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BI-RADIANT OVEN
A
LOW-ENERGY OVEN SYSTEM

VOLUME II—EXECUTIVE SUMMARY

PURDUE UNIVERSITY
West Lafayette, IN 47907

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VOLUME II - EXECUTIVE SUMMARY

Dr. D. P. DeWitt

Dr. M. W. Peart

PURDUE UNIVERSITY
West Lafayette, Indiana 47907

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FOREWORD

This report, prepared by the Heat Transfer Laboratory and Equipment Laboratory at Purdue University, concerns the technology for a new low-energy oven system, the Bi-Radiant Oven. This report summarizes the activities in Phase 2, Application and Transfer of the Technology, and is organized in three major parts: (1) Enclosure analysis for determining cavity efficiency, (2) Thermal performance and control, and (3) Food requirements and commercialization. Further details of the Phase 2 work are given in a separate report [6]. The accomplishments of activities in Phase 1 were published in April 1980 [5].

The project is organized and operated as a collaborative activity of the Heat Transfer Laboratory (Mechanical Engineering) and Equipment Laboratory (Consumer and Family Sciences) under the direction of Professors D. P. DeWitt and M. V. Peart, respectively.

The project staff in the Heat Transfer Laboratory included William T. Martin and Gordon G. Scheitlin, graduate research assistants, whose project assignments satisfied the thesis requirements for the Master of Science degree. Mr. S. Kulhman, ME-senior undergraduate student, served as an engineering assistant during the Summer 1980. Mr. George Urbanus, physics technician, and Mr. John Hudgins, electronics technician, provided support for the experimental activities in both project phases.

During the project, Professor Peart's staff included: Dr. Carolyn Garrison, visiting researcher and Assistant Professor from Brigham Young University; Adel Coates, Charlene Hatke and Susan Petrillo, graduate students in the CFS department. Ruth Havers, Deborah Schulz and Monica Lonergan served as technicians in the project on an intermittent basis.

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ABSTRACT

The new low-energy oven—referred to as the Bi-Radiant Oven—features highly reflective cavity walls, absorptive utensils, and upper/lower heating elements that are independently powered and operate at moderate temperatures. Three major technical areas are addressed in this project. The first area is concerned with a heat transfer enclosure analysis to relate cavity efficiency to oven parameters such as wall reflectivity, heating element configuration, insulation thickness and other oven parameters. The second area deals with the thermal performance of two ovens with wall materials having emissivities of 0.03 and 0.31; efficiencies of 22% and 18%, respectively, were obtained, which compare to a range of 12-16% for a conventional oven. A method of control was developed to provide constant net heat fluxes to the upper/lower surfaces of a product. Under simulated microprocessor control, satisfactory oven operation is demonstrated for repetitive cake baking. The third area is concerned with the food requirements and the establishment of oven element power settings to provide acceptable quality for a wide variety of foods. Foods were categorized into groups that require common power settings.

The technology for the Bi-Radiant Oven has been developed and demonstrated. The potential for commercialization, also addressed in the report, is most favorable and the opportunity exists for marketing of a practical, energy efficient oven.

ACKNOWLEDGEMENTS

The project investigators gratefully acknowledge the participation of Mr. A. J. Kloska, Group Manager, Department 817EM, Sears Laboratories, Sears, Roebuck and Co., for technical advice and discussions, particularly as relates to commercialization of the oven system.

Mr. R. J. Fiskum, Technology and Consumer Products Branch, Department of Energy, provided documentation and advice critical to bringing the computer code AGTAP operational at our facilities.

Considerable technical and management support was provided by the project technical monitor, Mr. William L. Cooper, Jr., Energy Division, Oak Ridge National Laboratory, Oak Ridge National Laboratory, Oak Ridge, TN.

STATEMENT OF WORK

LOW ENERGY OVEN SYSTEM PROJECT

This project is to research, develop, and promote a new baking and roasting method, a Bi-Radiant Oven System, which offers the potential for significant energy savings. The energy savings, relative to conventional ovens, that can be realized without compromising baking quality will be evaluated through experiments and analytical models. Barriers to commercialization will also be addressed. The project is separated into two one-year segments entitled: Phase 1 - Technology Development and Assessment, Phase 2 - Application and Transfer of the Technology. Continuation of the project into the second year will be dependent upon evaluation, by the sponsor, of the appropriations of the project to achieving U. S. Department of Energy goals. A major, but not the only, consideration in this decision regarding continuation will be the results of the first year of work.

Phase 1, Technology Development and Assessment, is organized into five tasks:

<u>Task1</u>, Develop experimental facilities/capabilities by (1) construction of flexible-design ovens and (2) instrumentation/techniques with emphasis on radiant heat flux measurement methods.

<u>Task2</u> Develop procedures for obtaining reliable/relevant heat/ mass transfer parameters by obtaining and evaluating baseline data for cooking which satisfies food requirements/qualifications.

Task3 Evaluate the baking process using analytical thermal modeling to identify relevant heat/mass transfer modes and verify the analysis with experiments.

Task4 Identify barriers to commercialization and develop strategies to impact research/development tasks, and identify important human factors.

Task5 Report activities.

Phase 2, Application and Transfer of the Technology, is organized into three tasks, details of which depend upon results of the first year; hence, these tasks can only be described in general terms.

Task1 Perform parametric studies and system design including (1) optimization of system performance based upon analytical model results and experimental trials (2) evaluation of prototype oven configuration(s).

Task2 Promote commercialization of the technology by (1) continuing studies relating to barriers and strategies to consider human factors and marketing problems, (2) developing suitable formulations (recipes) and oven requirements for use with prototype oven configuration(s), (3) technology transfer, e.g. describe the system(s) for manufacture and factors relating to its market potential, and (4) coducting

a one-day workshop at Purdue University on September 18, 1980 to provide a detailed technical presentation of the Bi-Radiant Oven to interested representatives of the appliance industry.

Task3 Report activities.

1. INTRODUCTION

The goal of this project is to research, develop and promote a new energy-efficient method for baking and roasting. The new low-energy oven system—referred to as the Bi-Radiant Oven—offers the potential for significant energy savings relative to conventional ovens without compromise to food quality.

1.1 Bi-Radiant Oven Principles

In the conventional domestic electric oven, the energy source (heating element) operating at high temperatures emits radiant energy to the highly absorptive oven cavity walls which in turn heat the product by radiation exchange and heat the cavity air by convection. The principle of the Bi-Radiant Oven is to more directly (thermally) couple the product and the energy source by the radiative heat transfer mode. This is accomplished by using reflective, rather than absorptive, cavity walls and using absorptive, rather than reflective, baking utensils. These features permit the energy source to operate at lower temperatures and combine to result in improved energy efficiencies with acceptable food quality.

The Bi-Radiant Oven concept shown in Figure 1 consists of three major elements:

(1) Two heating elements, independently operated at relatively low temperatures, provide required levels of radiant flux to the top and bottom of the product,

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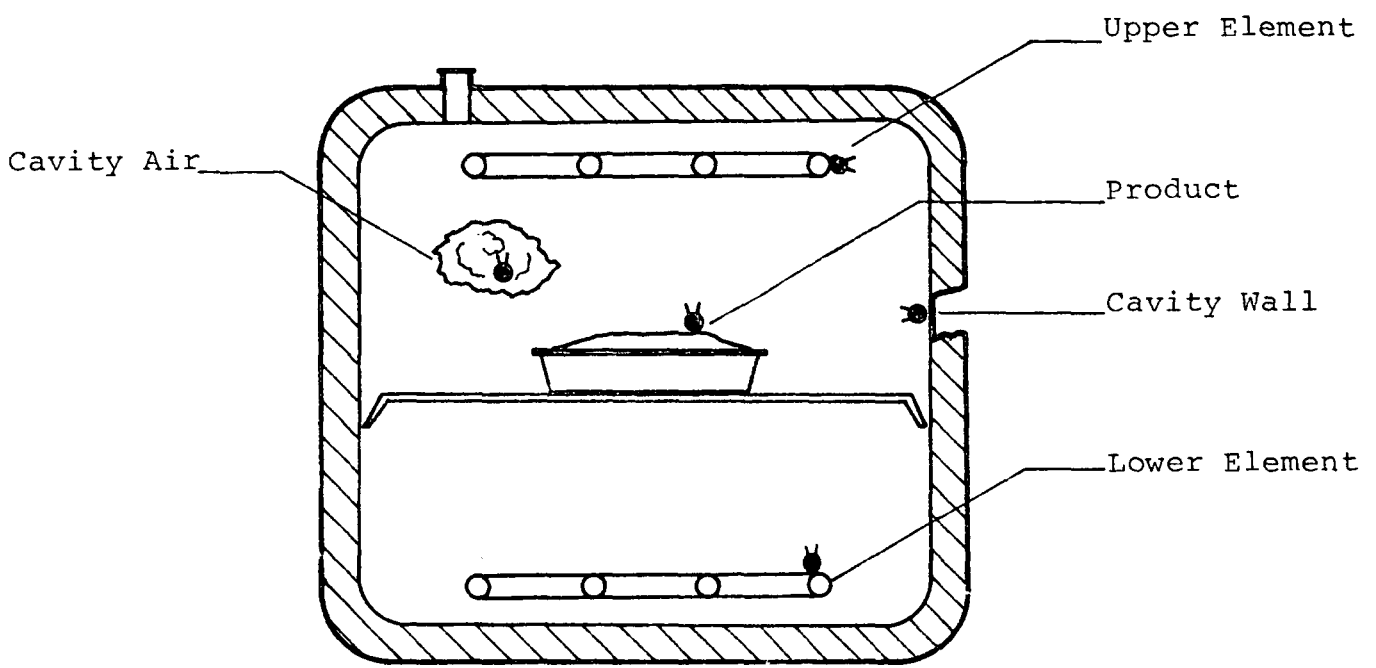

Figure 1 Identification of Temperatures Important to the Operation of the Bi-Radiant Oven.

(2) Oven wall surfaces are highly reflective of the radiant power from the heating elements; referred to as a cold-oven wall, the function of the wall surfaces is to reflect radiant flux to the product, and

(3) Utensil surfaces are highly absorptive of the radiant flux from the heating elements.

It is important to recognize the need for individually controlled upper and lower heating elements. Since the heat losses by evaporation occur from the upper surface, it is desirable to subject the product to unbalanced heating with a greater heat flux on the upper surface.

Power to the heating elements for achieving acceptable products has been controlled in two ways. The first and simpler approach used for demonstrating the capabilities of the oven is to operate the elements at constant power. That is, with the oven in a cold condition, the product/utensil is inserted in the oven and the elements powered to predetermined levels. No preheat cycle is necessary. The product/utensil experiences a steadily increasing heating rate since the elements, initially in a cold condition, require several minutes (6 to 9 minutes in the ovens subsequently described) to reach near steady-state conditions. By pre-setting the power level (W) and the time duration of the baking process, the product is subjected to an average heating rate suitable for achieving acceptable quality.

Recognizing that a cold-oven condition is impractical for domestic usage, there is a need for a control system which will permit sequential baking cycles and accomodate interruptions in the baking process due to door openings. In the conventional oven, a single air temperature sensor is employed and a thermostatic control approach is satisfactory. For the Bi-Radiant Oven, such a simple control strategy will not work since there are four surface temperatures plus the cavity air temperature which significantly influence the heating rate of the product. The four surface temperatures as illustrated in the Figure 1 are those of the cavity wall (average), upper element, lower element and product (average). From knowledge of these four surface plus air temperatures, it is, in principle, possible to control the power to the upper and lower elements such that desired net heat fluxes to the upper and lower product/utensil surfaces can be achieved.

This second approach for power control involves the sensing of these five critical temperatures and then by means of a predictor algorithm, provide information necessary to drive a power supply connected to the heating elements. A digital control system based upon the net heat fluxes at the upper and lower surfaces as the control variables is one approach - perhaps the most sophisticated - toward automatic control of the baking process. Whether simpler strategies using fewer sensors would be practical

and provide acceptable quality products can be readily evaluated with such an approach.

1.2 The Technical Problems

From the experiences of the first phase of the project directed toward assessment of the technology, we identified three major technical problems which needed to be addressed. They are: (1) Enclosure Analysis - What influence do oven features such as heating element configuration, cavity wall reflectivity and insulation thickness have on oven efficiency? (2) Control System - What is the thermal performance of the oven and how can the baking process be controlled? (3) Food Requirements - What upper/lower heating element power levels and baking times are required for baking acceptable quality foods? With the understanding generated by the studies on these problems, the technology for the Bi-Radiant Oven is well established.

Summaries of the research work associated with each of the three major technological problem areas are presented in the following sections. Also, detailed treatments of the problems are provided in a separate report, [6].

2. ENCLOSURE ANALYSIS

Rational design of an oven requires an understanding of the thermal processes which control the transfer of energy from the heating elements to the product and the cavity. The purpose of this aspect of the project is to develop

analytical methods for relating oven performance to oven design characteristics. Following a discussion of the study objectives, descriptions of the computer models are presented. Comparison of the analytical predictions with experimental observations are then summarized.

2.1 Objectives

The purpose of the present study is to provide detailed analytical and experimental methods for determining heat transfer characteristics within an oven enclosure. The objectives are:

- To develop heat transfer analytical models and computer codes for predicting radiant heat transfer rates to the product and cavity walls and irradiance* distributions as a function of heating element configuration.

- To develop a method for experimentally determining radiative and convective heat flux levels and distributions within an oven enclosure,

- To provide a capability for predicting oven performance (efficiency) and to compare predictions with experimental oven results.

2.2 Irradiance Distribution within the Oven

* Irradiance, $G[W/m^2]$, is the radiant power per unit area incident upon a surface; our concern is the distribution of the irradiance (due to the heating element emission and subsequent reflection from cavity walls) on the product and wall surfaces.

In a Bi-Radiant Oven it is important for a heating element to provide a uniform field of radiant flux over the surface of a product and utensil. While intuition alone might permit selection of a satisfactory element configuration, a quantitative calculational technique allows comparison of different configurations so that an optimal design can be chosen.

2.2.1 Computer Program COIL

Computer program COIL is based upon a heat transfer analysis to predict the irradiance distribution on the baking plane for a specified heating element configuration. The model assumes isothermal, circular cross-section heating elements with diffuse-gray radiating surfaces and that any reflection of radiation at the cavity walls is perfectly specular. Also, only direct emission from the heating elements and single reflections of this emission at the cavity walls are considered in determining the irradiation at the baking plane.

Referring to Figure 2, input to the model consists of element configuration and location; size, shape and location of the product utensil; cavity size; and baking plane elevation. Note that considering only the direct and single specular reflection paths of radiation emitted from the heating elements imposes a restriction on the analysis since irradiation at the product will also be due to multiple

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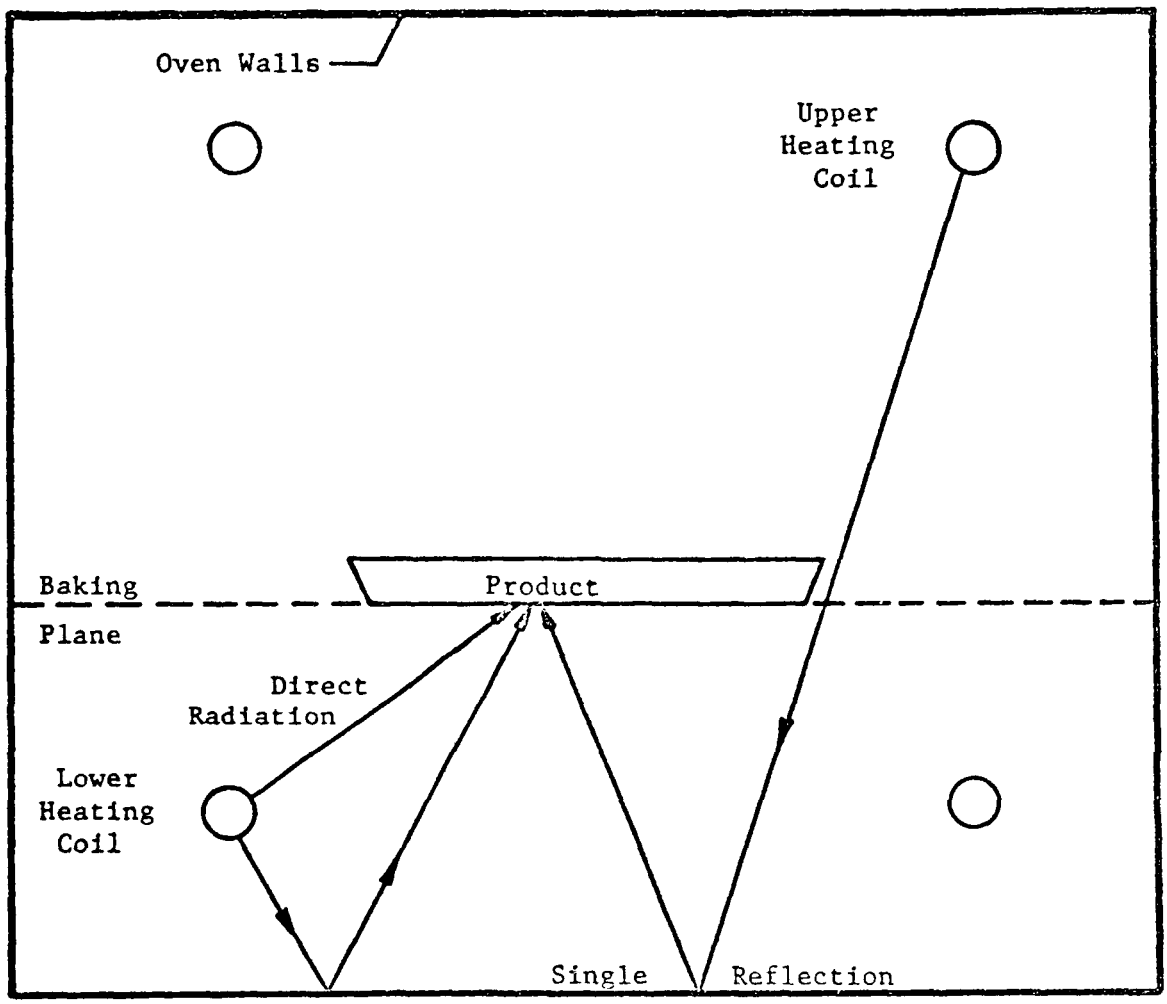

Figure 2 Front View of the Oven Cavity Depicting the Direct and Single Reflection of Radiation Emitted from the Heating Elements to the Product Utensil.

cavity wall reflections as well as cavity wall emission. These are considered to be secondary effects, which if included would seriously complicate model computations.

The output from the model, Progam COIL, includes the following parameters: (1) the view factor from a heating element to an arbitrarily small, differential area on the baking plane and (2) the ratio of the irradiance at any location on the baking plane to a reference value. The view factor is defined as the fraction of diffuse radiant energy emitted from the heating element which strikes the differential baking plane area either directly or after a single specular reflection at one of the cavity walls.

2.2.2 Evaluation of Heating Element Configurations

The output of the model applied to a given oven-heating element configuration can be displayed by a contour plotting routine to indicate lines of constant irradiance (iso-irradiance lines) over the baking plane.

The irradiance distribution results from the analysis of a modified diamond-shaped element are presented in Figure 3. The oven cavity is 43cm x 56cm x 41cm (depth x width x height); the elements of 6.6mm diameter and 222cm length are positioned 38mm from the upper or lower cavity wall and the baking plane is located 114mm from the lower wall. The results are for a no product condition with equal power to

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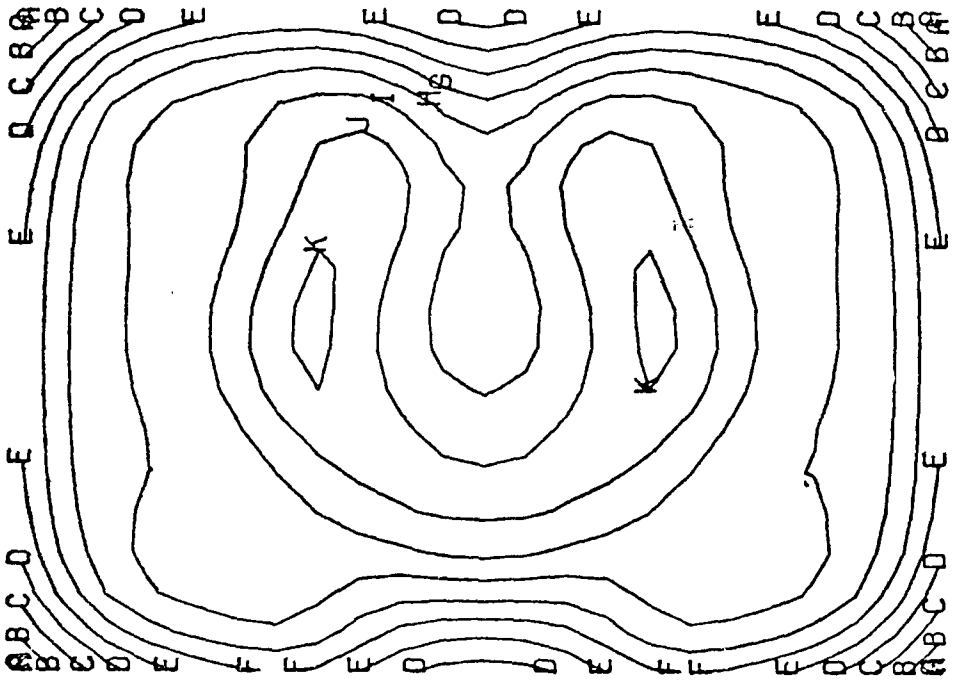
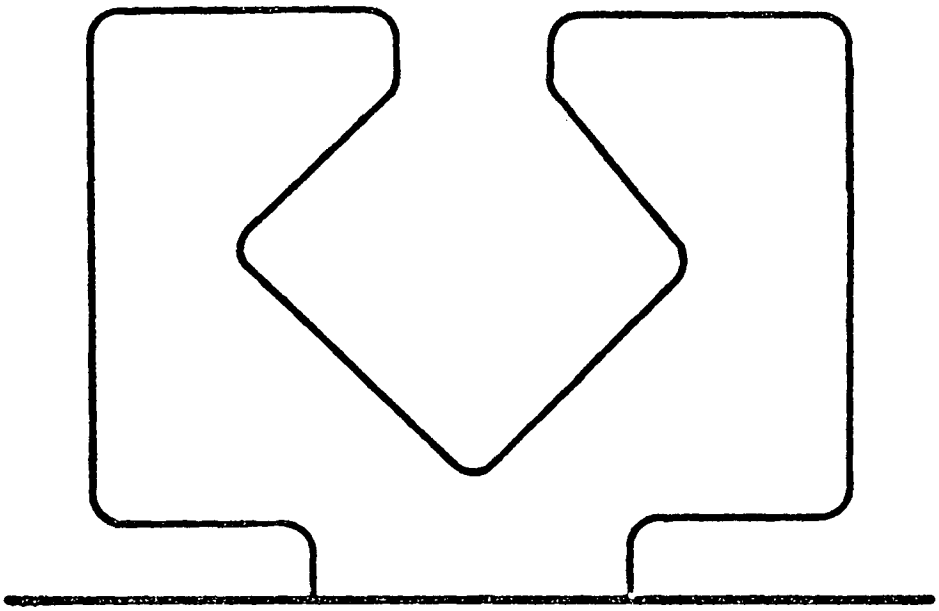


(b)



(a)

Figure 3 Irradiance Distribution for Modified Diamond Element
(a) Modified Diamond Shaped Element, Total Length = 222 cm.
(b) Irradiance Distribution, $G_{max}/G_{min} = 3.16$

the upper and lower heating elements.

The dimensionless irradiance distribution on the baking plane, Figure 3(b), is represented by eleven curves, labeled A through K, of constant irradiance. The maximum (95%) and minimum (5%) irradiance values occur along curves K and A, respectively. Intermediate iso-irradiance curves J to B represent irradiance levels from 90 to 10% (by 10% increments), respectively.

The dimensionless irradiance distribution of Figure 3(b) suggests two features which could be used for quantitative evaluation of a heating element configuration. First, it is desirable to have a small value of maximum-to-minimum irradiance, G_{max}/G_{min}, which indicates small changes in the irradiance levels over the baking plane. Second, a large region of widely spaced iso-irradiance lines is desirable particularly on the baking plane where products will be located. For the element of Figure 3, G_{max}/G_{min} is 3.16; this is to be compared with a value of 5.74 corresponding to the worst configuration evaluated in our study [6]. Note from the irradiance plot of Figure 3(b) that the iso-irradiance lines K through H (95 to 70% lines) encompass approximately 60% of the central portion of the baking plane. This is a very favorable situation for uniform baking conditions.

In our study we evaluated four element configurations,

but the most favorable design is that of Figure 3(a) which was used in Bi-Radiant Oven IV, the experimental oven previously reported upon [6].

2.3 Experimental Heat Flux Measurements

In order to experimentally characterize the heating evironment within an oven, a heat flux gage was developed to provide local measurements of the irradiance, $G[W/m^2]$ and the convective heat flux, q_c''. Use of the gage involves two types of measurements: time dependent heat flux measurements to determine the dynamics of heat flux levels at a single point within the oven cavity and steady-state heat flux measurements to obtain the irradiance distribution over an entire baking plane.

2.3.1 Description and Principles of the Heat Flux Gage

The body of the heat flux gage is a nickel-coated, water cooled copper plate serving as the mounting base for the flux sensors. The sensors are Gardon-type (thin discs) devices with highly reflective or highly absorptive surfaces. The water cooling supply lines and sensor output leads are wrapped in metallic shielding to minimize adverse thermal effects of the oven. Water cooling is essential in order to maintain the gage at a constant and uniform temperature.

The two sensors provide output signals proportional to the net heat flux on their surfaces. With the black suface, the dominant heat transfer process to the gage is irradiation absorption; with the reflective surface, the dominant process is convection. A detailed analysis has been performed to show how the irradiance, G, and convective heat flux, q_c'', (or local heat transfer coefficient, $h[W/m^2 \cdot K]$) can be obtained from the sensor signals and knowledge of the oven air and gage temperatures. The latter parameter is sensed by a thermocouple installed in the gage block. The procedure for calibration of the gage has been fully described and an error analysis performed to show that the precision of the parameter determinations is ±10%.

2.3.2 Time-Dependent Heat Flux Measurements

For time-dependent heat flux measurements, simultaneous recordings of the gage output signals are taken at various time intervals for a fixed location of the gage. Figure 4 presents typical results for Bi-Radiant Oven IV-B* with the gage mounted in the center of the cavity and facing upward. The upper and lower heating elements were operated at 1040W and 64W, respectively. Note that this condition approximates the 177°C (375°F) thermostat setting in a conventional oven.

* Refer to section 3.2.1 for description of oven IV-B.

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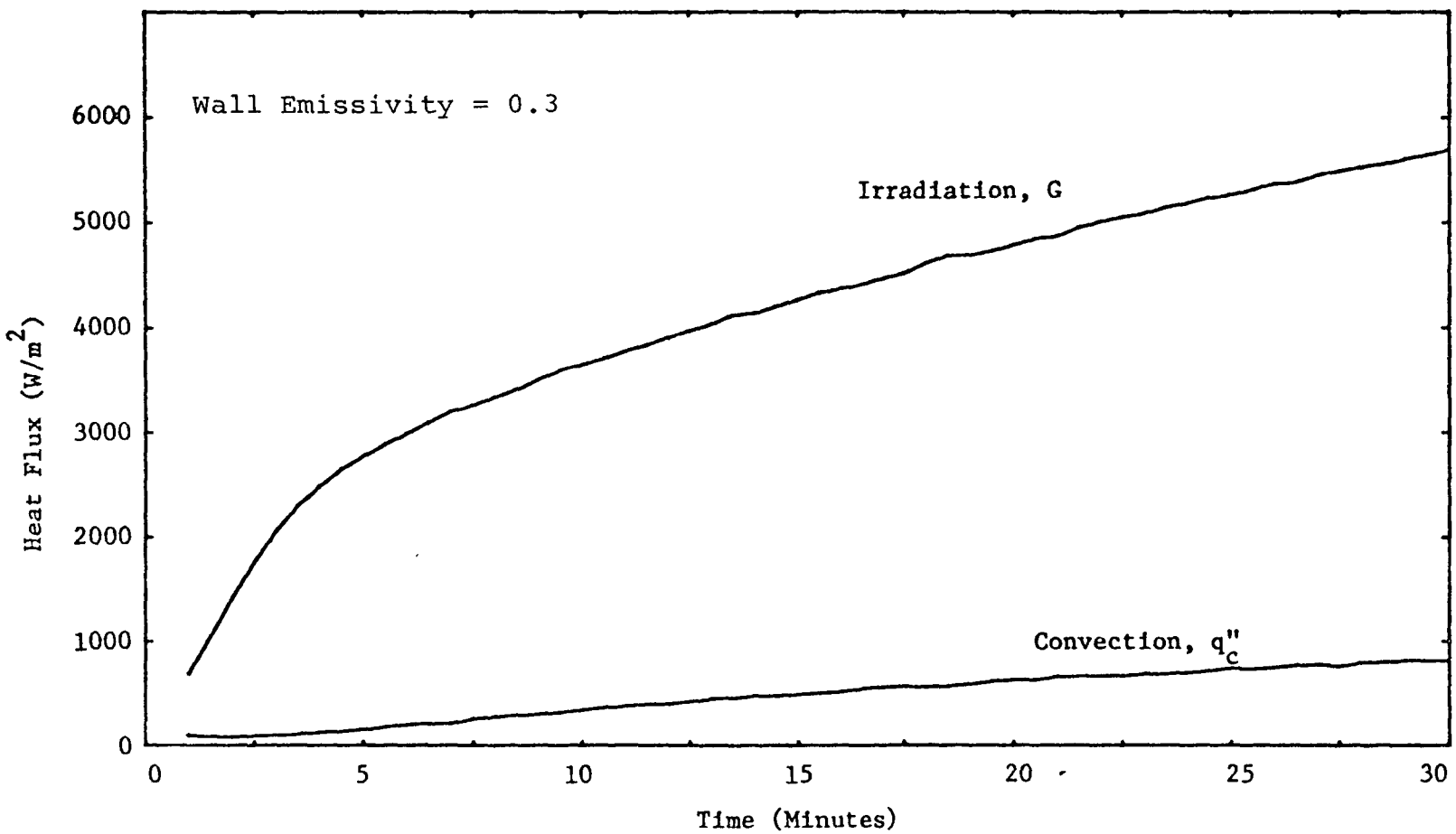

Figure 4 Irradiation and Convective Heat Flux in a Bi-Radiant Oven

The low initial heat flux levels, as indicated in Figure 4, are to be expected since there is no preheat period during normal use of the Bi-Radiant Oven. Note the relatively low convective heat flux level as compared to the irradiation level. Since the convection coefficient is expected to remain fairly constant, the increasing convective heat flux is a result of the increasing temperature difference between the gage and cavity air.

The irradiation curve displays the heating element and oven wall dynamics. The rapid increase in irradiation heat flux after oven turn-on is due to the rapid increase in heating element emission as element temperature rises. The later slow, steady increase represents the increasing emission from the oven walls as their temperatures rise.

2.3.3 Steady-State Measurements; Irradiance Distribution

The purpose in performing these measurements is to provide experimental confirmation of how well the model predicts irradiance using program COIL.

The experimental method is as follows. After steady-state conditions are achieved (about 10 hours), the heat flux gage is positioned at 42 discrete locations over half the baking plane. From these observations (and assuming symmetry) and the use of a computer contour plotting routine, the irradiance distribution can be obtained. Figure 5

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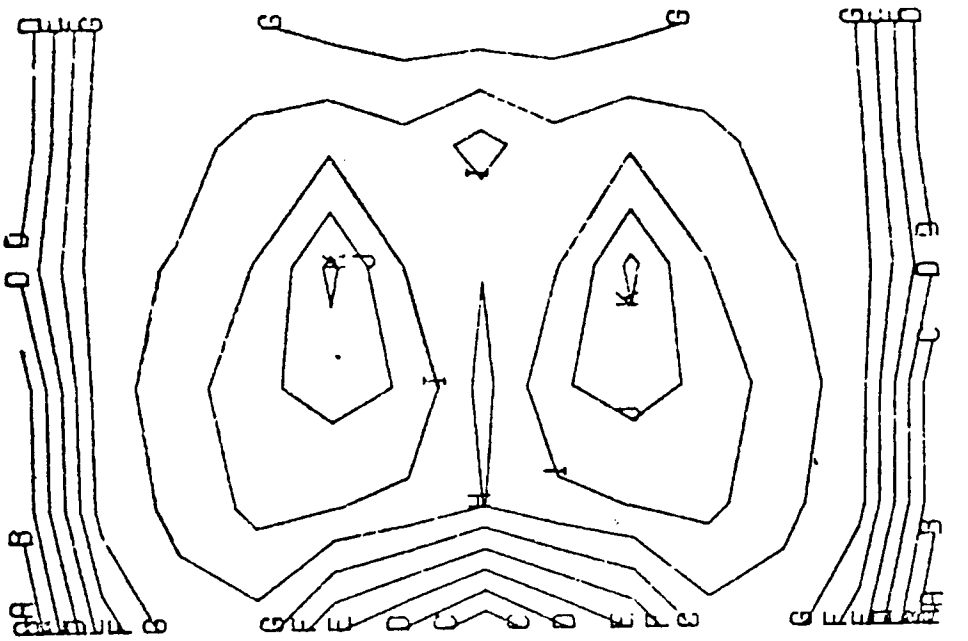
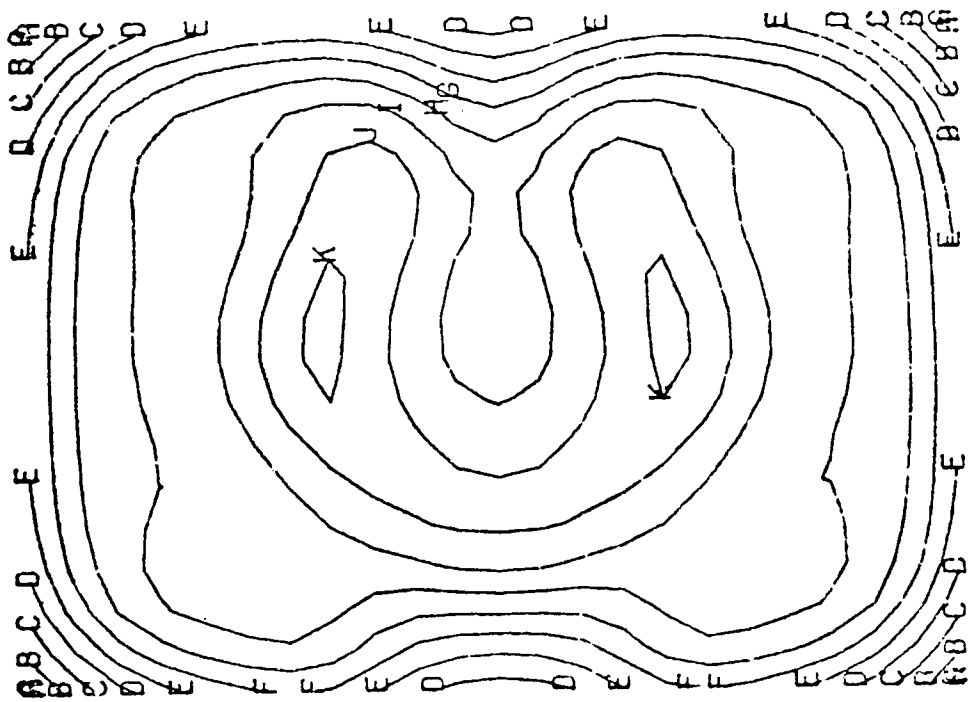


(b)



(a)

Figure 5 Comparison of Predicted (a) and Measured (b) Irradiance Distribution Maps for Bi-Radiant Oven IV-A (Wall emissivity 0.032).

provides a comparison of the predicted and experimentally determined irradiance distribution maps for the modified diamond-shaped heating element configuration shown in Figure 3(a).

The iso-irradiance curve designations (A through K) have the same meaning as explained earlier for Figure 3. Note that the two maps compare very favorably. The large region of relatively uniform irradiance and the steep irradiance decline near the cavity walls are indicated in both plots.

Since the experimental mapping is performed after the oven has reached steady-state conditions, wall temperatures will be nearly that of the element and therefore, emission from the walls will significantly increase the irradiance at the baking plane. The analytical model, program COIL, does not consider wall emission. Consequently, G_{max}/G_{min} ratios for the two maps are understandably quite different: prediction of 3.16 vs measurement of 1.06. A simplified analysis using averaged, observed wall temperatures can be applied to correct the measured G_{max}/G_{min} to be in reasonable agreement with the model prediction. The effect of the wall emission is to increase the level of and smooth out the distribution of irradiance across the baking plane. The correction procedure minimizes this effect such that the influence of the heating elements can be estimated.

2.4 Prediction of Oven Performance and Efficiency

The modeling of the oven performance with the DOE test block as the thermal load resulted in two related computer programs. The radiant exchange analysis, program OVENRAD, solves for the view factor matrix for determining the radiant exchange between surfaces within the oven cavity. The output from this program is inputted to the transient thermal analysis program, AGTAP, which defines the oven as a number of nodal points and calculates the temperature of each nodal point as a function of time. A general description of the programs is given and a comparison of prediction and experimental observations for Bi-Radiant Oven IV-B is presented.

2.4.1 Radiant Exchange Analysis, OVENRAD

The radiant exchange analysis considers the interior of the oven cavity as a combination of diffuse-gray surfaces and determines the radiant heat exchange between individual surfaces using the radiosity method. In this method, the interior cavity, comprised of the heating elements, product, and oven walls, is subdivided into isothermal regions (surfaces). The view factors between all these surfaces are calculated and expressed in matrix form, and are a function of only the geometry, location, and number of surfaces which are used to represent the oven interior. Once a particular cavity is subdivided into individual surfaces, and the view

factor matrix generated, this matrix remains unchanged throughout the remainder of the analysis.

The calculation of the view factor matrix is accomplished in Program OVENRAD. Much of the logic and programming methods used stem directly from the Irradiance Distribution Model, COIL. Output from OVENRAD, besides being printed for user scrutiny, is placed in semi-permanent storage to be used as input for the transient thermal analysis program.

The program is capable of handling any arbitrary heating element shape and location, any product size, and any cavity size. The limiting factors are that the heating elements be of conventional, circular cross-section, the product be either in a rectangular or round pan, and the oven cavity be a six-sided, cubical enclosure with walls of specified reflectivity.

2.4.2 Transient Thermal Analysis, AGTAP

The transient thermal analysis predicts temperatures at the numerous nodal points which define the oven. The analysis is subdivided into two parts. The first part is the radiation heat exchange between the interior oven cavity surfaces (nodal points) as a result of the given power inputs to the upper and lower heating elements. The second part is the conduction and convection transfer betwen all nodal points and the determination of the resulting nodal

temperatures through an energy balance. Estimation of the convective heat transfer occurring within the oven cavity is accomplished through the use of standard correlations and information generated from heat flux gage measurements.

The radiation heat exchange analysis is a separate subroutine which is called at the start of each time step during the transient analysis. This subroutine determines the magnitude of the radiant heat flux levels at each nodal surface involved in radiant exchange with the heating elements. Once these flux levels have been calculated, control is returned to the main program, AGTAP.

Program AGTAP determines the temperature at each nodal point as a function of the thermal capacitance of the node and the thermal resistance network adjoining nodes. The nodal network used to define the oven consists of a total of 162 nodes. There is 1 nodal point for each heating element, 1 nodal point for the DOE test block, 1 nodal point each for the upper and lower halves of the cavity air, 4 nodal points for each of the six inner cavity walls, and 1 nodal point representing the ambient surroundings. The remaining 132 nodes are divided among the insulation, exterior cover, and oven door.

The input to the transient thermal analysis program is simplified such that the effects of single parameters on oven efficiency can be examined. Wall emissivity, insula-

tion thermal conductivity, heating element input power, and heating element diameter are some of the parameters which can easily be varied within the program input. Output from the analysis, provided at specific time increments, consists of the temperatures for all nodal elements defining the oven. The oven efficiency is calculated and printed when the temperature of the node representing the DOE test block reaches 130°C above the its initial temperature. From the program output, plots are generated depicting the heating element temperature, DOE test block temperature, cavity walls and door temperatures, and average cavity air temperature versus time.

2.4.3 Comparison of Analysis and Experimental Observations

Comparisons of the predicted and measured oven temperatures and oven efficiency have been made for Bi-Radiant Oven IV-B. The measurements, following the procedures described in a separate report [6], correspond to constant input power to both elements (482W) with the DOE test block centrally located within the oven cavity.

Figure 6 represents the temperature-time history for the DOE test block; note the very good agreement between the predicted (solid line) curve and the measured points. Calculation of the oven efficiency is performed when the temperature of the block reaches 130°C above its initial temperature. For the conditions of this test, the predicted

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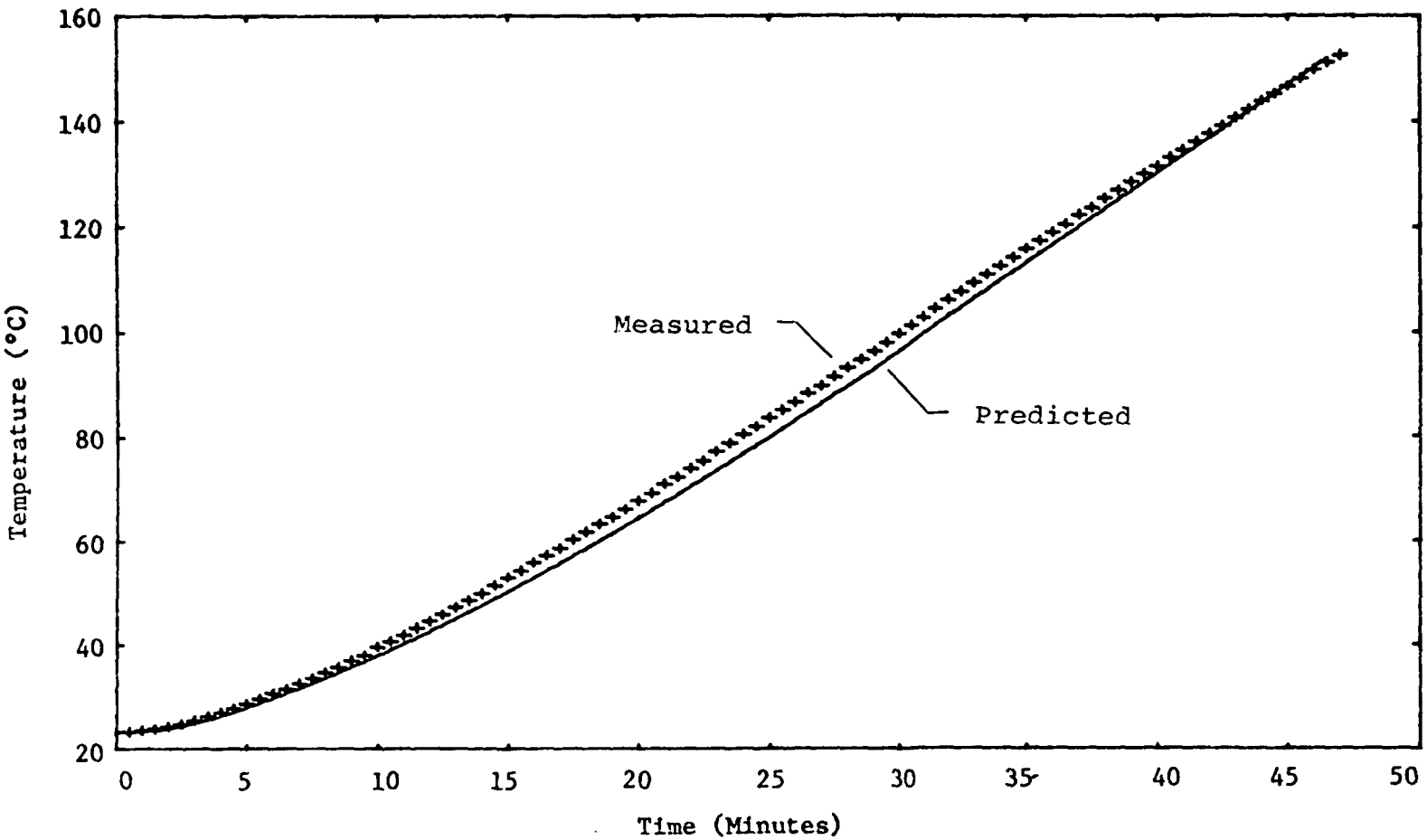

Figure 6 Comparison of Predicted and Measured DOE Test Block Temperature

oven efficiency was 17.92% and the measured efficiency was 17.83%,* an error of only 0.5%. This high accuracy is to be expected since very good agreement is shown to exist for the predicted and actual temperatures of the block. Note that a maximum error of only about 4°C is indicated over the entire 47 minute time span of the test.

A more detailed comparison of analysis and experimental observations includes considerations of heating element temperatures, average air cavity temperatues, and wall temperatures. Overall, the ability of the analytical model to predict the thermal respose of the oven is very good. It is important to recognize that the analysis parameters are selected from standard estimating procedures (e.g. convection correlations) and that no coefficients are adjusted to force favorable matches between the analysis and measured results.

2.5 Influence of Oven Design Parameters on Oven Efficiency

To estimate the influence of oven design parameters on oven efficiency, a parametric study using the enclosure analysis computer program was performed. Considering Bi-Radiant Oven IV-B as the baseline case, the program was run with a single parameter change to see the effect on oven efficiency. The parameters tested were the insulation ther-

* Recall that the wall emissivity is 0.31; this accounts for the low efficiency values.

mal conductivity, cavity wall emissivity, heating element diameter, and heating element input power. The last parameter has negligible effect but the remaining ones show interesting effects.

2.5.1 Effects of Insulation Thermal Conductivity

The effect of decreasing the thermal conductivity of the cavity insulation is to decrease the loss of energy through the cavity walls. It was found that over a range of insulation thermal conductance from 200% to 25% that of the baseline value, the oven efficiency only changes from 16.9% up to 18.9%. The small variation is due to the magnitude of other loss mechanisms besides conduction through the insulation. Other significant conduction losses at the walls include those through the oven door cover, oven support frame, and flange mounts.

2.5.2 Effects of Cavity Wall Emissivity

Radiant coupling between the cavity walls and heating element is a strong function of cavity wall emissivity. For wall emissivities less than 0.10, altering the wall emissivity has quite a dramatic effect on oven efficiency as shown in Figure 7(a). This is to be expected since as the wall emissivity approaches zero, so does wall absorption of irradiance; this implies that all radiation emitted from the heating elements would be reflected at the cavity walls

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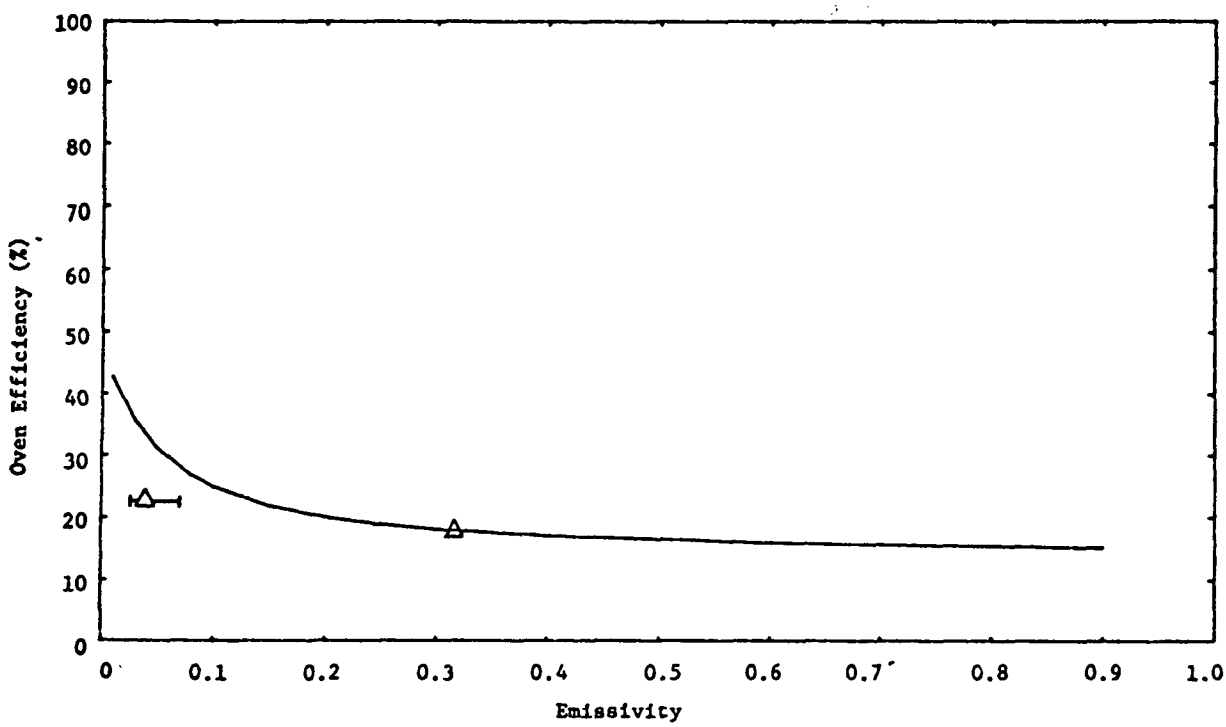

(a)

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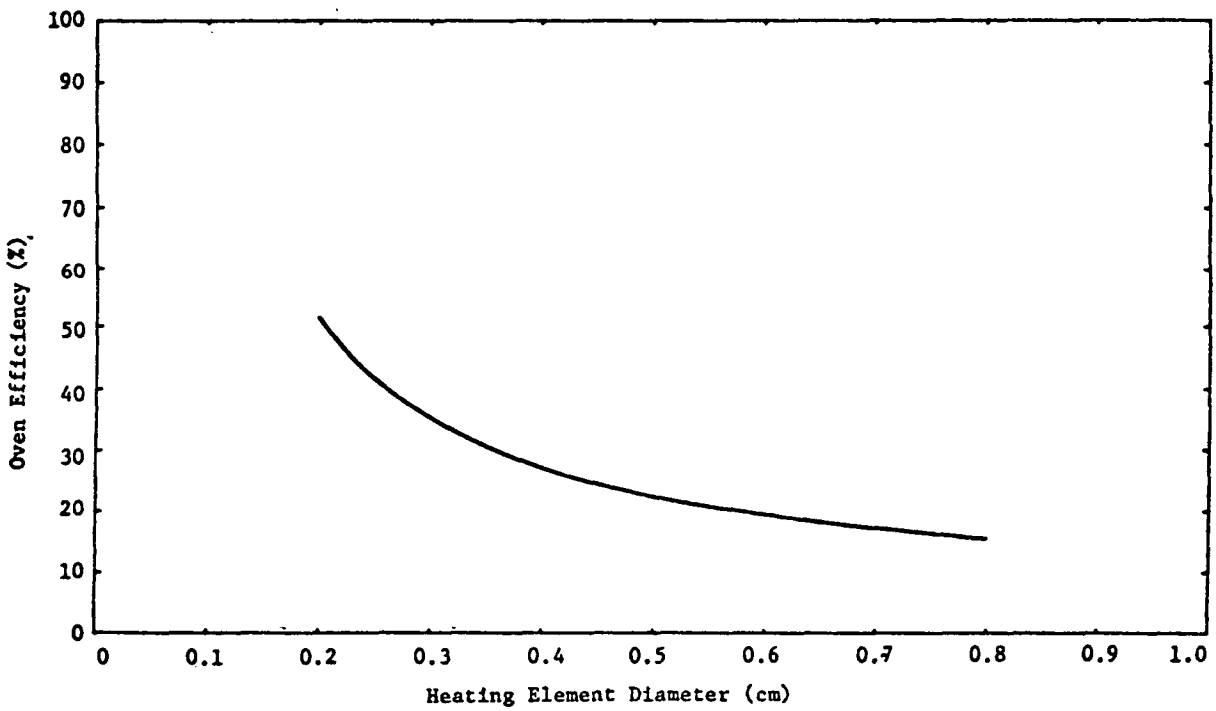

(b)

Figure 7 The Effects on Oven Efficiency due to (a) Cavity Wall Emissivity and (b) Heating Element Diameter.

until finally absorbed by the product (test block).

Also indicated in the figure are two data points obtained from laboratory measurements. The point at a cavity wall emissivity of 0.31 corresponds to the base case condition of Bi-Radiant Oven IV-B, and is seen to lie almost exactly on the analytical curve. The data point at a measured emissivity of less than 0.10 results from laboratory tests conducted in Bi-Radiant Oven IV-A. (This oven is the same as IV-B except for having specular walls of very low emissivity.) This data point seems in poor agreement with the analytical predictions. However, this discrepancy can be due in part to the uncertainty in the emissivity value itself. Measurements were initially taken on a clean sample, and the resulting emissivity was found to be 0.03, with a possible error of +0.04 and -0.01. This could raise the emissivity value to 0.07. Further, the oven walls had been subjected to numerous thermal cycles and contamination occured which would tend to increase their emissivity. Under these conditions, it would not be unreasonable to expect the emissivity of the actual cavity walls to be closer to a value 0.10. If this were the case, the measurements and predictions would be in closer agreement.

2.5.3 Effects of Heating Element Diameter

At constant power input to the heating element, decreasing the element diameter will cause an increase in

the element temperature. Since emission from the heating element is dependent on T^4, increasing the element temperature will cause the percent of the input power dissipated by radiation to increase. It follows that the percent of the total input power dissipated through convection must decrease.

The effect of decreasing the element diameter or increasing the percentage heat rate dissipated by radiation is to increase the oven efficiency, as shown in Figure 7(b). This is expected in a Bi-Radiant Oven due to the lower emissivity walls which tend to reflect the increasing amounts of radiation. As the element approaches a filament-type heater, the efficiency rises sharply, and should eventually level out and intersect the axis at a point less than 100%, depending on the cavity wall emissivity.

3. THERMAL PERFORMANCE AND CONTROL

To effectively utilize radiant heat transfer, three major modifications to the conventional oven were proposed: elements are operated continously and at lower power, the cavity walls are highly reflective and the baking utensil is highly absorptive. The study reported upon in this section has experimentally characterized the thermal performance of the oven during the baking process and determined cavity thermal efficiency. A major contribution of this study is demonstration of a control system for operation of the oven under conditions other than cold-start up.

3.1 Objectives

The goal of this study was to substantiate the concepts of the Bi-Radiant Oven principle by careful measurements on a working model. This goal implies not only an analysis of the energy utilization, but also identifying the manner in which energy should be delivered to the product. With this goal in mind, the following objectives were identified:

- Construct an experimental Bi-Radiant Oven to serve as an engineering prototype for generating a data base,
- Characterize the thermal performance of the prototype oven, both under real and standard conditions using detailed measurements of the prototype oven,
- Develop a method for controlling the power levels to the upper and lower heating elements so as to accommodate various products.

Summaries of the accomplishments associated with each of these objectives are given in the following sections.

3.2 Experimental Apparatus

The experimental apparatus consists of a prototype Bi-Radiant Oven featuring removable cavity wall liners, its associated instrumentation and data acquisition system. The procedures for measuring the important oven and product parameters are described.

3.2.1 Experimental Bi-Radiant Oven IV

The inner cavity dimensions of the experimental oven (58.4cmx43.2cmx43.8cm) were comparable to those of a full-sized conventional oven. The inner cavity was designed to permit replacement of the wall lining materials. Two sets of walls were evaluated, the first being constructed from 0.635mm thick 6061-T4 aluminum sheet which was mechanically polished to produce a highly specular surface with a measured normal total emissivity of 0.032 [+0.04,-0.01 uncertaintity] at 150°C. The second set was constructed from 0.635 mm thick 2024-T3 aluminum sheet which was sandblasted to produce a diffuse surface with a measured total emissivity of 0.30 ± 0.2 at 150°C. These two materials represent extreme wall conditions and, in subsequent discussion, the oven with these materials installed will be referred to as Bi-Radiant Oven IV-A (specular walls, $\epsilon = 0.032$) or IV-B (diffuse walls, $\epsilon = 0.31$).

Further details of the oven construction are presented in a separate report [6]. Major features include a side-hinged (for convenience in the testing work) front door with a seal of conventional silicone rubber. The space between the cavity walls and oven outer covers (including the door) were filled with a fiberglass, blanket-type insulation. The heating elements were conventional calrod type with a diameter of 6.58mm and length of 244cm, formed in the modified diamond-shaped configuration shown in Figure 3. Electrical

power to the upper and lower heating elements was controlled by separate powerstats. The oven rack (56.0 x 40.2 cm) from a conventional oven was modified to accomodate the suspension cables of the product weighing system subsequently described.

3.2.2. Instrumentation and Data Acquisition System

The experimental oven was instrumented for the measurement of temperatures within the enclosure and product, power consumption of the heating elements, and for the continuous measurement of product mass loss during baking. The water-cooled heat flux gage, described in Section 2.3.1, was used to measure heat fluxes within the enclosure.

Copper-constantan thermocouples were used for temperature measurements of the cavity inner wall surface (27), cavity air (8), product (3), test block (1) and external oven cover surfaces (30). Chromel-alumel thermocouples were used on the heating elements (6).*

The product mass loss was measured during the baking process by four cantilever type load cells attached to the four oven rack suspension cables and mounted in a thermally isolated fashion above the oven top cover. A resolution of ± 1 gram was achieved.

* Numbers in parentheses indicate number of the thermocouple.

The electrical power consumed by each heating element was measured by two AC watt transducers with an accuracy of better than 2% of full scale (1kW) rating. These transducers, as well as the other sensors, were connected to a data acquisition system consisting of three major components: Esterline Angus PD2064 data logger, Hewlett-Packard 9815S desk top calculator and Hewlett-Packard 7225A/17600A graphic plotter. This system was used for generating the figures of the experimental results shown in this report. Additionally, the calculator was used to implement the microprocessor function of the control scheme subsequently described.

3.3 Oven Performance Results

The major reason for characterizing the thermal performance of the Bi-Radiant Oven was to gain a better understanding of the heat and mass transfer processes occurring in the oven and of the overall energy utilization of the oven. Typical temperature responses of major oven components are presented, as well as, cavity thermal efficiency and an overall energy audit to characterize the loss mechanisms. A single-layer yellow cake was used to demonstrate actual baking conditions while the DOE test block was used to quantify the energy absorbed by a typical product.

3.3.1 Single-Layer Yellow Cake Measurements

Single-layer yellow cakes were baked in Bi-Radiant Oven IV-A (specular walls, ϵ=0.032) in a 22.9 cm diameter, black anodized aluminum cake pan having a total emissivity of 0.87 near 150°C. Initially the oven was isothermal at room temperature. With the product/utensil centrally positioned on the oven rack, electrical power to the elements -- 809W to the upper element and 46W to the lower -- was switched on at time zero and data recorded every thirty seconds. Baking was terminated when all three cake thermocouples reached 93°C. Temperature responses are shown in Figure 8 while the response (temperature and mass loss) of the product during the baking process is shown in Figure 9.

The temperature response of the heating elements as shown in Figure 8(a) represents the average of four thermocouples; the largest temperature difference observed among the thermocouples for the upper and lower elements was 23.8 and 4.6^{o}C, respectively. As expected, the upper element temperature is substantially higher than that of the lower element. Note also that the upper element temperature is nearly constant after 7 minutes, while that of the lower element experiences a continual increase during the baking process.

The oven air temperature measured along the vertical centerline of the oven at various heights above the bottom

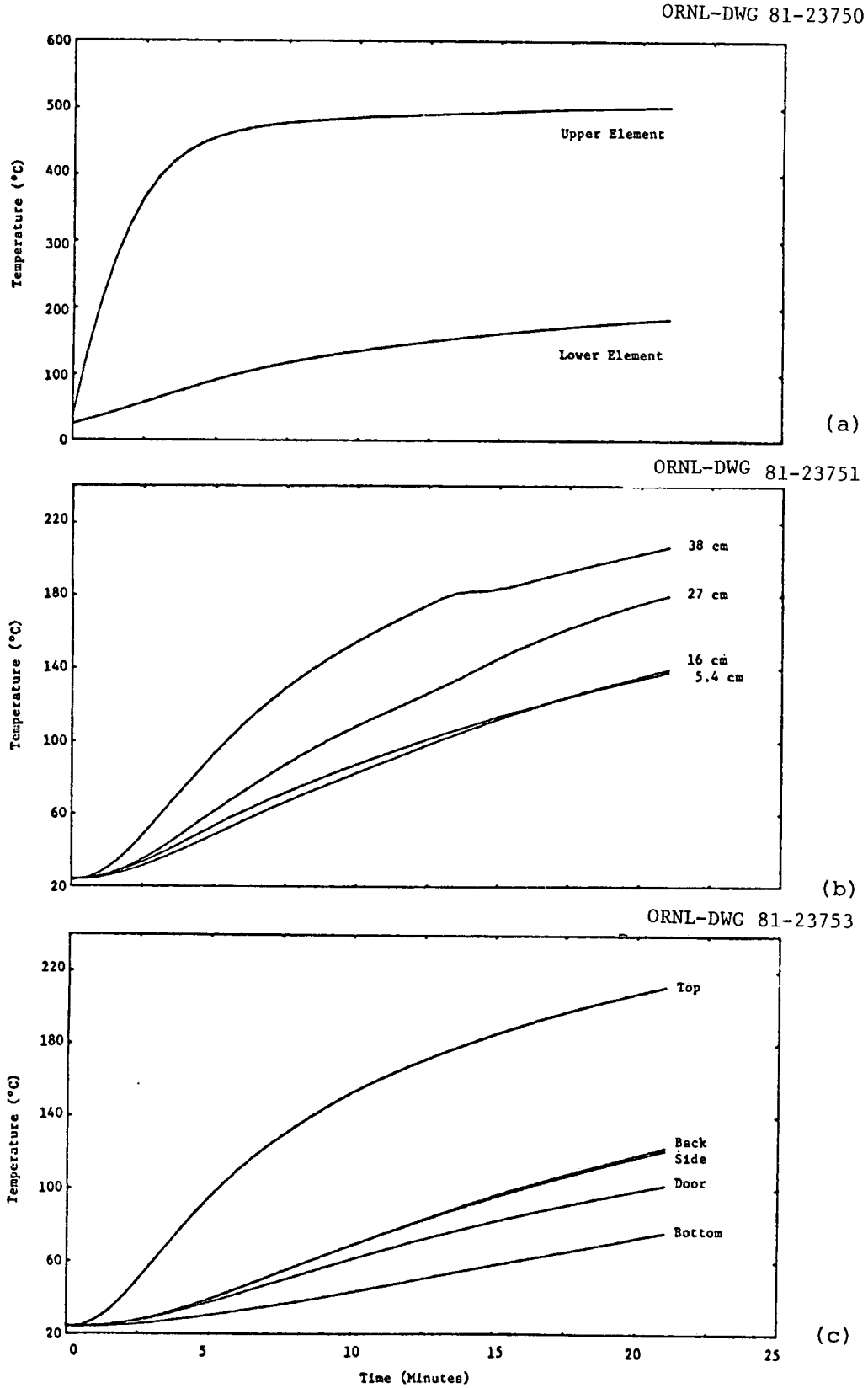

Figure 8 Temperature Response for Bi-Radiant Oven IV-A Components: (a) Heating Elements, (b) Centerline Cavity Air at Specified Distances above the Bottom and (c) Averages of Wall Surfaces.

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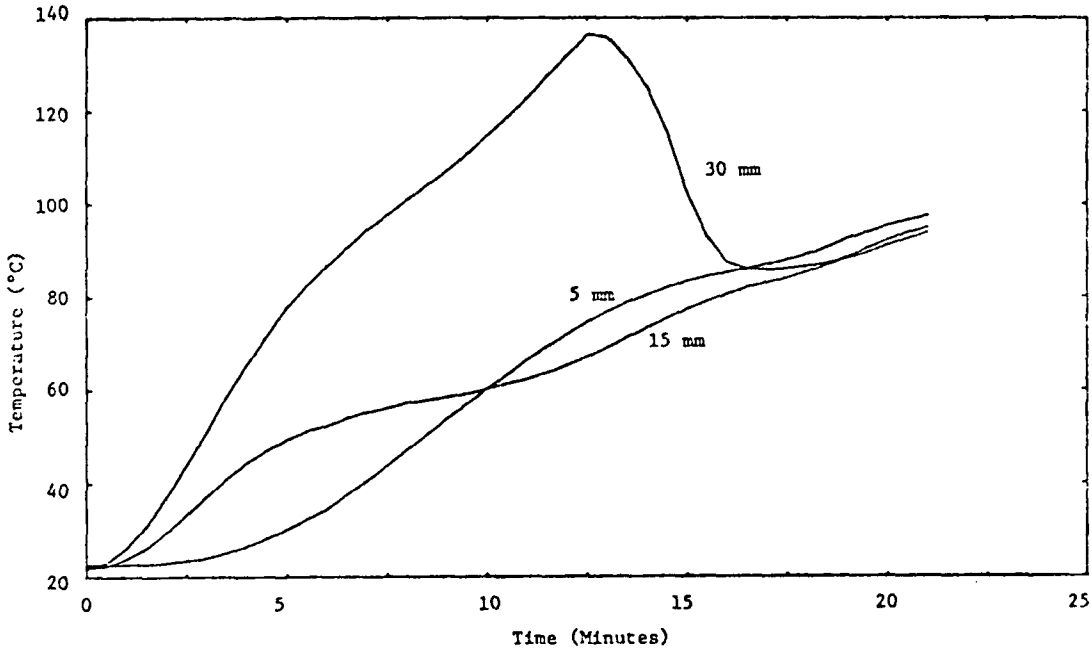

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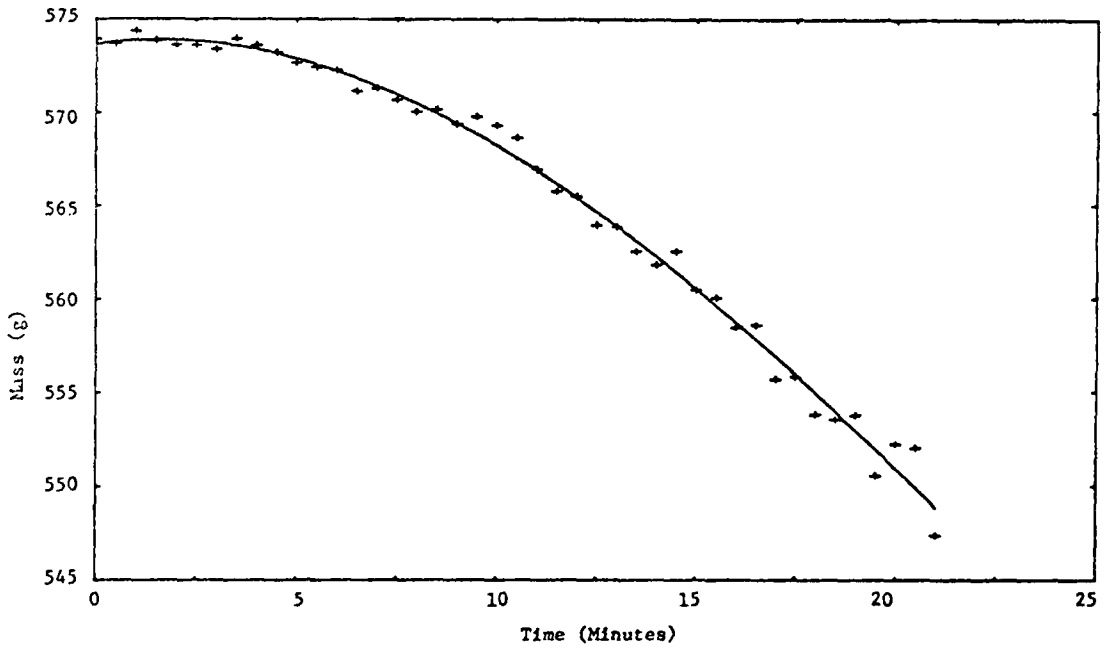

(b)

Figure 9 Response of single-layer yellow cake in Bi-Radiant Oven IV-A: (a) temperatures at three locations measured from utensil bottom, (b) mass loss. Power settings 809W (upper) and 46 W (lower).

are represented in Figure 8(b). A large gradient is evident indicating that hot stagnant air accumulates at the top of the oven.

The influence of the stagnant hot air at the top of the oven is seen in Figure 8(c) representing the cavity wall surface temperatures. At the end of the baking process, the hottest part of the oven is the top surface at a temperature of 200°C (392°F). Note that the other surfaces of the cavity walls are operating at substantially cooler temperatures. The average top and bottom wall temperatures are based upon averages of four thermocouples on each wall while the door and back results are averages of six thermocouples on each wall. The side wall curve is an average of the nine thermocouples on the right side wall. The side wall has essentially the same response as the back wall. A comparison of the center side wall thermocouples indicates that the left side was slightly warmer than the right side. A maximum difference of 5.5°C was observed at the end point. The maximum temperature difference among the four thermocouples on the top and bottom walls was observed to be 12.0 and 3.2°C, respectively, both of which occurred at the end point. The maximum vertical temperature gradients in each of the back, door, and right side walls also occurred at the end point. An area averaged vertical temperature gradient of 1.77°C/cm was observed for the back, door, and side walls at the end point. This value was calculated assuming that

the left side wall experienced the same temperature gradient as the right side wall.

Temperature and mass loss results for the cake are presented in Figures 9(a) and (b), respectively. The initial batter level (approximately 18 mm) covered the two lower thermocouples while the 30mm thermocouple was exposed to oven air until the batter rose above that level. The cake temperature response shows a reversal of the vertical temperature gradient and is in agreement with our earlier work, Marston [1]. The early positive gradient was expected because of the higher heat rates to the upper surface. The reversal of this temperature gradient appears to be caused by the evaporative cooling occuring near the upper surface. The slow temperature rise of the 15 mm probe after approximately five minutes is likely caused by the rise of cooler batter to that level. Insufficient data exists to confirm these explanations. These measurements provide a quantitative measure for doneness and an intercomparison between various oven operating conditions. Figure 9(b) shows the output of the product weighing system indicating the total mass of the cake and utensil. The curve is a least-squares cubic fit of the data and indicates a total mass loss of 24.8g. Mass loss data is very important information for energy balance analysis since the evaporation process is the major heat loss mechanism.

An identical series of observations were made with Bi-Radiant Oven IV-B, (diffuse walls, ϵ=0.31). For acceptable quality cakes, the upper and lower heating element power levels were 876 W and 221 W, respectively. The upper-to-lower power level ratio was 3.96 as compared to a value of 17.4 for Oven IV-A. Single-layer cake results showed that Oven IV-B reached higher overall air and wall temperatures but was more nearly isothermal than Oven IV-A. The smaller vertical gradients in Oven IV-B were due to the higher input power level to the lower element. As indicated by the higher air temperatures, the convective heat transfer to the walls was positive in both ovens except at the top wall which is heated as a consequence of its close proximity to the upper, high powered heating element. Comparison of average top wall temperature and the centerline air temperature responses shows that the top wall in Oven IV-A experienced minimal convective heat transfer with the oven air, while the convective heat transfer to the top wall in Oven IV-B was negative.

3.3.2 Efficiency Measurements

The problem of measuring the cavity thermal efficiency for conventional ovens involves three major considerations: first, quantifying the energy absorbed by a food product; second, identifying a "typical" product (mass, shape, absorptivity, initial and final temperature, etc.); and third, identifying "typical" oven operating conditions

(thermostat setting, preheat conditions, venting conditions, etc.). The U.S. Department of Energy (DOE), in conjunction with the National Bureau of Standards (NBS), has addressed the problem for conventional ovens and established a standard test block to have an initial temperature within ±2.2°C of ambient room air temperature and a final temperature rise of 130°C [2]. The oven thermostat is adjusted so that the average internal air temperature in an empty oven would be 180.5°C above ambient. This test further specified that the oven is not to be preheated.

This test is directly applicable to the Bi-Radiant Oven except for thermostat operation, therefore, oven efficiency was measured at various power settings. Table 1 gives results of these efficiency measurements for Ovens IV-A and IV-B. These values represent the ratio of the energy absorbed by the block to the energy consumed by the elements. The energy absorbed by the block is simply the product of its specific heat, mass, and temperature rise. The energy consumed by the elements was obtained by numerical integration of the input power data (approximately constant as it was for the single-layer cake results). The second, third, and fourth columns of Table 1 give the input power conditions which vary from full power at the upper element, to even power, to full power at the lower element. The fifth and sixth columns list the measured block temperature rise and time to achieve that temperature rise, respec-

Table 1 Overall Cavity Thermal Efficiency, Bi-Radiant Ovens IV-A and IV-B.

Oven	Input Power (W)			Block Temperature Rise (°C)	Test Duration (Minutes)	Efficiency (Percent)
	Upper Element	Lower Element	Total			
IV-A	413	413	826	130.7	54.0	18.24+
IV-A	449	448	897	131.0	49.0	18.55+
IV-A	325	325	650	130.2	59.0	21.15
IV-A	470	470	940	131.4	39.0	22.32
IV-A	1090	0	1090	131.5	33.5	22.42
IV-A	0	2333	2333	134.2	15.5	23.12
IV-B	478	478	956	130.7	47.5	17.92

+No insulation.

tively. Note that the first two lines of Table 1 give results for Oven IV-A without the fiberglass insulation.

Efficiency results of Table 1 show that the measured cavity efficiency was relatively insensitive to the power level and power ratio. The efficiency was, however, very sensitive to wall surface preparation. Oven IV-B had approximately a 29% lower reflectivity and a 20% lower efficiency (17.92% vs. 22.32%) than Oven IV-A.

An alternative method of evaluating the efficiency was to ratio the rate of energy absorbed by the block to the input power. This method allows the calculation of the efficiency at any point in time. Results from each oven are plotted in Figures 10(a) and (b) using this method. The rate of energy absorbed by the block was obtained by numerical differentiation of the block temperature data with respect to time represented by a fourth-order difference polynomial. The large variation in the data is due to a loss of accuracy in the numerical differentiation process. Lower efficiencies were expected early in the test when the elements were heating up. Under these conditions, the efficiency remained fairly constant after 15 minutes. The overall efficiency value, as discussed earlier, represents the time average of the instantaneous efficiency.

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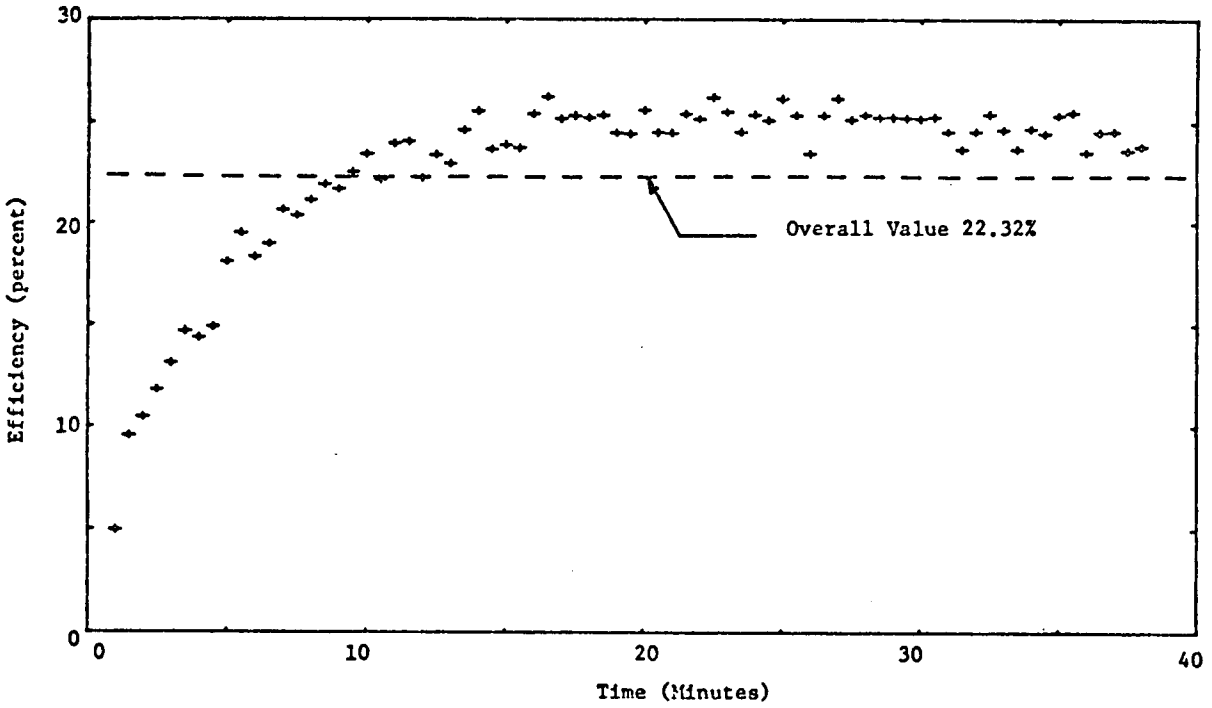

(a)

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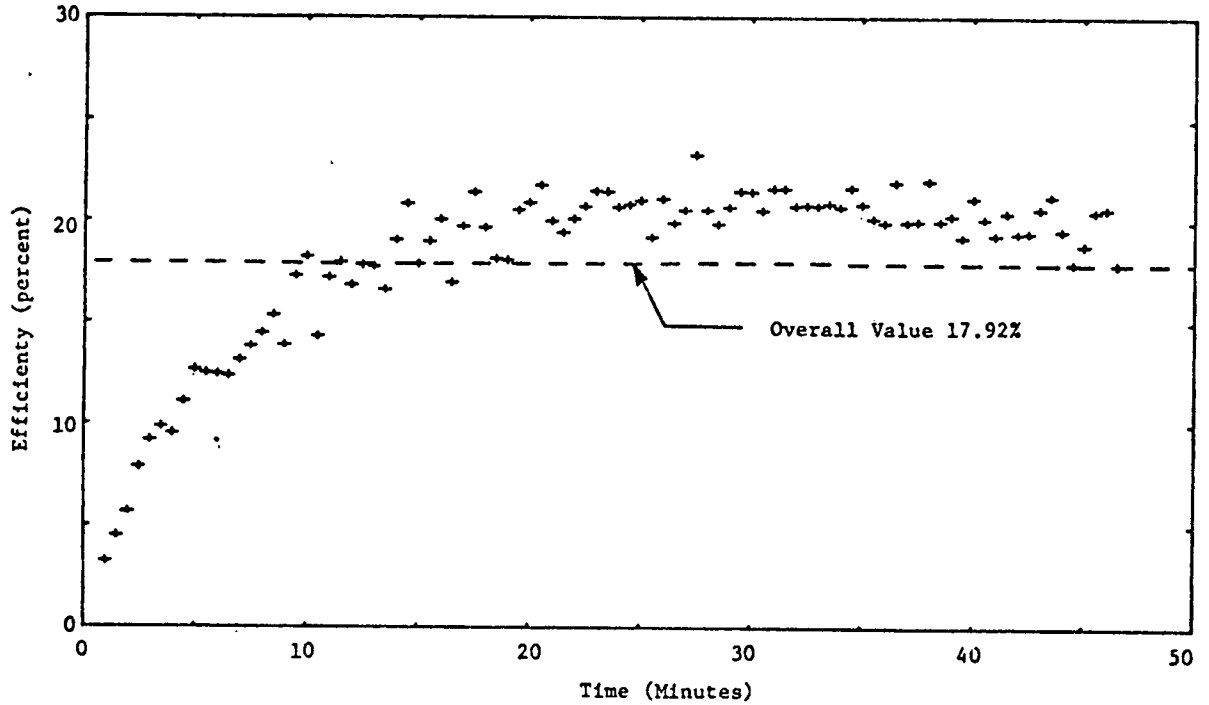


(b)

Figure 10 Cavity Thermal Efficiency by the Rate Method for Bi-Radiant Ovens (a) IV-A (940W) and (b) IV-B (956W)

3.3.3 Heat Loss Analysis

The 940 W and 956 W efficiency tests for Ovens IV-A and IV-B, respectively, Table 1, (fourth and seventh lines), were selected for an energy audit. The energy audit included both a rate method and an overall method as was done for the efficiency analysis. Stored energy in the oven components was estimated from temperature measurement. Heat lost to the environment was determined by correlating the steady-state losses of Oven IV-B at several operating points with the overall temperature difference between the outside covers and the room air. The heat absorbed by the air in the cavity was analyzed by treating the enclosure as a fixed volume, constant pressure, open, thermodynamic system.

Tables 2(a) and (b) summarize the results of the heat loss and efficiency analyses for Ovens IV-A and IV-B, respectively. Results from the rate or power analysis are presented at three times - near the beginning, middle and end of the test. Heat losses were determined for eight components. Six of these represent storage losses in each of the major oven components and block. Results tabulated for the block correspond to oven efficiency. Results tabulated for air losses correspond to the energy to raise its temperature. Loss to the surroundings represents heat lost to the environment from the outer oven structure. The values of the last row give an indication of how accurately the analysis accounted for all the input energy. The same

Table 2 Summary of Heat Loss and Efficiency Analysis for Bi-Radiant Ovens (a) IV-A (940W) and (b) IV-B (956W).

(a)

Component \ Elapsed Time (Min)	q/P_{in}^{*} (Percent) 2.0	20.0	38.0	Q/E_{in} (Percent) Overall
Block	10.45	25.59	23.85	22.32
Inner Cavity	33.70	27.89	15.55	30.49
Insulation	8.58	7.99	4.67	8.40
Rack (Single)	8.25	3.62	2.23	4.98
Cover & Support Frames	0.0	8.30	6.75	5.93
Elements	38.80	1.18	0.59	6.32
Air	1.93	0.62	0.33	0.95
Surroundings	0.91	10.63	27.91	12.08
Totals	102.62	86.02	81.88	91.47

(b)

Component \ Elapsed Time (Min)	q/P_{in}^{*} (Percent) 2.0	24.0	46.5	Q/E_{in} (Percent) Overall
Block	5.69	20.67	17.90	17.92
Inner Cavity	45.34	24.29	9.33	29.99
Insulation	11.62	7.60	3.27	8.39
Rack (Single)	6.82	3.28	1.48	4.12
Cover & Support Frames	0.0	11.89	4.85	6.89
Elements	38.72	0.80	0.23	5.18
Air	1.62	0.53	0.22	0.86
Surroundings	0.90	15.25	47.10	18.54
Totals	110.71	84.31	84.38	91.89

* q/P_{in} is the portion of input energy associated with the components.

numerical differentiation technique used to determine oven efficiency was also used to determine the rate of energy absorbed by various oven components. However, this technique causes a loss of accuracy and reduces the confidence with which the rate analysis can account for all the input power.

Comparison of the heat loss analyses for Ovens IV-A and IV-B from Table 2 shows a much faster temperature response of the inner cavity for Oven IV-B even though the final temperature rise was comparable to Oven IV-A. The effect of the early wall temperature response can be seen in the greater loss to the surroundings and larger storage losses in the cover and support frames for Oven IV-B. The higher wall emissivity in Oven IV-B improves the radiative coupling between the heating elements and the cavity walls causing element temperatures and storage losses to decrease (assuming identical input energy). The heat loss analyses systematically underpredicted the total input energy. A possible explanation is that the energy stored in the weighing sytem and base plate, located above the oven enclosure, was not included in the audit. No temperature data was taken for the product weighing system and thus its stored energy was neglected in the heat loss analysis.

3.4 Control System

The purpose of this study was to demonstrate the ability of a microprocessor-based controller to properly control

the input power levels (manipulated variables) to the Bi-Radiant Oven. The controlled variable is the net heat flux to the product; in contrast with a conventional oven in which the controlled variable is the cavity air temperature which is sensed directly by a thermostat. Since it is impractical to sense the net heat flux directly, an indirect approach must be taken to infer net heat flux from more easily measured parameters. A heat flux predictor algorithm using four or five measured temperatures is described. A summary is given of the performance evaluation of the controlled oven with the DOE test block and during repetitive cake baking.

3.4.1 Methodology

For surface heating, the local net heat flux at the product surface completely describes the thermal input to the product. Recognizing that the energy requirements of many products will be different on the upper and lower surfaces (due to moisture loss), the net heat fluxes at the upper and lower product surface were selected as the desired output of the controlled oven system. In using this approach, the thermal requirements of the product side surfaces are assumed to be adequately satisfied by the combined effects of the upper and lower baking environments.

In order to have a closed loop control system, the controlled variables (heat flux) must be measured or predicted

from measurable quantities. The complexity of heat flux sensors obviates the possibilities of direct measurement in favor of a predictive scheme. A suitable heat flux predictor algorithm based upon temperature data is presented in the following section.

Direct digitial control using a microprocessor provides a convenient means to implement such a predictor algorithm. Once the control variable is generated by the heat flux predictor algorithm, additional calculations must be performed to ascertain the proper control action on the manipulated variables. These additional calculations are referred to as the digital control algorithm which for our application is based upon proportional-integral (PI) action.

An overall schematic of the control system is given in Figure 11. The reference signals are the desired net heat fluxes at the upper and lower product surfaces. These parameters can vary in time and are either supplied by the user or generated by some internal device or auxiliary algorithm. The reference signals are compared to the inferred control variables (feedback signals) which were generated by the heat flux predictor algorithm. Based upon both error signals, the control algorithm specifies appropriate changes to the manipulated (or input) variables which are the input power to the upper and lower elements; the actuators act on the power supplies to achieve these changes. The product is considered as part of the controlled system because it is

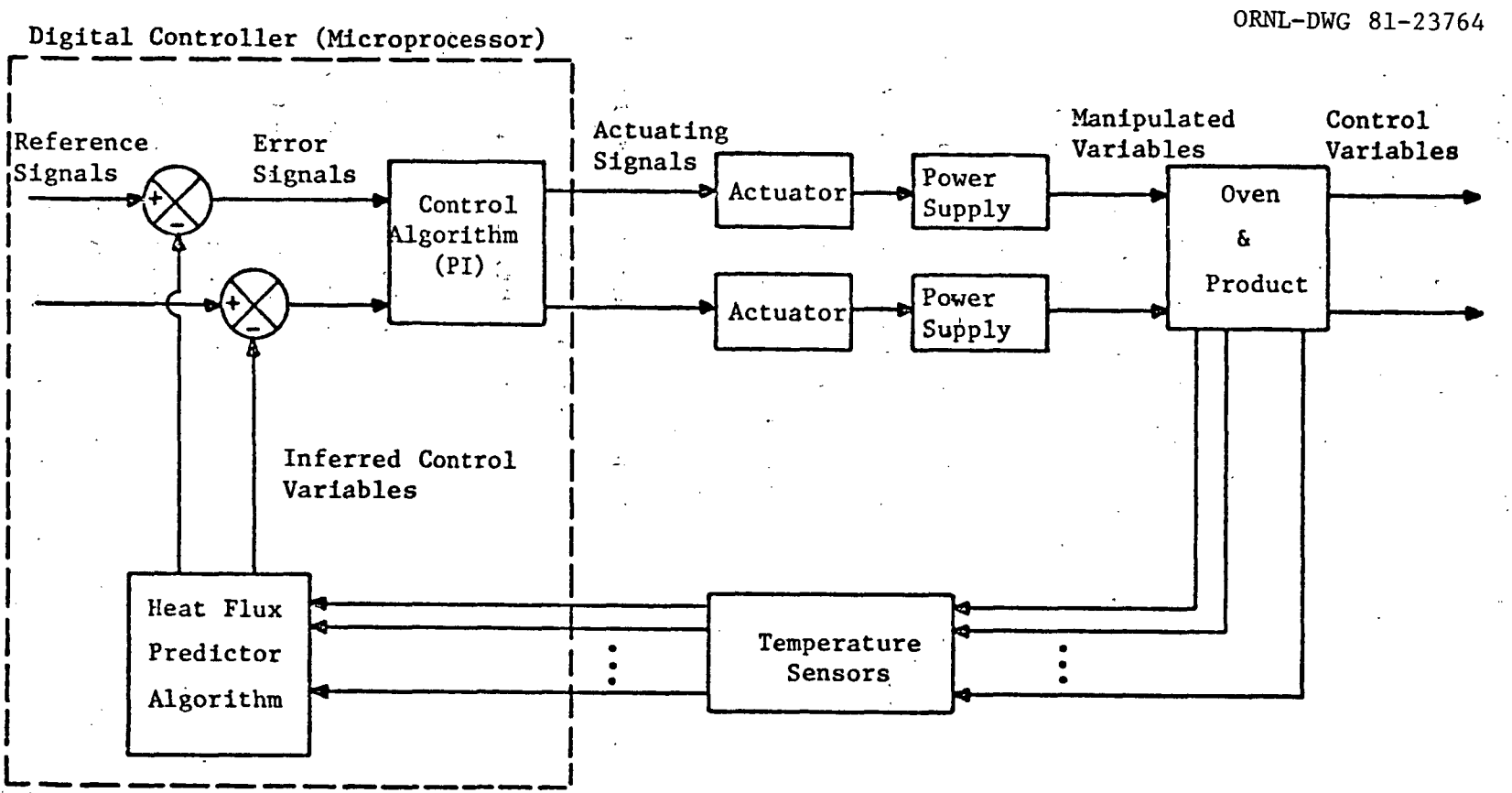


Figure 11 Schematic of the Digital Control System for the Bi-Radiant Oven.

the interaction of the oven and product which generates the output (net heat fluxes). Should the selection of various products have a major effect on the overall response of the oven, the coefficients in either or both of the control and heat flux predictor algorithms can be modified to obtain satisfactory control performance. A limited number of temperature sensors provides information to the heat flux predictor algorithm about the the temperature response of the major heat sources (elements, walls, and air).

3.4.2 Heat Flux Predictor Algorithm

The purpose of the heat flux predictor algorithm is to predict the net heat flux at the upper and lower surfaces of a food product from measured temperatures on various parts of the oven and/or product. The analytical development given in Appendix E of Part 2 results in an algorithm of this form for both upper and lower surfaces

$$q''_{net} = aT_{le}^4 + bT_{ue}^4 + cT_{wall}^4 + dT_{rod}^4 + h(T_{air} - T_{rod})$$

where a,b,c,d are constants determined from the analysis and h is the convective heat transfer coefficient. The first four terms represent radiative processes from the lower element (le), upper element (ue), wall (wall) and product (prod); the last term represents the convection process. The algorithm identifies the five temperatures which influ-

ence the baking process.

Experimental verification of the heat flux predictor algorithm was undertaken using the heat flux gage to obtain direct flux measurements. Comparison of the predicted with the measured heat fluxes for the upper surface was quite good, within the uncertainty limits of the individual fluxes. However, for the lower surface, the disparity is more evident probably as a consequence of erratic convection phenomenon on the lower side of the heat flux gage. Overall, the agreement was sufficiently good that the predictor algorithm could be expected to perform satisfactorily for all operating conditions.

3.4.3 Performance Evaluation

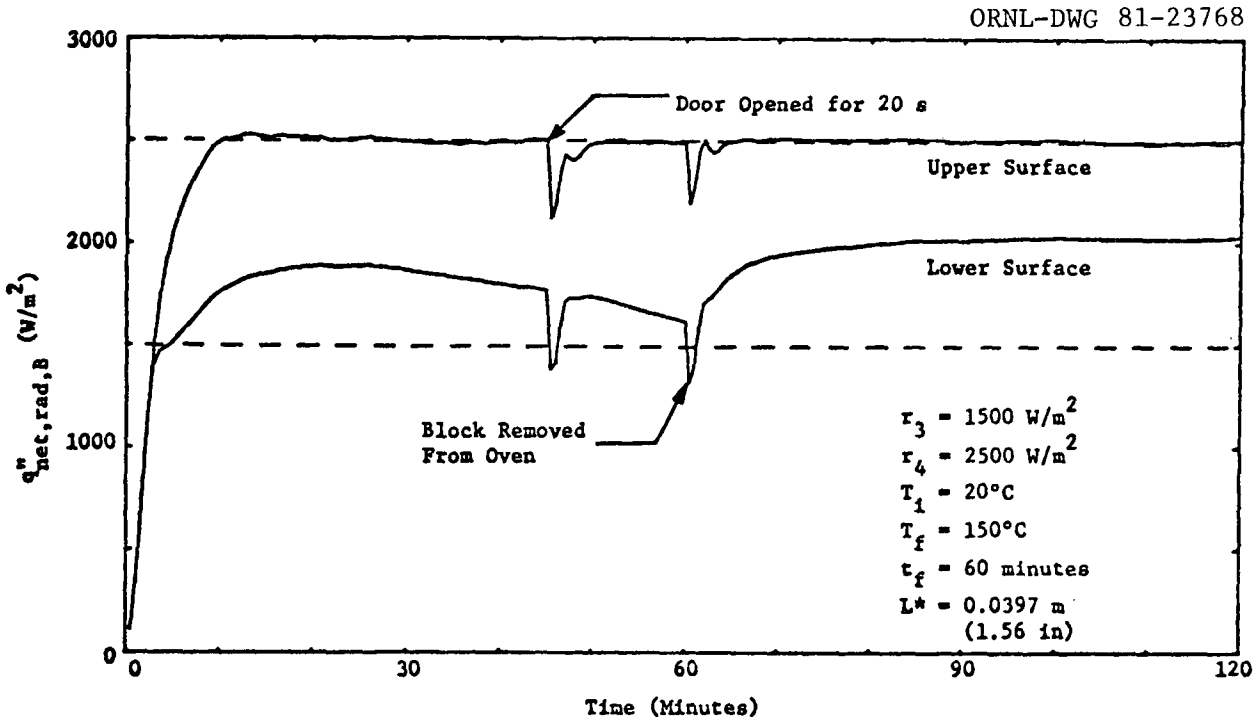
In order to evaluate the performance of the control system the control algorithm and the heat flux predictor algorithm were implemented into the software of the data acquisition system. The calculator served as the digital controller of Figure 11. The calculator was programmed to print out the input power in terms of the voltage output of the watt transducers. The powerstats were manually adjusted until the output of the watt transducers matched the print out from the calculator.

Two major tests were run to demonstrate the ability of the control system to handle both thermal transients at cold

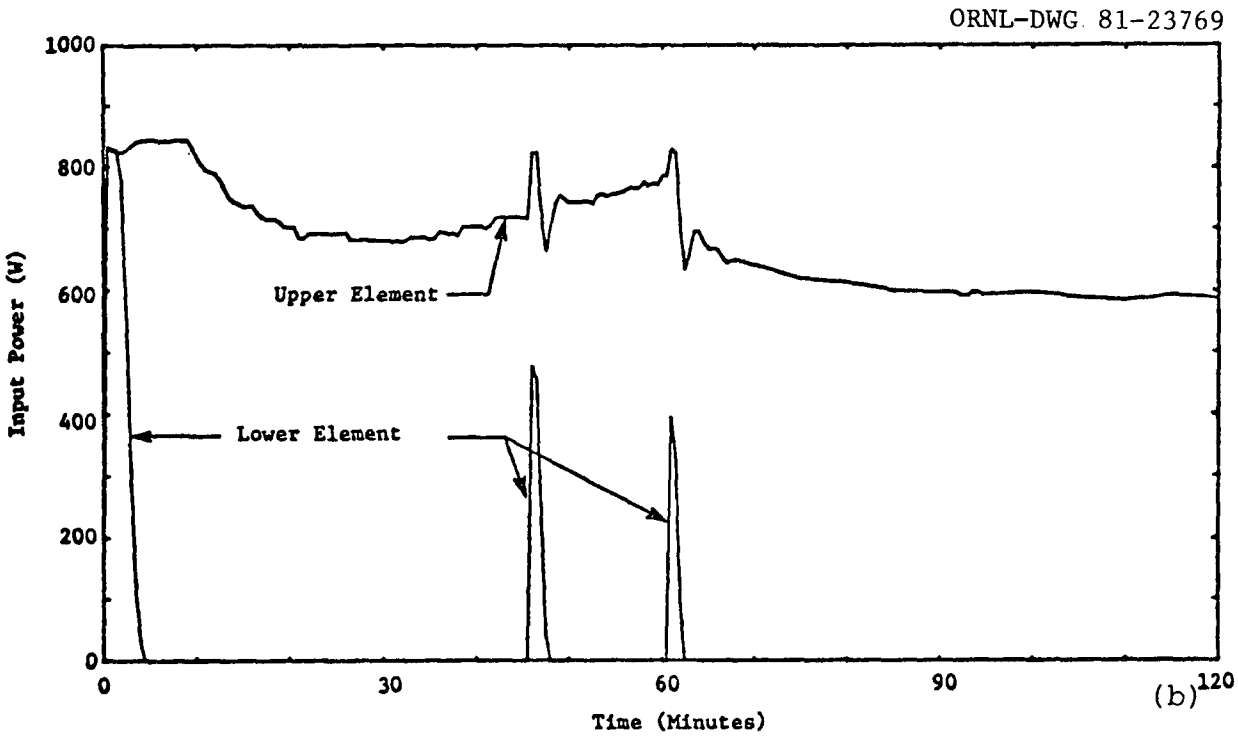
start-up and extended operation for repetitive baking, as well as, recover from a door opening and prevent overheating when the oven is accidently left on. Both the DOE test block and a series of single-layer yellow cakes were baked under controlled input power in Oven IV-B. For both of these tests a constant net heat flux was specified for lack of information concerning desirable heat fluxes to food products. The coefficients of the heat flux predictor algorithm were calculated using procedures previously described. The measured temperatures in the heat flux predictor algorithm were those of the elements (average of two thermocouples per element), wall (area average of 20 thermocouples) and cavity air (average of two thermocouples near the center. Since practical operation of the oven will generally prohibit the use of a product temperature sensor, the product temperatures -- required in the heat flux predictor algorithm -- was predicted from an auxiliary algorithm (linear response) based upon user supplied input data (initial and final product temperature and baking time). The final temperature also serves as a maximum temperature limit preventing the controller from creating a runaway condition. In addition the heat flux predictor algorithm needs the characteristic length of the product in order to estimate convection coefficient.

3.4.4 DOE Test Block Results

Results from the controlled baking test using the DOE test block are presented in Figures 12(a) and (b). The oven and block were initially at room temperature. The output of the heat flux predictor algorithm during the test is plotted in Figure 12(a). The user-specified inputs are listed where r_3 and r_4 are the desired net heat fluxes at the lower and upper product surfaces, respectively, and are plotted as dashed lines. Start-up was initiated by the step change in these parameters which caused the input power to both elements to switch to their full power condition, see Figure 12(b). As the net heat flux on the lower surface approached its set point the power to the lower element decreased. The set point value for the lower surface was maintained for the short period until the lower power was switched off. At this point the controller reached a physical constraint in the manipulated variable and the set point could no longer be maintained. This phenomenon demonstrates the limitation of the Bi-Radiant Oven to generate large disparities in the net heat fluxes to the upper and lower surfaces of products. After this point, essentially 100% of the input power went to the upper element. The lower element was reactivated only during the recovery periods after the door was opened for 20 seconds at a elapsed time of 45 minutes and at 60 minutes to remove the block from the oven. After the initial transient the net heat flux at the upper surface



(a)



(b)

Figure 12 Bi-Radiant Oven Controller Response with DOE Test Block Load: (a) Heat Flux Predictor Algorithm Output - Net Heat Flux at the Upper and Lower Block Surfaces and (b) Input Power to the Elements.

closely followed its set point and quickly recovered from the door and product removal disturbances. The oven was left on for an hour after the block was removed to demonstrate the overheat and runaway prevention capability of the control system. Note that once the block was removed, less power was needed to maintain the same baking environment.

3.4.6 Single-Layer Yellow Cakes

A series of three single-layer yellow cakes were baked successively for the purpose of demonstrating that the control system could maintain a suitable baking environment for repetitive baking.

The desired net heat fluxes were selected to be 1800 and 2500 W/m^2 on the lower and upper surfaces, respectively. When a new cake was inserted, the product temperature algorithm was reinitialized to calculate the elapsed time from the next data scan. The baking time of the three successive cakes were 21.7, 18.1, and 20.4 minutes, respectively. These values are based on a minimum done temperature (as measured by the three cake thermocouples) of 93° C. All three cakes were of satisfactory quality with the second cake having a darker appearance than the other two.

The output of the heat flux predictor algorithm during the repetitive cake tests is plotted in Figure 13(a). Again the user-specified inputs are listed with the figure and the

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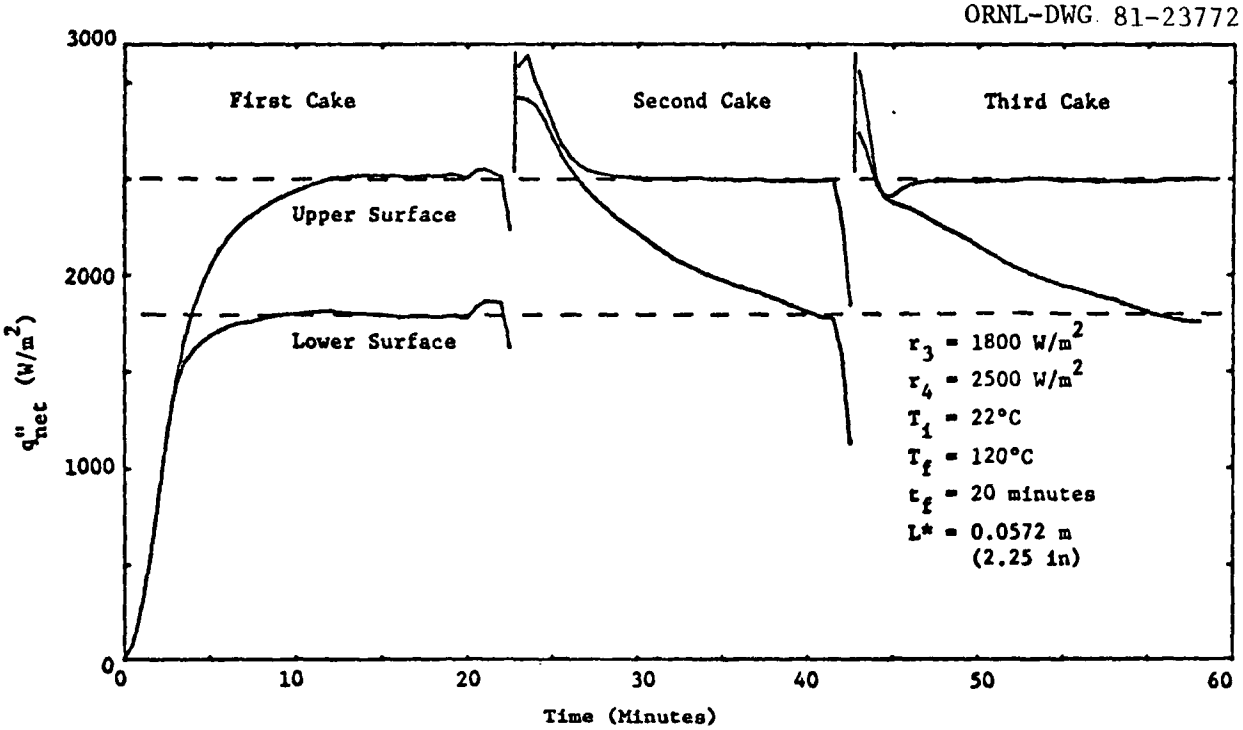

(a)

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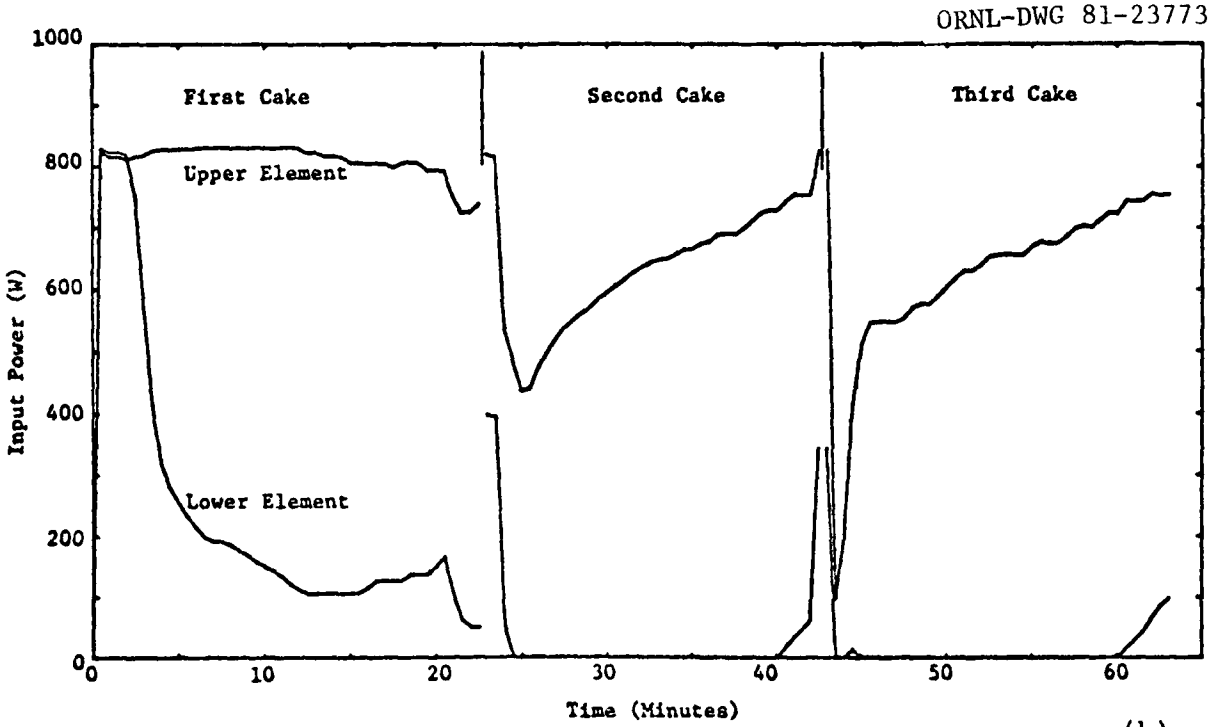

(b)

Figure 13 Bi-Radiant Oven Controller Response with Repetitive Cake Baking: (a) Heat Flux Predictor Algorithm Output--Net Heat Flux at the Upper and Lower Product Surfaces and (b) Input Power to the Elements.

set points are indicated by dashed lines. The abscissa represents the actual elapsed time from cold startup. As with the DOE test block, the controller initially switched both elements on at full power as shown in Figure 13(b). The upper element remained at full power for approximatey 12 minutes until the net heat flux approached its set point. The apparent disturbance in the net heat fluxes at 20 minutes was caused by the product temperature predictor algorithm reaching its estimated done time, thus causing the predicted product temperature to remain at the final value of 120°C. The decrease in the net heat fluxes at 22 minutes was caused by the opening of the door. When the controller sensed this decrease, the input power to both elements was increased. By the next data scan, the second cake was in place and the net heat fluxes drastically increases because of the lower product temperature. This caused the input power to the lower element to be switched off and the upper element to be greatly reduced. The lower element remained off until late into the baking period when the net heat flux had reached its set point. Again the decrease in the net heat fluxes at 41.5 minutes was caused by the opening of the door. The response of the third cake was similar to the second cake except that the net heat flux at the upper surface recovered faster. This faster recovery was caused by a greater reduction in the input power to the upper element as shown in Figure 13(b). The greater reduction in the input power occurred because of the lower net heat fluxes at the

end of the second cake, causing the controller to sense a much faster increase in the (apparent) net heat flux and thus take more drastic control action.

Further study of the controller response involved a sensitivity analysis on the individual terms of the heat flux predictor algorithm for the purpose of recognizing the effect each has on the net heat flux.

4.0 FOOD HEATING REQUIREMENTS

The objectives of the research activities by the Equipment Laboratory relate to food heating requirements for acceptable quality baked and roasted products. During Phase 1 of the project, work was directed toward developing an understanding of the food heating process. The major conclusions of the first year's work were: that excellent quality baked foods can be produced by irradiation only; that the upper and lower surface of foods require different heat absorption rates; that the ratio of upper-to-lower irradiation for heat absorption rates is different for different foods; that the ratio of upper-to-lower irradiation rates can be controlled by setting the operating wattage level of the upper and lower heating elements. It was established that the Bi-Radiant Oven uses less than half as much energy as a conventional oven in preparing the same baked and roasted foods. Energy balance analyses were made to assess how the heat that is absorbed during baking is

partitioned among the product being baked, moisture losses that occur during baking and the baking utensil.

In Phase 2 of the project, the work has been directed toward two objectives: food categorization and utensil effects. Foods have been categorized into groups that require common sets of upper and lower irradiation rates so that controls can be developed to meet the baking requirements of all foods. Size, capacity for absorbing and holding heat and thermal emissivity for each utensil requires special consideration in the selection of the upper and lower element wattages. A summary of these topics follows.

4.1 Description of Ovens and Measuring Devices

Bi-Radiant Oven III was used for all of the Phase 2 research in the Equipment Laboratory except for a study on the sensitivity of cakes to variations in irradiation. Descriptions of Bi-Radiant Ovens II and III appear in Table 3. They are similar but not identical in size and shape. The interior of Oven III was slightly more highly polished. The elements of Oven III cover a larger area and the elements are located closer to the oven top and bottom than were the elements in Oven II. The distances between the elements and the baking rack were different for each oven as well. There is no reason to believe that either of the oven designs is optimum as to the combination of baking performance and energy conservation. Both, however, do provide irradiation levels that produce acceptable baked foods and

Table 3
Description of Experimental Ovens

	Bi-Radiant Oven II	Bi-Radiant Oven III
Interior		
Dimensions		
Width	54.6 cm	58 cm
Height	40.7 cm	42.8 cm
Depth	48.4 cm	42.5 cm
Material	Aluminum Sheeting	Aluminum Sheeting
Finish	"as received"	Mechanically Polishe
Thickness	0.81 mm	0.8
Element		
Configuration	2 Loop	3 Loop
Area Covered	19.5 x 18.4 cm	35.3 x 30.3 cm
Diameter	0.6 cm	0.6 cm
Resistance	13 ohms	19 ohms
Distance from Oven Top and Oven Bottom	4.20 cm	2.5 cm
Baking Rack		
Distance from Top Element	23.5 cm	19.5 cm
Distance from Bottom Element	7.5 cm	17.5 cm

both are energy conserving relative to conventional oven design.

During the first phase, baking was done with a partitioning shelf in Bi-Radiant Oven III. During Phase 2, the full oven cavity was used.

The same set of controls was used for each of the two ovens. Auto transformers equipped with voltmeters were used to set the elements to the desired settings. Energy use was measured separately for each element. Temperatures of foods being baked and of the oven were also measured. Irradiation incident on the upper and lower baking planes were estimated from measurements made with a Irradiation Heat Flux Gauge [3] in the variety of utensils used for baking. Figure 14 displays an example of the millivolt output of the irradiation heat flux gauge for upper and lower surface irradiation levels over the initial 15 minute "oven on" period. The irradiation levels used in this report were calculated from an average millivolt output at 10 and 15 minutes.

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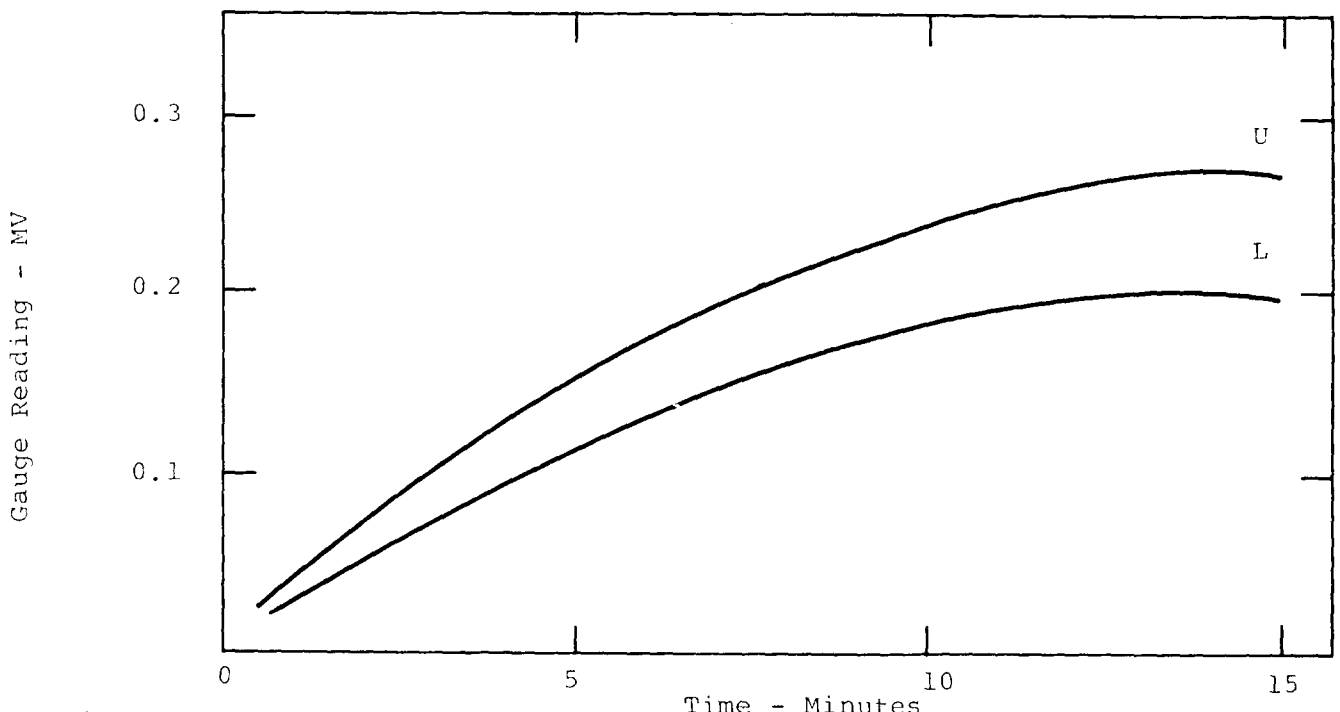


Figure 14 Gauge Response to Irradiation on the Upper and Lower Baking Planes at Upper and Lower Element Settings of 526W and 336W respectively. Bi-Radiant Oven III.

4.2 Experimental Procedures for Baking Foods

Yellow cake is a good product for evaluating irradiation levels in a Bi-Radiant Oven since the baking process must be carefully controlled to permit the activity of leavening agents, the denaturation of protein and the gelatinazation of starches to occur in proper sequence. Browning of the upper and lower surfaces of the cake occurs during the final period of the baking process.

A yellow cake mix was used for all cake tests reported. Four hundred grams of batter prepared by standardized procedures was used in 22.8 cm (9 in) diameter pans. The amount of batter was adjusted to provide the same depth when using 20.3cm (8 in) diameter pans. Cakes were weighed within five minutes of removal from the oven to measure moisture loss during baking. Additionally volume, texture and browning were evaluated based upon three replications for each tests. Nine thermocouples mounted within three vertical capillary tubes (3 per tube) permitted measuring temperatures at three radial positions: center, mid span (3.8 cm from pan edge and near the edge), and at three elevations in the cake (0.5, 1.6 and 3.2 cm from the bottom).

After irradiation levels had been established to simulate conventional oven baking results at common thermostat settings for various foods, detailed studies were performed.

Acceptability of baked products was determined by evaluating a combination of browning for both the upper and lower surfaces and thermal setting of ingredients in the center of the food or reaching an acceptable internal serving temperature.

4.3 Irradiation Levels for Baking

Because foods baked during the Phase 1 experiments did not fall into logical groups to be baked with common settings of the elements, various characteristics of foods were studied to determine how each might contribute to baking requirements of any food. The characteristics of the foods that were studied included the mass, specific heat, temperature change to produce a done product, the penetration depth or thickness of the food, moisture content, fat content and density. Also investigated were various utensil characteristics such as emissivity, mass, specific heat and size. The important factors appeared to deal primarily with the baking utensil. This is logical since some of the same utensil characteristics affect baking rates in a conventional oven. Looking at baking results, alterations had been made in early tests when utensils used had different emissivities or a greater heat holding capacity due to a greater mass. Additionally, the area covered by the utensil contributed to a need to adjust the element settings to produce the best foods. With these factors in mind, foods were

categorized into groups that require common thermostat settings for conventional oven baking.

Many foods are quite tolerant different baking rates if the rate of heat tranfer to the upper surface is properly balanced with the rate to the bottom surface. However, many leavened foods and meats are less tolerant of the baking rate. Because of tolerance to baking rate differences, it seems important to accept the baking times used by a conventional oven as standards for Bi-Radiant Oven baking. This would allow Bi-Radiant baking rates to correspond to the conventional oven thermostat settings. Once adaptations to accomodate various baking utensil characteristics have been defined, a Bi-Radiant Oven with solid state controls can be designed to provide the appropriate upper and lower irradiation rates to give optimum baking results.

4.3.1 Irradiation Levels for Cakes

Many foods, including cakes, are baked at 177°C (350°F) thermostat setting. Settings providing upper (U) and lower (L) irradiation levels of 2500 and 2000W/m^2 , respectively, produced acceptable cakes in the partitioned cavity form of Bi-Radiant Oven III (Phase 1). Higher irradiation levels, 3530/2020 W/m^2 (U/L), were required with the full-sized cavity. For Bi-Radiant Oven II, recommended irradiation levels were 3370/2410 W/m^2 (U/L). For the latter oven conditions, cakes baked to a minimum temperature of about 88°C in the

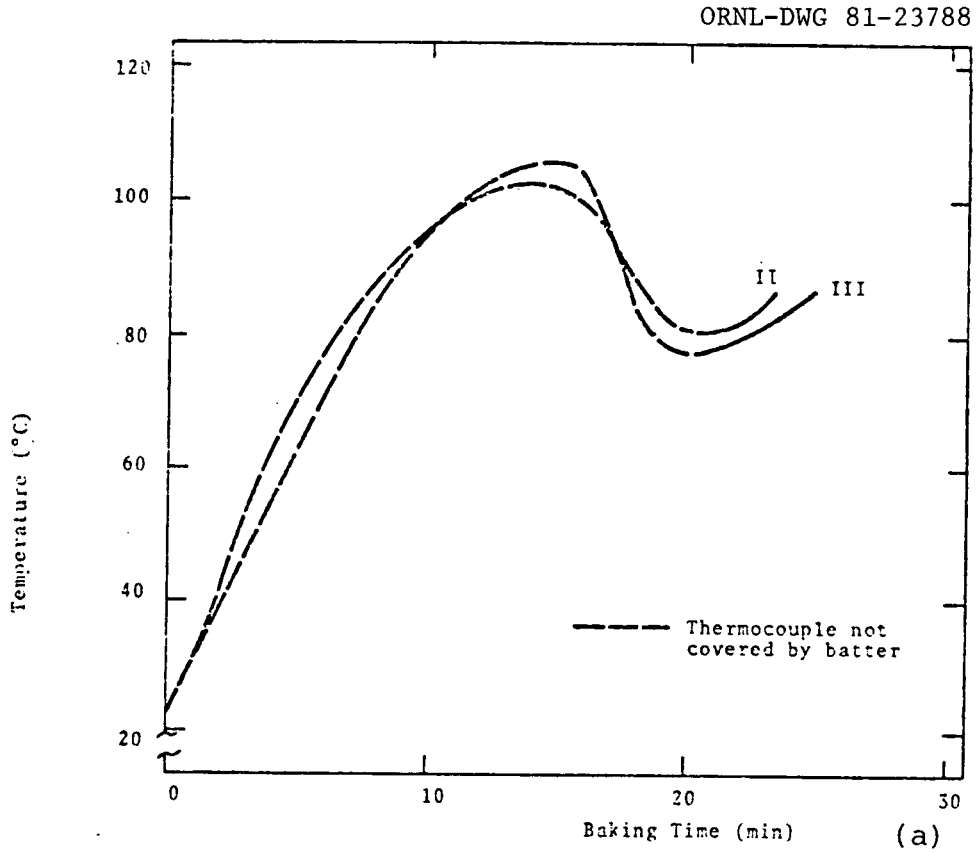
same length of time; the bottom crusts were very light in color and did not reach 100°C in either case (see Figure 15).

The ratio of upper-to-lower irradiations levels was reduced to about 1.3 to 1 and cakes were baked at two additional sets of irradiation rates: 3690/2930 W/m^2 and 3070/2330 W/m^2 (see Figure 16). Again cakes were baked to an internal temperature of about 88°C. Cakes baked at the higher U/L irradiation rates baked in 19.5 minutes and in 26.9 minutes at the lower rates. The temperatures of the center bottom of the cakes were both above 100°C for a long enough period for an acceptable degree of browning to occur.

Since the baking time of cakes baked at 3070/2330 W/m^2 more closely matched the conventional baking time of 30 minutes, it was selected as the normal setting for foods that are accommodated by a 177°C (350°F) conventional oven thermostat setting.

4.3.2 Accommodating All Conventional Oven Thermostat Settings

The progression of upper and lower irradiation levels to match conventional oven thermostat settings from 163°C (325°F) to 232°C (450°F) are shown in Figure 17. Table 4 shows the voltage and power settings of the upper and lower (U/L) elements that were required to produce each of the six baking rates. Only two voltage levels were required for the upper element setting, but cavity wall reflections in the



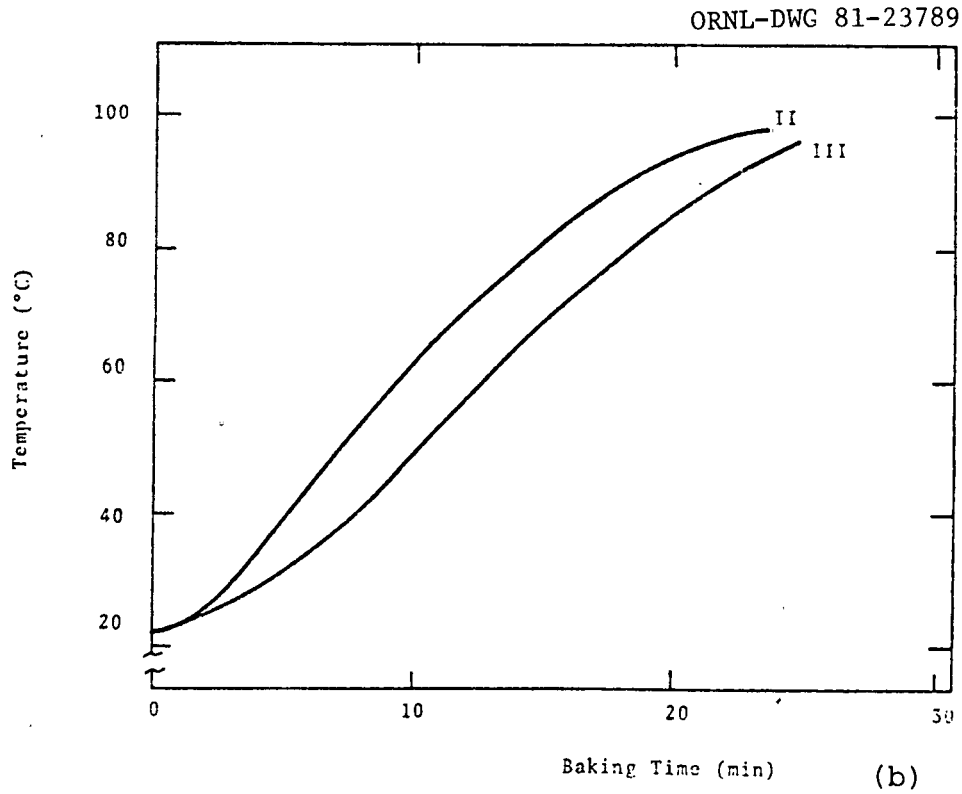


Figure 15. Comparison of Cake Temperatures at Irradiation Levels (U/L) of 3370/2410 W/m^2 in Oven II and and 3530/2200 W/m^2 in Oven III: (a) Center Top and (b) Center Bottom Thermocouple Positions.

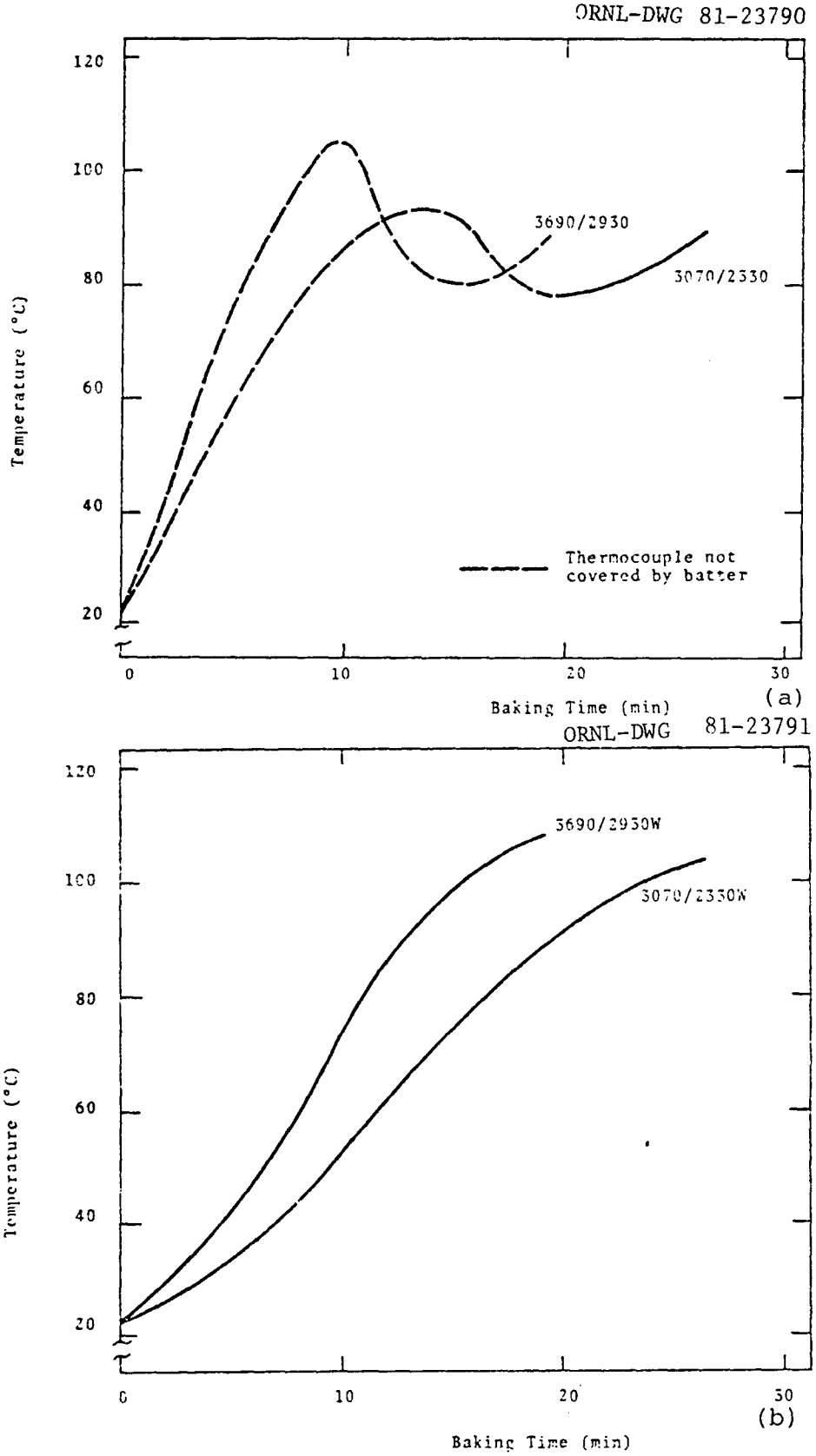


Figure 16. Comparison of Cake Temperatures at Irradiation Levels (U/L) of 3690/2930 and 3070/2330 W/m^2 in Oven III: (a) Center Top and (b) Center Bottom Thermocouple Positions.

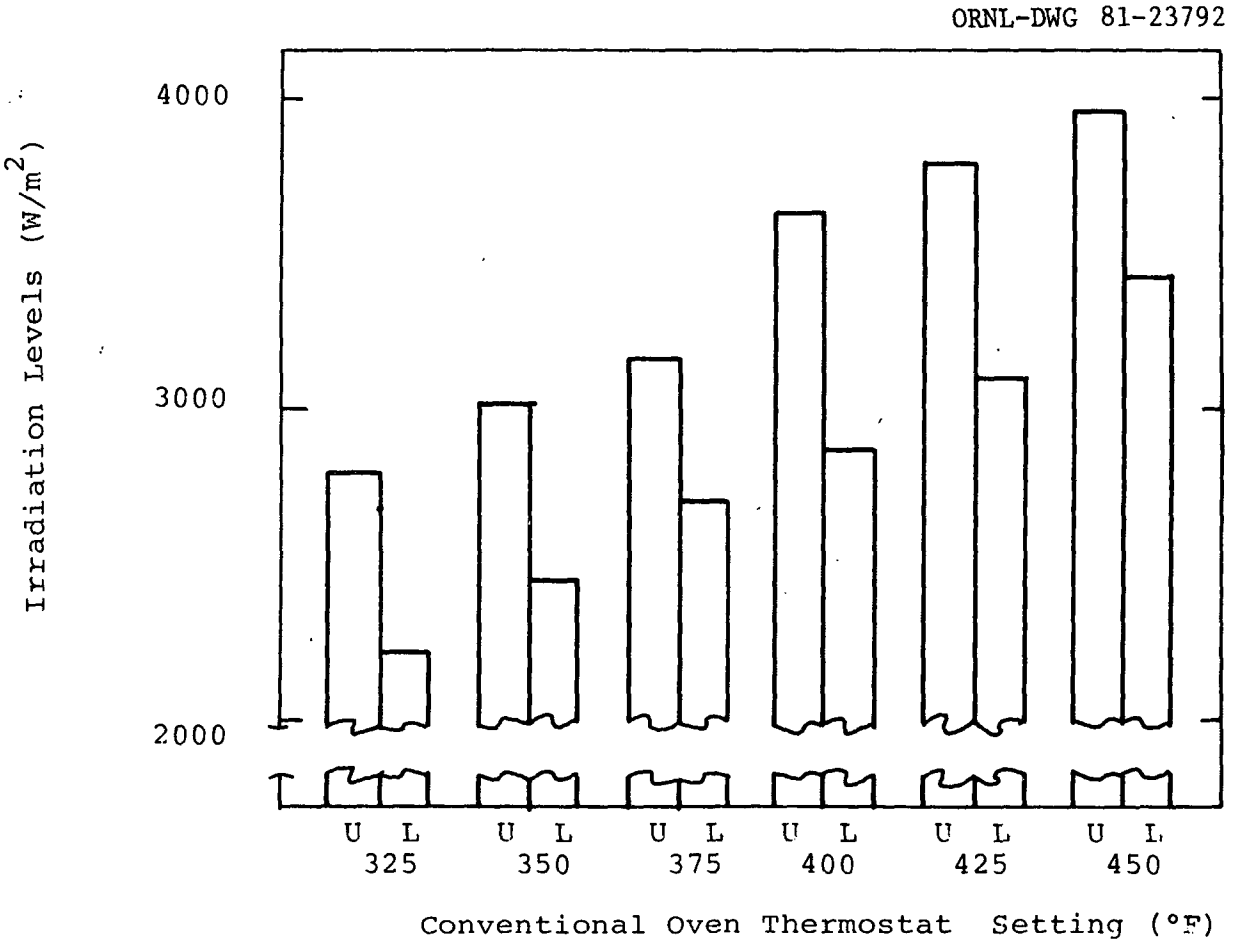


Figure 17 Bi-Radiant Oven Upper (U) and Lower (L) Irradiation Levels that Correspond to Conventional Oven Thermostat Settings.

Table 4
Bi-Radiant Oven Settings Used for Various Conventional Oven Thermostat Settings. Bi-Radiant Oven III

Conventional Oven Thermostat Setting °C (°F)	Element Voltage V U/L	Element Wattage W U/L	Baking Surface Irradiation W/m² U	L
163 (325)	100/70	526/257	2880	2210
177 (350)	100/80	526/336	3010	2430
191 (375)	100/90	526/426	3150	2680
204 (400)	110/90	636/426	3610	2840
218 (425)	110/100	636/526	3770	3110
232 (450)	110/110	636/636	3950	3420

oven from the lower element increased irradiation levels on both the upper and lower baking planes as the voltage for this element was increased from setting to setting.

A multiple regression analysis was performed to determine the relationship between the upper/lower irradiation levels and element voltages. Details of the analysis and the results are discussed in a separate report [6].

4.4 Results of Baking a Wide Variety of Foods

To demonstrate the adequacy of the upper and lower irradiation levels to accomodate the broad spectrum of foods normally baked in an oven, each of the settings shown in Table 4 was used. Previously all foods that had been tried could be baked successfully in either Bi-Radiant Oven II or III. Now an attempt was being made to categorize foods into logical groups that might each be accommodated in a Bi-Radiant Oven by similar upper and lower element settings. Table 5(a) shows a number of foods that baked well in their prescribed categories. Meats which require a slow oven 163°C (325°F), all baked or roasted well in a time about the equivalent of conventional baking or roasting. For conventional oven roasting, the use of a rack is recommended in roasting pans that are very absorptive. Placing a meat in contact with the bottom of an absorptive utensil in a conventional oven results in overcooking and often charring of the lower surface of the meat. The quality of the roast

Element Setting U/L Volts	Watts	Food	Baking Time hr.	min.
100/70 (325°F)*	526/257	Ham 2.9 kg	2	24
		Turkey 5.2 kg	3	35
		Chicken & Dressing 1.5 kg	1	26
		Rolled Rib Roast 2.4 kg	2	18
100/80 (350°F)	526/336	Lasagna		43
		Fish		31
		Yeast Bread		30
		Brownies		34
100/90 (375°F)	526/426	Angel Food Cake		30
110/90 (400°F)	636/426	Muffins		23
		Cream Puffs		30
		Baked Potatoes		60

*Conventional Oven Thermostat Setting Equivalent

(a)

Element Setting U/L	Food	Result	Solution
100/80 (350°F)*	Meat Loaf	Cooked too fast	Check utensil size
	Macaroni and Cheese	Took too long	Check utensil material
100/90 (375°F)	Yeast Rolls	Took too long	Check utensil size
	Chocolate Chip Cookies	Took too long	Check utensil size and short time
110/90 (400°F)	Quiche**	Bottom soggy	Check material
110/100 (425°F)	Blueberry Pie**	Bottom soggy	Check utensil material
110/110 (450°F)	Biscuits	Took too long	Check utensil size and short time
	Pizza	Took too long	Check material and size

*Conventional oven thermostat setting equipment.
**Some shielding of the edge crust with foil is needed to control browning of edge.

(b)

Table 5 Baking of Foods that (a) Follow and (b) Do Not Follow the Prescribed Upper (U) and Lower (L) Element Settings in Bi-Radiant Oven III.

will be poor. In the Bi-Radiant Oven a rack is not used for roasting. Contact of meat and the roasting pan will not result in overcooking since the rate of heat transfer can be controlled at a lower, more appropriate irradiation level.

The setting (100/80V) that corresponded to a 177°C (350°F) thermostant setting for a conventional oven produced lasagna, baked fish, a yeast sweet bread and brownies of excellent quality within a normal baking time. This setting, as discussed earlier, bakes cakes well also. Other products that baked well at the anticipated settings and times were angel food cake, muffins, cream puffs and baked potatoes. The foods in this group bake best in a conventional oven in reflective utensils and in the Bi-Radiant Oven in an abosrptive utensil. There seems to be a natural transfer between controlling the baking process if the change from a conventional oven to a Bi-Radiant Oven is accompanied by a change from a reflective to an absorptive baking utensil.

4.5 Important Factors in Determining Oven Settings

A second group of foods did not bake well at the prescribed settings (Table 5(b)). One of four factors, discussed in this section, seemed to be involved: a short baking time, the utensil size, the utensil emissivity, and utensil mass.

4.5.1 Short Baking Times

Biscuits and cookies which bake conventionally in a short time required 5 to 8 minutes longer in Bi-Radiant Oven III. Since the Bi-Radiant Oven isn't preheated, irradiation does not level off until 15 minutes or so. When four batches of cookies were baked consecutively, the first batch took 19.5 minutes. Subsequent batches took about 10 to 12 minutes. The control system developed by the Heat Transfer Laboratory would be able to deal with this situation.

4.5.2 Utensil Size

Utensil size influences the distribution of radiation in an oven. The loaf pan (12.7 by 20.3 cm) used for baking meat loaf covered a relatively small area, 257.8 cm^2 ; the lasagna pan (24.8 by 35.2 cm) covered 873 cm^2 and a cookie sheet (28.4 by 39.4 cm) covered 1119 cm^2.

To study the effects of utensil size on the radiant heat transfer in Bi-Radiant Oven III, irradiation measurements were made on the upper and lower surfaces of utensils of two additional sizes and for several combinations of upper and lower element wattages. Regression models were derived for two additional utensil sizes. The results of the models show that utensil size affects (by changing view factors) reflection of thermal radiation from the lower element to the upper surface of a food and from the upper ele-

ment to the lower surface of the utensil in which the foods is being baked. Thus, utensil size must be taken into account when designing oven controls.

The power required to produce the same irradiation levels in the upper and lower food surfaces determined for the three utensil sizes are shown in Table 6.

4.5.3 Utensil Emissivity

Foods such as filled pies and casseroles bake better with higher than normal (for cake) heat transfer rates to the utensil bottom. In a conventional oven, this is accomplished by using an absorptive utensil. When such foods are baked in a Bi-Radiant Oven, the heat transfer to the lower surface will be too slow, even in a utensil with a high emissivity, unless an adjustment is made to compensate for the difference between both radiation and convection which are experienced in a conventional oven and the radiation only that is experienced in the Bi-Radiant Oven.

Foods in Table 5(b) which did not bake well with the elements set as prescribed for their category were macaroni and cheese, quiche and blueberry pie. Following some experimentation, special settings were determined for these foods. For the macaroni and cheese casserole, new irradiation levels of 3150/2680 W/m^2 (199/90V) produced excellent quality (browned, thoroughly melted cheese) in 36 minutes

Table 6
Upper and Lower (U/L) Wattages Required to Produce Irradiation Levels for Baking at Six Equivalent Thermostat Settings. Baking Utensils of three sizes. Bi-Radiant Oven III

Conventional Oven Thermostat Setting °C (°F)	Prescribed Irradiation W/m^2	Utensil Size		
		Small W	Medium W	Large W
163 (325)	2880/2210	550/247	526/257	526/289
177 (350)	3010/2430	554/314	526/336	533/360
191 (375)	3150/2680	555/392	526/426	540/442
204 (400)	3620/2840	704/376	636/426	650/457
218 (425)	3770/3110	706/460	636/526	656/546
232 (450)	3950/3420	680/555	636/636	665/646

(compared to 48 minutes with the prescribed setting of 100/80V). Element voltage settings of 97/88V would produce irradiation levels of about 2600/2430 W/m^2 and keep baking time equal to the conventional time (45 min).

Blueberry pie baked in a black aluminum pie pan for 40 minutes in Bi-Radiant Oven III vs. 35 to 45 minutes at 218°C (426°F) in a conventional oven had an upper crust that was too dark and a soggy lower crust. Blueberry filling had not reached a bubbly stage. Upper and lower surface irradiation levels of 3770 and 3100 W/m^2 would require adjustment to 3600 and 3200 w/m^2 to balance browning of the lower crust and heating the pie interior with browning of the upper surface. This would require shifting Bi-Radiant Oven III upper and lower element voltages from 110/100V to about 104/105V.

Quiche was baked in a black pie pan for 34 minutes in Bi-Radiant Oven III at irradiation levels of 3150 and 2680 W/m^2 for the upper and lower surfaces of the quiche. These irradiation levels correspond to a 191°C (375°F) conventional oven thermostat setting. Though the baking time in the Bi-Radiant oven was shorter than the 35-45 minutes recommended for conventional oven baking, the top was browned nicely but the lower crust was undercooked and the bottom portion of the custard had a very fragile gel. It would be advisable to decrease the upper irradiation level to about 3000 W/m^2 and increase the lower irradiation level to about 2800 W/m^2. This would involve altering voltages

from 110 and 90V to about 94 and 97V for the upper and lower elements.

To summarize, baking foods in a Bi-Radiant Oven which are usually baked in a conventional oven in utensils that readily absorb thermal radiation, requires not only an absorptive utensil, but also a change in the balance of upper and lower irradiation levels.

The use of a highly reflective utensil in the Bi-Radiant Oven was also studied. When compared with absorptive utensils, it was found cakes in reflective utensils took 40% more time to bake and were of low quality - poorly developed and with very light, lower crust. Altering irradiation levels from 3010 annd 2430W/m^2 to 3050 and 3110W/m^2 for the upper and lower surfaces produced acceptable quality cakes. Voltage alterations from 100 and 80V to 90 and 110V for the upper and lower elements were required to accomplish this.

4.5.4 Utensil Mass

Some utensils made from materials such as heat-resistant glass, glass ceramic and pottery, have more mass than aluminum and therefore absorb more energy during the baking process. To demonstrate the effect of thermal mass, cakes were baked in utensils made of black steel, and heat-resistant glass. Aluminum utensils with reflective and absorptive finishes were used;

As expected, the black aluminum and black steel utensils produced done cakes in about the same time since they had approximately the same thermal capicitance. Since the thermal capacitance of the heat-resistant glass utensil is nearly five times that of the aluminum or steel, it is understandable that the baking time would be longer (30.6 min vs 26.1 min for the black aluminum utensil). An adjustment of the irradiation levels from 3010/2430 W/m^2 (the prescribed levels corresponding to the conventional 177°C thermostat setting) to 3150/2680 W/m^2 (100/90V) provides a satisfactory condition for baking in the heat-resistant glass utensil.

The mass of the baking utensil adds to the baking load in either a conventional or Bi-Radiant Oven. Using glass or glass-ceramic utensils, which have high emissivities, in a Bi-Radiant Oven for foods like cake which are normally baked in utensils with a low emissivity in a conventional oven requires compensation of upper and lower irradiation levels to accomodate the increased thermal capacity of these materials.

4.6 Other Characteristics Affecting Baking

The manner in which nonuniformities in irradiation affect a product is discussed in this section. Also, the influence of the wall condition (splatter,etc) is addressed.

4.6.1 Tolerance of Products to Uneven Irradiation

To study the effects of nonuniformities in irradiation levels, single cake layers were baked in Bi-Radiant Oven II in a centered position and in two off-centered positions--one with the cake partially extending to the right of the elements and one to the front. Irradiation levels were measured in the center, back, front, right and left areas of each cake pan position with the cake pan in the oven. The irradiation in the centered position showed radiation differences of 450 W/m^2 on the upper surface and 310 W/m^2 on the lower surface. Irradiation levels of 3340 and 2890 W/m^2 for the upper and lower surfaces produced a doe cake in 17.5 minutes. With this amount of variation in irradiation levels, cakes were still evenly baked.

The cakes baked in the right and front off-centered positions experienced greater irradiation nonuniformities than the centered cakes. Variations of more than 660 W/m^2 on either the upper or lower surface of a cake produces uneven baking within a hump in the region where the irradiation is lower. Batter on the low irradiation side of the cake became thermally set about one minute later than would be the case for a cake baked in the center position.

4.6.2 Maintaining the Oven Interior

Using normal baking procedures has produced few

spatters and spills during Bi-Radiant oven cooking. Only when an incorrect element setting was used for roasting did excessive grease spattering occur. When the oven door was opened after more than two hours of roasting there was grease running down the walls. Grease at the top of the oven had burned on. This is a stubborn problem that did not respond completely to any of a variety of cleaning procedures. A sheet of aluminum foil was trimmed to fit the top of the oven and attached with a silicone sealer. Irradiation levels were measured with spatters burned on the oven and with the foil treatment in place. The results show that the irradiation level on the upper baking surface was reduced about 6 percent and on the lower surface about 4 percent due to burned on spatters. The application of foil on the top surface of the oven cavity effectively restored the irradiation levels to that originally existing. Baking subsequent to the spattering-restoration incident proceeded with no change in results from earlier tests.

5. COMMERCIALIZATION OF THE OVEN

The technological aspects of commercialization of the Bi-Radiant Oven appear to be well in hand. The tools for analysis and design of an oven are developed; the oven thermal performances is understood; food requirements have been thoroughly identified. The merits of the new oven system include:

- o Energy Conservation. A 50% increase in efficiency of the Bi-Radiant Oven over the conventional oven can be achieved.
- o Baking capability. Separate upper/lower element power control provides more flexibility in baking and roasting.
- o Controls. The need for a microprocessor control system provides the opportunity for the user to achieve desired characteristics such as browning in products.
- o Construction. The Bi-Radiant Oven is similiar in construction to a conventional oven. Lower wall operating temperatures simplify materials selection and reduce insulation requirements.

To be sure, several important, practical concerns need to be addressed by the manufacturers including:

- o Oven lining material. A low emissivity (high reflectivity) surface, less than 0.10, is essential to achieve high efficiencies. The surface, operating at temperatures lower than those in a conventional oven, must be maintainabl
- o Oven controls. While microprocessor-based control systems are becoming more common in appliances, the need for multiple sensors (or a single elaborate one) in the Bi-Radia Oven presents a serious challenge.
- o Baking Utensils. Utensils with highly absorptive exteriors, suited for use with the Bi-Radiant Oven, are

on the market; provisioning of appropriate utensils should not be a problem.

6. SUMMARY

The objectives of this second phase of the project were to demonstrate the application of the technology to the Bi-Radiant Oven and to describe the technology to permit its transfer to the commercial sector. The three major technological problem areas--enclosure analysis, thermal performance and control, and food requirements-- have been addressed in great detail.

*The enclosure analysis study provides two computer codes essential for the rational design of the Oven. It is possible to model a Bi-Radiant Oven and conduct parametric analyses on the influence of various design features on efficiency. For example, questions on effects due to the degradation of wall surface emissivity and element location/configuration can be answered. This capability can reduce the need for cut-and-try testing and will provide a means toward optimizing a design before construction of an oven. These programs provide the appliance industry with an additional method [4] for analysis of oven performance.

The thermal performance and control study has first brought about improved understanding of the energy transfer

* Full Listings of the Programs COIL and OVENRAD are given in Reference [6].

mechanisms in the oven. Detailed measured temperature distributions in experimental ovens (component and product) have revealed the role of radiative and convective heat transfer. New instrumentation and experimental procedures developed during the project will be useful in evaluation of the conventional as well as the new oven. Energy audits on a time and overall basis have identified oven features which must be given attention in the design process. Another contribution of this study relates to the successful demonstration of a control system for operating the oven on a continuous or repetitive baking basis. While the present system is complicated by the need for four or five temperature sensors, simpler versions are likely to be possible. The methodology for devising a control strategy has been offered.

The food requirement study has provided critical information on two important aspects of oven operation. First, foods of acceptable or superior quality can be baked (in competitive times) in the oven using absorptive utensils. Second, foods can be categorized with respect to common upper/lower element settings. The user will not be faced with a bewildering selection of settings. Use of a microprocessor controller will further simplify the setting selection process.

The scope of the second phase has emphasized the technological areas. The aspects of manufacturing and marketing

of the technology are left to those having practical and consumer-related perspectives.

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