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**OAK
RIDGE
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LABORATORY**

**BI-RADIANT OVEN
A
LOW-ENERGY OVEN SYSTEM
VOLUME 1—DEVELOPMENT
AND ASSESSMENT**

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VOLUME I - DEVELOPMENT AND ASSESSMENT

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April 1980

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TABLE OF CONTENTS

	Page
PREFACE	iii
ABSTRACT	v
LIST OF FIGURES	vii
LIST OF TABLES	x
1.0 INTRODUCTION	1
1.1 Baking in the Conventional Oven	1
1.2 The Bi-Radiant Oven	2
1.3 Organization of the Report	4
2.0 INSTRUMENTATION AND BASELINE PERFORMANCE DATA	6
2.1 Description of the Experimental Facility	6
Bi-Radiant Oven III	6
Measurement Procedures	8
2.2 Oven/Product Parameters During the Baking Process	11
Heating Element Temperatures	12
Cavity Wall Temperatures	15
Cavity Air Temperatures	17
Product Cake Temperature Distribution	20
Product Mass Loss Rate	23
2.3 Preliminary Oven Efficiency Tests	23
3.0 THERMAL MODELING AND IRRADIANCE DISTRIBUTION	29
3.1 Irradiance Distribution on the Baking Plane	29
Irradiance Distribution Model I	31
Bi-Radiant Oven III	32
Comparison of Multiple-Loop Heating Elements	34
3.2 Experimental Heat Flux Observations	40
4.0 OVEN HEATING REQUIREMENTS FOR FOODS	43
4.1 Heat Absorption Rates	43
Conventional Oven Operation	43
Irradiation Measurements	44
4.2 Study on Beef Roasts	46
Procedures for Food Preparation and Measurements	46
Experimental Results	49
4.3 Study on Yellow Cakes	61
Procedures for Food Preparation and Measurements	61
Experimental Results	62

4.4	Energy Balance Analysis of the Baking Process	69
	Beef Roasts	73
	Yellow Cakes	75
	Other Selected Foods	77
4.5	Baking Rates for Assorted Foods	79
	Bi-Radiant Oven Performance	79
	Comparison of Energy Use: Conventional vs. Bi-Radiant Oven	82
5.0	CONCERNS IN COMMERCIALIZATION	84
	5.1 Production Costs	84
	5.2 Maintaining Energy Efficiency	85
	5.3 Convenience	86
	5.4 Utensils for Use in the Bi-Radiant Oven	87
6.0	PHASE 2 - APPLICATION AND TRANSFER OF THE TECHNOLOGY	90
7.0	REFERENCES	91
	APPENDIX A: STATEMENT OF WORK	92
	APPENDIX B: TEST CAKE INGREDIENTS AND PROCEDURES	94
	APPENDIX C: SAMPLE CALCULATION FOR DETERMINING SPECIFIC HEAT OF FOOD ITEMS (MEAT LOAF)	95

PREFACE

This report, prepared by the Heat Transfer Laboratory and Equipment Laboratory at Purdue University, concerns the development of the technology for a low-energy oven system, the Bi-Radiant Oven. The report covers the activities in Phase 1, Technology Development and Assessment, which is comprised of four major tasks: (1) Experimental facilities development, (2) Baseline performance data and food requirements, (3) Oven thermal modeling and (4) concerns in commercialization.

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, both MS candidates whose work with the project will constitute their thesis problems. Mr. John Hudgins, a third-year student in the School of Electrical Engineering Technology, provided technical support in the area of electronic instrumentation.

During the reporting period Professor Peart's staff included: Dr. Carolyn Garrison, visiting researcher and Assistant Professor from Brigham Young University; Charlene Hatke and Susan Petrillo, graduate students in the CFS department. Part-time student and professional technician support also participated in the project on an intermittent basis.

The second year of the project, Phase 2, will be concerned with the Application and Transfer of the Technology. The two major tasks are: (1) parametric studies including optimization of system performance based upon analytical and experimental results and evaluation of pre-prototype oven configuration(s) and (2) commercialization of the technology. A final report on

the project will be prepared at the completion of the second phase.

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.

The technical monitor for the project is Mr. William L. Cooper, Jr., Energy Division, Oak Ridge National Laboratory, Oak Ridge, TN.

ABSTRACT

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 without compromising food quality.

The Bi-Radiant Oven system has three important features which provide improved performance. First, the cavity walls are highly reflective rather than absorptive thereby allowing these surfaces to operate at cooler temperatures. Second, the heating elements, similar in construction to those in a conventional oven, but operating at much lower temperatures, provide a prescribed, balanced radiant flux to the top and bottom surfaces of the food product. And third, the baking and roasting utensil has a highly absorptive finish. These features, individually, have been utilized in conventional oven design, but never combined to give good thermal coupling between the energy source and food product.

This report covers Phase 1, Development and Assessment of the Technology. Instrumentation and methods of measurements have been developed for obtaining the important oven and food parameters during baking: wall, oven air, food and element temperatures; food mass loss rate; irradiance distribution; and convection heat flux. Observations on an experimental oven are presented and discussed. Thermal models relating the irradiance distribution to oven parameters have been compared with measurements using a new heat flux gage developed for the project. Using the DOE recommended test procedures, oven efficiencies of 20-23% have been measured; with improved design features, efficiencies above 25% appear to be possible.

The heating requirements (irradiance on upper and lower surfaces of the food) have been determined for seven food types: biscuits, meat loaf, baked foods, apple crisp, cornbread, macaroni and cheese casserole, and cheese souffle. Comparison of energy use in the Bi-Radiant Oven with a conventional electric

oven shows that energy savings greater than 50% can be realized. Detailed energy balances have been performed on two foods - beef roasts and yellow cake - in order to develop an understanding of the food and utensil energy processes during baking.

Consideration of consumer acceptability of this new oven concept have been addressed. The major concerns addressed are: production costs compared to the conventional electric oven; maintaining energy efficiency with minimum care; convenience and satisfaction; utensils; and controls.

The second phase of the project, Application and Transfer of the Technology, which began May 1980 has two major tasks. The first task relates to system design, fabrication and evaluation of engineering prototype oven configurations. The second task deals with commercialization of the technology especially as relates to developing suitable formulations (recipes) and oven heating requirements and to describing the oven system(s) for manufacture.

LIST OF FIGURES

<u>Number</u>		<u>Page</u>
1.1	Features of the Bi-Radiant Oven: preset levels of radiant flux from lower/upper heating elements; cool, reflective cavity walls; and absorptive utensil	3
2.1	Schematic of the Bi-Radiant Oven III	9
2.2	Photograph of the experimental facility for performance evaluation of Bi-Radiant Oven III	10
2.3	Heating Element Temperature Response for NORMAL Power Setting, Bi-Radiant Oven III	13
2.4	Heating Element Temperature for a Conventional Electric Range	14
2.5	Wall Temperature Response for NORMAL Power Setting, Bi-Radiant Oven III	16
2.6	Air and Wall Temperature Response for a Conventional Electric Range	18
2.7	Air Temperature Response for NORMAL Power Setting, Bi-Radiant Oven III	19
2.8	Cake Temperature Response for NORMAL Power Setting, Bi-Radiant Oven III	21
2.9	Cake Temperature Response for BOTTOM FAST Power Setting, Bi-Radiant Oven III	22
2.10	Single Layer Cake and Utensil Mass During Baking, NORMAL Power Setting	24
2.11	Comparison of Mass Loss Data for Single Layer Cakes	25
3.1	Radiation processes within the Bi-Radiant Oven	30
3.2	Irradiance distribution (a) configuration of the heating elements and (b) nondimensionalized iso-irradiance lines on the baking plane, Bi-Radiant Oven III	33
3.3	Irradiation distribution (a) configuration of the heating element and cake-pan utensil (23 cm diameter) and (b) nondimensionalized iso-irradiance lines on the utensil surface (Bi-Radiant Oven III)	35

3.4	Multiple-loop heating element configuration with (a) one, (b) two and (c) three loops	36
3.5	Irradiance distribution for the one-loop heating element configuration of Figure 3.4	37
3.6	Irradiance distribution for the two-loop element configu- ration of Figure 3.4	38
3.7	Irradiance distribution for the three-loop heating element configuration of Figure 3.4	39
3.8	Photograph of the Water-Cooled Heat Flux Gage	42
4.1	Input Power (W) of Upper (U) and Lower (L) Elements During Cooking of Semitendinosus Beef Muscle at Five Heat Rates (Bi-Radiant Oven II)	50
4.2	Irradiation (W/m^2) for Upper (U) and Lower (L) Surfaces During Cooking of Semitendinosus Beef Muscle at Five Heat Rates (Bi-Radiant Oven II)	51
4.3	Time for Cooking Semitendinosus Beef Muscle at Five Heat Rates (Bi-Radiant Oven II)	52
4.4	Total Energy Used During Cooking of Semitendinosus Beef Muscle at Five Heat Rates (Bi-Radiant Oven II)	53
4.5	Distribution of End Temperatures ($^{\circ}C$) for Semitendinosus Beef Muscle at Five Heat Rates (Bi-Radiant Oven II)	54
4.6	Temperature Changes During Cooking of Semitendinosus Beef Muscle at Five Heat Rates - Center Location (Bi-Radiant Oven II)	56
4.7	Temperature Changes During Cooking of Semitendinosus Beef Muscle with Five Heat Rates - Center Top and Center Bottom Locations (Bi-Radiant Oven II)	57
4.8	Cooking Losses by Drip and Evaporation from Semitendinosus Beef Muscle at Five Heat Rates (Bi-Radiant Oven II)	58
4.9	Temperature Changes During Cooking of Semitendinosus Beef Muscle at Five Heat Rates - Oven Air (Bi-Radiant Oven II)	59
4.10	Temperature Changes During Cooking of Semitendinosus Beef Muscle at Five Heat Rates - Oven Wall (Bi-Radiant Oven II)	60
4.11	Input Power (W) of Upper (U) and Lower (L) Elements During Cooking of Yellow Cake at Five Heat Rates (Bi-Radiant Oven III)	63
4.12	Irradiation (W/m^2) for Upper (U) and Lower (L) Surfaces of Yellow Cakes at Five Heat Rates (Bi-Radiant Oven III)	64

4.13	Time for Baking Cake at Five Heat Rates (Bi-Radiant Oven III)	65
4.14	Total Energy Used During Baking Yellow Cake at Five Heat Rates (Bi-Radiant Oven III)	66
4.15	Distribution of End Temperatures (°C) for Yellow Cake at Five Heat Rates (Bi-Radiant Oven III)	67
4.16	Moisture Losses from Yellow Cakes at Five Heat Rates (Bi-Radiant Oven III)	68
4.17	Distributions of Moisture (%) for Yellow Cakes at Five Heat Rates (Bi-Radiant Oven III)	70
4.18	Moisture Content at Start and End of Top Edge of Yellow Cakes at Five Heat Rates (Bi-Radiant Oven III)	71

LIST OF TABLES

<u>Number</u>		<u>Page</u>
2.1	Oven Thermal Efficiency, Bi-Radiant Oven III	27
4.1	Five Heat Rates for Baking or Roasting in the Bi-Radiant Oven	48
4.2	Energy Balance for Semitendinosus Beef Muscle Roasts, Bi-Radiant Oven II	74
4.3	Energy Balance for Baking Yellow Cake, Bi-Radiant Oven III	76
4.4	Energy Balance for Assorted Foods at Their Optimum Baking Rate, Bi-Radiant Oven II	78
4.5	Baking Rates - Upper/Lower - for Assorted Foods, Bi-Radiant Oven II	80
4.6	Comparison of Energy Use in a Conventional and the Bi-Radiant Oven for Baking Assorted Foods	83

LOW-ENERGY OVEN SYSTEM

Phase 1 - Technology Development and Assessment

1.0 INTRODUCTION

The goal of this project is to research, develop and promote a new 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. It is the purpose of this report to summarize activities relating to the development of the technology upon which the Bi-Radiant Oven is based. In particular, two major problem areas have been addressed. The first area deals with understanding how to efficiently couple an energy source with a food product. The second area, very much related to the first, considers the heating requirements for roasting or baking foods of acceptable quality.

1.1 Baking in the Conventional Oven

In the conventional, domestic oven, the energy source[†] operating at very high temperatures (900°C) emits radiant energy to the highly absorptive oven cavity walls which are heated and, in turn, heat the utensil/product by radiation exchange and heat the oven cavity air by convection. The utensil/product is heated by two modes: by radiative exchange with the cavity walls and by convection with the oven air. Numerous studies have been performed to show that the convection mode dominates; in some instances, ovens are designed such that direct radiation transfer from the energy source is avoided. It is known that only a small fraction of power to the heating element is transferred directly to the oven cavity air. This effect (for the bottom element) is not energetically significant but does induce convection currents within the cavity

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[†]The energy source in our work is restricted to resistance-heated elements.

that serve to increase the convection heat transfer coefficient between the oven cavity air and the utensil/product. This effect also influences the amount of air that is drawn into the oven cavity and eventually is expelled through the vent.

Erickson [1] has developed a thermal model of the domestic, electric oven which relates efficiency to various parameters including cavity dimensions, insulation, heating element area, vent flow rate, window glass area and rack height. For the baseline model, an efficiency of 13.6% is reported; this figure is in general agreement with the range of 12 to 15% observed in many ovens. Erickson concludes that if all the recommended energy improvements are implemented on oven designs, the efficiency could be increased to nearly 17%. This represents a significant energy savings and, if economically feasible without compromising food quality, would be attractive to the consumer.

1.2 The Bi-Radiant Oven

The principle of the Bi-Radiant Oven is to thermally couple the product and the energy source by the radiative heat transfer mode. This new oven concept is illustrated in Figure 1.1 which illustrates the three major features providing improved energy performance with acceptable food quality:

- (1) Two heating elements, operating at relatively low temperatures, provide the required levels of radiant flux to the top and bottom of the product; the flux levels are preset to meet food requirements; no pre-heat cycle is necessary and the heating elements may be operated under constant power,
- (2) Oven wall surfaces are highly reflective of the radiant power from the heating elements; referred to as a cold-oven wall, its function is to reflect radiant flux to the product, and

Figure 1.1 Features of the Bi-Radiant Oven: preset levels of radiant flux from lower/upper heating elements; cool, reflective cavity walls; and absorptive utensil.

- (3) Utensil surface finishes are highly absorptive of the radiant flux from the heating elements.

The technology of the Bi-Radiant Oven is based upon the power combination of features which have been utilized in various conventional oven designs. That is, the heating elements in both ovens are of the same construction; the use of reflective panels to improve uniformity of heating in conventional ovens has been practiced for years; and utensils with high radiant absorptivity have long been on the market. As a consequence, the new technology doesn't represent a radical departure from oven design and construction methods used currently by the appliance manufacturer. From a consumer-acceptance point-of-view, few demands or changes will be required (especially when compared to the microwave oven) when using this improved efficiency oven.

The Bi-Radiant Oven principle was first demonstrated in 1974 in a study directed by Professor Peart in the Equipment Laboratory at Purdue University [2]. Following this initial work, further activities resulted in the construction and evaluation of an experimental oven referred to as Bi-Radiant Oven II.[†] The results of this research are summarized in three publications [3, 4, 5] which served as the basis for a patent issued in 1979 [6]. The potential efficiency of the Bi-Radiant Oven is shown by this work to be much greater than possible with conventional ovens. The purpose then of our project is to develop the technology to the point that a commercial oven model, based upon the bi-radiant principle, can be designed and brought to market.

1.3 Organization of the Report

The project is a collaborative research activity of the Heat Transfer

---

[†] Bi-Radiant Oven II has cavity dimensions (height × width × depth) of 41 cm × 55 cm × 48 cm (16 in × 21.5 in × 19 in). The wall material is aluminum sheeting (0.81 mm thickness) with "as received" finish.

Laboratory and the Equipment Laboratory at Purdue University. The problem of developing the Bi-Radiant Oven is one requiring an integration of expertise in heat/mass transfer, in food technology, and in consumer-related matters.

The design and performance evaluation of the new oven has been the main concern of the Heat Transfer Laboratory. Sections 2.0 and 3.0 summarize the work directed toward oven/product instrumentation and baseline data. Oven thermal models have been developed for predicting irradiation distribution within the oven. The goal of this study is to generate oven models which could lead to improved designs.

The heating requirements to produce acceptable food quality has been the major concern of the Equipment Laboratory. Section 4.0 summarizes the research on determining irradiation levels to the top and bottom of selected types of foods. Detailed energy balance studies on two products - beef roast and yellow cake - are performed in order to gain understanding on the heating process. An important activity of this group has been concern for the concerns in commercialization which are discussed in Section 5.0.

Plans for the second phase - Application and Transfer of the Technology - are outlined in Section 6.0.

2.0 INSTRUMENTATION AND BASELINE PERFORMANCE DATA

An experimental facility has been developed with the capability to obtain important performance parameters of the oven and the food product during the baking process. A new oven, referred to as the Bi-Radiant Oven III, was constructed primarily to accommodate studies related to measurement techniques. The facility also includes a data acquisition system to provide for automatic collection of the various parameters and for display of the observations as well as calculated results.

In this section, the general features of the experimental facility are described and discussion given to the procedures that were developed for measuring temperatures in the oven: heating elements, cavity air and cavity walls. Also discussed are the procedures for obtaining the temperature distribution within a product and the rate of mass loss (evaporation rate) of the product as a function of baking time. The procedures relating to irradiation distributions on the baking plane are treated in Section 3.0. Observations on the Bi-Radiant Oven III are presented to illustrate typical performance of an oven based upon the bi-radiant principles. Preliminary results on the oven efficiency are discussed.

2.1 Description of the Experimental Facility

Bi-Radiant Oven III

To provide an experimental oven for use early in the project, a conventional electric oven was modified to operate on the bi-radiant heating concept. A commercial range with cavity dimensions width 58 cm $\times$ height 43 cm $\times$ depth 43 cm (23 in $\times$ 17 in $\times$ 17 in) was used as the main frame. The inner cavity and door surfaces were lined with mechanically polished, 0.8 mm (0.032 in) thick aluminum sheet having an emissivity of approximately 0.10. To reduce the

effective thermal mass of the oven, large sections of the original cavity liner were cut away such that its weight was reduced by a factor of two but yet provided sufficient support for the reflective liner. Asbestos sheeting 1.6 mm (0.062 in) thick was placed between the reflective liner and the original cavity walls to reduce thermal coupling. The vent and door seal were not modified.

An arrangement for supporting heating elements at the top and at various positions near the bottom of the cavity was devised. The elements, described in greater detail in Section 3.1, were powered by 120 V, 7.5 A Powerstats and the power was measured using watt transducers, American Aerospace Controls Model 415A-10-115. The transducers were calibrated against precision laboratory meters and were found to have better than $\pm 2\%$ full-scale accuracy in the power ranges likely to be encountered in the oven use.

Thermocouples of Type T, copper-constantan (30 gage), were installed on the reflective cavity liner at various locations in order to obtain average wall temperatures of the sides, top, bottom, back and door portions of the cavity. These thermocouples were affixed to the walls with a high-strength epoxy. For the heating elements, each leg of the thermocouple, Type K, was separately welded to the sheath which served as an intermediate metal. Special precautions were taken to temper the leads such that conduction errors would be minimized. To obtain air temperatures throughout the cavity an arrangement of the shielded thermocouples, Type T, was devised such that the entire assembly could be readily removed from the oven or its position within the oven adjusted. A total of 33 Type T thermocouples were provided for monitoring wall, vent, and air temperatures; 4 Type K thermocouples were found sufficient to monitor the heating element temperatures.

The oven, referred to as Bi-Radiant Oven III, is shown schematically in Figure 2.1 and the experimental facility illustrated in the photograph of Figure 2.2.

Preliminary tests with the oven suggested the cavity size and heater element combination was not satisfactory for obtaining quality food products. Reducing the effective cavity size was the simplest remedy and was accomplished by installing a partitioning shelf as shown in the Figures 2.1 and 2.2. This change resulted in improved quality of baked products but created a dead space which affected the temperature distribution in the lower portion of the oven. Since the primary objective of this phase of the project was to develop measurement techniques rather than configure a practical oven, experiments were performed with the partitioning shelf in the position shown.

Measurement Procedures

The mass loss (water evaporation) of a product during the baking process was determined from signal outputs of load cells which supported the oven rack suspended by cables through the top of the oven as shown in Figures 2.1 and 2.2. The load cells were dual strain gages (Micro-Measurements EA-13-125PC-120-LE) attached to the upper and lower surfaces of four 1.6 mm (0.062 in) thick cantilevered beams (aluminum alloy, 2024-T3) located at the corners of the rack. The strain gages were series connected and the output of the bridge circuit could be monitored as a function of time to obtain mass changes with a resolution of ± 1 g.

A new procedure for obtaining temperature distribution with a product (typically a single-layer cake) was devised. Previous techniques have used thermocouples imbedded in capillary tubing supported from the utensil vertically or horizontally in the product. This arrangement is very convenient for initial installation, cleaning and repetitive use; however, systematic errors due to conduction can be significant. The present technique of measuring cake temperature consists of three thermocouples directly exposed to the batter located at the tip of three horizontal, slender metal guide tubes (5, 15 and 30 mm from

Figure 2.1 Schematic of the Bi-Radiant Oven III

Figure 2.2 Photograph of the experimental facility for performance evaluation of Bi-Radiant Oven III

the pan bottom). From previous experiments it was determined that the radial temperature gradient in a single-layer cake was quite small and thus a horizontal arrangement should minimize conduction errors.

The data acquisition system consists of three major components. A 64-channel data logger, Esterline Angus PD 2064, provides the means to measure sensor outputs and provide a printed paper tape record. The unit has programmable features including scan time settings, direct thermocouple output indication, and channel selection. A one-way digital interface in the unit provides for data flow to a desk-top calculator, Hewlett-Packard Model 9815, which serves two functions. The calculator provides the means to record data observations on magnetic cassette tape. The observations for full-oven tests, spanning 25 minutes with 64 data channels and reading every minute, can be readily stored. A second function of the calculator is to process the observations and display results on the third major component of the system, a graphics plotter, Hewlett-Packard Model 7225A/17600A. The data system provides the means to make observations and to perform data analysis within the laboratory; currently under development is the means to display results, such as mass loss rate, while the experiment is in progress. Note that in the following sections the figures representing the experiments were generated directly from the graphics plotter.

2.2 Oven/Product Parameters During the Baking Process

To illustrate oven performance, oven and product parameters as described in Section 2.1 were observed during the baking of a single-layer yellow cake (400 g, Duncan Hines mix). The utensil was a 23 cm (9 in) cake pan, the outer surfaces of which were painted black providing an emissivity of approximately 0.95. Thermocouples to monitor the product temperature distribution as previously described were installed. Initially the oven was at room temperature and following insertion of the product, power was applied to the heating

elements signaling the start of the baking process. The product was baked for approximately 20 minutes with the doneness criteria being when the minimum temperature reached 93°C. From preliminary tests, it was found that the upper-to-lower power ratio of 16 (809 W/51 W or 860 W total) provided acceptable product quality.[†] In subsequent presentations of the observations, these heating rates are referred to as the NORMAL power settings. Note that because of multiple reflections, the actual ratio of top-to-bottom power presented to the product will be less than 16. In the sections that follow, results of the baking process are presented and discussed. Where appropriate the results are contrasted with those from a conventional oven in order to illustrate important features of the Bi-Radiant Oven which give rise to its improved energy performance.

Heating Element Temperatures

The temperatures of the upper and lower heating elements as a function of baking time are shown in Figure 2.3. Since the power to the upper element is sixteen times greater than to the lower element, it follows that the upper element temperature will be substantially higher. Note that the upper element reaches a steady rate of temperature rise in less than 10 minutes while the lower element never reaches this state during the baking period.

The two thermocouples installed on the lower heating element indicated a uniform temperature is likely to exist over the active length of the element. However, based upon the thermocouples at similar locations on the top element, a 35°C difference was observed. This could be due to air flow in the vicinity of the vent but insufficient evidence exists to clearly explain the effect.

It is useful to compare element temperatures of the Bi-Radiant Oven typified by Figure 2.3 with those of a conventional oven. Figure 2.4 presents element temperatures for a conventional oven during the baking of a yellow cake at

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[†]The effect of upper-to-lower element power ratios is discussed in Section 4.3.

Figure 2.3 Heating Element Temperature Response for NORMAL Power Setting, Bi-Radiant Oven III

Figure 2.4 Heating Element Temperature Response for a Conventional Electric Range

a thermostat setting of 177°C (350°F) [7]. Cyclic behavior is the dominant feature with a maximum temperature near 800°C after the preheat period is completed following which the peaks are near to 700°C. These temperatures should be compared to a maximum element temperature of 585°C in the Bi-Radiant Oven III. It should be pointed out that the top-to-bottom power ratio in the conventional oven was 1/4. To protect the product from excessively high heat fluxes, a highly reflective utensil is required.

Cavity Wall Temperatures

The temperature response of the cavity reflective walls for the NORMAL power setting are shown in Figure 2.5. Four thermocouples were attached to each of the wall panels representing equal area quadrants of the panel. The curve labeled Top is the output of the left rear thermocouple of the top wall; the curve labeled Side is the output of the upper rear thermocouple on the left side wall; and the curve labeled Door is the output of the upper left thermocouple on the door. From a separate analysis not reported here, the wall temperature distributions were nearly symmetrical between the left and right sides.

Note that the temperature of the top wall averages nearly 80°C warmer than the side walls. This can be explained first by recognizing that the upper-to-lower element power ratio is 16 to 1; therefore, more power is being dissipated in the upper portion of the cavity. Furthermore, air flow caused by free convection from the elements would enhance convective heat transfer to the upper wall. Because of higher temperatures in the upper portion of the oven, hot air will have a tendency to stagnate at the upper wall surface.

Note also in Figure 2.5 that the door temperature averages nearly 20°C cooler than the side walls. This may be due in part to reduced insulation in the door to maintain acceptable touch temperatures in the original oven design.

Figure 2.5 Wall Temperature Response for NCRMAL Power Setting, Bi-Radiant Oven III

Comparison of the Bi-Radiant Oven wall temperature responses to those representing a conventional oven demonstrates the marked difference in the two oven types. Figure 2.6 illustrates the cyclic behavior of the conventional oven. The function of the wall for this oven is to absorb radiant power from the elements thereby achieving a temperature sufficient to heat the cavity air (during the element off-cycle) and, of course, provide a net radiative heat transfer to the product. Note how the air and wall temperatures track one another as the power is cyclically applied to the heating elements.

Operation of the Bi-Radiant Oven walls at lower temperatures than for the conventional oven provide distinct advantages. First and most important is that total energy consumption will be reduced since the temperature difference between the oven and its surroundings is lessened thereby reducing stored energy and conduction losses (assuming comparable thermal mass and insulation effectiveness are considered). The second advantage of cooler walls relates to cleanliness; spilled foods can be more readily wiped clean from a wall whose temperatures remain cooler. For these reasons, a major design objective of the Bi-Radiant Oven is to maintain the walls at low temperatures without reducing insulation effectiveness.

Cavity Air Temperatures

The cavity air temperatures in the upper and lower region of the oven for the NORMAL power setting are shown as a function of baking time in Figure 2.7. These curves represent the output of the upper and lower (left side) shielded thermocouples in the active portion (between the heating elements, see Figure 2.1) of the Bi-Radiant Oven III.

There is a significant vertical gradient in the cavity air temperature which exists for the same reasons that gradients existed on the cavity walls. An additional factor contributing to this gradient is the air exchange to the inactive

Figure 2.6 Air and Wall Temperature Response for a Conventional Electric Range

Figure 2.7. Air Temperature Response for NORMAL Power Setting, Bi-Radiant Oven III

(lower) portion of the oven cavity. It should be recognized that the difference between the oven air temperature and the surface of a product being baked is smaller than the temperature difference that would exist for baking in a conventional oven. This implies that heat transfer by convection will be less than would be the case for the conventional oven where the air temperature is much higher than the product even near the done stage.

Product Cake Temperature Distribution

Using the thermocouple arrangement described in the previous section, the temperature distribution within a yellow cake product was measured near its center at elevations of 5, 15 and 30 mm measured from the utensil bottom. For the NORMAL power setting, this distribution is shown in Figure 2.8.

The initial batter level (18 mm from the pan bottom) was below the highest (30 mm) thermocouple and hence this thermocouple would indicate the local air temperature until the batter rose above the 30 mm level. The curves show a positive vertical gradient in the product for the first nine minutes; recalling that the upper to lower element power ratio is 16/1, a higher heat flux to the top surface is expected. For later times, the trend unexpectedly reverses. This effect could possibly be due to the increasing rate of moisture loss during the baking process. Attempts have been made to analytically describe the heat and mass transfer phenomena within the product [8] but as yet we cannot explain this observed effect. Note that near the done stage of the baking process, the temperature distribution is nearly uniform, approaching 93°C, the value representing the done temperature in our experiments.

The temperature distribution within the product with different power settings of the element power is shown in Figure 2.9. Referred to as BOTTOM FAST, the upper-to-lower element power ratio is 1.87/1 (677 W/363 W) with a total power of 1040 W representing a 21% increase over the NORMAL rate. Note that

Figure 2.8 Cake Temperature Response for NORMAL Power Setting, Bi-Radiant Oven III

Figure 2.9 Cake Temperature Response for BOTTOM FAST Power Setting, Bi-Radiant Oven III

the general characteristics of the temperature response remain unchanged. However, the temperature gradient reversal begins sooner (7 min vs. 9 min) and the temperature gradient in the done stage is larger than is the case for the product baked at the NORMAL rate. The baking time is reduced by 19% from 21 minutes for the NORMAL rate to 17 minutes. The quality of the product baked by the BOTTOM FAST rate was marginally acceptable.

Product Mass Loss Rate

The mass of a yellow cake product plus utensil as a function of baking time is shown in Figure 2.10. Using a least squares analysis, a cubic polynomial is fitted to the observations and provides a convenient means for determining mass loss and rate of mass loss as functions of time. Since nearly 40% of the energy absorbed by a cake product is required for evaporation, it is important to have product mass loss information to relate other thermal parameters of the product and oven.

A comparison of mass loss data for two power settings in the Bi-Radiant Oven III and a 350°F thermostat setting for a conventional oven is given in Figure 2.11. Again the curves for the Bi-Radiant Oven are cubic fits while the curve for the conventional oven is a quadratic fit.

An end (done) point criteria was selected to be a minimum cake temperature of 93°C. The end point for the NORMAL and BOTTOM FAST power settings were reached at 20.7 and 17.0 min with a total moisture loss of 28 and 23 g, respectively. The end point in the conventional oven at 350°F was reached in 28 min with a loss of 34 g.

2.3 Preliminary Oven Efficiency Tests

The Department of Energy regulations [9] describe the procedures for determining the efficiency of electric ovens. The efficiency is broadly defined as

Figure 2.10 Single Layer Cake and Utensil Mass During Baking, NORMAL Power Setting.

Figure 2.11 Comparison of Mass Loss Data for Single Layer Cakes

the fraction of power consumed by the oven which is absorbed by the product. For this procedure the test load is specified as an anodized 6061 aluminum block weighing 18.7 kg (8.5 lbm) with 15.9 cm (6.25 in) diameter and 7.1 cm (2.8 in) height. The regulations further specify that if the oven thermostat does not cycle on and off, then it is appropriate to adjust the thermostat setting to provide an average internal temperature of 163°C ($325 \pm 5^{\circ}\text{F}$) above room ambient air temperature. The initial test block temperature is required to be within 2.2°C (4°F) of ambient room air temperature, and is to be heated until the block reaches 130°C (234°F) above the initial block temperature. By knowing the test block specific heat and mass, and by measuring the temperature rise of the block and the energy consumed by the oven, the thermal efficiency of the oven can be calculated.

The efficiency test results given on the first line of Table 2.1 are based upon the DOE test regulations. Efficiency tests were also performed at more representative power settings for the Bi-Radiant Oven. To simulate actual operating conditions the Bi-Radiant Oven was not pre-heated. Oven energy consumption was obtained by numerical integration of the total power consumption with respect to time.

The first column of Table 2.1 gives the approximate RMS voltage applied to the top and bottom elements. At room temperature these elements had a resistance of 18 ohms. The second and third columns give the nominal input power ratio and the average total input power, respectively. The powerstats were manually (slightly) adjusted several times during each test to approximate constant input power.

Efficiency improves slightly with larger input power as would be expected. Note that the efficiency was improved by 6.6% when the input power was increased 65% above the NORMAL setting. Because of the importance of cavity size and

Table 2.1

Oven Thermal Efficiency, Bi-Radiant Oven III

Voltage Settings Top/Bottom (Volts)	Power Ratio Top/Bottom	Total Input Power (Watts)	Efficiency (Percent)	Duration of Test (Minutes)
0/100	0.00	580	20.26	71.4
120/30 NORMAL	16.0	873	21.70	44
110/80 BOTTOM FAST	1.87	1,040	21.75	37
115/115	1.00	1,438	23.13	25

thermal mass on oven efficiency, it is difficult to make a valid comparison of these results with full-sized conventional ovens which typically have efficiencies less than 14%. A full size oven cavity designed to operate under the bi-radiant concept is presently under construction. It is believed that this oven will show a marked improvement in thermal efficiency. Preliminary testing should be included in a subsequent report.

3.0 THERMAL MODELING AND IRRADIANCE DISTRIBUTION

Radiation is the dominant mode of heat transfer to a product within the Bi-Radiant Oven. Radiant power emitted from the heating elements reaches the product by direct incidence and by reflection(s) from the cavity walls. As such, the characteristics of the radiation field at the product, referred to as the irradiance distribution on the baking plane, depend on the emissivity and temperature distribution of the heating elements; on the cavity wall reflectivity and degree of diffuseness; and on the geometrical configuration of the heating elements, the cavity walls and the product.

An analytical model for predicting the irradiance distribution on the baking plane has been developed. Computer-generated irradiance distributions are presented to illustrate effects due to the heating element configuration. To obtain experimental values of irradiance within the oven, a new type of heat flux gage has been developed. The principle of operation and calibration procedures for the gages will be described. The results of experimental observations on Bi-Radiant Oven III include determination of the irradiance and convective heat flux from which estimates are made of the irradiance from the heating elements (direct plus reflected) and irradiance due to emission by the cavity walls.

3.1 Irradiance Distribution on the Baking Plane

The manner in which radiant power emitted from the heating element reaches the product is illustrated in Figure 3.1. The irradiance to the lower surface of a product utensil on the baking plane is shown to be due to direct irradiation from the lower heating element and due to reflected radiation originating from the upper and lower heating elements. The reflection process at the cavity walls can be idealized as either specular or diffuse, or more practically, as

Figure 3.1 Irradiation to the lower surface of a utensil within the BI-radiant oven.

some combination of both which can be expressed as the degree of diffuseness. If the cavity walls reach temperatures greater than the product, emission from the walls can cause significant irradiation on the product.

Irradiance Distribution Model I

An analytical model has been developed for predicting the irradiance distribution over any specified region on the baking plane. Model I allows for the comparison of irradiance distributions resulting from different element configurations. The model predicts which element, operating under ideal conditions (isothermal element with diffuse-gray radiating surface) will provide a more uniform irradiation to a product within the oven cavity. Referring to Figure 3.1, the model considers an oven cavity with upper and lower heating elements. The oven physical size, element configurations and locations, baking plane position, as well as all other geometrical parameters, are arbitrary and may be specified as input to the model. The model is based upon the following assumptions:

- (1) The heating element configuration can be specified as a series of straight line segments; no limit is imposed on the number of segments so that curved shapes may be accommodated.
- (2) The heating element of circular cross-section is isothermal and its surface is a diffuse-gray radiator.
- (3) The cavity walls have a specified specular reflectivity.
- (4) Only single reflections from the cavity walls are considered in determining irradiation at the baking plane.
- (5) The effect of shadowing by the product/utensil is considered.

Note that assumption (4) places a special restriction on the analysis since in a real oven operation, irradiation at the product may be due to multiple reflections as well as emission from the hot cavity walls. However, it should be recognized that multiple reflection and wall emission are likely to be

second-order effects. Considering these effects would seriously complicate the model but ignoring them does not detract from the utility of the model in comparing performance of various element configurations.

The analytical model provides the means to calculate the following parameters:

- (1) the view factor between either heating element and an arbitrary small area on the baking plane, and
- (2) the ratio of the irradiance at any location on the baking plane to a reference value; this generates a dimensionless distribution which is used in subsequent sections to illustrate performance of various heating element configurations.

Bi-Radiant Oven III

The configuration of the upper and lower heating elements used in the Bi-Radiant Oven III is shown in Figure 3.2(a). The elements are positioned 38 mm (1.5 in) from the upper or lower cavity wall. The baking plane is located 89 mm (3.5 in) from the lower surface; since the cavity height is 203 mm (8.0 in), the baking plane (rack position, Figure 2.1) is then approximately mid-way between the planes of the upper and lower heating elements.

The dimensionless irradiance distribution on the baking plane is shown in Figure 3.2(b) for the conditions of equal power to the upper and lower elements and no product. The ten curves, labeled A through J, represent lines of equal irradiance ($G, \text{W/m}^2$)[†] with the maximum value at J and the minimum value at A. The ratio of the maximum-to-minimum irradiance, $G_{\text{max}}/G_{\text{min}}$, is 4.7. The intermediate iso-irradiance lines identified by B through I represent irradiance increments of 10% between the highest (J) and lowest (A) values. It follows then

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[†]Do not confuse the iso-irradiance line G with the symbol G for irradiance.

Figure 3.2 Irradiance distribution (a) configuration of the heating elements and (b) nondimensionalized iso-irradiance lines on the baking plane, Bi-Radiant Oven III.

that widely spaced iso-irradiance lines indicate a more uniform region such as exists in the center; near the walls, the iso-irradiance lines are more closely spaced indicating that steep changes in irradiance occur.

The presence of a product in a utensil on the baking plane will change the irradiance distribution. Therefore, it is interesting to know how the irradiance to the product utensil will vary over the surface of the utensil. Consider a cake pan (23 cm diameter $\times$ 38 mm high) utensil on the baking plane positioned relative to the heating element as shown in Figure 3.3(a). The distribution over the utensil surface is represented in Figure 3.3(b) where curves A and J represent the minimum and maximum iso-irradiance values, respectively, and the intervening curves are spaced by 10% increments. Note that the maximum-to-minimum irradiance ratio, $G_{\max}/G_{\min}$, is only 1.24. This implies that the irradiance distribution over the utensil is fairly uniform and, furthermore, from the spacing of the iso-irradiance curves of Figure 3.3(b), it can be seen that the non-uniformity of irradiance is most noticeable near the forward edge of the pan.

Comparison of Multiple-Loop Heating Elements

The analytical model for predicting the irradiance distribution within the oven provides a basis for the rational selection of a heating element configuration. It is readily appreciated that the optimum configuration is one providing the largest region of uniform irradiance.

For the series of multiple-loop elements represented in Figure 3.4, the irradiance distributions on the baking planes are represented for the one-, two-, and three-loop elements in Figures 3.5, 3.6 and 3.7, respectively. As was the convention in the previous iso-irradiance distributions, Curves A and J represent the minimum and maximum irradiance, respectively, and the intermediate

Figure 3.3 Irradiation distribution (a) configuration of the heating element and cake-pan utensil (23 cm diameter) and (b) nondimensionalized iso-irradiance lines on the utensil surface (Bi-Radiant Oven III).

(a)

(b)

(c)

Figure 3.4 Multiple-loop heating element configuration with (a) one, (b) two and (c) three loops.

$$\frac{G_{\max}}{G_{\min}} = 3.6$$

J = max

A = min

Figure 3.5 Irradiance distribution for the one-loop heating element configuration of Figure 3.4.

$$\frac{G_{\max}}{G_{\min}} = 2.5$$

J = max

A = min

Figure 3.6 Irradiance distribution for the two-loop element configuration of Figure 3.4.

$$\frac{G_{\max}}{G_{\min}} = 1.64$$

J = max

A = min

Figure 3.7 Irradiance distribution for the three-loop heating element configuration of Figure 3.4.

curves are incremented by 10%. The parameter which expresses uniform irradiance is $G_{\max}/G_{\min}$. Note from the appropriate figure that the irradiance ratios, $(G_{\max}/G_{\min})$, are 3.6, 2.5, and 1.64 for the one-, two-, and three-loop elements, respectively. As anticipated, the three-loop element configuration provides the most uniform distribution. From further examination of the three figures, it follows that the three-loop element configuration provides the largest, most uniform usable, central baking region.

It should be recognized that the irradiance distribution of the Figures 3.5 to 3.7 have been nondimensionalized. To provide the same maximum levels of irradiance, the required power ratios are 2.05:1.22:1 for the one-, two-, and three-loop elements, respectively.

3.2 Experimental Heat Flux Observations

To characterize the heating process of a food product in the Bi-Radiant Oven, a heat flux gage was developed to provide measurements of the irradiance, $G[W/m^2]$, and the convective heat flux, $q_c''[W/m^2]$. A description of the gage, its principle of operation and method of calibration, will be given in a later report.

The heat flux gage is a useful tool for studies directed toward an understanding of the heat transfer phenomenon within the oven cavity. Operation of the gage permits separation of the total heat flux into its components of irradiation and convection. It is also possible through use of the irradiance distribution model to determine the fraction of irradiation on the gage due to direct radiation from the heating elements and due to reflections from the cavity walls.

A series of experiments were performed in Bi-Radiant Oven III to obtain the heat flux characteristics at a specified location as a function of time. The heat flux gage is mounted on the oven rack. The wrapped leads were exited

through the oven vent, allowing for the oven door to be closed and the heat flux gage to remain inside the oven cavity.

After the gage was positioned, both heating elements were switched on (top element: 809 W; bottom element: 51 W) and gage signal observations were taken at regular time intervals.

The heat flux characteristics for the above conditions as a function of time are represented in Figure 3.8. The upper curve labeled Irradiation (G) and the lower curve labeled Convection (q_c) result from the separation of total heat flux into these components. That is, these curves represent experimentally determined values of heat flux due to irradiation and convection. Note that the convection mode is approximately 10% of the radiation; this is indicative of the manner in which a product, if present in the oven, would be heated.

The middle curve of Figure 3.8 labeled Wall Emission & Multiple Reflections represents the portion of the total irradiation due to radiant flux emitted and/or multiple reflections from the walls. This flux is calculated as the difference between the observed irradiation (top curve) and the irradiation originating from the heating element plus single reflections from the walls. Note that this flux increases only slightly for the first seven minutes of heating and then begins to increase in a nearly linear fashion. This effect can be explained by recalling from Figure 2.3 that the heating element temperature does not reach a constant value until nearly 7 or 8 minutes after being switched on. After this period, the direct flux originating from the heating element will remain constant. It follows then that the increase in the flux curve, Wall Emission & Multiple Reflections, must be due to emission from the walls which are heating up as time elapses. Note that after 20 minutes nearly 30% of the total irradiation is due to indirect processes of wall emission and multiple wall reflection.

Figure 3.8 Typical heat flux measurements at the center of the baking plane for Bi-Radiant Oven III.
(Top and bottom element power. 809 W and 51 W, respectively.)

4.0 OVEN HEATING REQUIREMENTS FOR FOODS

In developing the potential of the Bi-Radiant Oven, the role of the Equipment Laboratory has been to determine heat absorption rates that will produce acceptable food products. Review of the technical literature indicated few studies had dealt directly with heat absorption rates for baking foods. There is, however, considerable information on the thermal properties of foods such as specific heat and thermal conductivity. There is a limited amount of data on the emissivity of foods; this is also the case for the emissive characteristics of materials suited for use as baking utensils and oven surfaces. Our review also indicated there was limited information on instrumentation and procedures for measuring radiative and convective heat transfer rates in a baking oven environment.

4.1 Heat Absorption Rates

Conventional Oven Operation

It is known that the thermostat control settings for an oven are artificial and are not meaningful for determining heat rates to foods. A 177°C (350°F) setting indicates a representative temperature of the oven air and walls, but doesn't relate to the temperatures of the surfaces of a food which would be useful in determining heat transfer to the food. It is also known that in an oven, two or more heat rates are important. Heat is transferred toward the center of a product being baked from the top, bottom and sides of the product. While the heat conduction rate in the product from each surface may be nearly the same, the rate at which energy can be absorbed from its surroundings (by convection and/or radiation processes) at each of the product surfaces may be very different. The food in contact with a baking utensil will conduct heat inward once it has been absorbed by the utensil. The temperature

at the product-utensil interface is dependent upon the rate at which heat is absorbed by the utensil from the surrounding areas by thermal radiation and convection, and upon the thermal conductivities of the utensil and the food. The upper surface of food exposed to the oven air loses heat through evaporation of moisture. This evaporation process competes for energy use with the heat being conducted into the food from this surface. The conductance of heat toward the center of a food from the top surface is slower because this evaporation of moisture keeps the top surface cooler.

In a conventional gas or electric oven, achieving satisfactory heat absorption rates to both the upper and lower surfaces of foods requires the use of appropriate baking utensils. Some foods are very sensitive to the heat absorption rate and to the ratio of rates for the upper and lower surfaces. Cakes and breads are among these foods. The best baking results - where a light, tender crust and good texture are desired - are obtained by using a bright, aluminum utensil. Considerable convection and thermal radiation occur on the bottom surface of the utensil when a food is baked in a conventional oven. The simplest way to reduce the risk of baking too quickly on the bottom of a product is to inhibit the absorption of heat by reflecting thermal irradiation. Some foods, such as casseroles, can tolerate faster heating from the bottom surface. Fruit-filled pies will have soggy lower crusts if baked in utensils that are highly reflective.

In the Bi-Radiant Oven, irradiation is the primary heat transfer mode. By developing a better understanding of the heat absorption requirements of foods, it will be possible to determine the levels of irradiation to the upper and lower surfaces of foods that will produce quality products.

Irradiation Measurements

The Cake Pan Radiometer (CPR) used in earlier studies [10, 11, 12] in the

Equipment Laboratory led to the development of an irradiation heat flux (IHF) gauge [13]. The IHF gauge is small and can be used to measure thermal irradiation distribution across the baking plane in an oven. In the Bi-Radiant Oven, this new device offers some distinct advantages. Since effectively all heat transfer within this oven is by radiation, measurements of irradiation levels required for the upper and lower surfaces of specific foods can be assumed to be the equivalent to the total amount of thermal energy available for baking. These measurements of irradiation, together with the emissivities of the various surfaces of a product being baked and of the utensil, the areas of these surfaces and the baking time provide information about the energy input to the food being baked. Observations of the end temperatures, together with the original temperatures, the specific heats and masses of the food and baking utensil, permit calculation of the energy stored during baking. Measurements of evaporative losses during baking can be used to estimate energy losses from the product. With knowledge of the energies associated with these processes, it is then possible to perform an energy balance analysis on the product.

Most foods baked in an oven are disc shaped. Horizontal food surfaces within utensils are relatively flat so that the top and bottom surfaces form planes. The heat conducted to the center of such products is likely to originate at the upper and lower surfaces in a Bi-Radiant Oven. This has been the primary reason to consider only the heat absorption rates of the upper and lower surfaces of foods.

In this portion of the study, two foods - yellow cakes and beef roasts - were selected for detailed examination of heat absorption rate effects. The objective was to determine the heat rates that produce the best products and to determine the effects on these foods when the heat rates were "too fast" or "too slow" or when the heat rates were unbalanced by being "too fast" from

either the top or bottom (baking utensil) of the food. Rates other than "normal" were selected during pretesting to loosely bracket the optimum baking or roasting irradiation levels as shown by undesirable effects on the food itself. Irradiation levels required to produce desirable baked products are different for different foods. The ratio of upper-to-lower irradiation levels required to produce a balanced top-to-center and bottom-to-center cooking differs too, depending on differences between the complex processes that occur within each food product. Yellow cakes and beef roasts were selected since it is known they are both sensitive to heat rates. The effects of undesirable heat rates could be measured both objectively and through visual assessments. A less detailed examination was made on a number of other foods to determine their sensitivity to heat rates and heat rate balances.

4.2 Study on Beef Roasts

Procedures for Food Preparation and Measurements

Semitendinosus beef muscle roasts were selected for this study because they are quite homogeneous in nature, the meat fibers are parallel and fat can be trimmed to minimize extraneous heat transfer effects at the surface. Small roasts, about 680 g (1.5 lb) and 8 cm high were supplied by the Animal Science Department at Purdue. All roasts were from the same breed and feed lot, thereby minimizing variations from sample to sample. Nine thermocouples of 0.075 mm (0.003 in) diameter copper and constantan wire were threaded into the beef muscle with the use of a hypodermic needle. The thermocouples were positioned at the following locations: center (top, middle, bottom) edge (top, middle, bottom) and about one-third of the way in from the edge (top, middle, bottom). The roast was positioned with the fibers running vertically in an open blackened (23 cm × 13 cm) loaf pan with an emissivity of approximately 0.8. Roasts were cooked in Bi-Radiant Oven II (see footnote, p. 4).

Several preliminary pre-tests were run in the Bi-Radiant Oven II to establish a set of top and bottom heat rates that would produce an evenly done product. Doneness was assumed when the center, middle thermocouple reached 60°C. The normal rate, NORMAL, corresponds to appropriately balanced upper and lower element power settings which balance the cooking from the top and bottom of the roast and which provide an acceptable product (Table 4.1). That is, an irradiation level of about 3200 W/m² for the upper surface and about 2500 W/m² for the lower surface of the utensil produced an acceptable rare roast in about 55 minutes. This was comparable to a similar roast baked at 162°C (325°F) for about the same length of time. Two additional rates provided balanced top and bottom cooking: FAST, faster (higher) rate than NORMAL, and SLOW, slower (lower) rate than NORMAL. The other rates provided unbalanced top and bottom settings: TOP FAST, top too fast; and BOTTOM FAST, bottom too fast.

Measurements taken during the tests include temperatures of the roast, the oven wall, the oven air and the utensil holding the roast, the energy used for roasting and the baking time. Roasts were weighed before and after baking and measurements made of both drip and evaporative losses. Visual evaluations and descriptions were used to evaluate the acceptability of each roast. Two roasts were tested for each heat rate.

Using the irradiation heat flux gage (IFG) measurements were made of irradiation on the upper and lower surfaces of the product and utensil for each heat rate setting. Heat rates to the sides of the foods could not be effectively measured since the roasts did not make contact with the utensil sides. In calculations it was assumed that the sides were subjected to the average of the top and bottom surface heat rates.

Table 4.1
 Five Heat Rates for Baking or Roasting
 in the Bi-Radiant Oven[†]

<u>Heat Rate</u>	<u>Description</u>
NORMAL	Power to the upper and lower element power settings to provide an acceptable product.
SLOW	Upper and lower element power settings, both lower than for NORMAL.
FAST	Upper and lower element power settings, both higher than for NORMAL.
TOP FAST	Upper and lower element power settings unbalanced with the upper element setting higher.
BOTTOM FAST	Upper and lower element power settings unbalanced with the lower element setting higher.

[†]The element power setting for NORMAL depends upon the heat absorption rates of specific foods. Different power settings were used for the five heat rates to the two products, semitendinosus beef muscle roasts and yellow cakes.

Experimental Results

The ratios of the power (W) in the upper element to the lower element used for preparing semitendinosus beef roasts is shown in Figure 4.1. Note that the power for the upper element was higher than for the lower element for all five heat rates used in the study. The irradiation levels produced by the element power levels are shown in Figure 4.2. The high reflectance of the oven walls ($\alpha = 0.05$) increased the irradiation on the lower surface of the roast in each case. This caused the upper and lower irradiation levels to be closer together than were the element wattages. Baking times, Figure 4.3, showed an inverse relationship to the irradiation levels, as expected. The unbalanced heat rates, TOP FAST and BOTTOM FAST, required longer times than the NORMAL. Note that the FAST rate did not take much less time than NORMAL. These effects are likely related to the thermal conductance of meats which is low. As shown in Figure 4.4, more energy was required for the FAST, TOP FAST and BOTTOM FAST heat rates.

The distribution of end temperatures within each roast is shown in Figure 4.5 for each of the five heat rates. Note that the center end temperatures of all the roasts were 60°C. Note also that the temperatures along the upper surfaces were always lower than the temperatures along the lower surface. This was true even though more irradiation was incident at the top surface for all heat rates except BOTTOM FAST and the emissivity of the utensil bottom was 0.8. The upper surface of the roast was assumed to be moist during roasting and to have an emissivity of 1.0. Evaporative losses resulted from the absorption of the heat of vaporization thus slowing heating near the surface. Otherwise, the differences in temperatures between the various heat rates follows anticipated trends. The distribution of temperatures within the NORMAL and SLOW roasts, which were judged to be the most acceptable products, indicates that the

Figure 4.1 Input Power (W) of Upper (U) and Lower (L) Elements During Cooking of Semitendinosus Beef Muscle as Five Heat Rates (Bi-Radiant Oven II)

Figure 4.2 Irradiation (W/m^2) for Upper (U) and Lower (L) Surfaces During Cooking of Semitendinosus Beef Muscle at Five Heat Rates (Bi-Radiant Oven II)

Figure 4.3 Time for Cooking Semitendinosus Beef Muscle at Five Heat Rates (Bi-Radiant Oven II)

Figure 4:4 Total Energy Used During Cooking of Semitendinosus Beef Muscle at Five Heat Rates (Bi-Radiant Oven II)

Figure 4.5 Distribution of End Temperatures (°C) for Semiterdinosus Beef Muscle at Five Heat Rates (Bi-Radiant Oven II)

tolerance of such a roast to higher temperatures is greater on a surface that is not being dehydrated during the cooking process. As shown in Figure 4.6 the centers of all roasts reached 60°C but at different times. There were differences among rates in the spread between the center top and center bottom temperatures, Figure 4.7. The temperature differences were least for the TOP FAST rate and greatest for the BOTTOM FAST rate. However, both of these rates produced poor quality roasts.

Visually all the roasts were pink inside, but the NORMAL and SLOW roasts were juicier than the roasts from faster and unbalanced rates. Slower roasting does not adversely affect the quality of cooked roast in the Bi-Radiant Oven if the upper and lower heating rates are appropriately balanced, however, more time will be required for cooking. Soon after cutting, the FAST prepared roast turned gray. TOP FAST and BOTTOM FAST roasts become duller in color as well, though some areas of pink remained. Upper surface browning was excessive and edges were crisp on FAST and TOP FAST roasts. The bottom surface was overly dark on FAST and BOTTOM FAST roasts. Drip and evaporative losses were greater for FAST, TOP FAST and BOTTOM FAST roasts as is illustrated in Figure 4.8. Unbalanced rates, TOP FAST and BOTTOM FAST tended to increase these losses.

Oven air temperatures, Figure 4.9, tended to reach a steady-state value at different levels for each heat rate: approximately 140°C for NORMAL. Oven wall temperatures, Figure 4.10, were in each case lower than oven air temperatures. Oven wall temperatures for SLOW, BOTTOM FAST and TOP FAST had leveled off by the end of the roasting period.

There appear to be upper limits for the upper and lower heating rates of roasts though more work will be required to define those more closely. Unbalanced heating rates require longer for a roast to reach the doneness and fast and unbalanced heating rates can be expected to produce greater losses of moisture.

Figure 4.6 Temperature Changes During Cooking of Semitendinosus Beef Muscle at Five Heat Rates - Center Location (Bi Radiant Oven II)

Figure 4.7 Temperature Changes During Cooking of Semitendinosus Beef Muscle with Five Heat Rates - Center Top and Center Bottom Locations (Bi-Radiant Oven II)

Figure 4.8 Cooking Losses by Drip and Evaporation from Semitendinosus Beef Muscle at Five Heat Rates (Bi-Radiant Oven II)

Figure 4.9 Temperature Changes During Cooking of Semitendinosus Beef Muscle at Five Heat Rates - Oven Air (Bi-Radiant Oven 11)

Figure 4.10 Temperature Changes During Cooking of Semitendinosus Beef Muscle at Five Heat Rates - Oven Wall (Bi-Radiant Oven II)

4.3 Study on Yellow Cakes

Procedures for Food Preparation and Measurements

Yellow cakes were baked from a recipe previously developed in the Equipment Laboratory (Appendix B). Yellow cake is a good product for evaluating heat rates in an oven since the baking process must be carefully timed to permit the activity of leavening agents, the denaturation of protein and the gelatinization of starches to occur in the proper sequence. Surface browning at acceptable levels occurs during the final period of the baking process. A 23 cm (9 in.) round cake pan with an outer surface emissivity of approximately 0.8 was equipped with nine small gauge (0.075 mm diameter) thermocouples placed in three capillary tubes (3 per tube). This arrangement permitted temperatures to be measured along the bottom of the cake pan (0.5 cm from the bottom) at the center of the pan, approximately 3.8 cm from the edge and 1.0 cm from the edge, across a mid-section (1.6 cm from the bottom) and across the cake top (3.2 cm from the bottom).

Standard procedures were developed for preparing the batter and cake pan and collecting data. Several preliminary tests were made baking cakes in the Bi-Radiant Oven III to establish the NORMAL element settings that produced an acceptable product. Four additional heat rates, SLOW, FAST, TOP FAST and BOTTOM FAST were established according to Table 4.1. Each cake was baked until the temperatures of all thermocouples had reached or exceeded 91°C.

In addition to the temperature distribution of each cake, the change in mass of the cake provided data on evaporative losses. Immediately after each cake was baked, samples of about 5 grams were taken from areas adjacent to each thermocouple. These samples were each wrapped separately, weighed and dried in a drying oven at a vacuum ≥ 700 mm Hg at 95°C. The moisture content of each of these areas within each cake was calculated. A browning scale was developed

and a panel of six judges evaluated samples of the top and bottom crusts for browning.

One layer of cake was baked at a time and two cakes were baked at each heat rate. Bi-Radiant Oven III was used for the cake tests.

Experimental Results

The element power levels, Figure 4.11, for the five heat rates show that the power for upper elements was greater than for lower elements in all cases. The irradiation levels, Figure 4.12, however, are more nearly equal due to the interreflections within the cavity which have the effect of making the irradiation distribution on the baking plane more nearly uniform. The Bi-Radiant Oven III used on these cake tests has a more highly reflective wall lining than did the Oven II used for the beef roast study. The larger elements, three-loop versus two-loop also contribute to the interreflectivity in this cavity.

Quality yellow cake is best produced in a Bi-Radiant Oven with irradiation levels of about 2500 W/m^2 on the upper surface of the cake and 2000 W/m^2 on the bottom surface of a utensil ($\alpha = 0.8$) in about 20 minutes.

As shown in Figure 4.13, approximately 20 minutes at the NORMAL heat rate was required to bake yellow cake. More time was required at the SLOW rate, while at the other three rates, less time was required. The energy used to bake the cakes was very nearly 0.3 kWh at all the heat rates as shown in Figure 4.14.

The temperature distribution within each cake, Figure 4.15, shows that the temperatures of the upper surfaces were lower than temperatures at the bottom of the cakes for all heat rates. There was a greater temperature difference in bottom and top areas for the three faster heat rates. The higher heat rates did not, however, result in greater losses of moisture (Figure 4.16). This could

Figure 4.11 Input Power (W) of Upper (U) and Lower (L) Elements During Cooking of Yellow Cake at Five Heat Rates (Bi-Radiant Oven III)

Figure 4.12 Irradiation (W/m²) for Upper (U) and Lower (L) Surfaces of Yellow Cakes at Five Heat Rates (Bi-Radiant Oven III)

Figure 4.13 Time for Baking Cake at Five Heat Rates (Bi-Radiant Oven III)

Figure 4.14 Total Energy Used During Baking Yellow Cake at Five Heat Rates (Bi-Radiant Oven III)

Figure 4.15 Distribution of End Temperatures (°C) for Yellow Cake at Five Heat Rates (Bi-Radiant Oven III)

Figure 4.16 Moisture Losses from Yellow Cakes at Five Heat Rates
(B1-Radiant Oven III)

be due, in part, to shorter cooking times. Measurements of the moisture content of the cake samples taken at various positions within each cake as shown in Figure 4.17 indicate typical moisture distribution at the end of baking.

NORMAL and SLOW heat rates produced cakes that were more homogeneous in moisture content, but the moisture content was generally lower. The cakes baked at the three faster rates were drier around the edge of the cake and moister toward the center as though the moisture had become trapped.

Browning of the cakes follows the expected pattern of excessive browning at faster baking rates, Figure 4.18. The SLOW baking rate produced almost no lower crust browning. Medium browning would score about 4.

4.4 Energy Balance Analysis of the Baking Process

Data from the semitendinosus beef roasts and yellow cakes were analyzed to perform an energy balance on the product. This was done to develop a better understanding of the heat absorption requirements of these two foods. The energy balance can be expressed as

$$Q_t + Q_b = Q_p + Q_u + Q_e + Q_x \quad (4-1)$$

where Q_t and Q_b are the estimates of energy into the product through the top and bottom surfaces. The irradiation incident on the sides of a utensil in the Bi-Radiant Oven could not be accurately measured. Since there is poor direct coupling of radiation from either element with the utensil sides, this value was assumed to be minimal and was not included in the model. The sides of foods in the Bi-Radiant Oven II do brown less than the bottom. The term Q_p represents the increase in internal energy of the product while Q_u represents the increase in internal energy of the utensil and Q_e represents the energy lost from the product through evaporation. The term Q_x is that quantity of

Figure 4.17 Distributions of Moisture (%) for Yellow Cakes at Five Heat Rates (Bi-Radiant Oven III)

Figure 4.18 Browning Scores for Baking Yellow Cakes at Five Heat Rates (Bi-Radiant Oven III)

energy that cannot be accounted for through estimates (by calculation or from observations) of the other terms. That is, Q_x represents all other processes present, but not specifically identified, and its value is determined by assuring the equality of Eq. (4-1) is satisfied. If Q_x is positive, presumably the energy input ($Q_t + Q_b$) is larger than can be accounted for by the change in internal energy of the product and utensil (the storage terms: $Q_p + Q_u$) and by the evaporative loss Q_e . If Q_x is negative, the reverse situation occurs.

The energy input terms, Q [J], for the top (t) and bottom (b) surfaces, respectively, can be estimated by the relations

$$Q_t = (\alpha_t \bar{G}_t) A_t \cdot \Delta t \quad (4-2)$$

$$Q_b = (\alpha_b \bar{G}_b) A_b \cdot \Delta t \quad (4-3)$$

The product $\alpha \bar{G}$ represents the absorbed heat flux where α is the absorptivity and $\bar{G}$ is the average irradiation [W/m^2] during the baking process of duration Δt [s] on the area A [m^2] of the product.

The energy storage terms, Q_p and Q_u have the form

$$Q_p = M_p c_{p,p} (T_{p,e} - T_{p,i}) \quad (4-4)$$

$$Q_u = M_u c_{p,u} (T_{u,e} - T_{u,i}) \quad (4-5)$$

where M [kg] denotes the mass and c_p [J/kg·K] the specific heat of either the product (p)[†] or utensil (u). The initial temperature of the pan or utensil is designated as T_i [K] while T_e represents the end temperature reached at the end of the baking process.

[†]See Appendix D for sample calculation procedure.

The energy loss by evaporation, Q_e , of moisture from the product is given by

$$Q_e = \Delta M h_{fg} \quad (4-6)$$

where ΔM [kg] is the moisture loss (or change in mass of the product) and h_{fg} [J/kg] is the heat of vaporization of water. Heating of the moisture loss, ΔM , from $T_{p,i}$ to $T_{p,e}$ is included in the term Q_p of Eq. (4-4). It follows from rearrangement of Eq. (4-1) that Q_x which accounts for all other processes will be given as

$$Q_x = (Q_t + Q_b) - (Q_p + Q_u + Q_e) \quad (4-7)$$

Beef Roasts

The energy balance was calculated for beef roasts at each of the five heat rates and the various terms are presented in Table 4.2. For the NORMAL heat rate, input energy to the roast was 192 kJ to the top surface and 123 kJ to the bottom surface. The energy required to heat the roast to the done stage was 69 kJ while 18 kJ was required to heat the utensil and 217 kJ was lost by evaporation of moisture. Most of the energy is accounted for by these terms such that Q_x is only +11 kJ. In all cases the energy absorbed at the upper surface is greater than at the bottom surface; the energy required to evaporate moisture accounts for more energy than is required to sensibly heat either the roast or the utensil.

Note that Q_x is relatively small for the first three heat rates in Table 4.2. The larger Q_x values for the TOP FAST and BOTTOM FAST heating rates indicate more energy absorption than could be accounted for by irradiation. Estimates of heat absorption of the roasts were analyzed to study the contribution various factors might make: (1) as the surface of the roasts dried, the

Table 4.2
Energy Balance for Semitendinosus Beef Muscle Roasts
Bi-Radiant Oven II

<u>Energy Balance</u> [†] (kJ)	Q_t	+	Q_b	=	Q_p	+	Q_u	+	Q_e	+	Q_x
<u>Heat Rate</u>											
NORMAL	192		123		69		18		217		+ 11
SLOW	153		107		81		16		194		- 31
FAST	232		152		93		23		232		- 25
TOP FAST	297		149		115		20		400		-107
BOTTOM FAST	213		174		121		17		362		-113

[†]Subscripts on energy terms denote:

- t energy absorbed at top surface of product
- b energy absorbed at bottom surface of product by utensil
- p increase in product internal energy (sensible)
- u increase in utensil internal energy
- e energy lost from the product through evaporation
- x unaccounted energy

emissivity would be less, and (2) no account was made for melting fat. Corrections for either of these factors would further increase the negative value of Q_x . Q_e was much higher for TOP FAST and BOTTOM FAST roasts. Possibly unbalanced rates caused fluid loss to occur faster than could be evaporated from the meat surface. This fluid ran to the bottom of the utensil, covered a larger surface of the baking utensil, and absorbed irradiation from a larger surface than had occurred with the balanced heat rates.

Yellow Cakes

The energy balance was also calculated for each cake and the various terms are presented in Table 4.3. For the NORMAL heat rate, the input energy was 138 kJ to the upper surface and 90 kJ to the bottom. This energy was utilized to heat the cake (69 kJ), heat the utensil (12 kJ), and evaporate moisture (57 kJ). Q_x indicates that more energy (90 kJ) was presented to this product than could be accounted for through energy stored in the product and utensil and lost through evaporation. Possible solutions to this imbalance of energy are: melting fat, activity of leavening agents, changes in the surface that reduce emissivity, and moisture in vapor form trapped within cake cells at the end of baking.

Energy required to melt the fat is not known, but would likely be small. Whether the activity of leavening agents within a cake absorb or produce heat is not known, but would likely be a small contribution. Since the surface of these cakes stayed moist and cooler, this factor is not believed to be significant. Vapor within the cake also seems to be a plausible explanation. In any event the large Q_x values for all the cakes show that the energy balance for this product is different from that for a product like meat. The processes involved in producing a cooked product from a raw one in each case are very

Table 4.3
Energy Balance for Baking Yellow Cake
Bi-Radiant Oven III

<u>Energy Balance (kJ)</u>	Q_t	+	Q_b	=	Q_p	+	Q_u	+	Q_e	+	Q_x
<u>Heat Rate</u>											
NORMAL	138		90		69		12		57		+ 90
SLOW	164		90		64		11		63		+116
FAST	154		92		74		13		54		+105
TOP FAST	171		82		69		12		54		+118
BOTTOM FAST	139		110		72		12		45		+120

different. It is likely that difference among foods vary considerably.

Other Selected Foods

Energy balances were calculated for additional foods. Each of these foods was prepared in a conventional oven to determine terminal temperatures and characteristics of the food that would provide an acceptable product. Each food was in turn prepared in the Bi-Radiant Oven II at settings of the upper and lower elements that produced acceptable products. Other heat rates were not used for these foods, but observations were made so that energy balances could be performed. For each product the specific heat was estimated by combining the specific heats of the recipe components. A sample case is given in Appendix C. In the absence of reliable data, an emissivity of unity was assumed for all food surfaces.

For all the foods represented in Table 4.4, the energy introduced at the top surface, Q_t , was greater than that at the bottom surface, Q_b . More energy was required to heat each product, Q_p , than to heat the utensil in which it was baked, Q_u . The variety of utensils used, their weights, specific heats, and temperatures were related to differences in the heat absorbed by the utensils. Differences in mass, specific heat and baking times as well as irradiation rates caused differences in the heat absorption of each food. Energy used to evaporate moisture, Q_e , varied considerably from product to product. In several cases Q_e was greater than Q_p ; in others the reverse was true. A larger Q_e was associated with meat and high protein products.

Q_x was positive in all cases indicating that all the input energy could not be accounted for. It is possible that some moisture was trapped in vapor form within the products. It was observed that these products all shrank somewhat upon cooling. Cutting into the center of such products immediately upon

Table 4.4
Energy Balance for Assorted Foods at Their Optimum Baking Rate
Bi-Radiant Oven II

<u>Energy Balance (kJ)</u>	Q_t	+	Q_b	=	Q_p	+	Q_u	+	Q_e	+	Q_x
<u>Food</u>											
Biscuits	112		55		66		40		44		+ 17
Meat Loaf	377		221		182		12		331		+ 73
Baked Fish	387		286		77		40		101		+455
Apple Crisp	260		166		75		13		60		+278
Cornbread	237		189		100		27		95		+204
Macaroni and Cheese	222		137		56		43		24		+236
Cheese Souffle	327		180		80		66		108		+252

removal from the oven releases steam (confirming the trapped vapor effect). Additionally, moisture loss continued upon removal from the oven for a period of time which depended upon product characteristics. Another consideration may be the alteration of emissivity of the upper surface of these foods during baking; this could be significant especially if a crust is formed that is not readily permeable. A drier upper surface would result in a lower emissivity. Thus Q_t should be lower than estimated.

The energy balance analyses demonstrate the variability of foods and food types. The processes that occur within each product results in different amounts of heat absorbed (Q_p) and different amounts of heat lost through evaporation of moisture (Q_e). Other processes occur that use heat within the product or which may interfere with the absorption of heat (Q_x).

4.5 Baking Rates for Assorted Foods

Bi-Radiant Oven Performance

The upper and lower baking rates in conventional ovens result from the thermostat setting at which a food in the amount prescribed in a recipe - and in the prescribed baking utensil - is cooked to give the best results. The baking time is usually prescribed as well. The baking rate for the top surface of a product is probably mainly a function of the irradiation incident on the upper surface. The baking rate for the lower surface is a combination of convection and radiation depending on the emissivity of the utensil. The upper and lower baking rates are the true baking rates. True baking rates are more useful in prescribing baking rates for a Bi-Radiant Oven.

The data collected and used to calculate energy balances for baking foods in the Bi-Radiant Oven provide the basis of expressing baking rates by the three methods identified in Table 4.5. In the first column are the irradiation

Table 4.5

Baking Rates - Upper/Lower - for Assorted Food Products

Bi-Radiant Oven II

Food	Product Irradiation (W/m ²)	Product Input Power (W)	Product Power Absorption (W)
Biscuits	5400/3300	156/95	129/79
Meat Loaf	4000/2900	126/72	110/65
Baked Fish	3500/2800	261/168	99/63
Apple Crisp	3500/2800	133/85	46/29
Cornbread	3400/2800	129/85	74/79
Macaroni and Cheese	3700/2200	116/55	40/19
Cheese Scuffle	2600/1800	82/45	41/22

ratios which are measurements in Watts per square meter (W/m^2) of the irradiation incident on the upper and lower surfaces for each product. The irradiation ratio expressed for each food produces an acceptable product in a Bi-Radiant Oven with a utensil having an emissivity of approximately 0.80.

When the surface areas of each product are taken with the irradiation rates and surface emissivities of the product and utensil, product input power rates are derived (Column 2, Table 4.5). For instance, the radiant power incident on the upper surface of all the biscuits in the recipe used was 156 W and for the lower surface, 95 W. Product power absorbed (Column 3) was accounted for by the terms Q_p , Q_u and Q_e (from Eqs. 4-2, 4-3 and 4-4). Upper and lower allocations were made using the ratios shown in Column 2.

The product input power ratio and the product power absorption ratio are both approximations of the energy rates required by each of the foods to produce an acceptable baked product. The ratio of heat rates portrays the actual baking requirements of each of the foods and describes the amount of energy that must be made available to properly bake in any oven - conventional, convection or bi-radiant type. The difference between the product input power ratio and the product power absorption ratio is due to Q_x , the energy that could not be accounted for in the energy balance. This unaccounted for energy (Q_x) varied considerably between the food products used in this study, confirming the heterogeneous nature of the foods and the processes that occur within them during baking. Until Q_x can be further defined, it must be assumed that the true baking rates for upper and lower surfaces must lie somewhere between the input power ratio and the power absorption ratio.

Comparison of Energy Use: Conventional vs. Bi-Radiant Oven

The concern for conservation suggests that the energy consumption for baking the products studied be reviewed (Table 4.6). In every case foods baked in the Bi-Radiant Oven consumed less energy, between 57 and 73 percent less than consumed in a conventional electric range oven. The energy usage for the Bi-Radiant Oven are based on tests performed in the Bi-Radiant Oven II, an early version of the concept which has not been subjected to any optimization. Similar savings have been observed in Bi-Radiant Oven III though testing with foods other than cake had been limited at the time of writing this report.

Table 4.6
Comparison of Energy Use in a Conventional and
the Bi-Radiant Oven for Baking Assorted Foods

Product	Conventional Oven (Wh)	Bi-Radiant Oven (Wh)	Percent Savings (%)
Biscuits	925	249	73
Meat Loaf	1,777	642	63
Baked Fish	824	237	71
Apple Crisp	1,095	380	65
Cornbread	1,085	395	63
Macaroni and Cheese	847	360	57
Cheese Souffle	1,392	565	59

5.0 CONCERNS IN COMMERCIALIZATION

The capability of the Bi-Radiant Oven to produce quality baked products has been demonstrated in the Equipment Laboratory at Purdue University. The heat absorption requirements of baked foods can be met very satisfactorily by thermal radiant power. The levels of radiation for the upper and lower surfaces of various types of foods is being established. Work in the Heat Transfer Laboratory at Purdue University has been directed toward understanding the heat transfer processes within the Bi-Radiant Oven. Computer modeling will be useful in integrating the effects of such entities as element configuration, utensil and oven lining properties and spatial arrangements in the Bi-Radiant Oven to produce the appropriate upper and lower irradiation levels required to bake quality products of all the assorted food types.

Consideration must also be given to consumer acceptability of the Bi-Radiant Oven. Can the Bi-Radiant Oven become accepted as an attractive alternative to a conventional oven for residential use? It can be safely assumed that quality baked and roasted foods can be produced and that the cost of operation will be less because of reduced energy use. The capability of producing designs and orientations of oven components that will provide uniform radiation at the appropriate levels is now within reach. There remain, however, a number of other concerns. Each of these is listed and discussed in light of observations made during research to date.

5.1 Production Costs

How will the cost of production of a Bi-Radiant Oven compare to the cost for conventional electric ovens?

This appears to involve in part a trade-off between the costs of porcelain enamel which is currently being used as a lining for the oven interior and an

alternate material that is highly reflective in the infrared range. This might involve a choice of several materials including:

	<u>Absorptivity</u>
Aluminum	0.04 to 0.06
Chromium	0.08 to 0.26
Iron (polished)	0.05 to 0.37
Porcelain Enamel	~ 0.8

The surface coating could be very thin, since reflectance is a surface phenomenon. A thin reflective surface applied to a rigid insulating material would reduce the oven wall mass that is heated non-productively in an oven.

Insulation, another costly factor, might be considerably reduced since it has been observed that the walls of a bi-radiant oven stay considerably cooler than would be the case for a conventional oven ($< 121^{\circ}\text{C}$ vs. $> 177^{\circ}\text{C}$ for a cake). Exact cost comparisons cannot be made, but a range of options are available to the innovative manufacturer.

5.2 Maintaining Energy Efficiency

Can high energy efficiency be maintained with minimum care (to protect surface finishes, etc.) by the consumer?

It has been observed that temperatures attained by walls in the Bi-Radiant Oven during baking and roasting are considerably lower than in a conventional oven. Less spattering occurs and spillovers that do occur, primarily through careless cooking practices, have not been a problem. Spilled cake batter, for instance, dries but doesn't darken. Partly this is due to the reflective surfaces in the oven. Additionally, the heat produced in the lower element is controlled at a much lower temperature than it is in a conventional oven. The prognosis is that a cleaning process (self-cleaning or continuously cleaning) would not be

necessary for residues from baking or roasting. In ranges which provide surface broiling facilities oven broiling would not need to be considered. Where broiling is to be done in a Bi-Radiant Oven studies should be made of the effects of broiling on various materials and of design options to control spatters such as shields, etc.

5.3 Convenience

Will convenience of and satisfaction in use match or exceed that of a conventional oven?

To understand how the Bi-Radiant Oven can match or exceed consumers' expectations when baking, it is important to understand how baking rates for the upper and lower surfaces of foods are controlled.

In a conventional oven baking rates are determined through the combination of a thermostat selection and the choice of a utensil that absorbs or reflects radiant power depending on the recipe directions and implied appropriate utensil. That is, a 177°C (350°F) thermostat setting might be prescribed for both a layer cake and a casserole. The prescribed utensil for baking a cake is understood to be a bright aluminum that reflects more than ninety percent of the thermal irradiation incident upon it. The prescribed utensil for the casserole is understood to be glass or ceramic material with a high absorptivity of thermal irradiation. Effectively, both the cake and casserole bake from the top down at about the same rate. The baking rates at the bottom of these two products will be very different from each other. Both radiant and convective heat transfer to the bottom surface of the casserole will permit faster absorption of heat by the food than possible for the cake where the bottom surface bakes primarily by convection.

In a Bi-Radiant Oven, where utensils that readily absorb thermal radiation are to be prescribed for all foods, the balance of upper/lower baking rates

can be controlled by the element settings. Studies to categorize foods into five or six sets of upper/lower baking rates are scheduled for 1980-81. In addition to the selector controls for a choice of baking rates it would be possible to provide the user with an overriding control for each element to allow the user to boost or decrease either the upper or lower power rate to provide foods that meet the individual tastes of consumers. For example, if someone wants a browner lower crust on a pizza or a pie he can manipulate the controls to do this. Such control and flexibility would offer a distinct attraction compared to that offered in a conventional oven. The use of micro-computers and other solid state devices would allow the user to provide input about the product and utensil that would ensure the desired characteristics in the product when done. A temperature sensor might be used as well to further automate the cooking process.

It must also be recognized that determining baking and roasting endpoints, without the use of a temperature sensor that will cut off cooking, is always a problem for consumers because of variations in the starting temperatures of foods and variations in the amounts cooked as well as individual preferences for degree of browning and/or doneness. Characteristics of the utensil, such as mass, specific heat, emissivity/absorptivity and size also affect the rate of cooking. These same factors can be expected to influence baking rates in a Bi-Radiant Oven as well. Even so, the problem should not be any greater than that experienced with a conventional oven and certainly less than for a microwave oven where a fifteen second misjudgment for some foods and amounts causes food losses.

5.4 Utensils for Use in the Bi-Radiant Oven

Will the ownership of a Bi-Radiant Oven dictate costly changes in accessories for baking and roasting?

A Bi-Radiant Oven with utensils that readily absorb thermal radiation will result in the most energy efficient oven/utensil system. Many utensils with suitable emissivity characteristics are now available in the marketplace. Some of these materials that have been tested with the Leslie cube technique are:

	<u>Thermal Absorptivity</u>
Enamel Coated	0.79
Black Coating	0.89
Black Painted Foil	0.80

Enamel, pottery, heat treated glass as well as glass ceramic absorb radiation well, withstand thermal shock well and are competitively priced. Black painted foil has reappeared on the market recently and would satisfy the requirements for the most energy efficient utensil for the Bi-Radiant Oven.

Many of these materials, that readily absorb thermal radiation, produce poor quality baked and roasted foods when used in a conventional oven.

In instances when a consumer might want to use a reflective utensil from an "old" oven, baking might be accommodated by increasing the power to the lower element. Tests in the Equipment Laboratory have demonstrated that food quality can be maintained while using reflective utensils at a sacrifice in energy use. Even so, less energy was required in the Bi-Radiant Oven with a reflective utensil than when it was used in a conventional oven.

The greater mass of the glass or glass ceramic utensils increases energy use even though they absorb thermal irradiation well. Even so, the energy use by any of these utensils is considerably less than the 0.7 - 1.0 kWh required to preheat and bake in a conventional oven.

Yellow Cake Layer
Utensil Material vs. Energy Use and Time
Bi-Radiant Oven II

<u>Utensil</u>	<u>Energy Use</u> (kWh)	<u>Baking Time</u> (Min.)
Black ($\alpha = 0.8$)	0.240	19
Shiny ($\alpha = 0.075$)	0.305	20
Heat Treated Glass	0.338	22
Glass Ceramic	0.341	25

The subjects discussed cover the more obvious barriers to commercialization of the Bi-Radiant Oven that have been brought to our attention thus far. Some of the concerns offer opportunities for developing, testing and using new materials for the interior surfaces of the oven or for new ways of providing heat such as gas or new, more responsive resistant heater types. Additionally, controls for the bi-radiant concept should inspire the imaginations of both electronic engineers and marketing specialists.

6.0 PHASE 2 - APPLICATION AND TRANSFER OF THE TECHNOLOGY

At the outset of the project, the second phase was to concern the application of technology developed during the first year's activities and the transfer of this technology to an appliance manufacturer such that the next project would be of a demonstration nature. The two major tasks identified then are still appropriate now and are as follows: Task 1, Parametric studies and system design including subtasks (1) optimization of system performance based upon analytical model results and experimental trials and (2) evaluation of prototype oven configuration(s) and Task 2, Commercialization of the technology including sub-tasks (1) continued 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) and (3) technology transfer: describing the system(s) for manufacture and factors relating to its market potential.

The focus of the Heat Transfer Laboratory group will be the evaluation of a prototype oven presently under construction. The oven features (1) replaceable cavity walls, (2) relocatable heating elements, and (3) controlled venting to the environment. The oven will be instrumented such that relevant heat and mass transfer measurements can be routinely made. Performance of the oven will be compared with analytical models in an attempt to assess the design and possibly optimize performance. Attention will be given to the broiler design since the consumer is likely to desire this feature in a domestic oven. The problem to be addressed is one minimizing the thermal coupling between the heating element and the cavity wall which is in close proximity to the heater. As new experimental results are generated, further discussions will be held with the National Bureau of Standards on the appropriateness of the DOE recommended practices for determining the efficiency of the bi-radiant oven.

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APPENDIX ASTATEMENT OF WORK FOR THE
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 appropriateness 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:

Task 1, Develop experimental facilities/capabilities by

- (1) construction of flexible-design ovens and
- (2) instrumentation/techniques with emphasis on radiant heat flux measurement methods.

Task 2, Develop procedures for obtaining reliable/relevant heat/mass transfer parameters by obtaining and evaluating baseline data for cooking which satisfies food requirements/qualifications.

Task 3, Evaluate the baking process using analytical thermal modeling to identify relevant heat/mass transfer modes

and verify the analyses with experiments.

Task 4, Identify barriers to commercialization and develop strategies to impact research/development tasks, and identify important human factors.

Task 5, 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.

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

Task 2, 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) and (3) technology transfer, e.g. describe the system(s) for manufacture and factors relating to its market potential.

APPENDIX B

TEST CAKE INGREDIENTS AND PROCEDURES

Ingredients

Cake flour	250 g
Sugar	300 g
Baking powder	10 g
Salt	5 g
Shortening	112 g
Milk	250 ml
Vanilla	8 ml
Eggs	96 g

Quick Mix Procedure

1. Have all ingredients at room temperature.
- *2. Have oven cycling at 350°F (177°C).
3. Grease and flour the bottom only of two 8" or two 9" shiny aluminum baking pans.
4. Sift and measure cake flour into large mixer bowl. Measure all other ingredients into mixer bowl.
5. Blend one-half minute on speed one.
6. Scrape bowl and beaters.
7. Beat three minutes on speed four.
8. Weight 354 g batter into an 8" pan or 425 g batter into a 9" pan.
9. Spread batter by tilting pan, then dropping three times onto a hard, flat surface from a height of six inches.
10. Place cake in oven immediately following cycling off. Mark pan where it is facing the door.
- *11. Bake 30 minutes.
12. Test with fingerprint.
13. Weigh cake while in pan.
14. Allow to cool ten minutes and weight before removing from pan.
15. Allow to cool one hour before cutting and evaluating. Cut from front to back through center for testing.

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* Applies to procedures when baking in conventional oven.

APPENDIX C

SAMPLE CALCULATION FOR DETERMINING SPECIFIC HEAT OF FOOD ITEMS (MEAT LOAF)

Ingredients	Mass, M g	Mass Fraction x_i	Specific Heat, $c_{p,i}$ (kJ/kg·K)	$x_i c_{p,i}$
1 lb. ground beef	454	0.3755	3.181	1.194
1/4 lb. ground pork	114	.0943	3.111	.293
1/4 lb. ground veal	114	.0943	3.382	.319
1 c. dry bread crumbs	113	.0935	1.838	.172
1 1/4 c. milk	305	.2523	3.870	.976
1 egg	50	.0414	3.525	.146
1/4 c. minced onion	34	.0281	3.912	.110
1 1/4 t. salt	8	.0066	1.679	.011
1/4 t. each pepper, celery salt, garlic salt, dry mustard, sage	--	--	--	--
1 T. worchest. sauce	15	.0124	--	--
Totals	M = 1209			$c_p = 3.221$