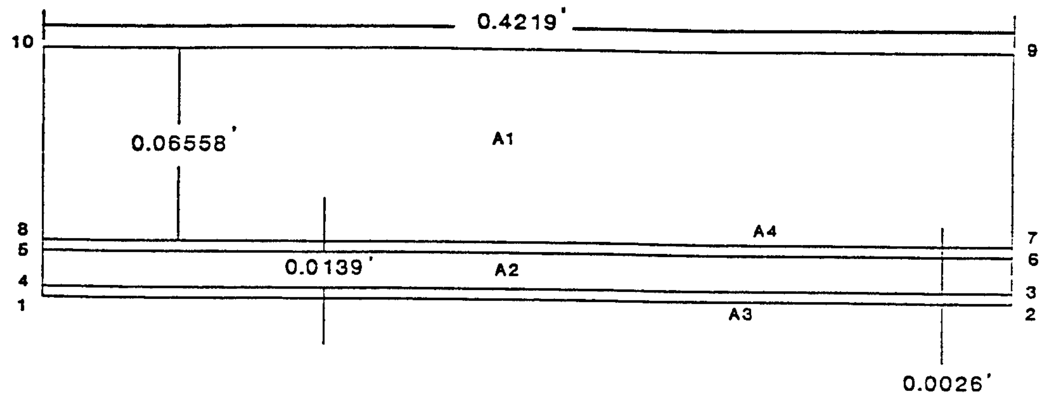


Figure 5. Cross-section of A Self-heating Food Package

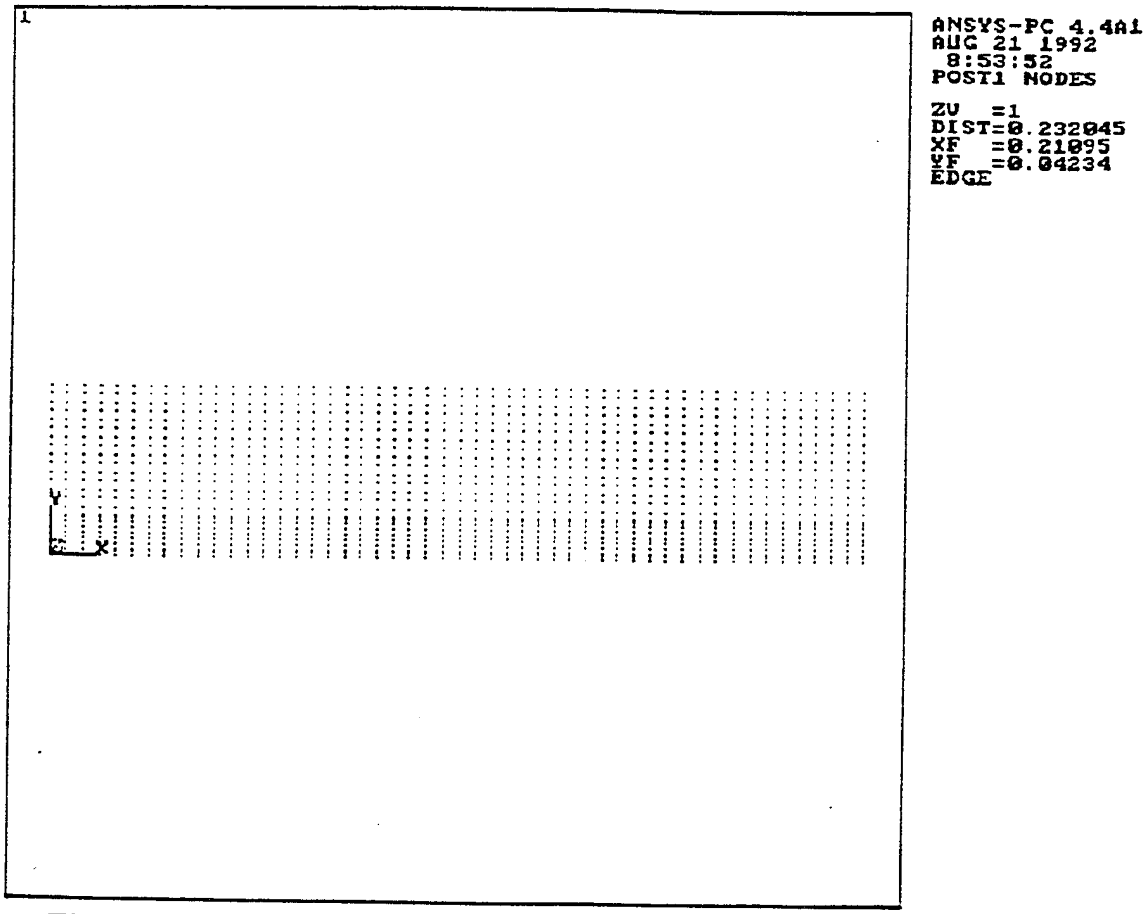


Figure 6. Nodes Created for the Container Model

thermal elements with 2-dimensional conduction capability as shown in Figure 7. The variable temperature in each element was approximated as a function of temperature values at the nodes. For transient analysis the time step and number of iterations were set at this stage, too.

The heater was simulated with temperature boundary conditions set at nodes created for the heater and the step loading method was used to simulate heat generation for the time-temperature profile of the heater. The boundary conditions at both the top and bottom wall were for heat convection.

The solution stage solves the model and sends the output to a file that can be accessed by the Postprocessor. The solution yields temperature and heat flux values at each node in the model for different time steps.

The two major options in the Postprocessing stage of the ANSYS Program were time temperature profile graphs and isothermal contour color diagrams. The former shows the changes of temperature at specific nodes along the simulation time and the latter shows contours of the same temperatures with nine different colors.

The model was developed flexibly so that design variables in the model could be changed. The model enabled comparisons of the thermal performances of different design variables on the same basis. Results from the model were compared with experimental data and thermal properties were adjusted, within a reasonable range, until data and model agreed. ANSYS modeling processes, including set-up, modeling, loading, solving and displaying, are detailed in Appendix B.

Results

First, the model was simulated for the three different size heaters at different times after activation of the heater. The times chosen were: 1, 3, 5, 10, 15, 20, and 30 minutes for the full-size heater; 1, 3, 5, 10, and 30 minutes for the half-size heater; and 1, 3, 5, 10, 15, and 50 minutes for the two one-third size heaters. At this time, the material for the container was not a variable for the simulation. Polypropylene was selected for both upper and lower tubs, as is used in the current SHIMM.

The results showed that there were differences in the heat transfer rate and mode among the heaters. The full-size heater showed the highest heating rate and ideal uniformity. The one-third size heater showed similar uniformity, but slower heating than the full-size heater because of having one-third the amount of a full-size heat source. The half-size heater showed not only the lowest heat rate, but also the least uniformity of heating. Their cooling pattern was also different. The two one-third size heaters cooled faster than the full-size heater, but slower than the half-size heater. The most significant temperature changes were in the first 10 minutes for all the heaters.

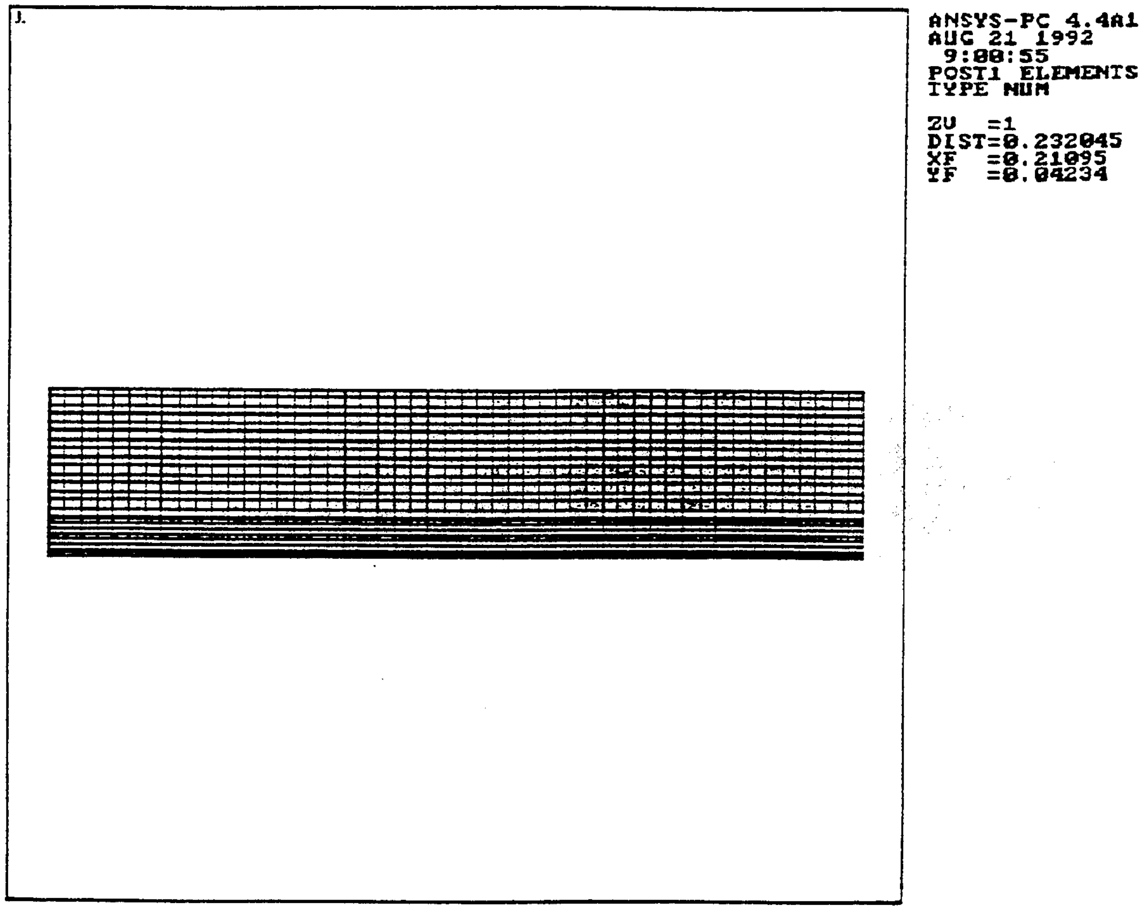


Figure 7. Parametric Thermal Elements Dividing the Model

The isothermal contour diagrams show that heat generated from the heater warms the activator in the space between the upper and lower tubs first before transferring through the food. This can be explained by the boiling of the activating solution immediately after activation. Figures 8 through 13 are diagrams of the full-size heater at seven different times after activation. The isothermal lines are straight because of the full-size heater that covers the whole bottom area of the upper tub.

As shown in Figures 14 through 18, the half-size heater shows a unique heat transfer pattern from the heater. Most of the heat transfer was in the middle of the container. Differences in heat transfer between the center and the corner resulted in uneven heating. Figures 19 through 24 are for the two one-third size heaters. This heater showed much better heating uniformity than expected. The heating rate of this heater was between the full-size and the half-size heaters.

For the time-temperature profile graphs, three nodes were selected: one for the heater, one for the top center of the food and one for the top corner of the food. These graphs show the time-temperature profiles of the nodes for the three different sized heaters. The graphs were a convenient way to check the temperature changes and heat uniformity during the heating period at a glance, while the contour diagrams were good for demonstrating the heat transfer at specific times.

So far the model has used polypropylene as a container material. However, another design variable is the material for the upper (food) tub. Four materials: polypropylene, polyethylene, tin and aluminum foil were selected for tub while polypropylene was still kept for the lower tub. The same simulated four different materials for each heater size for a total of twelve combinations. Figures 25 through 36 show the time-temperature profiles for the three nodes in the various combinations of design variables. The polyethylene material allowed more heat transfer into food than the polypropylene did during the heating period. Tin and aluminum foil, however, were much better than the polymers. They showed a very sharp temperature rise in the first five minutes and a slow temperature drop. The highest temperature the metals achieved was approximately 8 to 10 degrees higher than the polymers. They raised the target food temperature 8°F (4.4°C) higher than the polymer's. There isn't a large difference in the thermal diffusivity between tin and aluminum foil, although tin has better durability and fabricability than aluminum. The metals also showed the problem of uneven heating with the half-size heater.

An individual meal module integrated with a tin food tub and two one-third size heaters (Figure 35) showed almost the same (or a little better) heating performance as the current module with polypropylene food tub and a full size heater (Figure 25). Based on the results, the best material for the top food tub is tin and the bottom tub is polypropylene. These materials maximize the heat transfer rate to the food and minimize the heat loss through the bottom of the tub. The two one-third size heaters are recommended to save heater material without sacrificing heating rate or uniformity.

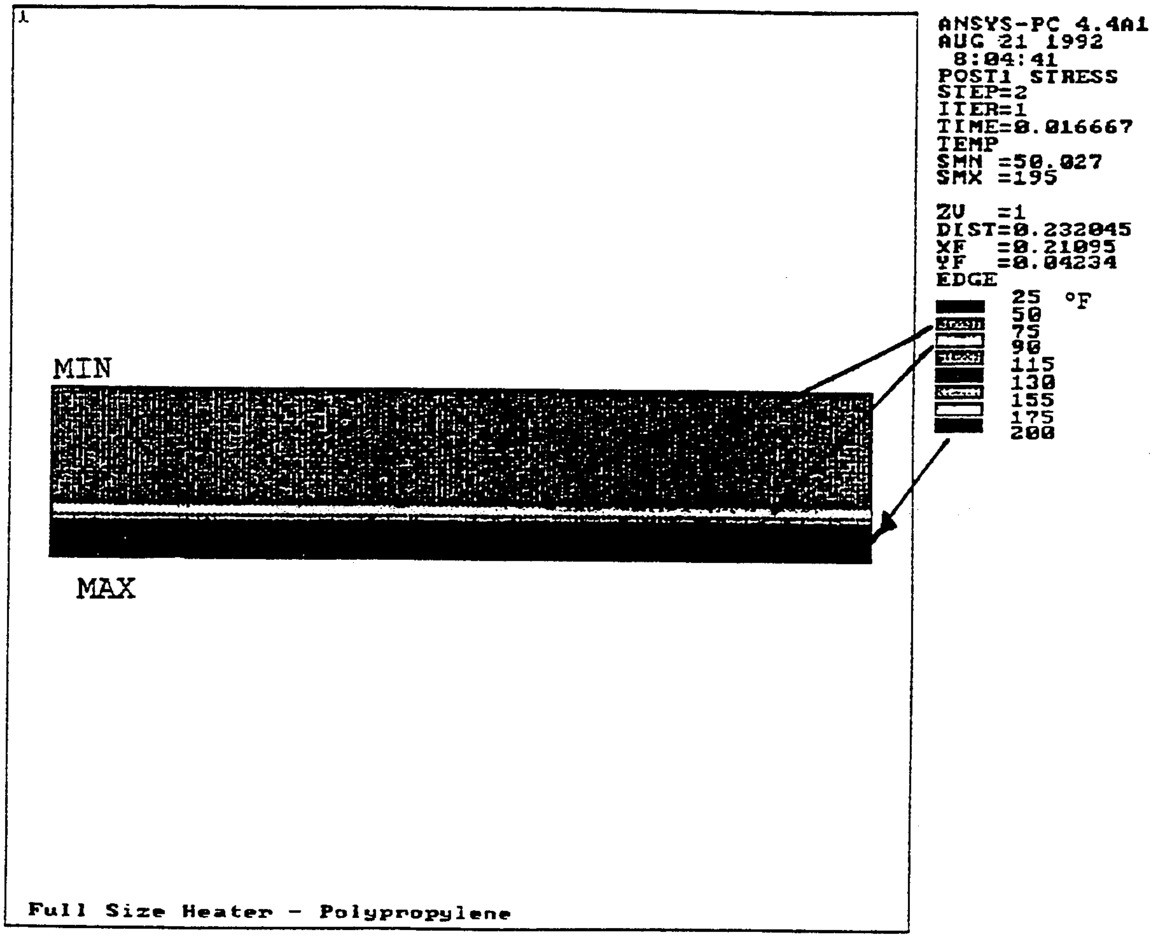


Figure 8. One Full-Size Heater, Time = 1.0 min.

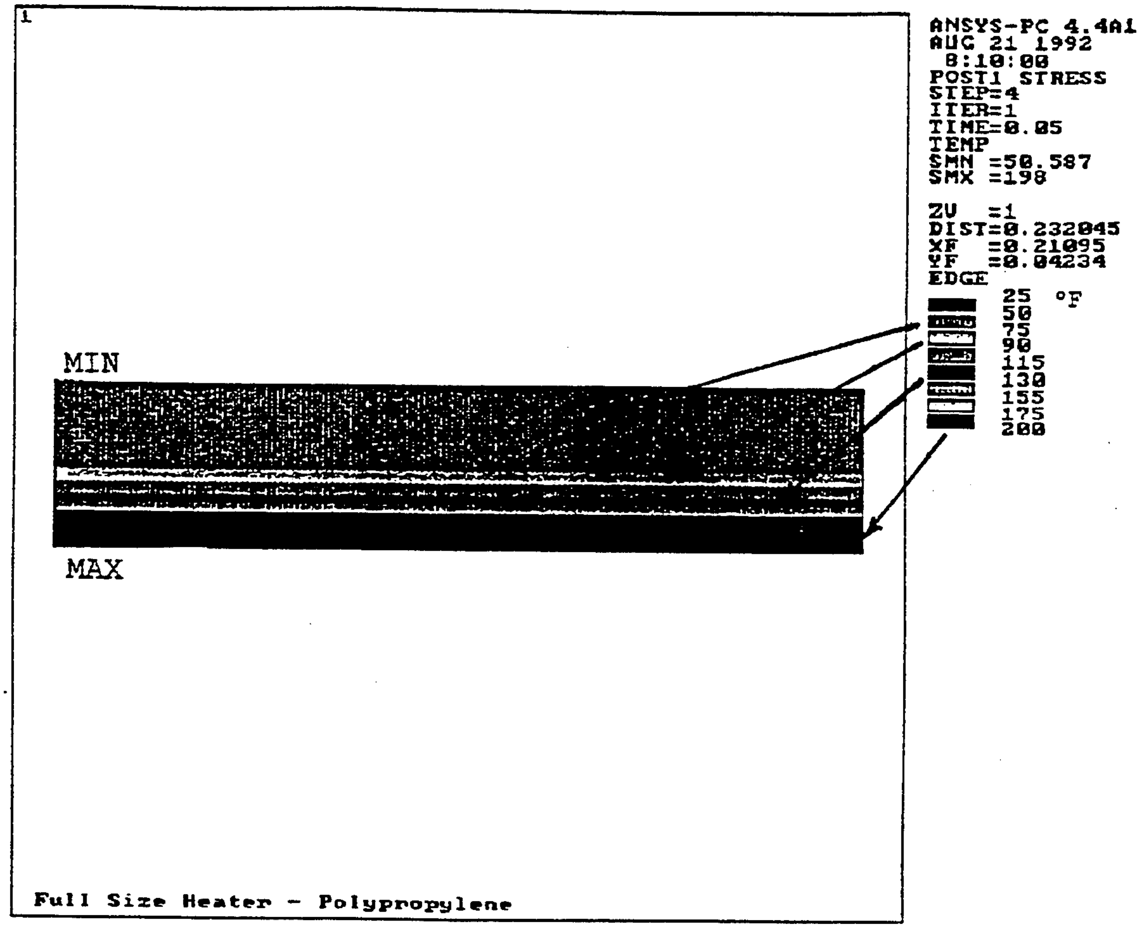


Figure 9. One Full-Size Heater, Time = 3.0 min.

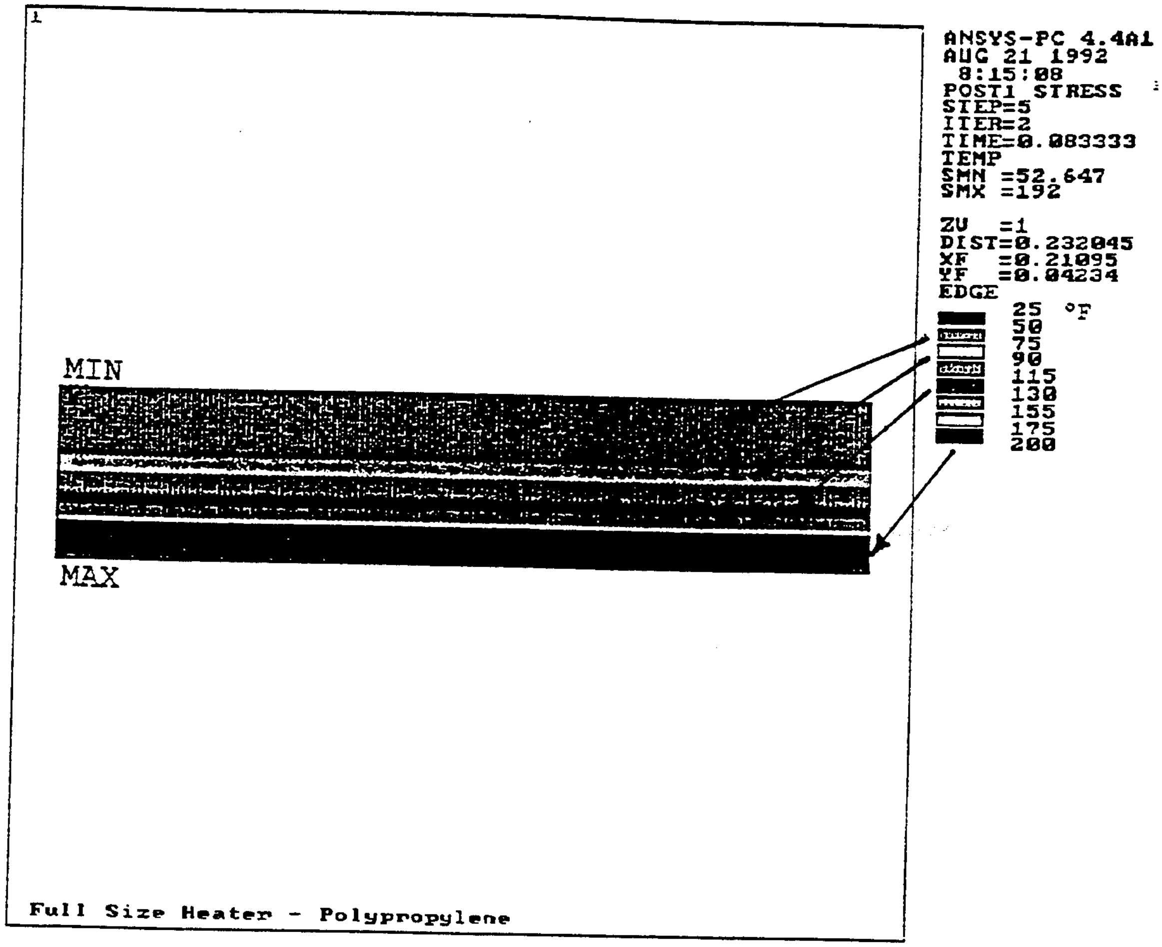


Figure 10. One Full-Size Heater, Time = 5.0 min.

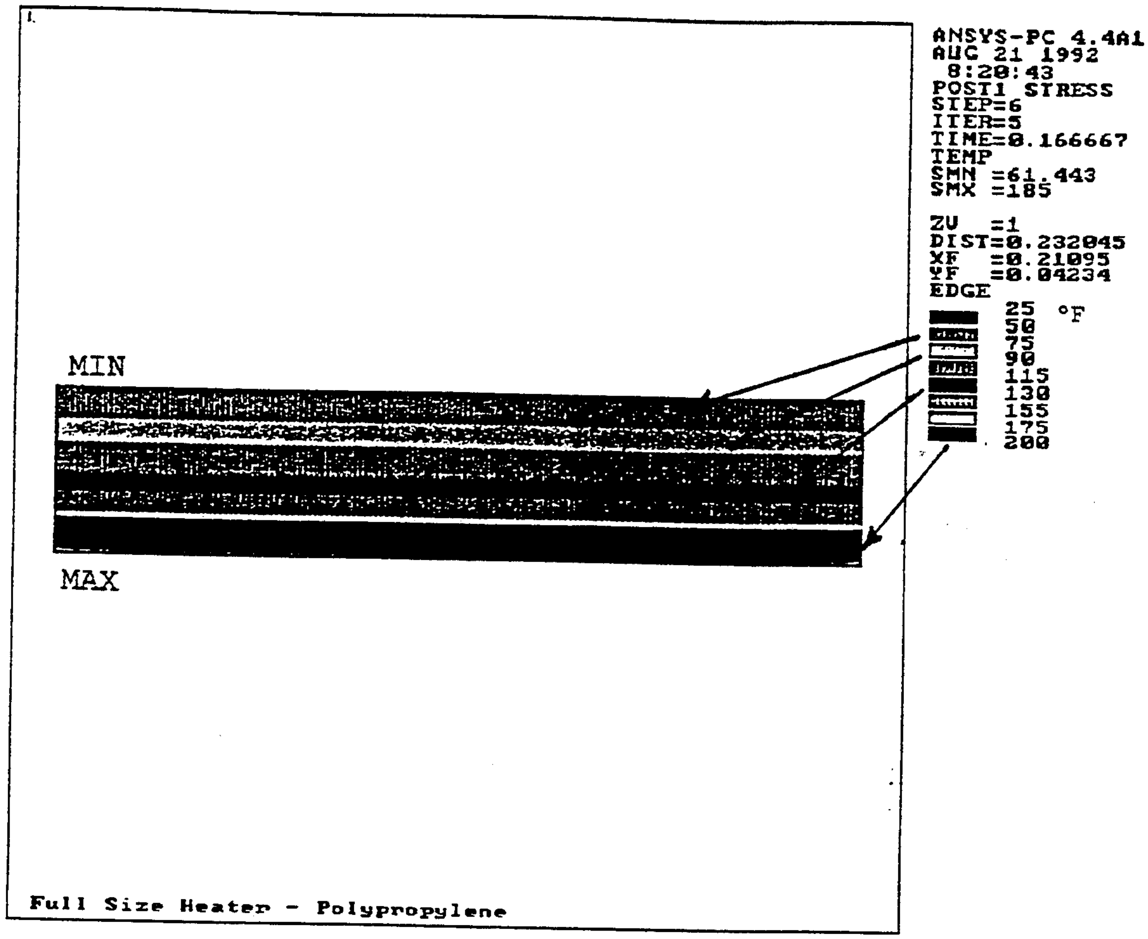


Figure 11. One Full-Size Heater, Time = 10.0 min.

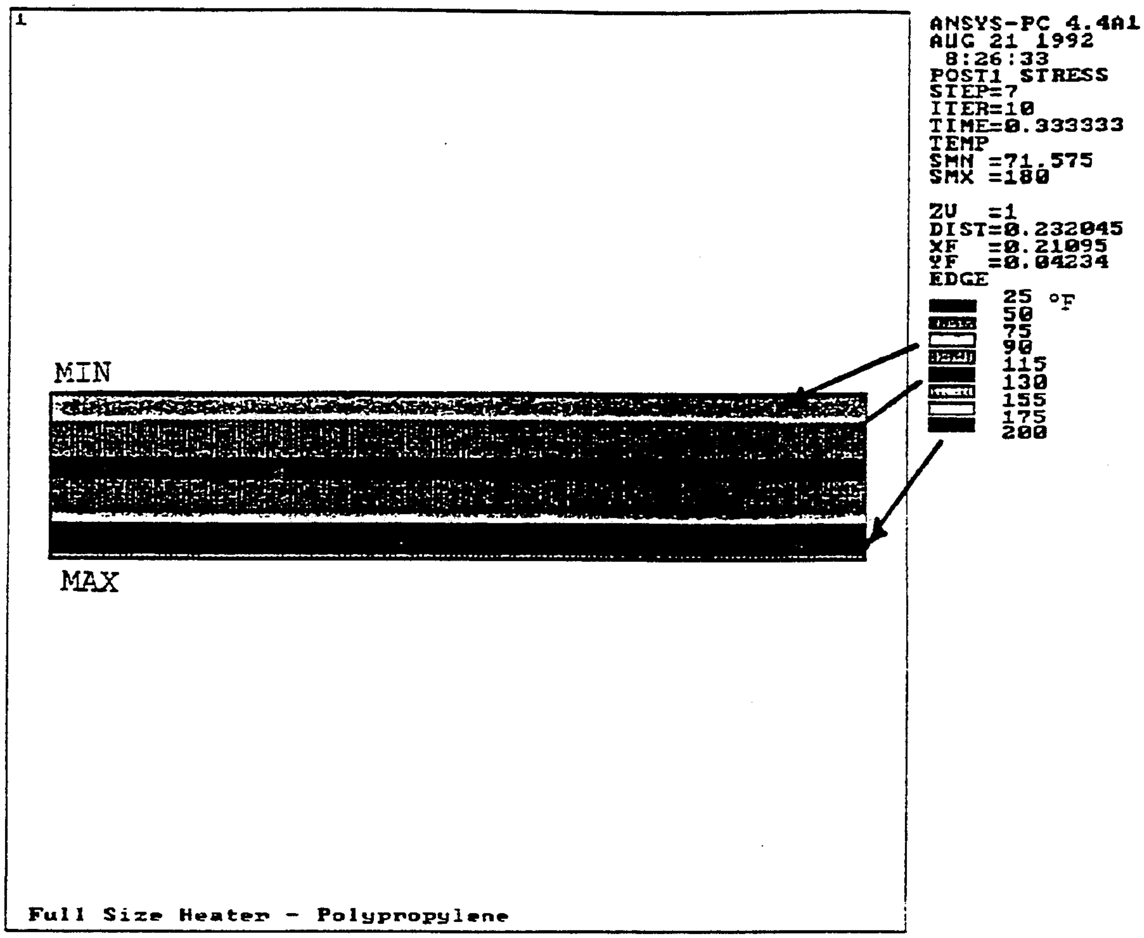


Figure 12. One Full-Size Heater, Time = 20.0 min.

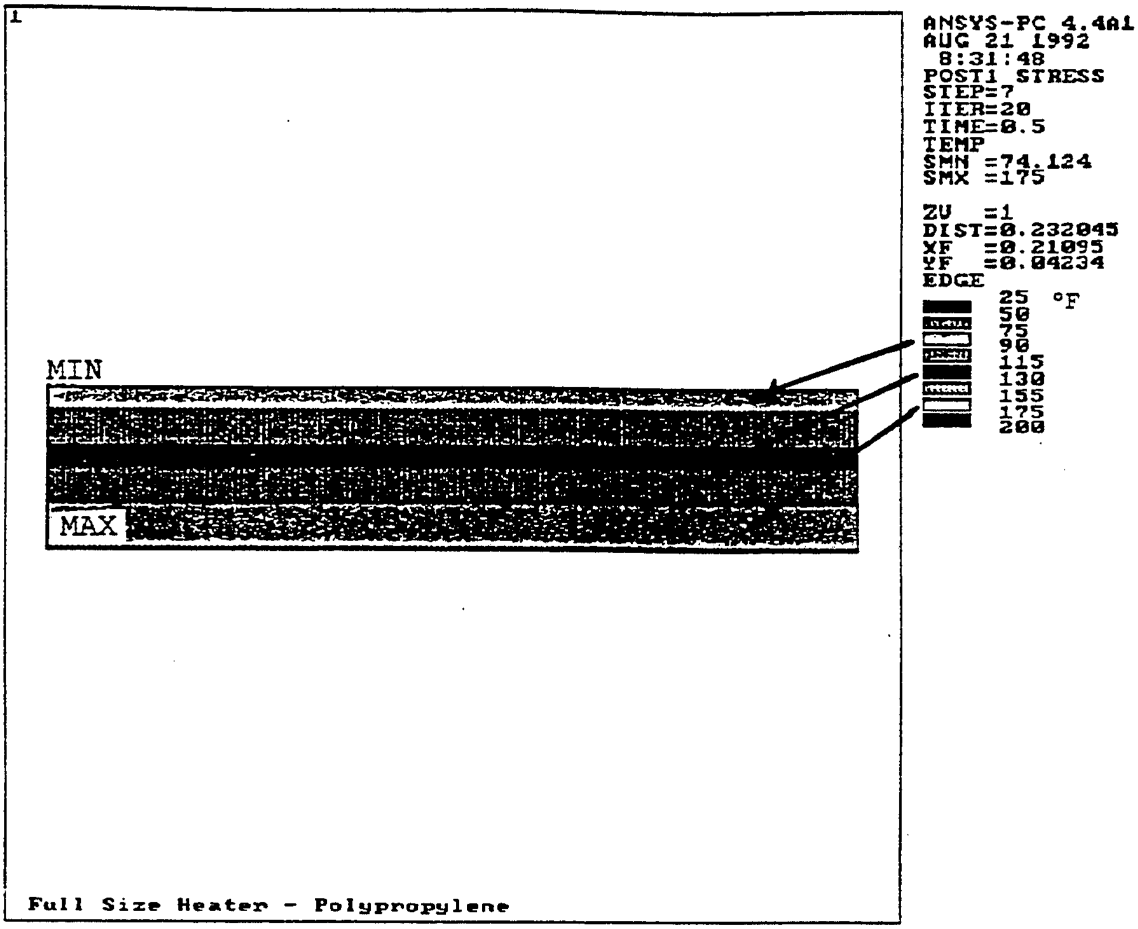


Figure 13. One Full-Size Heater, Time = 30.0 min.

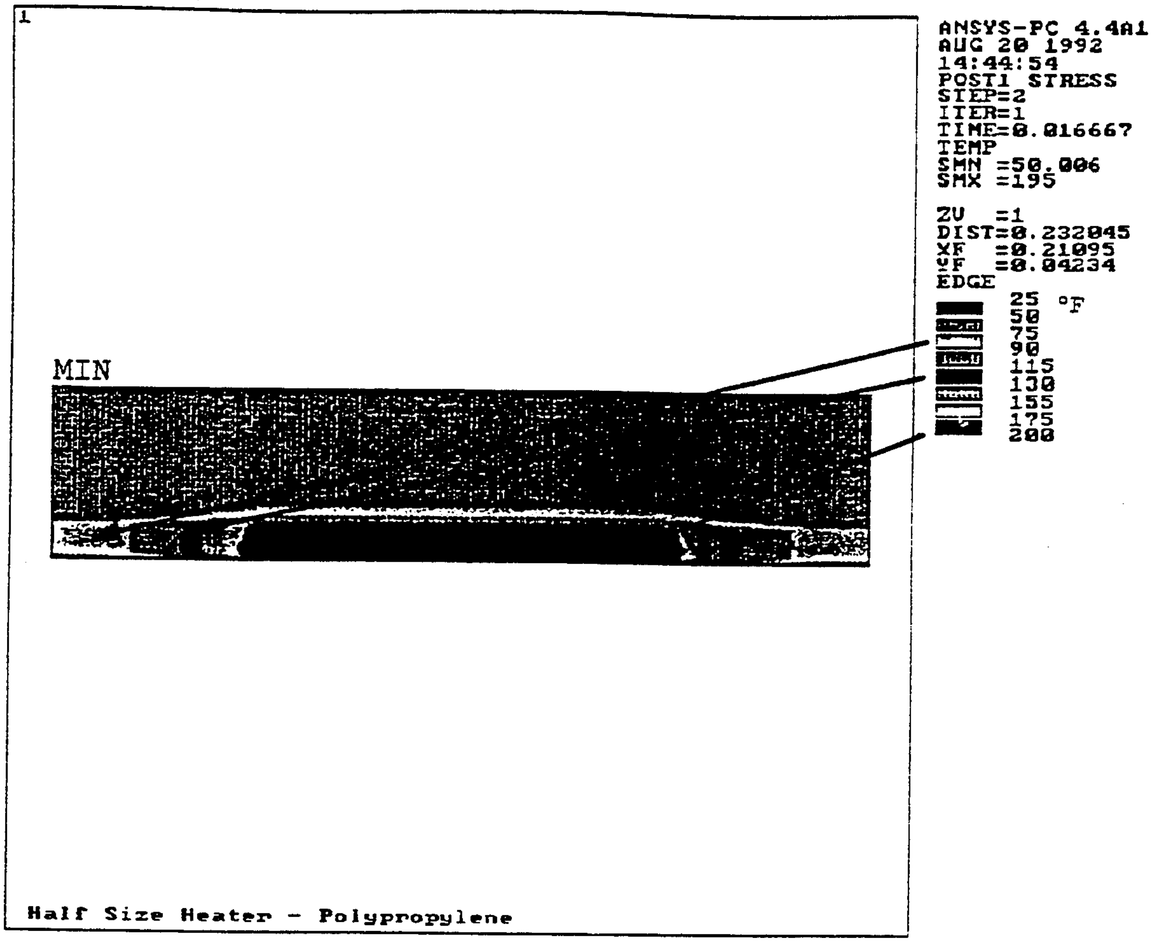


Figure 14. One Half-Size Heater, Time = 1.0 min.

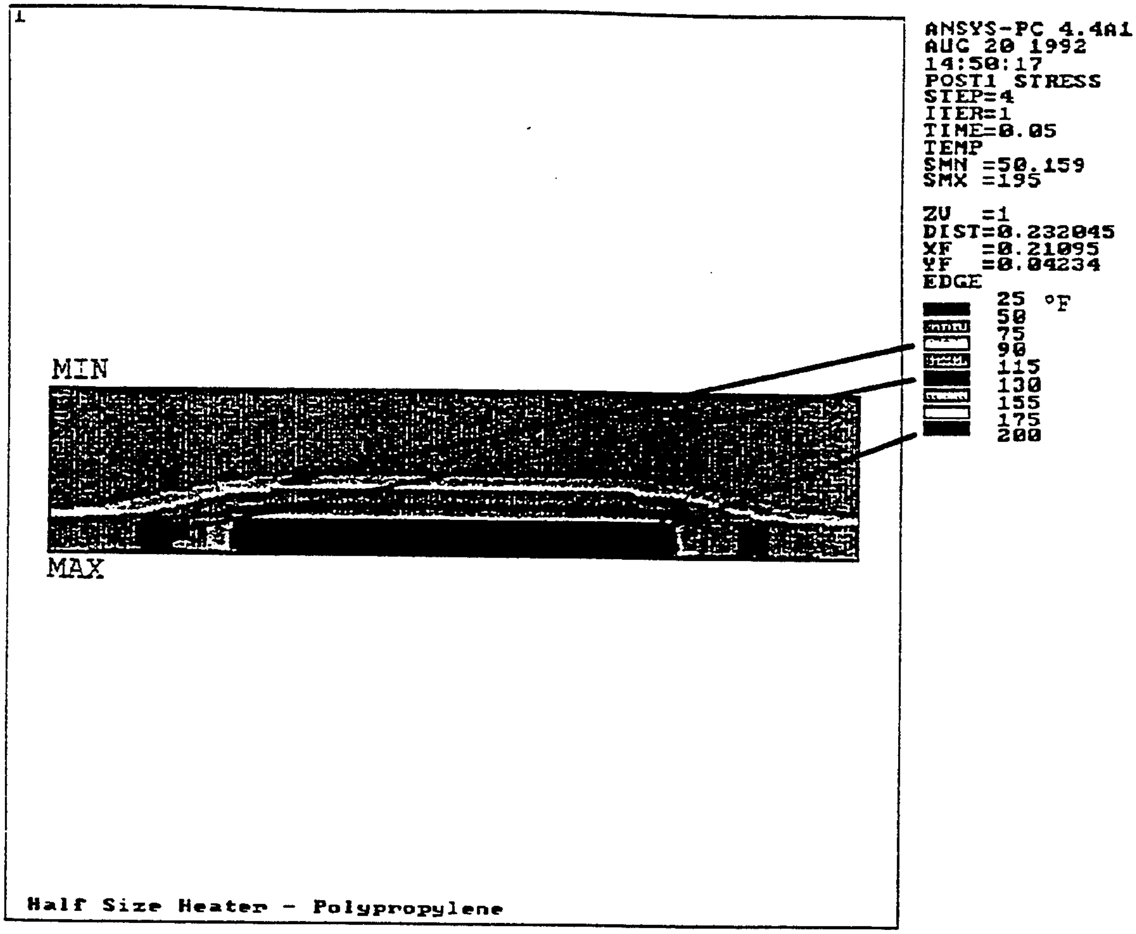


Figure 15. One Half-Size Heater, Time = 3.0 min.

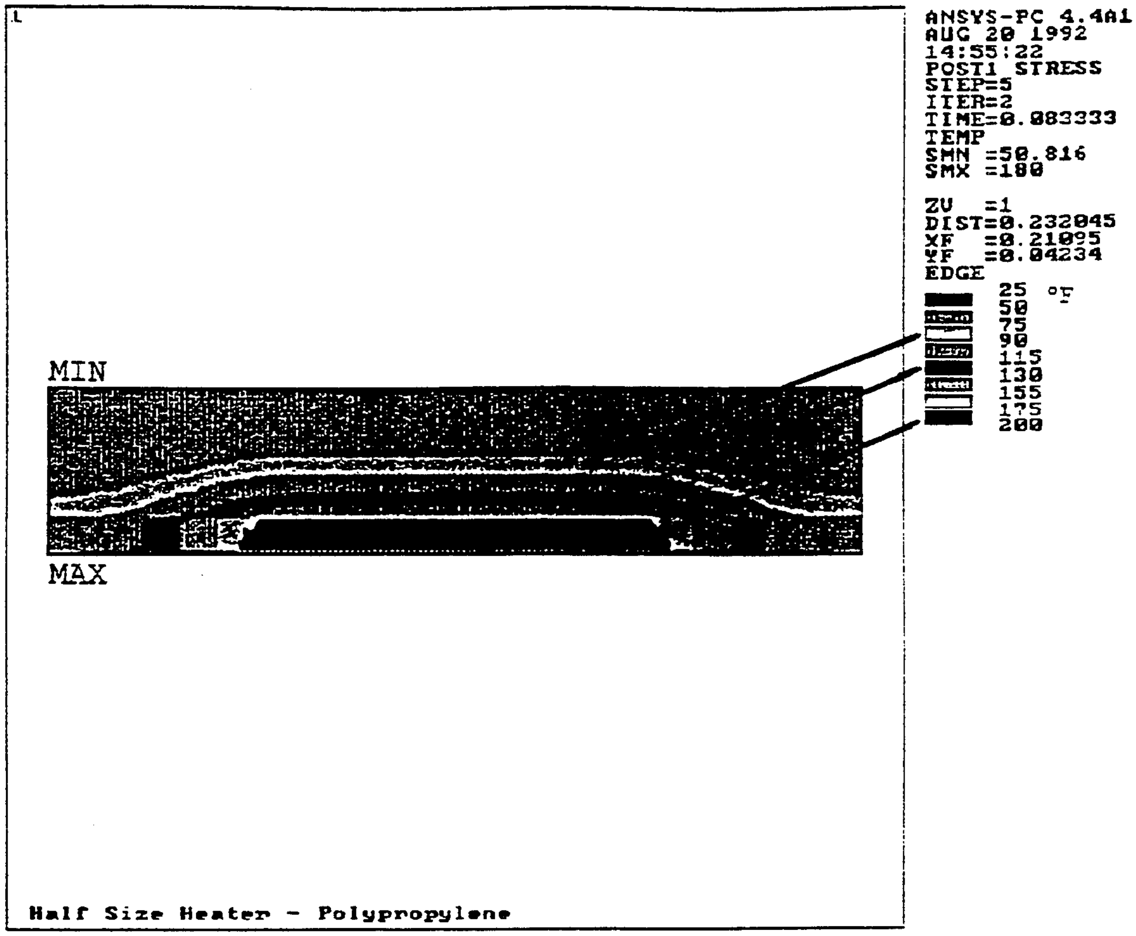


Figure 16. One Half-Size Heater, Time = 5.0 min.

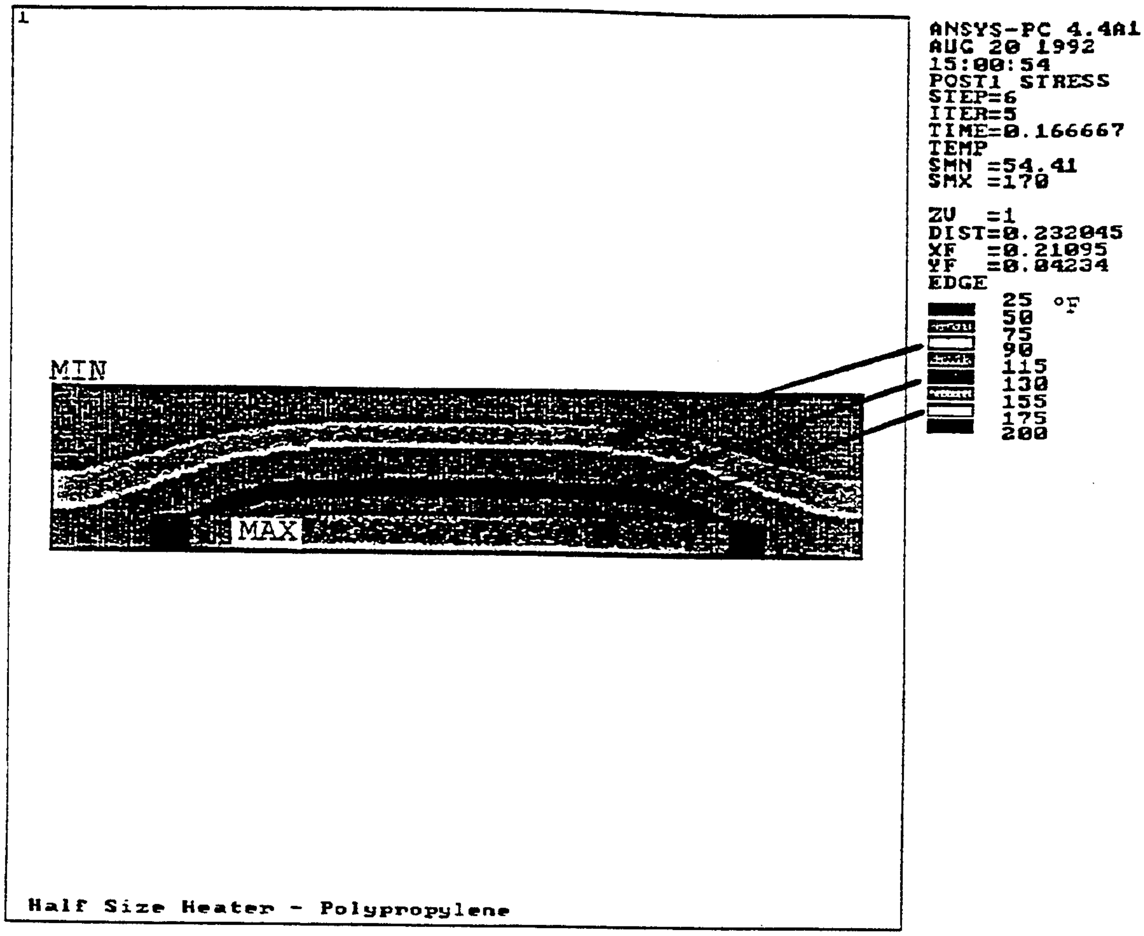


Figure 17. One Half-Size Heater, Time = 10.0 min.

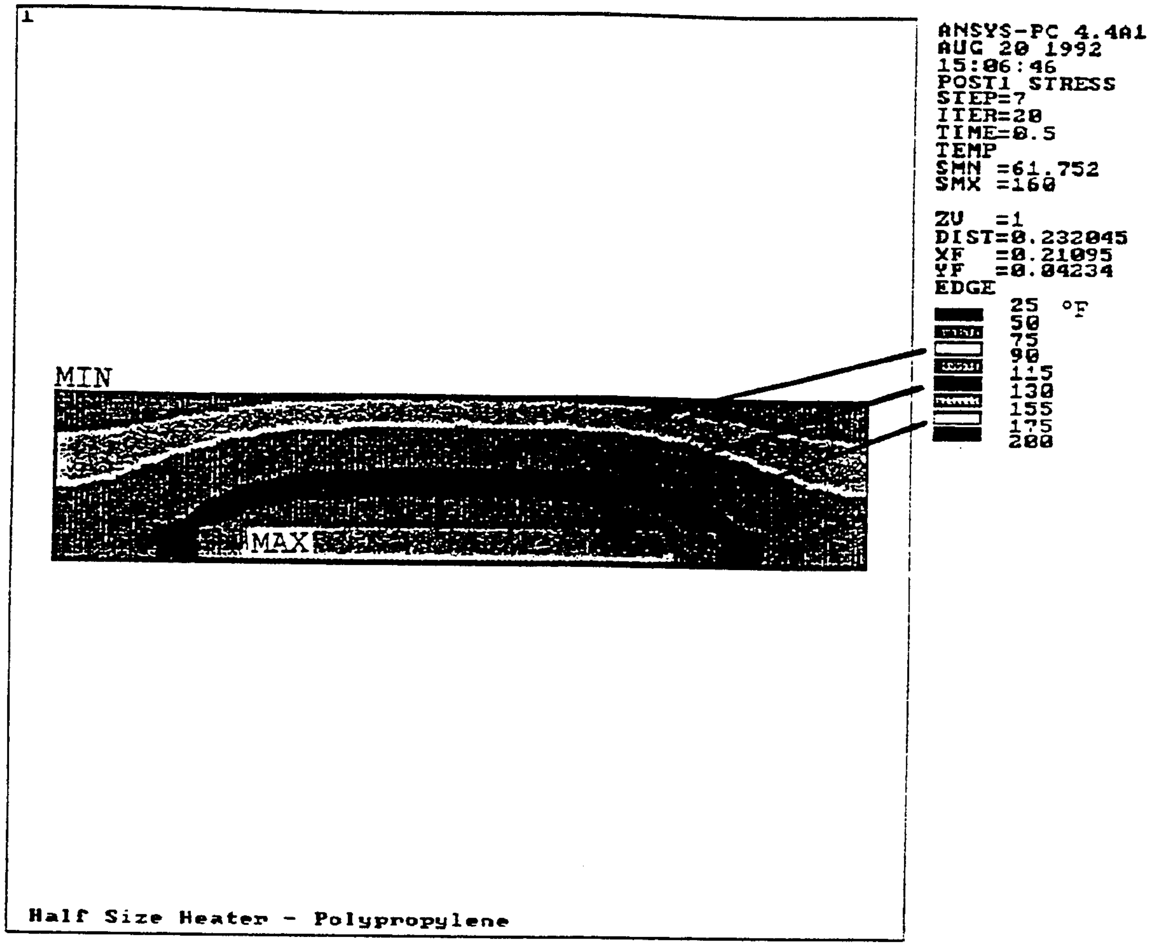


Figure 18. One Half-Size Heater, Time = 30.0 min.

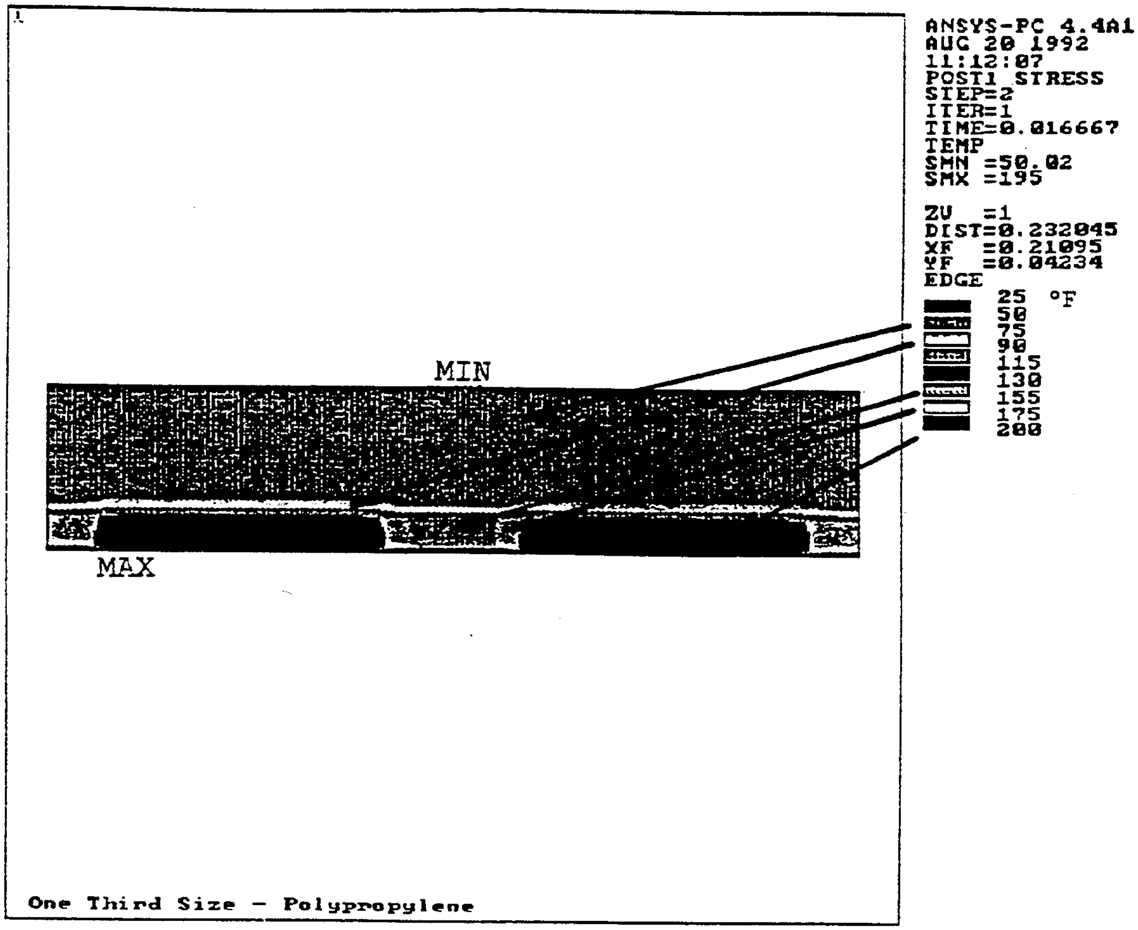


Figure 19. Two One-Third Size Heaters, Time = 1.0 min.

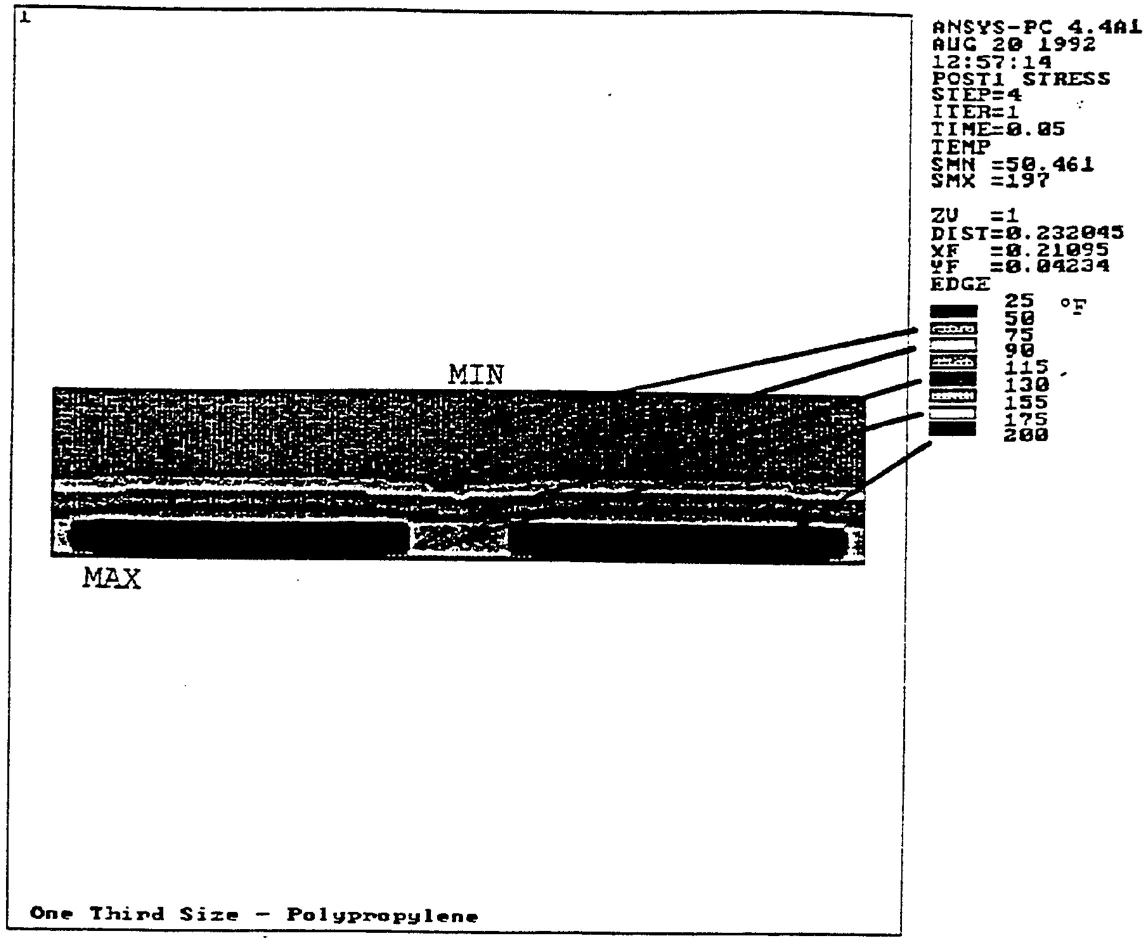


Figure 20. Two One-Third Size Heaters, Time = 3.0 min.

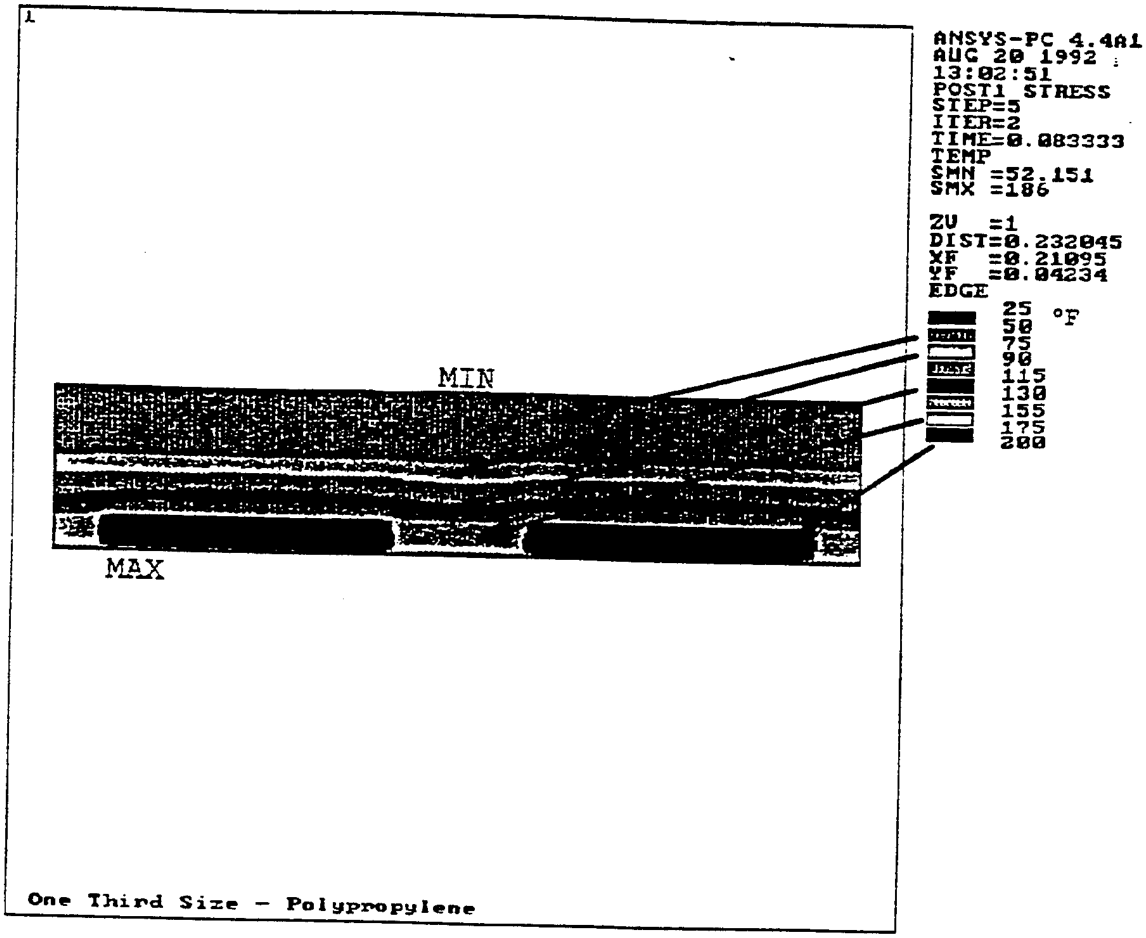


Figure 21. Two One-Third Size Heaters, Time = 50. min.

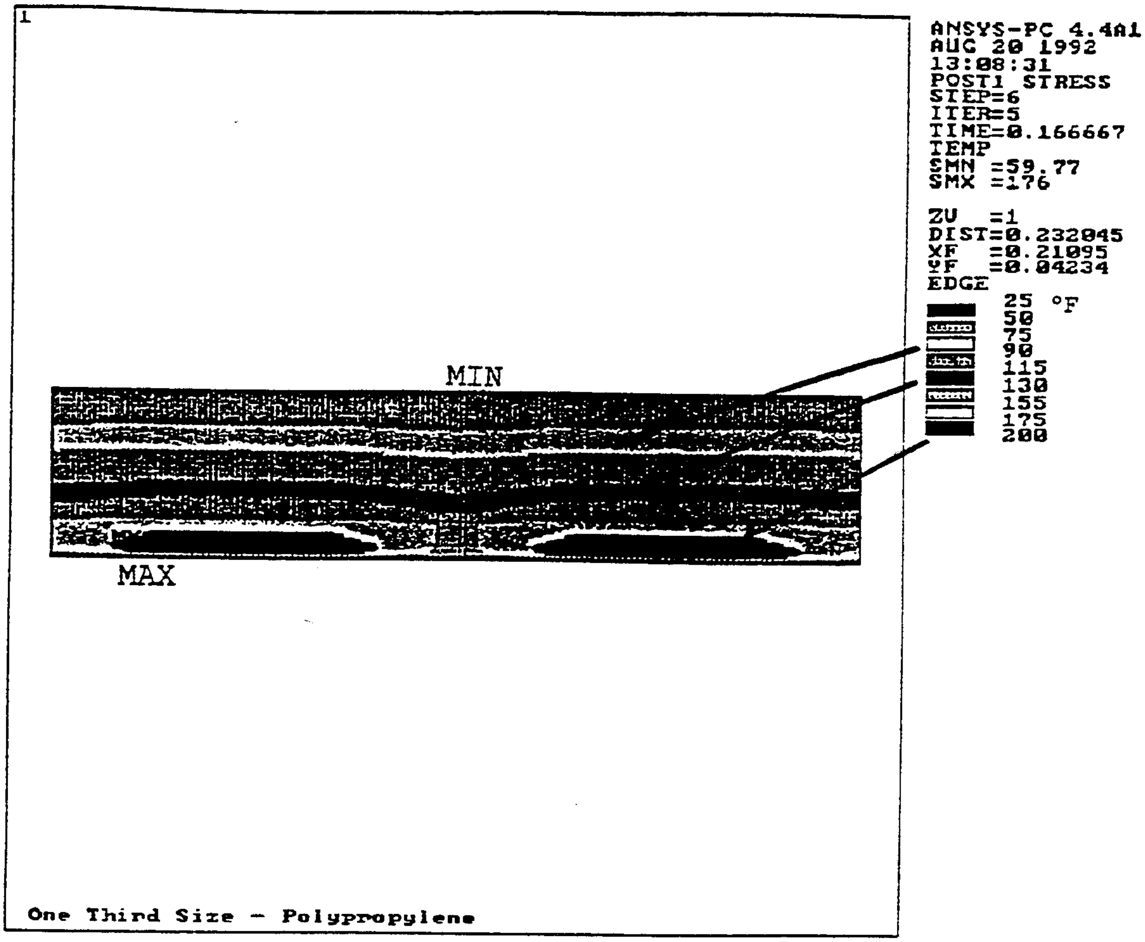


Figure 22. Two One-Third Size Heaters, Time = 10.0 min.

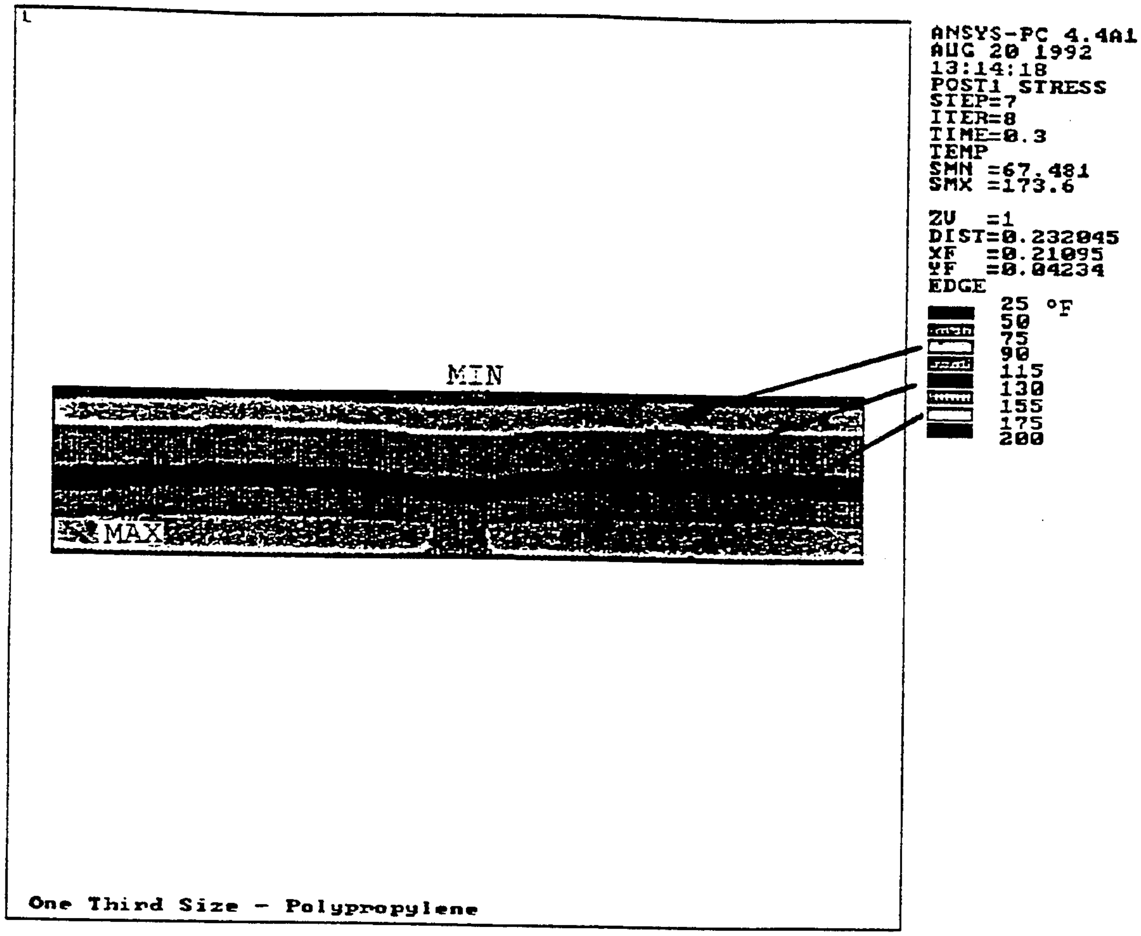


Figure 23. Two One-Third Size Heaters, Time = 15.0 min.

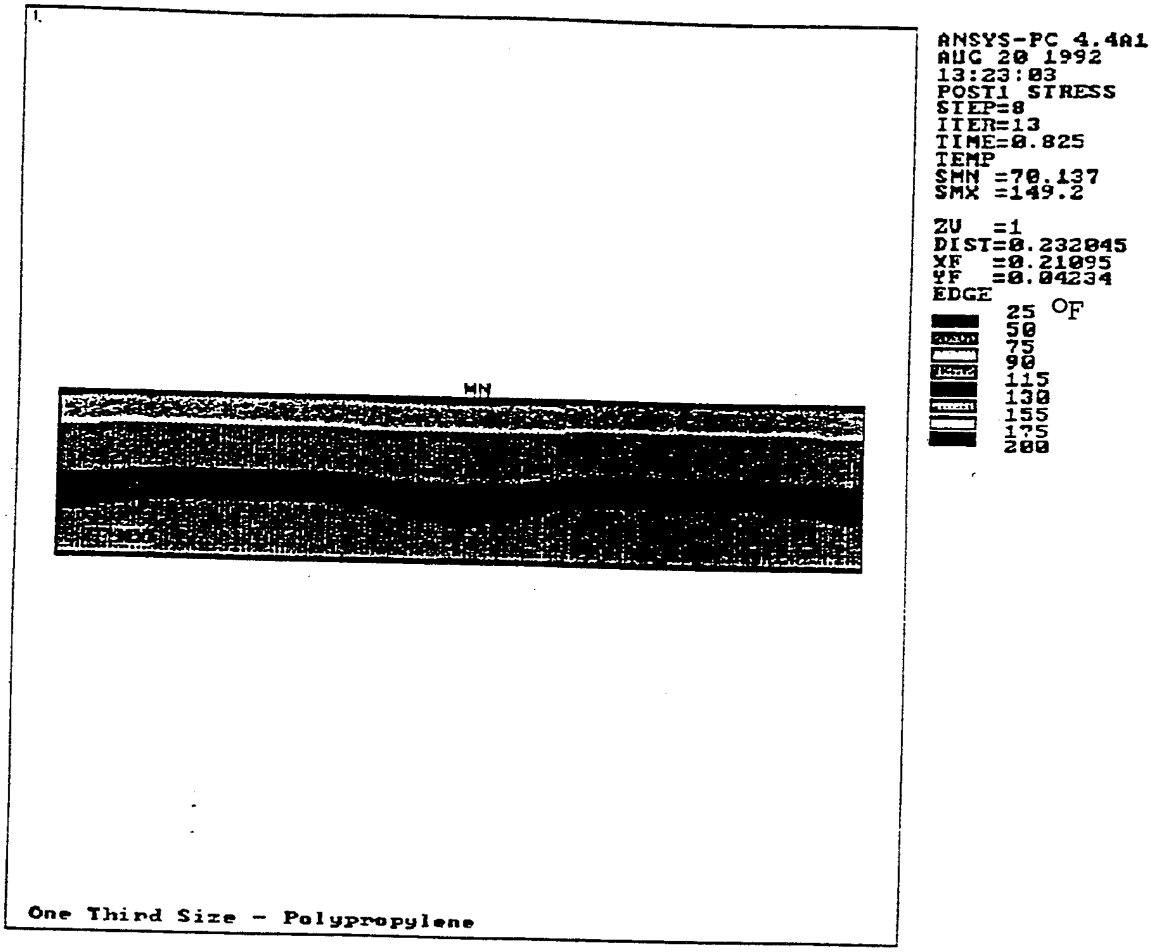


Figure 24. Two One-Third Size Heaters, Time = 50.0 min.

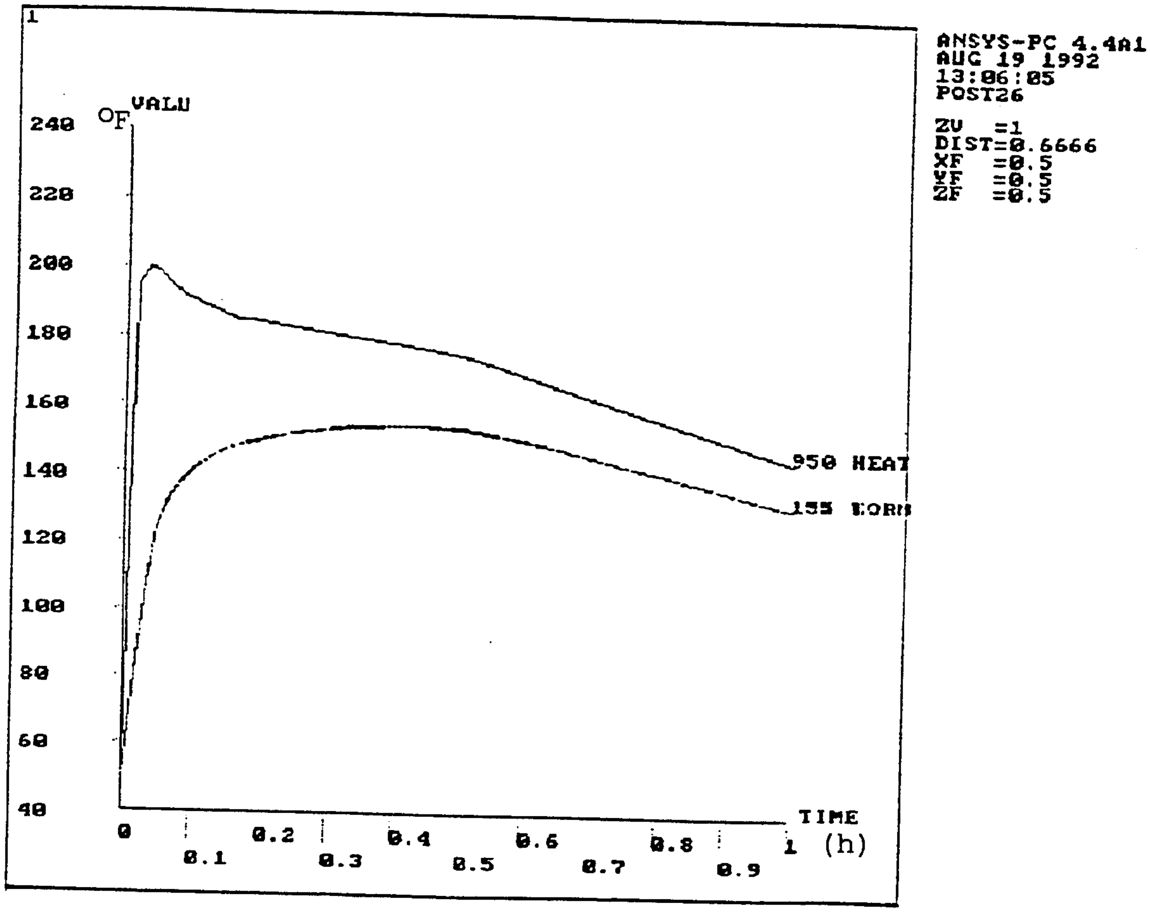


Figure 25. Two One-Third Size Heaters, Polypropylene

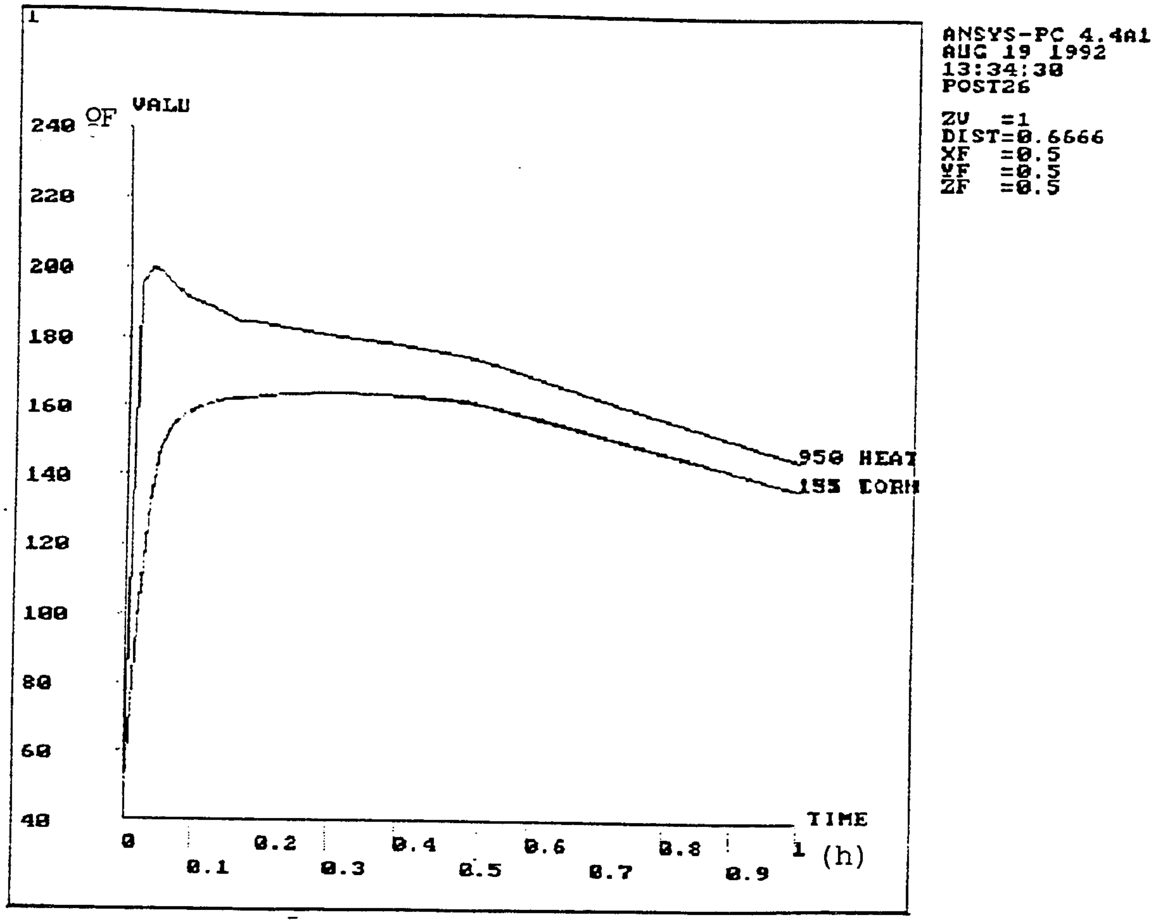


Figure 26. One Full-Size Heaters, Polypropylene

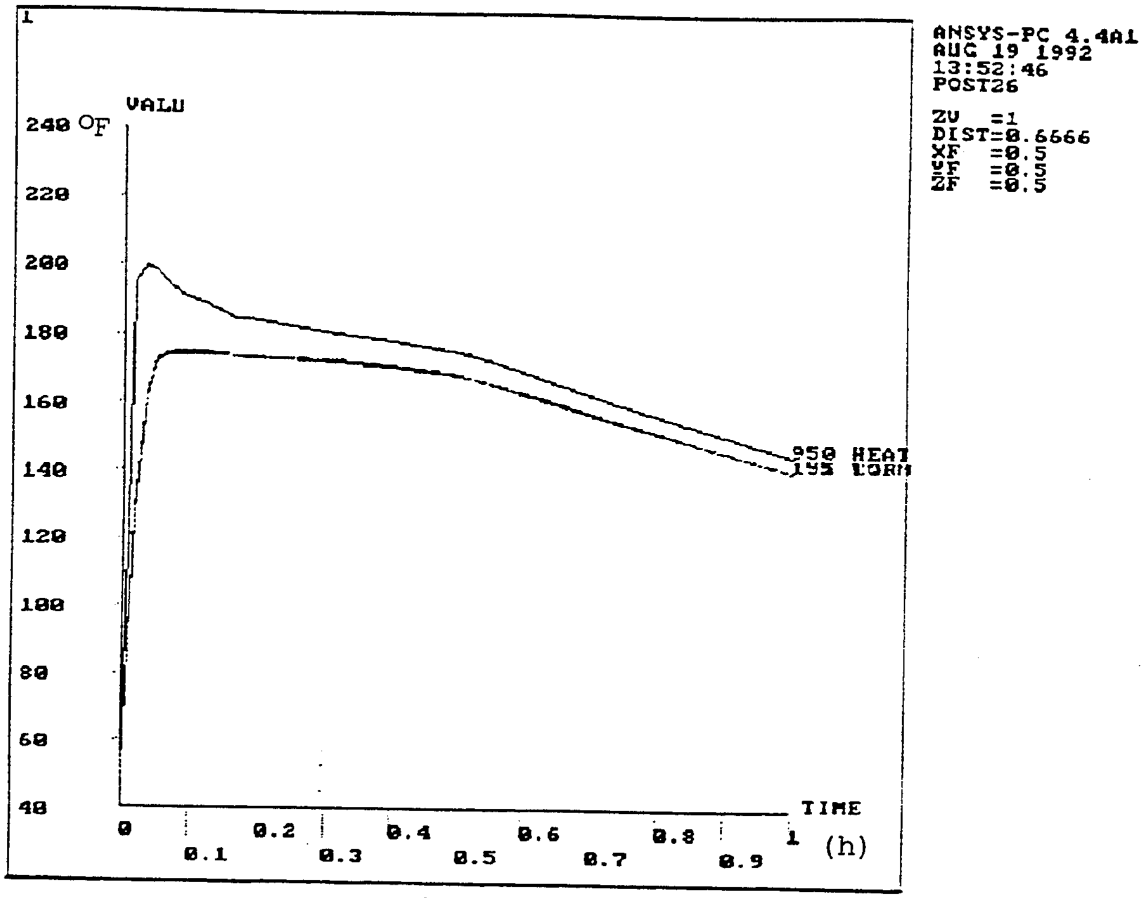


Figure 27. One Full-Size Heater, Tin

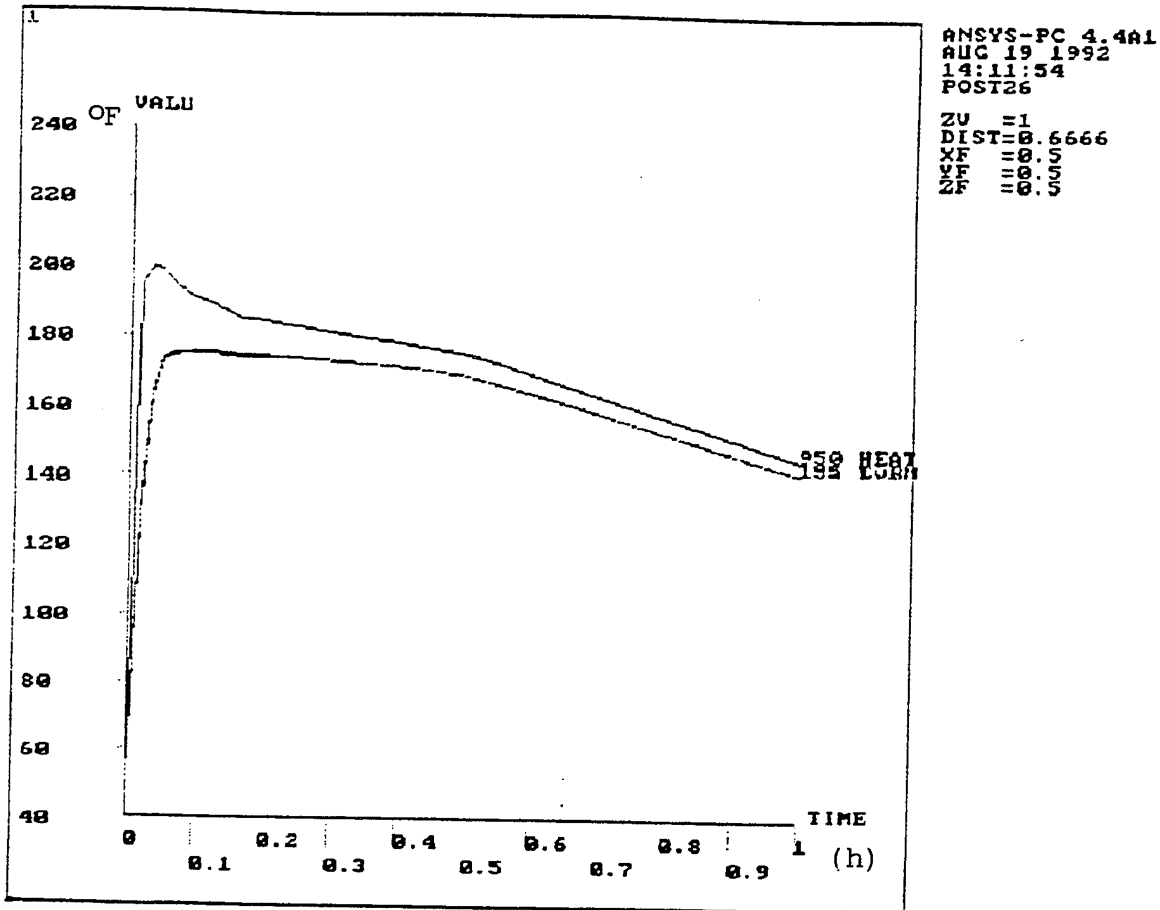


Figure 28. One Full-Size Heater, Aluminum

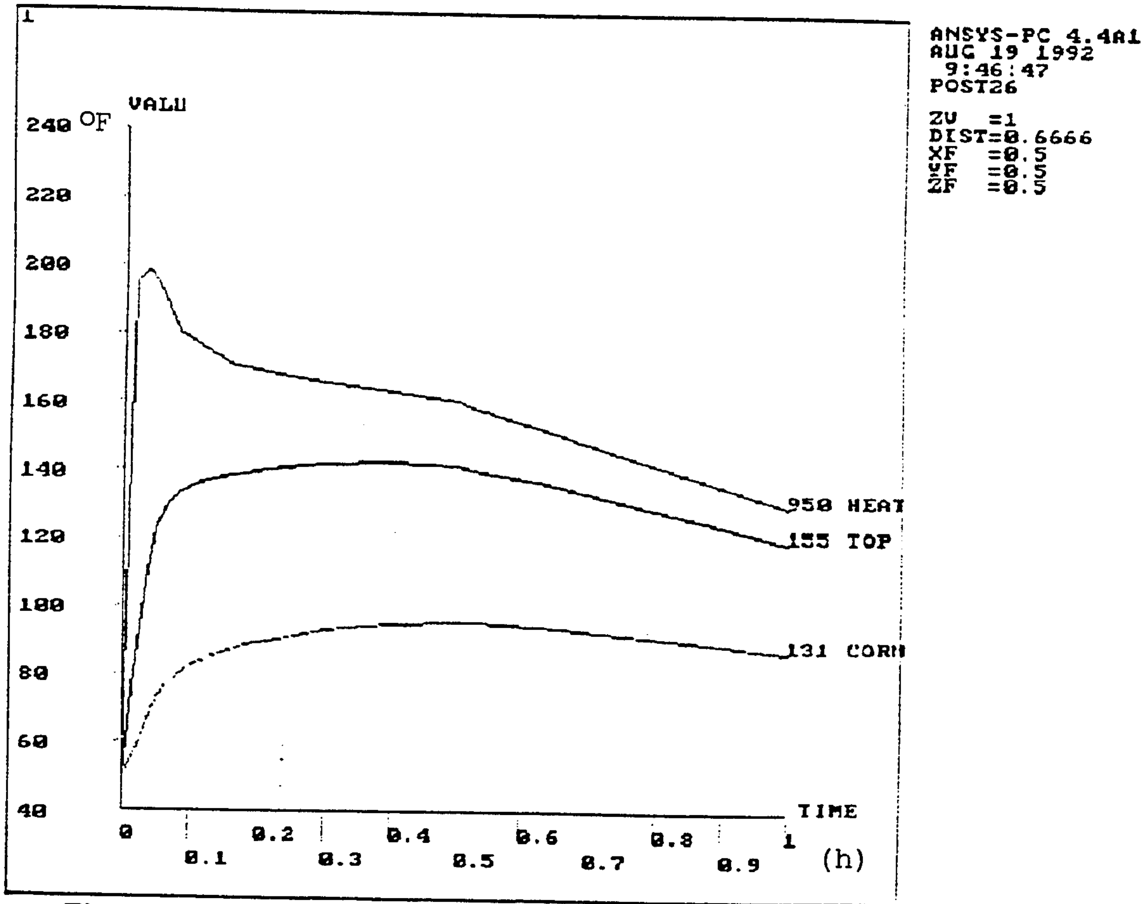


Figure 29. One Half-Size Heater, Polypropylene

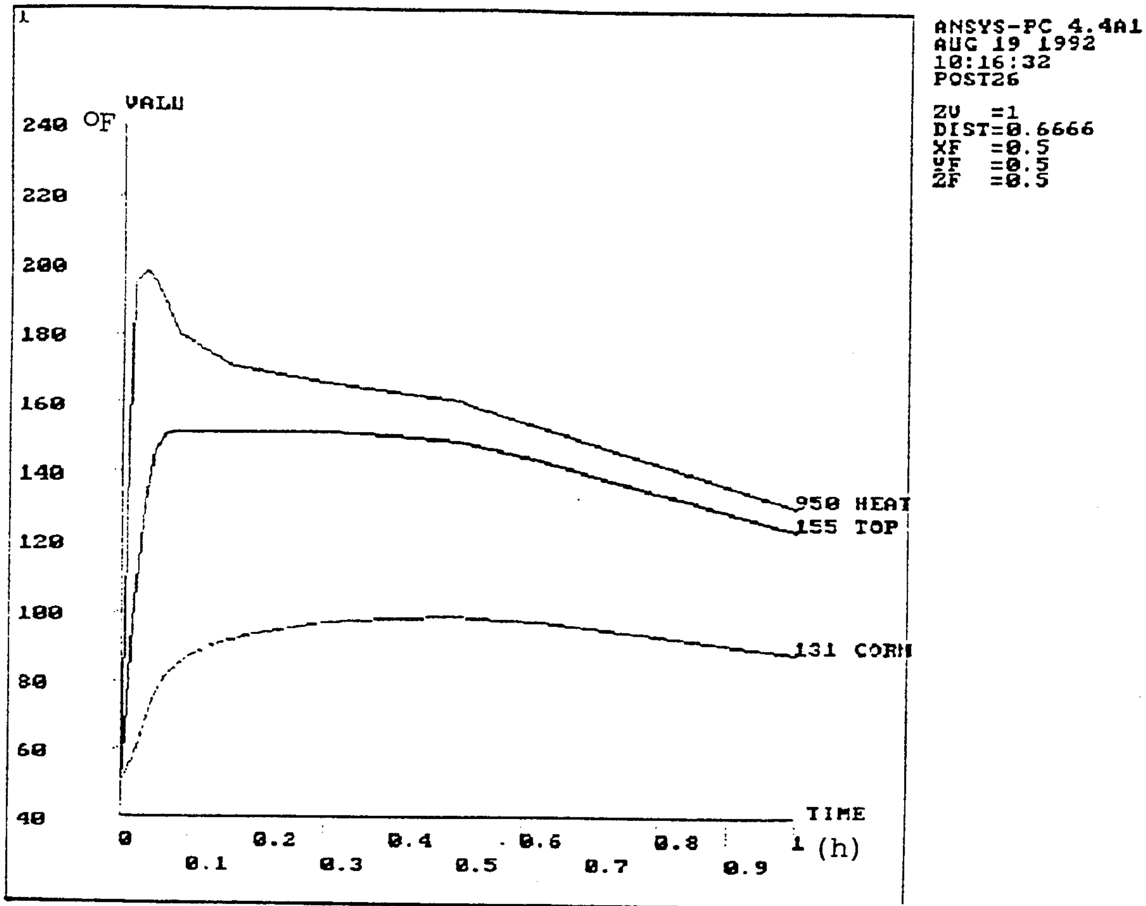


Figure 30. One Half-Size Heater, Polyethylene

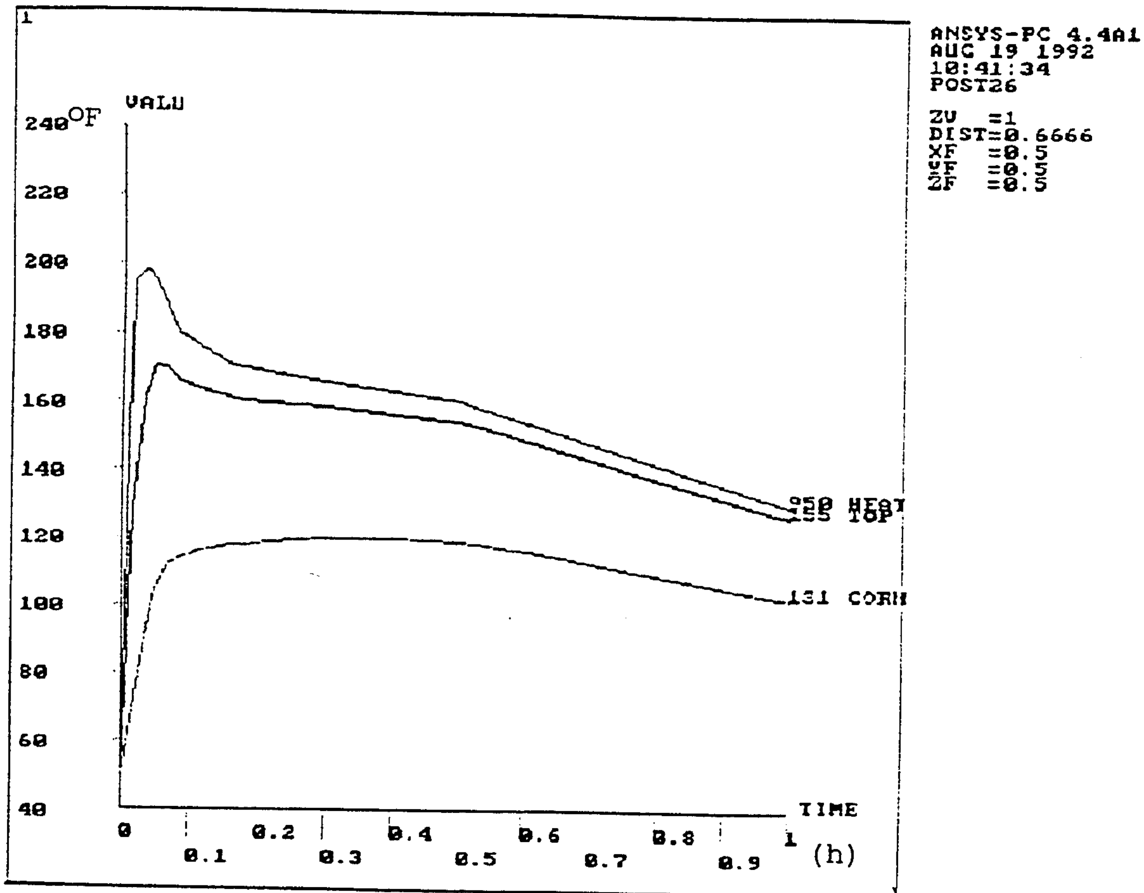


Figure 31. One Half-Size Heater, Tin

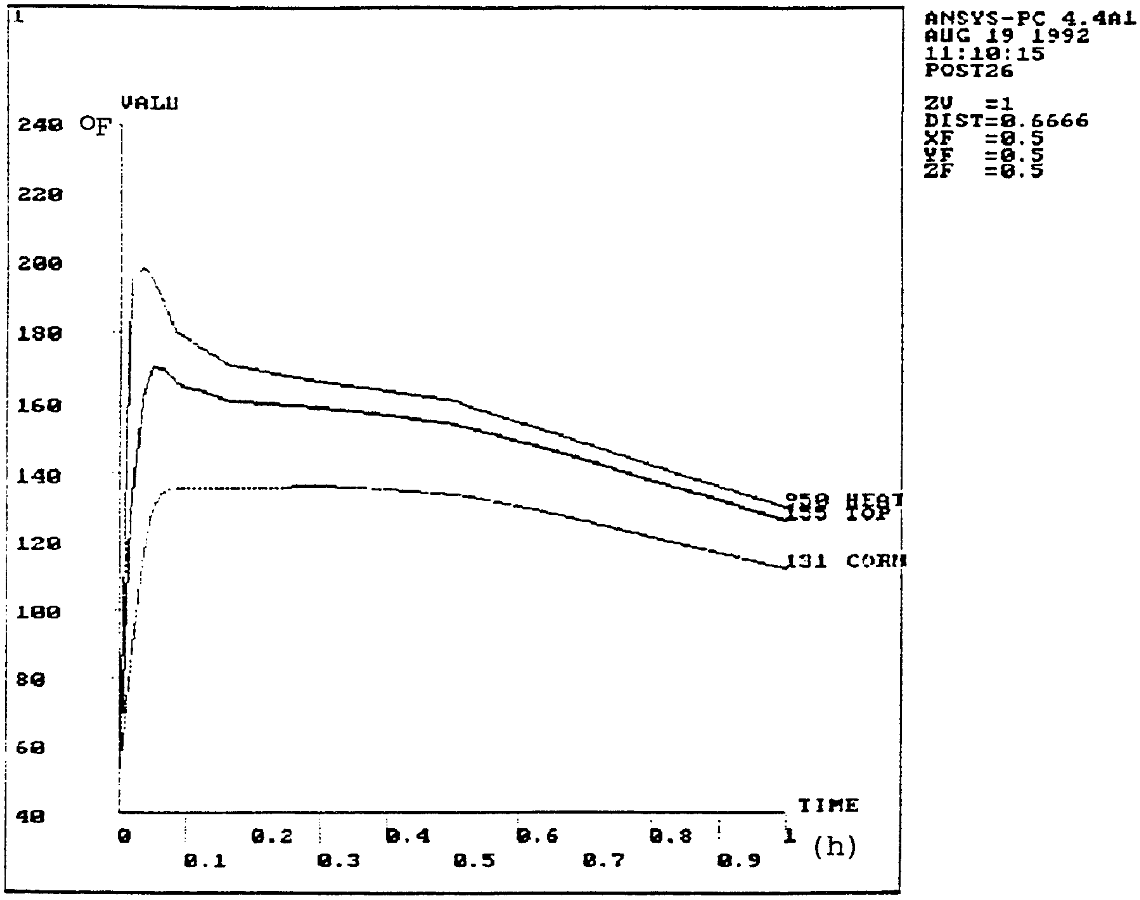


Figure 32. One Half-Size Heater, Aluminum

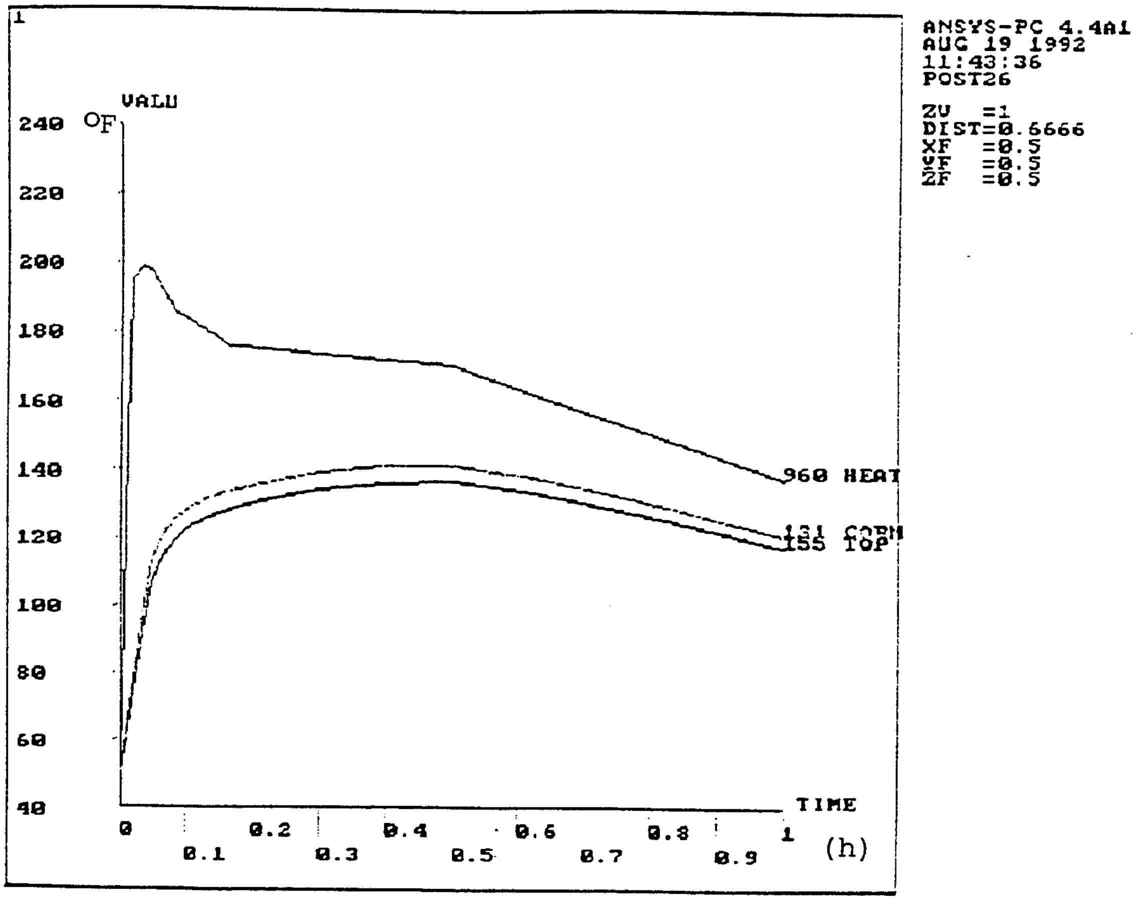


Figure 33. Two One-Third Size Heaters, Polypropylene

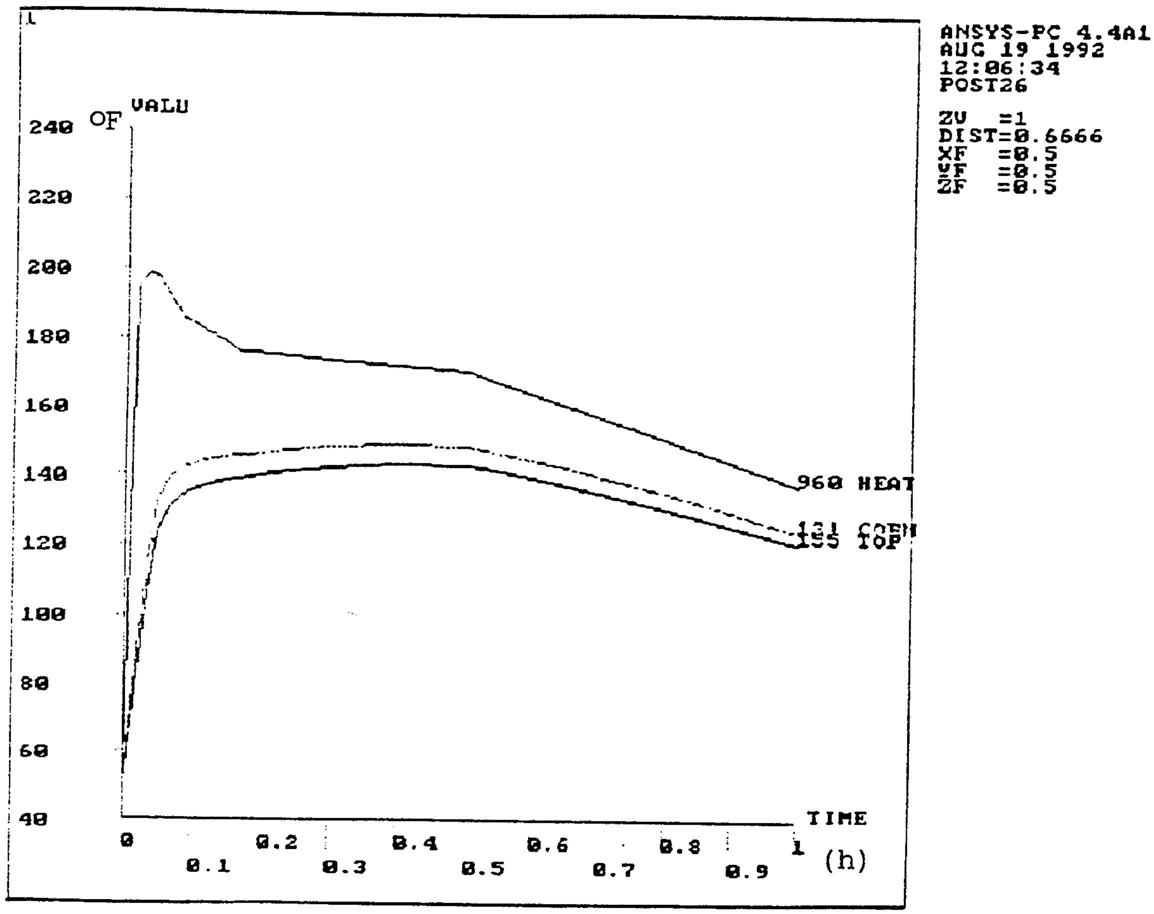


Figure 34. Two One-Third Size Heaters, Polypropylene

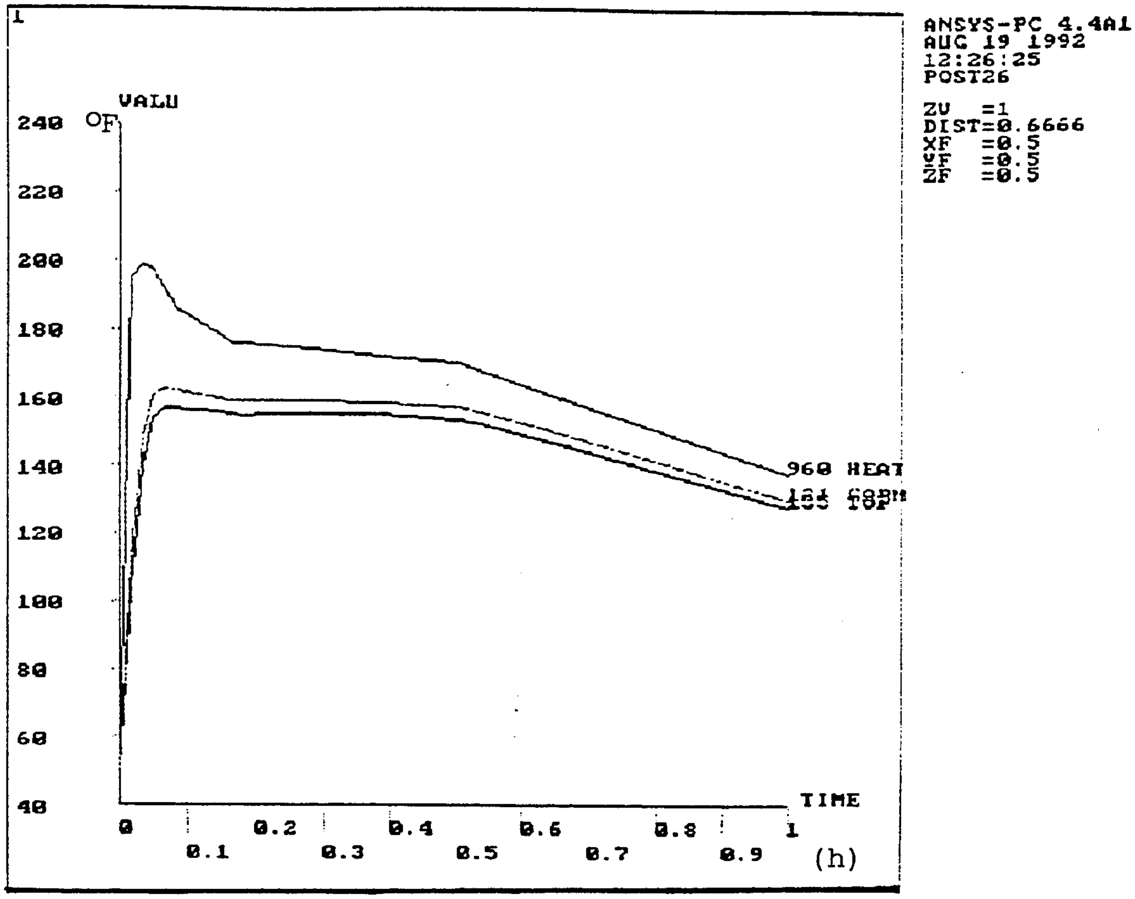


Figure 35. Two One-Third Size Heaters, Tin

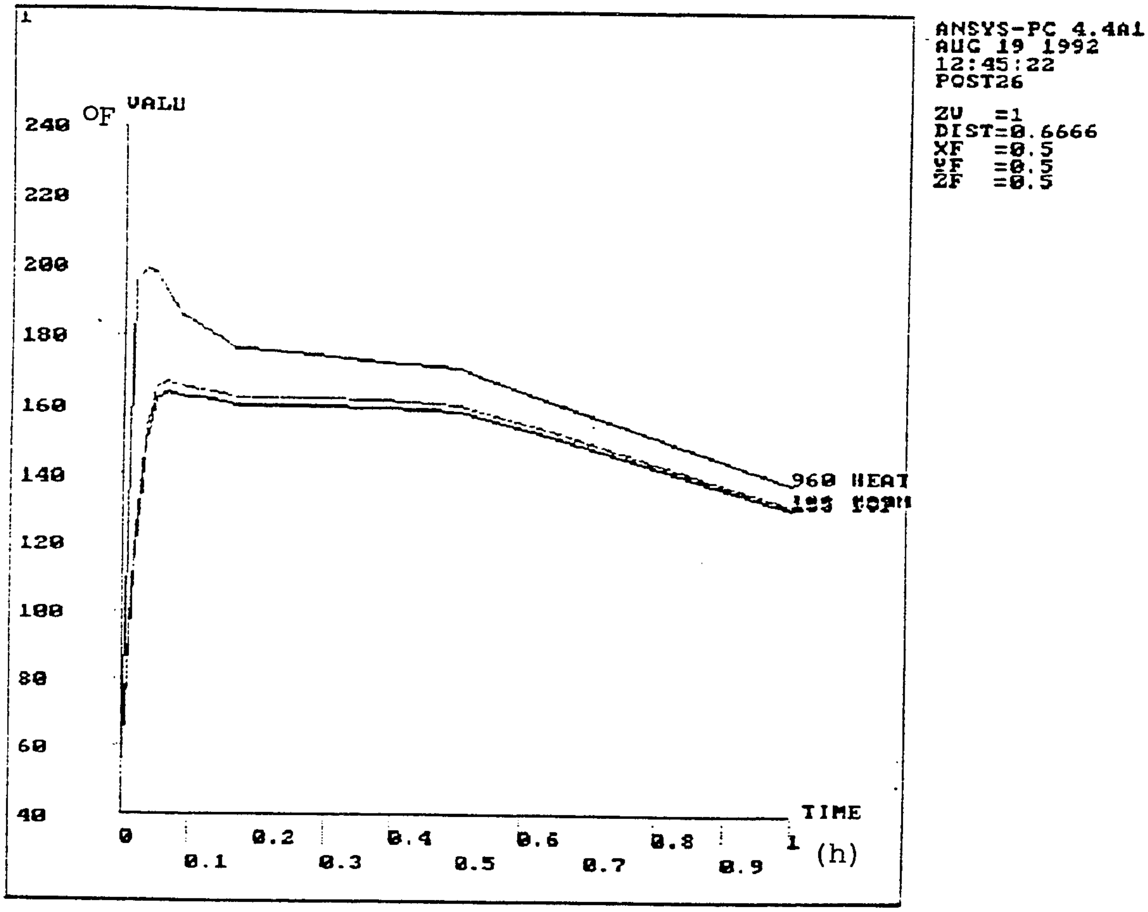


Figure 36. Two One-Third Size Heaters, Aluminum

RECOMMENDATION

There are two design options to improve the thermal performance of the current SHIMM.

1. Replacement of the upper tub material and heater size.

Thermal efficiency of the current self-heating individual meal module can be improved considerably just by changing the upper tub material and using a heat sealing design between the two tubs. The change from a full-size heater to two of the one-third size heaters is also recommended to reduce the material used for the heat source. However, the basic design of current SHIMM will not change. These options are the least expensive because the reduced heater size saves material.

2. New design concept for separate heater and food package.

Another option is changing the design and materials of the current module's container to increase its versatility in logistics and user convenience. This would include fabricating a food tub replica similar to the current Tray Pack (T ration) except smaller and using the same material (tin). The current bottom tub would be modified to fit the tin food tub and packed with a chemical heater and activator. The food tub and the heater tub would then be fabricated, packed and delivered separately until needed (Figure 37). The food tub could be heated in hot water or by the chemical heater. Some type of fastening method, like a snap fit, would provide a tight fit between the food tray and heater to minimize the heat transfer loss between them.

For this option, the most important design effort is an efficient thermal and structural coupling system between the two tubs. Heat sealing or ultrasonic sealing would be evaluated for this type of application. Snap fitting would also be evaluated.
Once the fundamental design change is completed, the general concept could be enhanced and applied to other food packages.

CONCLUSION

The size and location of the heater and packaging materials were optimized using a heat transfer model that used the finite element method. For the SHIMM, polypropylene was recommended for the lower tub and tin for upper tub. For the heat source, the two one-third size heaters provided adequate heat for the SHIMM when using the new tub materials. The two one-third size heaters also provided a large enough heat source. Finally, a new design concept using a separate heater and food package was discussed.

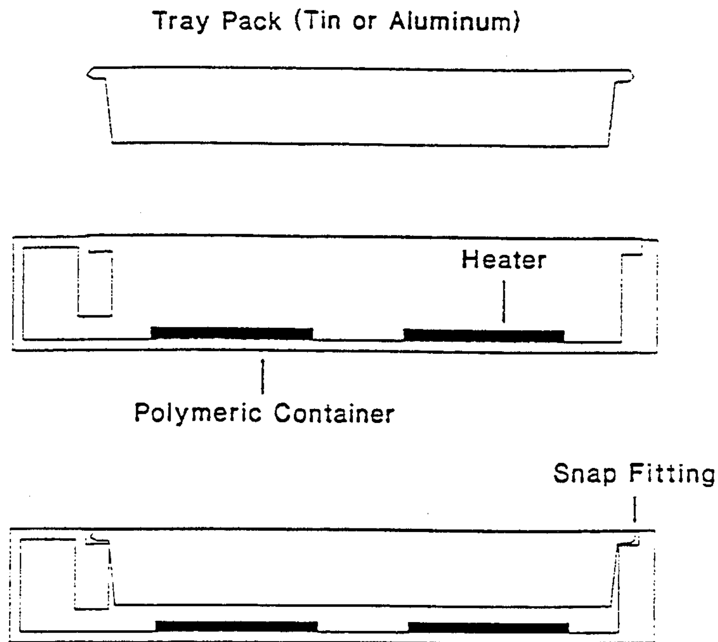


Figure 37. New Design Concept for Separate Heater and Food Package

FUTURE WORK

A computer program will be developed to collect critical data to understand heat transfer in the heater space and between the different materials. The study to evaluate the use of computational fluid dynamics code to simulate the heat convection in the heater space will be very useful even for the design optimization of self-heating group ration. The shape optimization for self-heating food package is another challenge for this specific project.

This document reports research undertaken at the U.S. Army Soldier Systems Command, Natick Research, Development and Engineering Center and has been assigned No. NRDEC/TR-96/028 in the series of reports approved for publication.

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APPENDICES

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APPENDIX A

HEAT TRANSFER MODES IN A SELF-HEATING FOOD CONTAINER

Appendix A

Three modes of heat transmission: conduction, convection, and radiation, are recognized in the polymeric food container with an integral heater as possible ways heat is transmitted. Heat is generated from an exothermic chemical reaction in which metallic compounds react with an activator. During the reaction, the heater reaches a temperature of about 200°F (93°C) which boils the activator solution (water). The boiling water fills the heater space gap between the upper (food) and lower tubs and functions as a medium for heat convection. Heat radiation is observed in the heater space gap because there are temperature differences between the heater and tub surfaces. Heat is also transferred from the outer surface of the container to the cooler ambient environment not only by convection but also by radiation. Heat conduction, however, through solid materials, such as foods and polymeric packaging materials, is the predominant mode of heat transmission in this model.

Heat Conduction

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\dot{q}}{k}$$

The above equation shows two-dimensional transient heat conduction with heat generation. This is a mathematical expression for the conservation of energy in a solid substance. The temperature is a function of time and two coordinate dimensions. The first and second terms on the right side represents the net rate of heat conduction into the control volume per unit volume. The third term on the right side is the rate of energy generation per unit volume inside the control volume. The left side represents the rate of increase in internal energy inside the control volume per unit volume. α is the thermal diffusivity, and is defined as $\alpha = k/c$. This equation will simulate heat conduction in solid foods and packaging materials.

Although conduction also occurs in liquid, it is rarely the predominant transport mechanism in fluid food. Once heat begins to flow in a fluid, even if no external force is applied, density gradients are set up and convective currents are set in motion. Because of both macroscopic and microscopic transport of energy, convective currents are generally more effective in transporting heat than conduction, where the mechanism is limited to submicroscopic transport of energy. The above conduction equation is still valid to simulate heat convection by using thermal diffusivities adjusted for fluid foods and boiling water in the heater space.

When different conducting surfaces are placed in contact, a thermal resistance is present at the interface of the solids. The interface resistance (or contact resistance) is developed when two materials will not fit tightly together and a thin layer of fluid is trapped between them. And this is what likely happens at the interface packaging material and food. The interface resistance is primarily a function of surface roughness, the pressure holding the two surfaces in contact, the interface fluid, and the interface temperature. Due to smooth surface and high contact pressure between food and the container, the temperature drop across the interface will not be significant and can be ignored.

There are some assumptions to simplify the calculation for the model; all thermal properties are constant in the range of operating temperature, and there are no differences in properties in the same material regardless of different locations. Solutions of this model by numerical methods will show temperature distribution and heat flow in a two-dimensional system as a function of time.

Heat Radiation in the Heater Space

At this initial design stage, the study of heat radiation is focused on the possibility of preventing heat loss by using a shield. Therefore, our primary concern is heat radiation at the gap between the heater and the inner surface of the bottom tub, where such a shield as Aluminum foil can be used to reflect radiated heat to the food tub. The quantity of energy leaving a surface as radiant heat depends on the absolute temperature and the nature of the surface.

$$\frac{X}{D} = \frac{6.5}{0.2} = 32.5 \quad \frac{Y}{D} = \frac{4.75}{0.2} = 23.75$$

Where

X = x coordinate of heat radiation space
Y = y coordinate of heat radiation space
D = space gap

From Figure 8 - 12 (p 393, Holman, 6th edition),

$F_{12} = 0.85$

$q = A F_{12} \sigma(T_1^4 - T_2^4)$

Where

F_{12} = radiation shape factor
A = thermal radiation area (ft^2)
σ = Stefan-Boltzman constant - 0.174×10^{-8} ($Btu/hr \cdot ft^2 \cdot {}^\circ R^4$)

$q = (6.5)(4.75)/144)(0.174 \times 10^{-8})(650^4 - 610^4)$
$\quad = 8.58$ Btu/hr (2.51 W)

As the temperature at the inner surface of the bottom tub equilibrates with the temperature of heater in the first few minutes, the amount of heat radiation is decreased very quickly. Heat emitted by the heater surface to the inner surface area of the polymeric packaging material is 8.58 Btu/hr and most of it will occur during the first five minutes before equilibrium is reached.

Heat radiation can be reflected with a shield. The difference in the heat radiation produced when using and not using a shield is shown in the following calculation.

a. Without shield

$$\frac{q}{A} = \frac{\sigma(T_1^4 - T_2^4)}{1/\epsilon_1 + 1/\epsilon_2 - 1}$$

Where

ϵ_1 = Emissivity of the body 1
ϵ_2 = Emissivity of the body 2

Here

$\epsilon_1 = 0.91$
$\epsilon_2 = 0.9$

$$\frac{q}{A} = \frac{\sigma(T_1^4 - T_2^4)}{1/0.91 + 1/0.9 - 1}$$

$$= 0.826\ \sigma(T_1^4 - T_2^4)$$

b. With shield of Aluminum foil

$$\frac{q}{A} = \frac{\sigma(T_1^4 - T_2^4)}{1/\epsilon_1 + 1/\epsilon_2 + 1/\epsilon_3}$$

Where

ϵ_1 = Emissivity of the body 1
ϵ_2 = Emissivity of the body 2
ϵ_3 = Emissivity of the shield

Here

$\epsilon_1 = 0.91$
$\epsilon_2 = 0.9$
$\epsilon_3 = 0.04$

Therefore,

$$\frac{1 - \epsilon_1}{\epsilon_1} = \frac{1 - 0.91}{0.91} = 0.0989$$

$$\frac{1 - \epsilon_2}{\epsilon_2} = \frac{1 - 0.91}{0.9} = 0.1111$$

$$\frac{1 - \epsilon_3}{\epsilon_3} = \frac{1 - 0.04}{0.04} = 24.0$$

The total resistance is

$$0.0989 + 2(24.0) + 2(1) + 0.111 = 50.21$$

And heat radiation is

$$\frac{q}{A} = \frac{\sigma(T_1^4 - T_2^4)}{50.21}$$

$$= 0.0199\, \sigma(T_1^4 - T_2^4)$$

$$\text{Heat Radiation Ratio} = \frac{\text{With a shield}}{\text{Without a shield}} = \frac{0.0199\ \sigma(T_1^4 - T_2^4)}{0.826\ \sigma(T_1^4 - T_2^4)}$$

$$= 0.024$$

Using a shield, 97.6% of the total heat radiation can be reflected to prevent the heat loss from the bottom surface area. However, the savings is not more than 8.37 Btu/hr (2.45 W), only 4.187 Btu (4.4 J) for the first half-hour of the heating period, which is negligible and can be ignored for this model.

Heat Convection

Natural heat convection is a major heat transfer mechanism around the container for losing heat to the surroundings. The convection calculation is based on the assumptions that the food container is exposed to ambient room air without an external source of motion ($h = 0.2 - 0.5$ Btu/ft^2. hr.°F) and that the average temperature on the outer surface of the container is 160°F (71°C) during the heating process.

$$q = A\, h\, (T_s - T_\infty)$$

where

A = heat transfer area (ft^2)
h = heat transfer coefficient (Btu/ft^{2}hr.°F)
T_S = surface temperature (°F)
T_∞ = Ambient temperature (°F)

The maximum amount of heat transferred by convection around the outer surface area of the container is:

$$q = (184/144)(0.32)(160 - 50)$$

$$= 44.97 \text{ Btu/hr } (13.18 \text{ W})$$

The calculations for heat radiation and convection are based on the maximum temperature difference between the heater and the container surface, instead of the actual temperature difference that continuously decreases during heating process. Therefore the real amount of heat lost by radiation and convection is less than the value calculated. The calculation shows that the primary heat transfer mode in this system is heat conduction. Heat transfer by convection and radiation inside the container are not the major heat transfer modes and the amount of heat lost by these modes can be ignored.

APPENDIX B

ANSYS MODELING PROCESS

Appendix B

PREPROCESSING

STEP 1. SET-UP

```
/PREP7
KAN,-1

ET,1,55
ET,2,55
ET,3,34

R,1,0.4219*0.06558
R,2,0.4219*0.0139
R,3,0.4219*0.0026

MP,KXX,1,0.375
MP,KXX,2,6.0
MP,KXX,3,0.08
MP,KXX,4,0.19
MP,KXX,5,38.7
MP,KXX,6,136.33

MP,C,1,1.0
MP,C,2,0.1
MP.C,3,0.46
MP,C,4,0.55
MP,C,5,0.0542
MP,C,6,0.18

MP,DEN,1,62.05
MP,DEN,2,37.45
MP,DEN,3,56.18
MP,DEN,4,57.39
MP,DEB,5,358.97
MP,DEN,6,168.68

SET,A,0.4219
SET,B,0.06558
SET,C,0.0139
SET,T,0.0026
```

```
SET,H1,C+T
SET,H2,H1+T
SET,H3,H2+T
```

STEP 2. MODELING

```
K,1
K,2,A
K,3,A,T
K,4,,T
K,5,,H1
K,6,A,H1
K,7,A,H2
K,8,,H2
K,9,A,H3
K,10,H3
KPLOT

L,1,2,50
L,2,3,2
L,3,4,50
L,1,4,2
L,4,5,5
L,5,6,50
L,3,6,5
L,6,7,2
L,7,8,50
L,8,5,2
L,8,10,15
L,7,9,15
L,10,9,50
LPLOT

A,8,7,9,10
AATT,1,1,1
AMESH,1
A,4,3,6,5
AATT,2,2,1
AMESH,2
A,1,2,3,4
AATT,3,4,1
AMESH,3
```

```
NSEL,EXT
NRSEL,Y,0.0
CVSF,ALL,,,20.0,50
NSEL,EXT
NRSEL,Y,H3

CVSF,ALL,,,20.0,50
/PBC,ALL,1
SBCTRA
SAVE
FINISH
/EOF

/PREP7
RESUME
/TITLE
A,5,6,7,8
NALL
EALL
ARASEL,AREA,4
AATT,,, (MATERIAL,REAL,TYPE) * See Table 5
AMESH,4
NPLOT
```

STEP 3. LOADING

```
*CREATE,LOAD,,
TIME,ARG1,,
ITER,ARG2,1,1,
NTDELE,ALL,TEMP,,

NSEL,NODE,927,975,1,, (FULL SIZE HEATER)
NSEL,NODE,938,964,1,, (HALF SIZE HEATER)
NSEL,NODE,930,972,1,, (TWO, ONE THIRD SIZE HEATERS)
NUSEL,NODE,947,955,1,, (TWO, ONE THIRD SIZE HEATERS)

NT,ALL,TEMP,ARG3,,
NALL,
LWRITE,
*END
```

TIME, 0
ITER,-1,0,1
NT,ALL,TEMP,50
LWRITE

FOR FULL SIZE HEATER
*USE,LOAD,1/60,-1,195
*USE,LOAD,2/60,-1,200
*USE,LOAD,3/60,-1,198
*USE,LOAD,5/60,-2,192
*USE,LOAD,10/60,-5,185
*USE,LOAD,0.5,-20,175
*USE,LOAD,1.0,-20,145

FOR HALF SIZE HEATER
*USE,LOAD,1/60,-1,195
*USE,LOAD,2/60,-1,198
*USE,LOAD,3/60,-1,195
*USE,LOAD,5/60,-2,180
*USE,LOAD,10/60,-5,170
*USE,LOAD,0.5,-20,160
*USE,LOAD,1.0,-20,130

FOR TWO OF ONE THIRD SIZE HEATERS
*USE,LOAD,1/60,-1,195
*USE,LOAD,2/60,-1,199
*USE,LOAD,3/60,-1,197
*USE,LOAD,5/60,-2,185
*USE,LOAD,10/60,-5,175
*USE,LOAD,0.5,-20,170
*USE,LOAD,1.0,-20,138

CHECK
AWRITE
FINISH

SOLVING

/INPUT,27
FINISH

POSTPROCESSING

```
/POST1 (General)
SET,,,,,(TIME)

/CVAL,1,50,75,90,115,130,155,175,200
/EDGE,1,1
PLNSTR,TEMP

/POST26 (Time History)
DISP,2,960,TEMP,HEATER
DISP,3,155,TEMP,TOP
DISP,4,131,TEMP,CORNER
PLVAR,2,3,4

/MENU,OFF
/SHOW,AHDIBMV,,,,3
HALO,PRINT,AHDPJET,.9
PLNSTR,TEMP
/SHOW,VGA
ON
```

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