1942

Studies in radiant heat baking.

Edwin F. Schumacher 1912-1966

University of Louisville

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UNIVERSITY OF LOUISVILLE

STUDIES IN RADIANT
HEAT BAKING

A Thesis
Submitted to the Faculty
of the Graduate School
of the University of Louisville
in Partial Fulfillment of
the Requirements
for the Degree of

MASTER OF CHEMICAL ENGINEERING

Department of Chemical Engineering

Edwin F. Schumacher

1942
STUDIES IN RADIANT
HEAT BAKING

Edwin F. Schumacher

Approved by Examining Committees

Director

May 20, 1942
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ACKNOWLEDGEMENT

The Author wishes to acknowledge
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directed this research
ABSTRACT

Comparisons were made between the drying behavior of enamels baked with radiant heat and in a convection oven at equal panel temperatures. No significant differences could be found in the drying behavior of the enamels when baked in the two types of equipment.

Absorptivities were determined for black, green, red, yellow, and white gloss enamels. An analysis was made of the distribution of energy in heating these enamels with radiant heat. A study was made of the influence of convection currents and thermal conduction on radiant heat baking.

The mathematical development of theoretical equations of heating and cooling based on thermodynamic principles was discussed.

The influence of the percentage of polymerizing material in a series of film forming compositions upon the rate of hardening when baked with radiant heat was determined. This gave a picture of what could be done with high temperature, short schedule baking such as is usually obtained with radiant heat baking under good conditions.
INTRODUCTION
The experimental work performed in conjunction with this study consisted of three parts.

Part I - Comparison of Radiant Heat and Convection Oven Baking.

Two commercial baking enamels were used to determine the relative rate of baking of surface coatings with radiant heat and in the convection oven. The enamels were baked at equal panel temperatures. White and black were chosen because they represented the extremes of adaptability to radiant heat baking.

Part II - Thermodynamic Principles for Radiant Heat Baking.

Five synthetic enamels representing five distinct colors were used to determine absorptivities as well as the general distribution of energy in heating at equal densities with radiant heat. These enamels were made from five different pigments. The vehicle consisted of a combination of alkyd and melamine synthetic resins. Heating and cooling data were collected.

Part III - Effect of Chemical Composition of Vehicle on Rate of Film Hardening.

Sward hardness readings were determined for enamels varying in composition from 100% alkyd resin to 100% melamine-urea resins when baked for different lengths of time with radiant heat. In this way the effect of polymerizing material on the rate of film hardening was determined.
HISTORICAL
All the industrial development of radiant heat baking has taken place within the last decade. While heat transfer by radiation has for some years been the subject of study by engineers and physicists because of the part it plays in industrial problems, the creation of an energy source to emit radiant energy solely to furnish the heat necessary for large scale industrial processes is a rather recent innovation. The radiant energy obtained from the sun has been used by man over the years to perform such tasks as the drying of clothing, drying of fruits, and the vaporization of water from salt brine. A few radiant heat developments such as electric strip heaters have been in existence for some time. The development of the tungsten filament radiant heat lamp for industrial baking and heating may be considered a completely new tool in American industry.

The use of radiant heat units in large scale production schedules had its inception several years ago in the Ford Motor Company in Dearborn, Michigan. Many electrical appliance companies have since been engaged in the development and manufacture of radiant heat lamps; consequently, rapid strides have been made in the construction of steadily improving lamps. This progress in construction has been matched with an ever increasing use of radiant heat lamps in industrial processes. Many applications of radiant heat have been used in the baking of protective coatings. Numerous articles have been written on the practical as well as the theoretical aspects of radiant heat baking for this purpose. A new and interesting field has arisen in industrial America, and this new enterprise promises to find a suitable and lasting niche in the American production schedule.
Heat may be transferred by three distinct methods: Conduction, convection, and radiation.

The transfer of heat by conduction involves the passing along, from one layer of molecules to another, the kinetic energy of the molecules in excess of that of the adjacent layer—kinetic energy which the molecules have by virtue of their temperature. Convection is the transfer of energy by mass motion of a large portion of fluid or a gas. Radiation is, however, different in that it may pass apparently unaffected by temperature gradient through successive molecular layers to a distant receiver of radiation. Radiation is the energy emitted in all directions from a hot body in radiant form. When radiant energy strikes another body, part of it may be reflected, part may be transmitted unchanged through the body, and the remainder absorbed and quantitatively transformed into heat. (8)

For the development of the theory of heat transfer by radiation, definitions of terms have been established.

The total emissive power $E_A$ of a surface $A$ is the total radiant energy emitted in all directions from one side of the surface per unit of time, per unit area of the surface.

The absorptivity, $a$, of a surface is the fraction of radiant energy, incident on the surface, which is reflected.

The transmissivity of a substance is the fraction of radiation upon it, which is transmitted through it by radiation.
The sum of absorptivity, reflectivity, and transmissivity equals one. For opaque solids of appreciable thickness, the transmissivity equals zero, and the sum of absorptivity and reflectivity is one.

A black body is a surface which absorbs all the radiation which falls upon it and reflects, transmits, and scatters none.

Although there are no perfectly black surfaces in nature, this concept gives a useful standard for comparing absorptivities of actual surfaces.

Kirchhoff's law states that the total emissive power, $E_x$, of a surface, divided by its absorptivity, $a$, for black body radiation of its own temperature, is the same for all surfaces at a given temperature and is equal to the total emissive power, $E_B$, of a black body at that temperature:

$$\frac{E_x}{a} = E_B$$

According to Kirchhoff's law a black body represents a surface with maximum emissive power at the temperature in question.

The emissivity, $\rho$, of a surface is the ratio of its emissive power to that of a black body:

$$\rho = \frac{E_x}{E_B}$$

Kirchhoff's law states that the emissivity of a surface is numerically equal to its absorptivity at the same temperature:

$$\rho = a$$
The term, $p$, may be used to denote both emissivity and absorptivity.

The emissive power of a black body depends on its temperature only. The Stefan-Boltzmann law states that there is a definite relationship between the total emissive power of a black body and the fourth power of its absolute temperature.

$$E_\varepsilon = \sigma T^4$$

$\sigma$ is a proportionality constant known as the Stefan-Boltzmann constant.

Wien's Displacement Law states that when the temperature of a radiating black body increases, the wave length corresponding to maximum energy decreases in such a way that the product of the absolute temperature and wave length is constant.

$$\lambda_{\text{max}} T = \omega$$

$\omega$ is known as Wien's constant.

The radiant heat lamps used today are chiefly tungsten filament lamps, although carbon filament lamps have been used. Radiant heat lamps are operated at lower filament temperatures than are the lamps used solely for lighting purposes. The greater portion of the energy emitted by radiant heat lamps lies in the near infra-red portion of the spectrum just beyond the visible red. For this reason, radiant heat lamps are popularly called infra-red lamps. According to Wien's displacement law, changes in the filament temperature will be accompanied by changes in the distribution of energy in the spectrum.
Experiments have been conducted on the most suitable filament temperatures for radiant heat lamps. Various temperatures may be used between 1200° and 3200°K. Haynes and Oetting (4) reported that a color temperature of 2500°K. was considered suitable for a drying lamp, and advantages gained from increasing above this temperature would be offset by more rapid lamp deterioration. Ickis and Haynes (7) give curves showing the effect of radiating temperature on the distribution of energy in the spectrum.

Parabolic reflectors are used to redirect the energy emitted by the filament lamp. Gold plating has been found to be the most suitable surface for reflecting energy.

The laws governing radiation would be pertinent to the heating of objects with radiant heat lamps. The character of the receiving surface determines the monochromatic emissivity, $p_\lambda$, and absorptivity, $a_\lambda$, of that surface. If the values of, $p_\lambda$, for an actual body were constant at all wave lengths, the spectral distribution curve for that body would be similar in shape to that for a black body at the same temperature. A body that meets this requirement is known as a gray body. The monochromatic effects may then be ignored when considering total energy exchange. A true gray body will have a total absorptivity and total emissivity unaffected by temperature. The majority of solids approximate the gray body state under conditions of infra-red radiation. This simplifies markedly the calculations involving absorptivities and emissivities. (15)
In the heating of objects by radiant energy, conduction and convection effects control to a great extent the results obtained. The underlying theory of the part these two forms of heat transmission play in the heating of the objects by radiant heat will be treated as the cases arise. In general, much of the theory will be discussed in the section devoted to experimental work so that a closer connection with the prevailing type of work will be maintained.
Part I

Theory and Experimental
When radiant heat lamps were first introduced industrially, startling claims were made for their applicability and advantages in the baking of paint films. It was found that baking schedules of paint products were shortened considerably, and it was at first thought that the infra-red radiation had a catalytic effect on the drying of paint films. This belief had no sound theoretical basis, and several articles soon appeared which suggested methods for disproving the theory. Bennett and Haynes (1) suggested that a time-temperature curve be determined for a specimen under a radiant heat lamp and the baking conditions then be duplicated in a convection oven. They stated that no difference would be found between two such baked films. They also suggested that the shortened baking schedules encountered with radiant heat lamps were probably due to the attainment of higher temperatures, in a shorter time. No experimental results were given.

It was also originally claimed that the type of drying obtained with the lamps was different from that obtained in a convection oven. It was said that paint films baked under the lamps dried from the inside out, the process of film hardening beginning at the metal-paint film interface and then proceeding to the top of the film which was in contact with air. This would mean that a better through dry was obtained, a condition which is always desirable. There is probably no theoretical premise to substantiate such a belief.
The object of this investigation then was to obtain, if possible, experimental data for comparing the rate of baking in the two types of equipment and to make comparisons of the characteristics of the baked films in the two types of equipment.

Since the temperature maintained is usually the governing factor in the rate of baking, the logical procedure would be to make comparisons at equal panel temperatures. This would necessitate the determination of time-temperature curves for any given film baking. The temperature of the panel could be most easily and accurately determined by means of an attached thermocouple. It was decided to determine the time-temperature curve of a paint under the lamp and then try to duplicate it in a convection oven. The drying behavior was to be recorded at given periods of baking time. The determination of drying progress presented several problems. Since the enamels were to be applied by spraying, measurement of Sward hardness was discounted because of inaccuracies arising from variable film thickness. Drying behavior was, therefore, at first determined by empirical methods, surface tack being obtained by pressing the finger flatly on the film, and through dry or toughness by digging the film with the finger nail or knife. This method eventually proved unsatisfactory, and a procedure involving the measurement of Sward hardness was adopted, special film application methods being used.
EXPERIMENTAL

Two baking enamels were made up for the comparison tests. Since the heat energy absorbed in radiant heat baking varies with color, white and black enamels were chosen as representing extremes of adaptability to radiant heat baking. The pigment used in making the white enamel was titanium dioxide while carbon black was used in the black enamel. In both cases the vehicle consisted of a baking type synthetic resin solution, a linseed oil modified glycerol phthalate resin. These enamels were ground in laboratory ball mills. Both enamels were found to bake satisfactorily in a convection oven. The enamels were called Synthetic White #1 and Synthetic Black #1.

The experimental apparatus used for the radiant heat baking tests consisted of a box form framework made from iron pipe, the lamp being fastened to a cross-bar in the top of the box and directed vertically downward on the object being baked. This cross-bar was movable and the lamp could be raised or lowered at will. Three ten inch sticks of small cross section were mounted on a wooden base in such a way that they projected vertically upward. The panel being baked rested on these sticks, thereby minimizing loss by heat conduction through contact, and permitting circulation of air about the panel. During the baking operations, a cardboard draft shield encircled the object being baked. The thermocouple wires were led through an opening in the draft shield to a potentiometer on an adjoining table.
The convection oven apparatus was also very simple. The oven itself was electrically heated, thermostatically controlled, and had an air circulating system. When a panel with a thermocouple attached was being baked, the thermocouple wires were led under the door of the oven to a potentiometer on an adjacent table.

The radiant heat lamps used were manufactured by the C. M. Hall Lamp Company of Detroit, Michigan. These lamps are commercially available under the name of "Thermalamp". The lamps have tungsten filaments, are equipped with gold plated parabolic reflectors, are completely enclosed, and have special lens for distributing energy uniformly.

The convection oven used was made by the Despatch Oven Company. It was a 2900 watt, 220 volt oven, and was equipped with a thermostat for controlling temperature, and an air circulating system.

The potentiometer was a Leeds and Northrup thermocouple potentiometer containing a cold junction correction device. Thermocouples were made from three foot lengths of Leeds and Northrup standard copper and constantan thermocouple wires.

The panels were oval shaped 20 gage steel panels, 6 inches on the long diameter and 5-3/4 inches on the short diameter. These panels were highly polished smooth steel.

Hardness readings were determined with a standard Sward Hardness Rocker as made by the Henry A. Gardner Laboratories of Washington, D.C. This rocker was calibrated to a
reading of 100 ± 3 rocks on a white porcelain plate for all tests.

A copper-constantan thermocouple was soldered to the back of a steel panel for determining the rise in panel temperature under the radiant heat lamp. It was found in heating the black enamel under the lamp that when a temperature of about 360°F. was reached, the thermocouple broke loose. Several types of high melting solders were tried but in each case the thermocouple detached itself. The white enamel caused no difficulty, for the temperatures attained were much lower because of the lower absorptivity of the white. In order to overcome the difficulty caused by the black coated panels, the distance between the lamp and the panel was increased. In this way the final temperature reached could be kept below 350°F. This lowering of temperature by increasing distance was due primarily to increased convection losses and decreased heat density at the receiving plane. This will be explained more completely in part II. The final temperature attained under the lamp also had to be kept within the heating range of the convection oven.

Using Synthetic Black Enamel #1, a time-temperature heating schedule was established by baking a sprayed panel under the lamp at a distance of twelve inches. These data are shown in Table I. Since this heating curve was to be duplicated in the convection oven, some preliminary tests had to be made with the oven also. An uncoated panel equipped with a thermocouple was placed in the oven and comparisons
were made between the temperature indicated by the thermocouple and the oven temperature as indicated by a mercury thermometer. For all readings taken the oven was allowed to attain an equilibrium temperature. The readings obtained by the two methods at various settings of the thermostat are shown in Table II. The results were considered sufficiently accurate for the experimental work planned. The heating of panels in the convection oven offered another problem. The thermostat could be set for any desired temperature, and this temperature could be maintained within limits of 10°F, but in opening the door of the oven to insert a panel, the oven temperature always dropped somewhat, and a short time was required for it to reach equilibrium again. The panel temperature curves obtained in the heating of the black and white enamels in the oven at two different settings is given graphically in Figure I.

Since a final panel temperature of 335°F. was obtained for the black enamel under the lamp, the thermostat on the convection oven was set for this temperature and a time-temperature heating curve was determined for baking the panel in the oven. The observed data are given in Table III. The plotting of the radiant heat time-temperature data and those obtained for the convection oven are shown in Figure II. The heating up portion of the radiant heat curve lagged the oven panel temperatures all the way, primarily because of the high convection losses obtained in baking at the farther distance from the lamp. By baking at a closer distance the
Table I.

Radiant Heat Baking

Synthetic Black Enamel #1

<table>
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Panel 12 inches from lamp

Room Temperature - 71.5°F.
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</table>

Room Temperature 80.5 °F.
FIGURE 1: TIME-TEMPERATURE CURVES

-△ OVEN TEMPERATURE - SYNTHETIC BLACK ENAMEL #1
-× PANEL TEMPERATURE - SYNTHETIC BLACK ENAMEL #1
-○ OVEN TEMPERATURE - SYNTHETIC WHITE ENAMEL #1
-○ PANEL TEMPERATURE - SYNTHETIC WHITE ENAMEL #1
Table III
Convection Oven Baking
Synthetic Black Enamel #1

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<td>12</td>
<td>7.50</td>
<td>336</td>
</tr>
<tr>
<td>15</td>
<td>7.50</td>
<td>336</td>
</tr>
</tbody>
</table>

Thermostat set for 335° - 336°F.
Figure 11: Time-Temperature Curves

Radiant Heat vs. Convection Oven

Synthetic Black Enamel #1
heating up portion of the curve could have been duplicated, but the final temperature attained would have been higher.

While the experimental conditions used to obtain these curves were maintained, a series of panels were baked under the lamp and in the oven for various lengths of time and the condition of dry noted. The enamel was applied by spraying, and each panel was allowed to stand in the air for a definite period of time (7 minutes) before the baking was begun. For both types of equipment, panels were baked for total periods of 3, 5, 7, 8, 10, and 15 minutes. The observations made on drying behavior are given in Table IV. In making these observations, the personal element was always a factor. The controlling of film thickness in spraying was also a troublesome feature. In general, fairly uniform films were obtained.

From this comparison no significant differences could be noted between the two types of baking for this particular enamel. Even though the heating up period was slower under the lamp, no adverse effect of consequence was noted on the drying behavior of the enamel. At the end of three minutes the panel under the lamp was definitely stickier than the one removed from the oven, but both were in a very tender stage of drying, and the oven panel had the advantage of warm convection currents as well as slightly higher temperatures.

While this series indicated conclusions, the testing methods were not considered sensitive enough, the personal element being predominant. A new series was therefor
Table IV
Comparison of Radiant Heat and Convection Oven Baking
Synthetic Black Enamel #1

<table>
<thead>
<tr>
<th>Baking Time</th>
<th>Condition of Film</th>
<th>Radiant Heat Lamp</th>
<th>Convection Oven</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minutes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Surface Tack</td>
<td>Still wet</td>
<td>Set to touch</td>
</tr>
<tr>
<td></td>
<td>Toughness</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Surface Tack</td>
<td>Very Slight</td>
<td>Slight</td>
</tr>
<tr>
<td></td>
<td>Toughness</td>
<td>Poor</td>
<td>Poor</td>
</tr>
<tr>
<td>7</td>
<td>Surface Tack</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Toughness</td>
<td>Fair</td>
<td>Fair</td>
</tr>
<tr>
<td>8</td>
<td>Surface Tack</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Toughness</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>10</td>
<td>Surface Tack</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Toughness</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>15</td>
<td>Surface Tack</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Toughness</td>
<td>Very Good</td>
<td>Very Good</td>
</tr>
</tbody>
</table>
inaugurated using Sward hardness readings as an index to drying progress.

The comparison of the two types of baking by using Sward hardness readings necessitated much experimental work in order to develop suitable testing methods and technique. The measurement of Sward hardness under ideal conditions demands diligent care, but the features of this comparison were such that additional factors had to be watched and the testing carried out to conform to the other requirements of the investigation.

A smooth glass surface is ideally suited to the measuring of Sward hardness. In this comparison, however, a fundamental requirement was that the baking be performed at equal temperatures in the two types of equipment. Glass panels offered some difficulties. These were:

1. It would be difficult to determine actual panel temperature.

2. Heat transfer by conduction is slow in glass.

3. Glass is not representative of materials commonly used in industrial finishing.

Metal panels were therefore used in this testing scheme.

Two essential requisites for obtaining reproducible and comparable results from hardness readings are that the testing surface be smooth and level, and that the thickness of the film being tested be of constant depth.

The fulfilling of the first requirement given above demanded much laboratory work. Suitable panels had to
be selected. The selection of panels was done by visual inspection and determination of Sward rocker readings on the bare metal panels. The Sward Rocker was calibrated to give a reading of $100 \pm 3$ rooks on a standard white porcelain plate. This rocker setting was high, but the higher sensitivity was found advantageous in the comparisons. Throughout the tests the rocker was calibrated to this reading. A number of panels were examined for uniformity and smoothness. Rocker readings were then made on the bare panels in order to select those which yielded equal rocker readings. This process consumed much time, and the technique used for measuring the rocker readings was varied until a method of measurement was found which was considered to give reproducible results. It was found that a panel could not be laid flat upon a level surface for rocker determination as the slightest irregularity in the panel itself caused notable variations in the rocker readings. The method which was considered the most reliable and successful proceeded as follows: A smooth heavy marble slab was used as a foundation. Two wooden blocks of equal thickness were laid upon the slab and so placed that the metal panel could be supported between them at a distance of about $\frac{1}{2}$ inch from the ends of the panel. Pencil marks were made upon these blocks, and each time the panel was suspended the same way and supported the same distance from the ends. The whole system was then leveled so that the panel was in a horizontal plane. A sketch of
this laboratory set-up is shown in Figure III. It was found that in using this system, rocker readings were reproducible even for extremely high readings.

Five panels were selected to be used in these tests. These panels were numbered and were used throughout the tests. Where comparisons were made between the two types of baking, the same panel was used under both conditions. The enamel films were removed with paint and varnish remover after each baking. The readings obtained for the bare metal panels were as follows:

<table>
<thead>
<tr>
<th>Panel Number</th>
<th>Average Rocker Reading</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>72</td>
</tr>
<tr>
<td>2</td>
<td>73</td>
</tr>
<tr>
<td>3</td>
<td>74</td>
</tr>
<tr>
<td>4</td>
<td>73</td>
</tr>
<tr>
<td>5</td>
<td>82</td>
</tr>
</tbody>
</table>

Panel #5 was higher in reading than the other panels. This was, however, the closest to be found among the available panels, and tests made upon baked films showed that the differences in bare metal panels had little effect on the hardness readings of the films themselves. The fact that all the comparisons were made on the same panel also minimized this difference.

The effect of film thickness on reproducibility of results required some study also. In these tests a Bird applicator was used to cast the films. The production of films of constant depth with this applicator is dependent
APPARATUS FOR DETERMINING HARDNESS

FIGURE III
largely on the experience of the operator. The Bird applicator is essentially a rectangular heavy metal block, having a wedge cut out. It is a carefully machined instrument, and the wedge portion is slightly higher than the horizontal plane upon which the applicator would rest in use, thus permitting paint to pass under it and deposit a film. To apply a film the applicator is placed upon the testing surface and a small amount of paint is spooned under the wedge. The applicator is then pulled along the surface, depositing the film as it traverses. It casts a film two inches wide and approximately 0.003 inches thick. The author has made a number of tests on the reproducibility of film thickness with this applicator by measuring the films deposited with an Ames Film Thickness Gauge and has found that two factors are essential for producing films of constant depth. These factors for any given paint are that the volume of paint placed under the wedge should be nearly equal in all cases, and that the rate of speed with which the applicator is drawn should be constant each time. With practice films of suitable constancy can easily be made.

Two enamels were used for the tests. Both were synthetic baking enamels and were obtained from commercial manufacturers. The white enamel, Commercial White Enamel, was made from titanium dioxide, and the vehicle portion consisted of 75% glycerol phthalate resin and 25% melamine resin. The black enamel, Commercial Black Enamel, was made from bone black and carbon black pigments, and the vehicle
portion consisted of 75% glycerol phthalate resin and 25% urea-formaldehyde resin. Both enamels were considered acceptable for industrial baking.

Since the film applied with a Bird applicator was only two inches wide, and the panel itself was 5 1/2 inches wide, there was a section of exposed metal on each side of the film on every panel. In convection oven baking this made no difference, but in radiant heat baking the heat absorptive properties of the surfaces were affected. For purposes of comparison this was not worrisome, as the time-temperature curves were to be established under the lamp and then duplicated in the oven. The nature of the curve obtained under the lamp using a panel having a film cast on it was, however, different from one completely covered with the enamel by spraying.

The first comparisons were made using the white enamel. The testing procedure was as follows. The panels were numbered one to five so that when direct comparisons were to be made the proper panel could be identified and used. A film 0.003 inch thick was cast on a panel equipped with a thermocouple. The panel was allowed to stand two minutes and was then placed at a distance of nine inches under the lamp. A time-temperature curve was obtained for this bake by measuring the panel temperature at regular time intervals. Using the same lamp set-up and identical testing methods, the enamel was baked on the selected panels for various lengths of time. Panels were baked for 6, 9, 12, 15, and 18 minutes. When the total baking time had elapsed,
the panel was quickly removed from under the lamp, allowed to cool to room temperature, and its Sward hardness determined. From three to five readings were taken on every panel and an average value computed. Remarks were also made concerning the surface tack and toughness of the film.

These tests were then repeated in the convection oven. In every case where a panel had been used for a bake for a certain length of time under the lamp, the same panel was used to perform this bake in the convection oven. Thus for a total baking time of six minutes, the same panel was used for both types of baking. The time-temperature curve derived for the radiant heat bakes was used as a basis for making the convection oven setting. Difficulties were encountered in trying to match this curve. When the oven was set to yield a final panel temperature equal to that obtained under the lamp, the heating up period was found to be considerably more rapid in the oven. When the oven temperature was lowered somewhat, the heating up period more nearly approached that obtained under the lamp, but the final panel temperature was, of course, lower. This condition greatly complicated the comparisons. Data were therefore collected for both oven settings, and bakes were made for time intervals corresponding to those used for the lamp at both settings. The comparison was first made using an oven setting in which the final panel temperature was equal to that obtained under the lamp, but the heating up period was more rapid, and then another one was made where the heating up period conformed closely to that obtained under the lamp, but the final panel
temperature was lower. The time-temperature data representing the three conditions are given in Tables V, VI, and VII. The plotted curves are shown in Figure IV.

It will be noted that the heating up period under the lamp appreciably lagged that of the oven set for 310°F. The extent of the temperature differences in the early stages can be shown from the following figures:

- At 1 minute - Radiant heat panel was 34°F. lower.
- At 2 minutes - Radiant heat panel was 35°F. lower.
- At 3 minutes - Radiant heat panel was 23°F. lower.
- At 4 minutes - Radiant heat panel was 20°F. lower.
- At 5 minutes - Radiant heat panel was 15°F. lower.

After fifteen minutes the panel temperatures were only 3°F. apart. The differences in temperature during the heating period had a marked effect on the drying data collected for the two conditions. When the oven was set for 200°F., the difference in temperature between panels heated in it and those baked under the lamp were lowered substantially in the very early stages of the bake and from Figure IV are seen to cross at a point equivalent to five minutes of baking time. After they had crossed, the radiant heat curve had a continuous temperature advantage over the oven curve.

Rocker readings were obtained for the three conditions represented by these curves, and all the data collected are given in Table VIII.

The hardness readings given in Table VIII are shown plotted in Figure V. As was to be expected, panels baked in the convection oven at a temperature of 310°F.
Table V.
Radiant Heat Baking
Commercial White Enamel

<table>
<thead>
<tr>
<th>Minutes</th>
<th>Millivolts</th>
<th>Panel Temperature °F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>.25</td>
<td>1.07</td>
<td>106</td>
</tr>
<tr>
<td>.50</td>
<td>2.00</td>
<td>121</td>
</tr>
<tr>
<td>1</td>
<td>2.89</td>
<td>158</td>
</tr>
<tr>
<td>1.5</td>
<td>3.52</td>
<td>184</td>
</tr>
<tr>
<td>2</td>
<td>4.11</td>
<td>207</td>
</tr>
<tr>
<td>2.5</td>
<td>4.60</td>
<td>226</td>
</tr>
<tr>
<td>3</td>
<td>5.01</td>
<td>242</td>
</tr>
<tr>
<td>4</td>
<td>5.60</td>
<td>265</td>
</tr>
<tr>
<td>5</td>
<td>6.00</td>
<td>280</td>
</tr>
<tr>
<td>6</td>
<td>6.22</td>
<td>289</td>
</tr>
<tr>
<td>8</td>
<td>6.48</td>
<td>298</td>
</tr>
<tr>
<td>10</td>
<td>6.62</td>
<td>304</td>
</tr>
<tr>
<td>12</td>
<td>6.70</td>
<td>307</td>
</tr>
<tr>
<td>15</td>
<td>6.75</td>
<td>308</td>
</tr>
<tr>
<td>18</td>
<td>6.78</td>
<td>310</td>
</tr>
<tr>
<td>25</td>
<td>6.90</td>
<td>314</td>
</tr>
</tbody>
</table>

Panel 9 inches from lamp
Room Temperature 80.5°F.
Table VI.

Convection Oven Baking

Commercial White Enamel

<table>
<thead>
<tr>
<th>Minutes</th>
<th>Millivolts</th>
<th>°F.</th>
<th>°F.</th>
</tr>
</thead>
<tbody>
<tr>
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<td>2.19</td>
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<td>304</td>
</tr>
<tr>
<td>.75</td>
<td>3.29</td>
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</tr>
<tr>
<td>1</td>
<td>3.75</td>
<td>192</td>
<td>304</td>
</tr>
<tr>
<td>1.5</td>
<td>4.49</td>
<td>222</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>5.01</td>
<td>242</td>
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</tr>
<tr>
<td>2.5</td>
<td>5.46</td>
<td>260</td>
<td></td>
</tr>
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<td>5.74</td>
<td>270</td>
<td>307</td>
</tr>
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<td>4</td>
<td>6.12</td>
<td>285</td>
<td>308</td>
</tr>
<tr>
<td>5</td>
<td>6.39</td>
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<td>310</td>
</tr>
<tr>
<td>10</td>
<td>6.80</td>
<td>310</td>
<td>310</td>
</tr>
<tr>
<td>12</td>
<td>6.81</td>
<td>310.5</td>
<td>311</td>
</tr>
<tr>
<td>15</td>
<td>6.82</td>
<td>311</td>
<td>310</td>
</tr>
<tr>
<td>18</td>
<td>6.82</td>
<td>311</td>
<td>310</td>
</tr>
<tr>
<td>21</td>
<td>6.86</td>
<td>312.5</td>
<td>312</td>
</tr>
</tbody>
</table>

Thermostat set for 310°-311°F.
Table VII.
Convection Oven Baking
Commercial White Enamel

<table>
<thead>
<tr>
<th>Minutes</th>
<th>Panel Temperature</th>
<th>Oven Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Millivolts</td>
<td>°F.</td>
</tr>
<tr>
<td>.25</td>
<td>1.89</td>
<td>116</td>
</tr>
<tr>
<td>.75</td>
<td>3.00</td>
<td>163</td>
</tr>
<tr>
<td>1</td>
<td>3.36</td>
<td>177</td>
</tr>
<tr>
<td>1.5</td>
<td>4.11</td>
<td>207</td>
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<td>4.69</td>
<td>229</td>
</tr>
<tr>
<td>3</td>
<td>5.31</td>
<td>254</td>
</tr>
<tr>
<td>4</td>
<td>5.72</td>
<td>270</td>
</tr>
<tr>
<td>5</td>
<td>5.97</td>
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<tr>
<td>6</td>
<td>6.03</td>
<td>282</td>
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<td>8</td>
<td>6.19</td>
<td>287.5</td>
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<td>6.19</td>
<td>287.5</td>
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<tr>
<td>12</td>
<td>6.23</td>
<td>289</td>
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<tr>
<td>15</td>
<td>6.23</td>
<td>289</td>
</tr>
<tr>
<td>20</td>
<td>6.23</td>
<td>289</td>
</tr>
<tr>
<td>25</td>
<td>6.23</td>
<td>289</td>
</tr>
</tbody>
</table>

Thermostat set for 288°-289°F.
Figure IV: Time-Temperature Heating Curves

Radiant Heat and Convection Oven Baking

Commercial White Enamel
Table VIII.
Sward Hardness Readings
Commercial White Enamel

<table>
<thead>
<tr>
<th>Total Baking Time</th>
<th>Average Rocker Readings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minutes</td>
<td>Radiant Heat</td>
</tr>
<tr>
<td>6</td>
<td>8.2</td>
</tr>
<tr>
<td>9</td>
<td>13.8</td>
</tr>
<tr>
<td>12</td>
<td>23.6</td>
</tr>
<tr>
<td>15</td>
<td>25.8</td>
</tr>
<tr>
<td>18</td>
<td>30</td>
</tr>
</tbody>
</table>
Figure V: Sward Hardness Curves

Commercial White Enamel

- Radiant Heat
- Convection Oven 288°F
- Convection Oven 310°F
showed decidedly more rapid film hardening than did like panels baked under the lamp. This was especially true during the earlier stages of the bake and was diminishing toward the end. The readings taken on panels baked at 288°F. in the oven were higher than those obtained for radiant heat baking in the earlier stages of the baking, but lower in the later stages. The hardness curves of Figure V, however, followed a pattern that probably would have been predicted from the time-temperature curves shown in Figure IV. The 310°F., oven curve shows its continued temperature differential advantage, but this was diminished toward the end. The comparison between the 288°F. curves and those obtained with radiant heat show that in both cases the curves cross, the elevated temperature of the lamp in the later stages of the bake manifesting its effect on the hardness reading in the very late stages. The notes on surface tack and toughness again show that while such comparisons are indicative of the relative drying behavior, they cannot be considered more than approximations. These results are shown in tabular form in Table IX.

A similar series of baking tests were made using the black enamel. The time-temperature curve was established under the lamp, the panel being baked at a distance of ten inches from the lamp. Maintaining the set-up and procedure, panels were baked for 6, 12, 18, and 24 minutes. The testing procedure was identical with that used for the white enamel, and the same type data were collected. The maximum
Table IX.
Comparison of Radiant Heat and Convection Oven Baking
Commercial White Enamel

<table>
<thead>
<tr>
<th>Baking Time</th>
<th>Surface Tack</th>
<th>Radiant Heat</th>
<th>Condition of Film</th>
<th>Oven at 310°F</th>
<th>Oven at 299°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minutes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Surface Tack</td>
<td>Bad - Sticky</td>
<td>Slight</td>
<td>Fair</td>
<td>Fair</td>
</tr>
<tr>
<td></td>
<td>Toughness</td>
<td>Poor</td>
<td></td>
<td></td>
<td>Mediu</td>
</tr>
<tr>
<td>9</td>
<td>Surface Tack</td>
<td>Very Slight</td>
<td>None</td>
<td>Fair</td>
<td>Very Slight</td>
</tr>
<tr>
<td></td>
<td>Toughness</td>
<td>Fair</td>
<td>Fair - Good</td>
<td></td>
<td>Fair</td>
</tr>
<tr>
<td>12</td>
<td>Surface Tack</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Toughness</td>
<td>Fair - Good</td>
<td>Good</td>
<td></td>
<td>Fair - Good</td>
</tr>
<tr>
<td>15</td>
<td>Surface Tack</td>
<td>None</td>
<td>None</td>
<td>Very Good</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Toughness</td>
<td>Good</td>
<td></td>
<td>Good</td>
<td>None</td>
</tr>
<tr>
<td>18</td>
<td>Surface Tack</td>
<td>None</td>
<td>None</td>
<td>Very Good</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Toughness</td>
<td>Very Good</td>
<td></td>
<td>Excellent</td>
<td>Good-Very Good</td>
</tr>
</tbody>
</table>
temperature attained under the lamp with this set-up was 314°F. In making a time-temperature curve for the convection oven, the thermostat was set for 314°F. For this setting it was found that the time-temperature curve was reasonably close to that obtained for the lamp. The data collected for the time-temperature curves are given in Tables X and XI. The curves are shown in Figure VI.

An examination of these time-temperature curves shows that the temperature of the panels under the lamp were consistently lower than those obtained for the panels in the convection oven in the very early stages of the heating period. At the end of five minutes, however, the difference in temperature was but 8°F., and from that point the differences became progressively smaller.

Panels were baked in the oven for periods of time equivalent to those used for the radiant heat tests. The Sward hardness readings were determined for all panels and these data are given in Table XII. In Figure VII these data are shown plotted.

In Figure VII the radiant heat hardness curve is lower than the convection oven curve during the first part of the baking. This is in accord with the time-temperature curves. Toward the end of the bake the radiant heat curve overtook and crossed to a position slightly above that of the convection oven. The curves were plotted on a rather large scale and the differences between the two curves at the last two points are but 1.6 and 1.2 rocks for the 13 and 24 minute
Table X
Radiant Heat Baking
Commercial Black Enamel

<table>
<thead>
<tr>
<th>Minutes</th>
<th>Millivolts</th>
<th>Panel Temperature °F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>1.70</td>
<td>108</td>
</tr>
<tr>
<td>0.5</td>
<td>2.20</td>
<td>129</td>
</tr>
<tr>
<td>1</td>
<td>3.10</td>
<td>167</td>
</tr>
<tr>
<td>1.5</td>
<td>3.71</td>
<td>191</td>
</tr>
<tr>
<td>2</td>
<td>4.41</td>
<td>218</td>
</tr>
<tr>
<td>2.5</td>
<td>4.97</td>
<td>240</td>
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<tr>
<td>3</td>
<td>5.41</td>
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<td>6.01</td>
<td>281</td>
</tr>
<tr>
<td>5</td>
<td>6.57</td>
<td>294</td>
</tr>
<tr>
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<td>6.57</td>
<td>302</td>
</tr>
<tr>
<td>8</td>
<td>6.82</td>
<td>311</td>
</tr>
<tr>
<td>10</td>
<td>6.85</td>
<td>312</td>
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<tr>
<td>12</td>
<td>6.91</td>
<td>314</td>
</tr>
<tr>
<td>15</td>
<td>6.91</td>
<td>314</td>
</tr>
<tr>
<td>20</td>
<td>6.91</td>
<td>314</td>
</tr>
<tr>
<td>25</td>
<td>6.91</td>
<td>314</td>
</tr>
</tbody>
</table>

Panel 10 inches from lamp
Room Temperature 75°F.
### Table XI.

**Convection Oven Baking**

**Commercial Black Enamel**

<table>
<thead>
<tr>
<th>Minutes</th>
<th>Panel Temperature</th>
<th>Oven Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Millivolts</td>
<td>°F.</td>
</tr>
<tr>
<td>.25</td>
<td>2.11</td>
<td>126</td>
</tr>
<tr>
<td>.75</td>
<td>3.39</td>
<td>174</td>
</tr>
<tr>
<td>1</td>
<td>3.71</td>
<td>191</td>
</tr>
<tr>
<td>2</td>
<td>5.13</td>
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<td>3</td>
<td>5.90</td>
<td>276</td>
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<td>4</td>
<td>6.31</td>
<td>292</td>
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<td>5</td>
<td>6.57</td>
<td>302</td>
</tr>
<tr>
<td>6</td>
<td>6.74</td>
<td>308</td>
</tr>
<tr>
<td>8</td>
<td>6.89</td>
<td>313.5</td>
</tr>
<tr>
<td>10</td>
<td>6.91</td>
<td>314</td>
</tr>
<tr>
<td>12</td>
<td>6.98</td>
<td>315</td>
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<tr>
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<td>6.95</td>
<td>315</td>
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<td>6.95</td>
<td>316</td>
</tr>
<tr>
<td>25</td>
<td>6.95</td>
<td>316</td>
</tr>
</tbody>
</table>

Thermostat set for 314°-315°F.
**Figure VI** Time-Temperature Heating Curves

Radiant Heat and Convection Oven Baking

Commercial Black Enamel
Table XII
Sward Hardness Readings
Commercial Black Enamel

<table>
<thead>
<tr>
<th>Total Baking Time</th>
<th>Average Rocker Readings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Radiant Heat</td>
</tr>
<tr>
<td>Minutes</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td>12</td>
<td>20.6</td>
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<tr>
<td>18</td>
<td>28.4</td>
</tr>
<tr>
<td>24</td>
<td>30</td>
</tr>
</tbody>
</table>
readings respectively. That these curves should follow the same contour as closely as they did, is good evidence that they are at very nearly equivalent drying stages when subjected to nearly equal baking temperatures for equal lengths of time.

Notes on drying behavior were also made and are given in Table XIII. The previously mentioned limitations of such observations also apply to this set of data. The Wilkinson Pencil Method of measuring film toughness (2) was attempted, but it did not seem dependable, for slight variations in technique caused great variations in the results obtained.
Table XIII.
Comparison of Radiant Heat and Convection Oven Baking

Commercial Black Enamel

<table>
<thead>
<tr>
<th>Baking Time (Minutes)</th>
<th>Condition of Film</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Radiant Heat</td>
</tr>
<tr>
<td>6 Surface Tack</td>
<td>Very Slight</td>
</tr>
<tr>
<td>Toughness</td>
<td>Fair</td>
</tr>
<tr>
<td>12 Surface Tack</td>
<td>None</td>
</tr>
<tr>
<td>Toughness</td>
<td>Good</td>
</tr>
<tr>
<td>18 Surface Tack</td>
<td>None</td>
</tr>
<tr>
<td>Toughness</td>
<td>Very Good</td>
</tr>
<tr>
<td>24 Surface Tack</td>
<td>None</td>
</tr>
<tr>
<td>Toughness</td>
<td>Excellent</td>
</tr>
</tbody>
</table>
CONCLUSIONS
The experimental data collected for the enamel used in this work have indicated that there is no essential difference in the rate of drying or film hardening between the enamels baked under radiant heat lamps and in the convection oven if the materials being baked are kept at the same temperature level. For the enamels employed the type drying was found to be generally the same.

The tests made with the commercial black enamel were conclusive. In these tests few of the difficulties which arose in baking whites were present. Black of all the colors is the most efficient absorber of radiant heat, and the time-temperature curve of the black enamel under the lamp conformed closely enough with that obtained in the oven under the conditions of the test. This made the comparison of the two types of baking rather easy, and yielded good experimental data.

The difficulties encountered with the white enamel were caused by an inability to match time-temperature curves. White reflects much radiant energy and absorbs relatively little. This property was manifested in the long heating up periods encountered in baking the white enamel under the lamp. The long, gradual heating up period did not conform at all with that obtained in the oven, and it would have been difficult to slow the oven period down to conform
with that of the lamp. This led to the method of determining data at two oven conditions - one in which the final panel temperature was equal to that obtained under the lamp but the heating up period was considerably faster, and the other in which the heating up period conformed rather closely but the final panel temperature was lower. From the time-temperature curves and the Sward hardness curves it seems evident that the degree of hardening would be much the same under the two baking methods, if the baking could be performed under comparable conditions. The pattern followed by the Sward hardness is in keeping with the nature of the time-temperature curves.

It will be noted that in the comparisons the period of baking was not extended very long. It was thought that in any baking work the aim would be to obtain the desired film drying in the shortest period of time, and therefore, in comparing the two types of baking, the early stages would be the critical ones, and comparisons involving long baking schedules would not be representative of the information sought.

Since panels of equal mass were used in the comparison, the attainment of like baking schedules would represent the utilization of equal amounts of heat energy. Experimental difficulties prevented complete conformity with this ideal. The experimental results do show, however,
that where nearly equal amounts of energy were utilized, the drying process was nearly equal, limited, of course, by the sensitivity of the testing methods employed. This then would indicate that the results obtained in the use of radiant heat lamps are governed solely by thermodynamic principles. This has generally been considered to be true in the more recent publications. In Part II the factors which determine the adaptability of radiant heat baking will be treated. The enamels used in this last comparison contained a fairly large percentage of polymerizing type resin. The premise established that film hardening in the two types of equipment is a function of heat energy utilized will of necessity be limited somewhat by the chemical properties of the enamel. A protective coating that dries entirely by oxidation would probably dry more rapidly in a convection oven because of air circulation.
Part II
Theory and Experimental
The results obtained in baking with radiant heat may be subjected to mathematical analysis by thermodynamic principles. In heating an object with radiant heat all three forms of heat transmission, conduction, convection and radiation are involved. While the energy source is entirely radiant heat, conduction and convection effects materially influence the temperature rise obtained in the object being heated.

Cartwright and Strong (12) give procedures for precise measurement of radiant energy. Their treatment of the subject forms a good basis for the analysis of energy distribution in commercial radiant heat baking. The following excerpts will aid in the mathematical development.

A radiometric instrument consists of a blackened receiver, which is heated by the radiant energy to be measured. The instrument is provided with some physical means for measuring the rise in temperature of the receiver produced by the radiant energy. In infrared spectroscopy, the radiometric instrument is the most sensitive instrument now available. When a radiometric instrument is giving its full response to a beam of light incident on the receiver, the rate at which the heat is lost by the receiver is in equilibrium with the rate at which heat is absorbed from the light beam, \( \phi_a \). Inasmuch as the heat lost by the receiver is proportional to the produced rise in temperature, \( \Delta T \), we can write

\[
\phi_a = L_1 \Delta T + L_2 \Delta T + L_3 \Delta T + L_4 \Delta T
\]
where the L's represent the heat losses in unit time per unit temperature change. Thus, $L_1$ represents the loss of heat by radiation from the receiver, $L_2$ the loss by air conduction, $L_3$ the loss by conduction through members touching the receiver, $L_4$ any other means of losing heat, such as, in the case of a thermopile, Peltier heat loss. Obviously, it is desirable to have the L's small, and for this reason the energy is to be concentrated onto a small receiver to reduce $L_1$. Furthermore, the receiver is usually mounted in a high vacuum in order to make $L_2$ vanish."

The heating of any object by radiant heat follows the principle given above that the rate at which heat is lost by the receiver is in equilibrium with the rate at which heat is absorbed from the energy source. The measurement of radiant energy is most effectually accomplished by reducing losses to a minimum. Industrial radiant heat baking is, however, accompanied by these losses, and it is the scope of this portion of the thesis to evaluate them. The most efficient operation of industrial baking would be that which holds losses to a minimum, thus allowing a maximum of available energy to produce a greater rate of temperature rise in the object being baked. This is shown in the equation given above, for at a constant rate of energy absorption, $\Delta T$ will be greatest when the rate of heat loss by conduction, convection, and radiation is lowest, and will decrease directly with an increase in rate of heat loss.
The experimental work was carried out in a manner consistent with conditions likely to prevail in industrial baking. The equipment was on a laboratory scale. The Thermodynamic treatment of radiant heat baking given by Goodell (3) was used as a basis for the laboratory work. The ensuing mathematical development was taken bodily from Goodell's publication. All equations in Goodell's treatment have been expressed in terms of rate of temperature change. A change in nomenclature will be made here in order to avoid confusion at another portion of this thesis. The symbol \( n \) will be used in place of the \( k \) used by Goodell for the proportionality constant in Newton's Law of Cooling.

If one considers the heating of a thin object from the standpoint of energy required to raise it to a given temperature, the following equation would hold:

\[
Q = \text{sm} \Delta t
\]  
\( (1) \)

where 
- \( Q \) = Btu's per minute
- \( s \) = specific heat of object
- \( m \) = mass in pounds
- \( \Delta T \) = temperature rise in degrees Fahrenheit

One Btu per minute is equivalent to 17.58 watts. The mass may be expressed as \( \rho A d \), where \( \rho \) is density in pounds per cubic inch, \( A \) is area in square inches, and \( d \) is thickness in inches. Therefore

\[
\text{Watts} = 17.58Q = 17.58 \times (\rho A d) \Delta t \]  
\( (2) \)

The energy received can be expressed in watts per square inch and the \( A \) term then becomes unity.
As the object is being heated, heat losses are encountered. Newton’s law of cooling states that the rate of heat loss from any body to its surroundings is proportional to the difference in temperature between that body and its surroundings. These losses, as given in Newton’s law, are both radiation and convection losses. The law is approximately true when the difference of temperature is not large. Newton’s law of cooling may be expressed mathematically as follows:

\[ \frac{dt}{d\theta} = n (t - t_a) \quad \text{where } n < 0 \quad (3) \]

Here \( t \) = temperature of the object
\( t_a \) = surrounding temperature
\( n \) = proportionality constant

Separating the variables and forming the integral

\[ \int_{t_0}^{t} \frac{dt}{t - t_a} = \int_{0}^{\theta} n \, d\theta \quad (4) \]

The limits of the integration are determined by the mass cooling from \( t_0 \) to a temperature \( t \) at a time \( \theta \). Integration of equation (4) gives

\[ \log_e \left(\frac{t - t_a}{t_0 - t_a}\right) = n \theta \quad (5) \]

or solving for \( t \) to obtain the theoretical time-temperature cooling curve

\[ t = t_a + (t_0 - t_a)e^{n\theta} \quad \text{where } n < 0 \quad (6) \]

Assuming a constant lamp energy output and no heat losses (conduction, convection, and radiation), the
rise in temperature would become a function of energy received and time and would be theoretically limitless. Mathematically this could be expressed as

$$\frac{dt}{d\theta} = h$$  \hspace{1cm} (7)

Here \( h \) is a constant expressing rate of temperature rise without heat losses. Materials vary in their ability to absorb radiant energy. Thus a true black body has an emissivity of 1 and will absorb all the radiant energy incident upon it. No materials are true black bodies, and for various surfaces the energy absorbed will be a fraction of that received and will be equal in value to the absorptivity of the surface times the energy received. Goodell calls the energy received in watts per square inch, \( w \), and the ratio of watts per square inch absorbed to watts per square inch received the reflection factor or \( r \). Here the symbol \( p \) will be used for absorptivity and will be equal in value to Goodell's term \( r \). The constant \( h \) is proportional to energy absorbed and may be expressed as:

$$h = \frac{p \cdot w}{17.383 \cdot pd}$$ \hspace{1cm} (8)

Because of heat losses the rate of temperature rise is not a linear function of time. The equation must be modified to account for heat losses:

$$\frac{dt}{d\theta} = h + m (t - t_a) \hspace{1cm} \text{where} \hspace{1cm} m < 0$$ \hspace{1cm} (9)
Separating the variables and integrating from \( t_a \) when \( \Theta = 0 \) to \( t \) at time \( \Theta \)

\[
\int_{t_a}^{t} \frac{dt}{h+n(t-t_a)} = \int_{0}^{\Theta} d\Theta 
\]

(10)

The solution of this yields

\[
\ln \left( \frac{h+n(t-t_a)}{h} \right) = \Theta \quad (11)
\]

Solving for \( t \) gives the theoretical time-temperature curve for heating

\[
t = t_a + \frac{h}{n} \left( e^{\Theta} - 1 \right) \quad \text{where} \quad n < 0 \quad (12)
\]

The initial rate of temperature rise, \( h \), may be expressed as

\[
h = \frac{n(t-t_a)}{e^{\Theta} - 1} \quad (13)
\]

Equating (8) and (13)

\[
\frac{Pw}{17.58s \rho d} = \frac{n(t-t_a)}{e^{\Theta} - 1} \quad (14)
\]

\[
P = \frac{17.58s \rho d n}{w} \left[ \frac{t-t_a}{e^{\Theta} - 1} \right] \quad (15)
\]

This development applies strictly only to thin objects of high thermal conductivity.

The theoretical heating equation (12) given by Goodell is strictly valid only if the surrounding air temperature is the same as the initial panel temperature. Calling the initial panel temperature \( t_i \), the equation would hold for \( t_a = t_i \).
In commercial radiant heat ovens the surrounding air temperature is probably higher than the initial temperature of the object in most cases. The integration of equation (9) for the condition where \( t_a \) is actually higher than the initial temperature of the object \( t_i \) would be as follows:

\[
\int_{t_i}^{t} \frac{dt}{h+n(t-t_a)} = \int_{0}^{\Theta} d\Theta \quad \text{where} \quad n < 0 \quad (16)
\]

Integrating

\[
\log_e \frac{h+n(t-t_a)}{h+n(t_i-t_a)} = n \Theta \quad (17)
\]

Simplifying

\[
t = t_a + \frac{h}{n} (e^{n\Theta} - 1) + e^{n\Theta} (t_i-t_a) \quad (18)
\]

An object being put into a radiant heat oven when \( t_a > t_i \) will have no convection losses until it attains a temperature equivalent to \( t_a \). Part of the heat rise up to this point would be derived from the higher air temperature in the oven.

With this theoretical background, laboratory work was planned for the determination of absorptivity constants and distribution of energy in the baking of various enamels with radiant heat. Synthetic enamels
made with five different pigments were used for this study. The vehicle in each case consisted of a combination of alkyd and melamine synthetic resins. These enamels represented five distinct colors. Time-temperature heating and cooling curves were determined for each enamel. Using Goodell's mathematical development, absorptivities were calculated for the enamels. Likewise the ratio of useful energy employed to energy received from the lamp was determined for each enamel.
Experimental.

An oval steel panel (20 gage) was used for the baking tests. A 1/16 inch hole was drilled through the center of this panel. The hot junction of a copper-constantan thermocouple was inserted in this hole, bent over, and securely soldered on both sides of the panel with aluminum solder. This panel was used for all bakings, the enamel being removed each time with paint and varnish remover. This panel had a face area of 27.6 square inches and was 0.0418 inches thick.

The lamp set-up was similar to that used in Part I with some minor changes. The rays from the lamp were directed vertically downward onto the panel which rested on three thin vertical sticks of wood mounted on a wooden base. The leads of the thermocouple were connected to the potentiometer. A cardboard draft shield encircled the panel during heating and cooling periods.

All enamels used for the baking tests were ground in laboratory ball mills. The vehicle for these enamels consisted of melamine resin plasticized with semi-drying and non-drying alkyd resins. The resin non-volatile consisted of approximately 50% melamine and 50% alkyd. This type vehicle bakes quite hard in a short time and is representative of the type of materials used in industrial finishing. In the ensuing discussion these enamels will be referred to by color name. They are as follows:
The volatile portion of these enamels consisted of approximately 90% xylol, the remaining 10% being a mixture of butanol, hydrocarbons, and a very small amount of pine oil. A summary of the general composition of these enamels is given in Table XIV.

The enamels were applied by brushing just prior to baking. A period of two minutes was allowed between the application of the enamel and the beginning of the baking. In the case of the red enamel and the white enamel it was necessary to apply one coat of enamel and bake it and then apply another coat for the determination of the data. The poor hiding power of these two enamels necessitated this procedure, for it was essential that the panel itself be completely obliterated.

From the equations previously given for the calculation of absorptivity it can be seen that the energy received from the lamp must be known. The precise determination of this would require the use of a radiometric instrument as outlined in the method given by Cartwright and Strong (12). This method would require meticulous experimental technique and the careful construction of a suitably evacuated black body receiver.

<table>
<thead>
<tr>
<th>Name</th>
<th>Pigment Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>White</td>
<td>Titanium Dioxide</td>
</tr>
<tr>
<td>Yellow</td>
<td>C.P. Chrome Yellow Light</td>
</tr>
<tr>
<td>Red</td>
<td>Toluidine Toner</td>
</tr>
<tr>
<td>Green</td>
<td>C.P. Chrome Green Medium</td>
</tr>
<tr>
<td>Black</td>
<td>Carbon Black</td>
</tr>
</tbody>
</table>
Table XIV
Composition of Enamels

<table>
<thead>
<tr>
<th>Color</th>
<th>Pigment Used</th>
<th>Wt. Gal.</th>
<th>% Pigment</th>
<th>% Resin Solids</th>
<th>% Volatile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black</td>
<td>Carbon Black</td>
<td>8.22#</td>
<td>1.24</td>
<td>40.20</td>
<td>58.56</td>
</tr>
<tr>
<td>Green</td>
<td>C.P. Chrome</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Green-Medium</td>
<td>9.10</td>
<td>5.28</td>
<td>31.38</td>
<td>63.34</td>
</tr>
<tr>
<td>Red</td>
<td>Toluidine Red</td>
<td>8.24</td>
<td>5.16</td>
<td>34.24</td>
<td>60.60</td>
</tr>
<tr>
<td>Yellow</td>
<td>C.P. Chrome</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yellow-Light</td>
<td>10.12</td>
<td>5.20</td>
<td>31.40</td>
<td>63.40</td>
</tr>
<tr>
<td>White</td>
<td>Titanium Dioxide</td>
<td>9.50</td>
<td>6.28</td>
<td>31.05</td>
<td>62.67</td>
</tr>
</tbody>
</table>

Resin solids consisted of approximately 50% melamine resin and 50% alkyd resins.

Volatile portion consisted of 90% xylol and 10% of a mixture of butanol, petroleum hydrocarbons and pine oil.
The energy received was in this case evaluated by a method based on the equations developed above. Mc Adams (9) gives emissivities for coatings of lamp black in sodium silicate. The values given vary from 0.952 to 0.967 for various temperatures. Assuming an average value of 0.96 for such a coating, time-temperature heating and cooling curves were determined using the same experimental procedure employed in all the baking tests. Based on the assumed absorptivity of 0.96, an average value for \( w \), or watts per square inch received, was calculated from the data. Since the data were collected under identical experimental conditions, this value of \( w \) applied also to the baking of the other enamels and could be used for the factor \( w \) in these cases also. Having established the value of \( w \), all other constants and factors could be obtained by the use of the equations and the data collected.

In Tables XV to XXI are given the heating and cooling data collected for the various enamels. The data in Table XV were taken by heating and cooling a previously hardened coating of lamp black in sodium silicate. These data were used for the calculation of \( w \), which value in turn was used in the calculations for the other enamels. Table XVI shows the data collected in heating and cooling the black enamel starting with a freshly applied coating. In heating this coating, a portion of the energy was consumed in driving off the volatile solvents from the enamel. Table XVII shows the data collected upon reheating and cooling the same panel, thus avoiding the loss of heat involved
Table XV
Lamp Black in Sodium Silicate
Heating and Cooling Data

<table>
<thead>
<tr>
<th>Heating Period</th>
<th>Cooling Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minutes</td>
<td>Millivolts</td>
</tr>
<tr>
<td>17&quot;</td>
<td>2.59</td>
</tr>
<tr>
<td>31&quot;</td>
<td>3.89</td>
</tr>
<tr>
<td>46&quot;</td>
<td>5.13</td>
</tr>
<tr>
<td>1'07&quot;</td>
<td>6.70</td>
</tr>
<tr>
<td>1'19&quot;</td>
<td>7.74</td>
</tr>
<tr>
<td>1'50&quot;</td>
<td>8.85</td>
</tr>
<tr>
<td>2'24&quot;</td>
<td>10.14</td>
</tr>
<tr>
<td>2'53&quot;</td>
<td>10.81</td>
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<td>3'19&quot;</td>
<td>11.26</td>
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<td>3'58&quot;</td>
<td>11.65</td>
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<tr>
<td>5'0&quot;</td>
<td>11.88</td>
</tr>
<tr>
<td>6'03&quot;</td>
<td>12.09</td>
</tr>
<tr>
<td>7'18&quot;</td>
<td>12.20</td>
</tr>
<tr>
<td>11'0&quot;</td>
<td>12.20</td>
</tr>
<tr>
<td>12'20&quot;</td>
<td>12.35</td>
</tr>
<tr>
<td>15'</td>
<td>12.35</td>
</tr>
</tbody>
</table>

Room Temperature 77°F.
Table XVI
Black Enamel (Wet Film)
Heating and Cooling Data

<table>
<thead>
<tr>
<th>Heating Period</th>
<th>Cooling Period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Minutes</td>
<td>Millivolts</td>
</tr>
<tr>
<td>---------</td>
<td>------------</td>
</tr>
<tr>
<td>25&quot;</td>
<td>3.00</td>
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<tr>
<td>50&quot;</td>
<td>4.75</td>
</tr>
<tr>
<td>1:19&quot;</td>
<td>6.39</td>
</tr>
<tr>
<td>1:36&quot;</td>
<td>7.11</td>
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<tr>
<td>2:04&quot;</td>
<td>8.02</td>
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<tr>
<td>2:35&quot;</td>
<td>8.71</td>
</tr>
<tr>
<td>3:21&quot;</td>
<td>9.54</td>
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<tr>
<td>4:04&quot;</td>
<td>9.72</td>
</tr>
<tr>
<td>5:22&quot;</td>
<td>10.09</td>
</tr>
<tr>
<td>6:20&quot;</td>
<td>10.12</td>
</tr>
<tr>
<td>9:40&quot;</td>
<td>10.39</td>
</tr>
<tr>
<td>12:00&quot;</td>
<td>10.39</td>
</tr>
<tr>
<td>15:00&quot;</td>
<td>10.39</td>
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</tbody>
</table>

Dry Film Thickness - 0.0015 inches
Room Temperature 69°F
Table XVII
Black Enamel (Dry Film)
Heating and Cooling Data

<table>
<thead>
<tr>
<th>Heating Period</th>
<th>Cooling Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minutes</td>
<td>Millivolts</td>
</tr>
<tr>
<td>32&quot;</td>
<td>3.61</td>
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<tr>
<td>50&quot;</td>
<td>4.86</td>
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<td>1'25&quot;</td>
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</tr>
<tr>
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</tr>
<tr>
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</tr>
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<td>2'58&quot;</td>
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</tr>
<tr>
<td>3'40&quot;</td>
<td>9.89</td>
</tr>
<tr>
<td>5'14&quot;</td>
<td>10.33</td>
</tr>
<tr>
<td>6'04&quot;</td>
<td>10.42</td>
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<td>8'00&quot;</td>
<td>10.42</td>
</tr>
<tr>
<td>10'00&quot;</td>
<td>10.42</td>
</tr>
</tbody>
</table>

Dry Film Thickness - 0.0015 inches
Room Temperature 69°F
### Table XVIII

**Green Enamel (Wet Film)**

**Heating and Cooling Data**

<table>
<thead>
<tr>
<th>Heating Period</th>
<th>Panel</th>
<th>Cooling Period</th>
<th>Panel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minutes</td>
<td>Millivolts</td>
<td>Temperature°F</td>
<td>Minutes</td>
</tr>
<tr>
<td>20&quot;</td>
<td>2,41</td>
<td>138</td>
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<tr>
<td>42&quot;</td>
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<tr>
<td>1'12&quot;</td>
<td>5,12</td>
<td>214</td>
<td>37&quot;</td>
</tr>
<tr>
<td>1'35&quot;</td>
<td>6,08</td>
<td>285</td>
<td>1'06&quot;</td>
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<tr>
<td>2'03&quot;</td>
<td>7,00</td>
<td>313</td>
<td>1'43&quot;</td>
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<tr>
<td>2'33&quot;</td>
<td>7,73</td>
<td>344</td>
<td>2'53&quot;</td>
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<td>3'16&quot;</td>
<td>8,57</td>
<td>375</td>
<td>3'34&quot;</td>
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<td>8,91</td>
<td>387</td>
<td>4'44&quot;</td>
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<td>399</td>
<td>5'45&quot;</td>
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<td>9,60</td>
<td>411</td>
<td>6'12&quot;</td>
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<td>7'10&quot;</td>
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<td>8'13&quot;</td>
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<tr>
<td>7'55&quot;</td>
<td>9,70</td>
<td>415</td>
<td>9'25&quot;</td>
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<tr>
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<td>9,70</td>
<td>415</td>
<td>10'00&quot;</td>
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<tr>
<td>12'00</td>
<td>9,70</td>
<td>415</td>
<td></td>
</tr>
<tr>
<td>15'00</td>
<td>9,70</td>
<td>415</td>
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</table>

*Dry Film Thickness = 0.0012 inches*

*Room Temperature 75°F*
<table>
<thead>
<tr>
<th>Heating Period</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Minutes</td>
<td>Millivolts</td>
</tr>
<tr>
<td>17&quot;</td>
<td>2.05</td>
</tr>
<tr>
<td>31&quot;</td>
<td>2.89</td>
</tr>
<tr>
<td>37&quot;</td>
<td>3.04</td>
</tr>
<tr>
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<td>2522&quot;</td>
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</tr>
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<td>658&quot;</td>
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<td>1250&quot;</td>
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Dry Film Thickness - 0.0022 inches
Room Temperature 74°F
Table XX
Yellow Enamel (Wet Film)
Heating and Cooling Data

<table>
<thead>
<tr>
<th>Heating Period</th>
<th>Cooling Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minutes</td>
<td>Millivolts</td>
</tr>
<tr>
<td>16&quot;</td>
<td>1.94</td>
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<td>29&quot;</td>
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<tr>
<td>46&quot;</td>
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<tr>
<td>1'03&quot;</td>
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<tr>
<td>1'59&quot;</td>
<td>5.30</td>
</tr>
<tr>
<td>2'23&quot;</td>
<td>6.28</td>
</tr>
<tr>
<td>2'50&quot;</td>
<td>6.79</td>
</tr>
<tr>
<td>3'54&quot;</td>
<td>7.31</td>
</tr>
<tr>
<td>5'03&quot;</td>
<td>7.73</td>
</tr>
<tr>
<td>6'46&quot;</td>
<td>7.90</td>
</tr>
<tr>
<td>3'26&quot;</td>
<td>7.96</td>
</tr>
<tr>
<td>9'23&quot;</td>
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</tr>
<tr>
<td>12'0&quot;</td>
<td>8.00</td>
</tr>
<tr>
<td>15'0&quot;</td>
<td>8.00</td>
</tr>
</tbody>
</table>

Dry Film Thickness - 0.0013 inches
Room Temperature 78°F.
### Table XXI
White Enamel (Wet Film)
Heating and Cooling Data

<table>
<thead>
<tr>
<th>Heating Period</th>
<th>Cooling Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minutes</td>
<td>Millivolts</td>
</tr>
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<td>19&quot;</td>
<td>1.7</td>
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<td>33&quot;</td>
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<td>48&quot;</td>
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<td>1.29&quot;</td>
<td>3.79</td>
</tr>
<tr>
<td>1.57&quot;</td>
<td>4.37</td>
</tr>
<tr>
<td>2'24&quot;</td>
<td>4.79</td>
</tr>
<tr>
<td>2'58&quot;</td>
<td>5.21</td>
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</tr>
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<td>6.22</td>
</tr>
<tr>
<td>6'57&quot;</td>
<td>6.30</td>
</tr>
<tr>
<td>8'00&quot;</td>
<td>6.38</td>
</tr>
<tr>
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<td>6.57</td>
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<td>11'51&quot;</td>
<td>6.60</td>
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<td>14'20&quot;</td>
<td>6.68</td>
</tr>
<tr>
<td>15'00&quot;</td>
<td>6.68</td>
</tr>
</tbody>
</table>

Dry Film Thickness - 0.0032 inches
Room Temperature 73°F
in driving off solvents. Tables XVIII, XIX, XX, and XXI show heating and cooling data for the green, red, yellow, and white respectively. In all of these, a freshly applied coating was heated and allowances had to be made for heat lost in vaporization of the solvents.

Calculations.

The heating curves obtained by plotting the data of Tables XV to XXI are shown in Figure VIII. According to equation (12) the theoretical heating equation is

\[ t = t_a + \frac{h}{n} (e^{n \theta} - 1) \quad \text{where} \quad n > 0 \]

It is essential that \( w \), or energy received expressed as watts per square inch be evaluated. Rearranging terms in equation (15) we have

\[ w = \frac{17.58 \text{ sq ft}}{p} \left[ \frac{t - t_a}{e^{n \theta} - 1} \right] \quad (16) \]

The data collected for the lamp black in sodium silicate panel were to be used to determine \( w \), the value of 0.96 being taken for \( p \). The value of the proportionality constant \( n \) was also unknown and had to be evaluated. It was thought that the value of \( n \) could be calculated from the cooling curve data as suggested by Goodell, using experimentally determined values of \( \frac{dt}{de} \) in the equation

\[ n = \frac{\left[ (\frac{dt}{de})_1 - (\frac{dt}{de})_2 \right]}{t_1 - t_2} \]
Figure VIII. Time-Temperature Heating Curves for Various Enamels.
This equation is the result of eliminating \( t_a \) in the solution of simultaneous equations involving the cooling equation

\[
\frac{dt}{de} = n(t-t_a)
\]  

By solving simultaneous equations over the entire range of the cooling curve an average value of \( n \) was obtained. Substituting this value back into equation (3) (as suggested by Goodell), an average value for \( t_a \) was obtained. These average values of \( n \) and \( t_a \) used in the theoretical cooling equation (6) gave a theoretical cooling curve in good conformity with the actual curve for a good portion of the curve. The use of these values of \( n \) and \( t_a \) in equation (16) for the evaluation of \( w \) yielded values which varied greatly with \( \Theta \) and which when used in the heating curve equation were found to be impossible. From the cooling data, \( n \) was found to be -0.436 and \( t_a \) 168°F. It is obvious that such a value for \( t_a \) is not applicable to the initial stage of the heating process, as the panel was initially at room temperature of 77°F. Using these values of \( n \) and \( t_a \), the theoretical cooling curve was found to conform only up to a point slightly above the calculated value for \( t_a \). By using these values in equation (16), \( w \) was found to have an average value of 4.5 watts per square inch in the range of the heating curve from \( \Theta = 1.5 \) to \( \Theta = 4.5 \) minutes. Great variations occurred for values of \( \Theta \) above and below these limits. Since \( h = \frac{R_w}{n} \) (3), \( h \) for this
value of \( w \) is 173 degrees per minute. This should represent the rate of temperature rise without heat losses. On plotting \( \int \frac{dt}{d\theta} = h \) against the heating curve actually obtained for lamp black in sodium silicate, it was seen that value of \( h \) was low and that the actual rate of temperature rise with heat losses was considerably greater in the initial stages than was this calculated rise involving no losses. The value of \( n \) determined from cooling data is therefore not applicable to the heating equation, nor can it be used in the calculation of \( w \). Values of \( n \) and \( t_a \) were calculated from the cooling data of the other enamels. These values are listed in Table XXII.

In every case these values when substituted in the theoretical cooling equation (6) yield calculated temperatures in close conformity with the actual values obtained up to a point slightly above the calculated \( t_a \). This verifies the form of the cooling equation, but indicates that the rate of heat loss in free cooling is different from that actually taking place in the heating cycle.

The value of \( n \) for the heating period must be determined from the heating data. An examination of equation (12) shows that the term \( \frac{h}{n} (e^{n\theta} - 1) \) represents the total \( \Delta t \) at time \( \theta \), and is of course zero at \( \theta = 0 \). The term \( t_a \) in this equation is the point where \( t \) meets the \( Y \) axis, i.e., the initial panel temperature. As the value of \( e^{n\theta} \) approaches zero, total \( \Delta t \) reaches a maximum. Therefore \( \Delta t \) maximum is equal to \( -\frac{h}{n} \cdot \Delta t \) in the heating curve is equal to \( t - t_a \) or the panel temperature minus the initial temperature.
Table XIII

Cooling Constants and Values of $t_a$
Calculated from Cooling Data

<table>
<thead>
<tr>
<th>Color</th>
<th>$n$</th>
<th>$t_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>White</td>
<td>-0.357</td>
<td>126°</td>
</tr>
<tr>
<td>Yellow</td>
<td>-0.363</td>
<td>131°</td>
</tr>
<tr>
<td>Red</td>
<td>-0.469</td>
<td>152°</td>
</tr>
<tr>
<td>Green</td>
<td>-0.434</td>
<td>151°</td>
</tr>
<tr>
<td>Black</td>
<td>-0.505</td>
<td>147°</td>
</tr>
<tr>
<td>Lamp Black in Sodium Silicate</td>
<td>-0.436</td>
<td>168°</td>
</tr>
</tbody>
</table>
Using experimentally determined values of $\Delta t$ at $\Theta$ and $\Delta t$ maximum ($t_{\text{max.}} - t_a$) in the equation

$$h = \frac{n(t-t_a)}{\text{e}^{n\Theta} - 1} \quad (13)$$

and equating the two expressions to each other, values of $n$ were calculated for different values of $\Theta$, and an average determined for the entire range of the heating curve. This value was found to be -0.70 for lamp black in sodium silicate. Using the assumed value of $p = 0.96$, $w$ was found to be 7.8 watts per square inch. How well these values satisfy the actual heating curve for lamp black in sodium silicate can be seen from Table XXIII, where the calculated theoretical temperatures are compared to the temperatures actually obtained. For this value of $w$, $h$ equals 300°F per minute. The plotting $\int \frac{dT}{d\Theta} = h$ for lamp black in sodium silicate is shown in Figure VIII. The shape of the actual heating curve for lamp black in sodium silicate in the same figure is seen to be in agreement with this straight line heat rise without losses. Curves plotted with the data of Table XXIII would coincide at most points.

The differences shown in the values of $n$ calculated from the cooling data on the one hand and the heating on the other show that the rate of heat loss by convection and radiation when heating an object in air would be greater than that indicated by the value derived from the data collected upon shutting off the heat and allowing the object
Table XXIII
Lamp Black in Sodium Silicate

Comparison of Theoretical Heating Temperature
With Experimentally Observed Values

\[ w = 7.8 \text{ watts per square inch} \]
\[ p = 0.96 \]
\[ t_0 = 77^\circ F \]
\[ n = -0.70 \]

<table>
<thead>
<tr>
<th>Minutes</th>
<th>Theoretical ( t-^\circ F )</th>
<th>Observed ( t-^\circ F )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>204</td>
<td>198</td>
</tr>
<tr>
<td>1.0</td>
<td>292.5</td>
<td>289</td>
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<tr>
<td>1.5</td>
<td>355.5</td>
<td>355</td>
</tr>
<tr>
<td>2.0</td>
<td>400</td>
<td>400</td>
</tr>
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<td>2.5</td>
<td>431</td>
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<td>453</td>
<td>458</td>
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<td>4.0</td>
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</tr>
<tr>
<td>5.0</td>
<td>492.5</td>
<td>493</td>
</tr>
<tr>
<td>6.0</td>
<td>499</td>
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</tr>
<tr>
<td>10.0</td>
<td>505</td>
<td>504</td>
</tr>
</tbody>
</table>
to cool in the air. In all the subsequent calculations, only heating data will be used.

The value of $w$ was considered constant for the other enamels. The next task was to calculate the absorptivities of the five enamels from the experimental heating data. In every case there were two unknowns, $p$ and $n$. For calculating $n$, the same method was used that had been used for the lamp black panel. Knowing $n$, $p$ could easily be calculated.

For the black enamel two sets of data had been collected. In Table XVI are given the data collected starting with a freshly applied coating, while the data of Table XVII represent the values obtained by reheating the previously baked panel. The curves plotted from these data are shown in Figure IX. It will be noted that both curves had an equal final temperature; but in the case of the wet enamel, the heat loss from solvent vaporization shows up in the slower rate of temperature rise.

For the heating of the dry film black enamel, $n$ was found to be -0.76 and $p$ was 0.905. A comparison of theoretical temperatures based on these constants and the observed temperatures is shown in Table XXIV. In order to calculate $p$ for the wet film baking corrections had to be made for the vaporization of solvent. The value of $n$ was first calculated. This was 0.722. The amount of solvent vaporized per square inch surface area of film was calculated from the measured dry film thickness and the volume per cent of volatile originally present in the
Figure IX: Time-Temperature Curves for Black Enamel, Showing Effect of Solvent Evaporation

- O Black Enamel Wet Film
- △ Black Enamel Dried Film
Table XXIV

Black Enamel (Dry Film)

Theoretical Versus Observed Temperature

\( w = 7.8 \) watts per square inch
\( p = 0.905 \)
\( t_e = 69^\circ F \)
\( n = -0.76 \)

<table>
<thead>
<tr>
<th>Minutes</th>
<th>Theoretical ( t^\circ F )</th>
<th>Observed ( t^\circ F )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>186.4</td>
<td>182</td>
</tr>
<tr>
<td>1.0</td>
<td>266.8</td>
<td>263</td>
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<td>359</td>
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<td>2.5</td>
<td>385</td>
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<td>3.0</td>
<td>402.5</td>
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<td>4.0</td>
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<tr>
<td>10.0</td>
<td>440.3</td>
<td>441</td>
</tr>
</tbody>
</table>
enamel as given in Table XIV. Since the volatile was at least 90% xylol, the heat capacity and latent heat of vaporization of xylol were used to determine heat lost in driving off the solvents. This loss was considered to be distributed over the section of the heating curve from \( \Theta = 0 \) at room temperature to a value of \( \Theta \) equivalent to the boiling point of xylol. The theoretical \( \Delta t \) for a given period of time as determined from the heating equation (12) minus the \( \Delta t \) representing the heat lost in heating or vaporizing volatile matter in that period would give the actual \( \Delta t \) obtained. After all the solvents have been driven off, the increments in \( t \) should follow the heating equation. The sum of \( \Delta t \)'s from \( \Theta = 0 \) to the point where \( \Delta t = 0 \) (\( t_{\text{max.}} \)) would then build up a theoretical heating curve which should coincide with the observed data. Using the calculated value of \( n \) given above, \( p \) was found to be 0.89. The theoretical and observed values of \( t \) for the heating of the wet film are shown in Table XXV.

To calculate the absorptivities for the other enamels the same method had to be used as given above for the black enamel wet film data. First the value of \( n \) was determined. Using this value of \( n \) in the heating equation, and assuming a value for \( p \), \( \Delta t \)'s were calculated over regular time intervals from \( \Theta = 0 \) to the point where \( \Delta t \) was 0 (\( t_{\text{max.}} \)). The \( \Delta t \) loss from solvent vaporization was subtracted from the theoretical \( \Delta t \) in the proper time intervals. This gave the equivalent of the actual \( \Delta t \). By
Table XXV

Black Enamel (Wet Film)

Theoretical Versus observed Temperatures

(Vaporization Losses Accounted For)

\( w = 7.8 \text{ watts per square inch} \)
\( p = 0.89 \)
\( t_a = 690^\circ F \)
\( m = 0.722 \)

<table>
<thead>
<tr>
<th>Minutes</th>
<th>Theoretical ( t^\circ F )</th>
<th>Observed ( t^\circ F )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>183.4</td>
<td>182</td>
</tr>
<tr>
<td>1.0</td>
<td>262.5</td>
<td>257</td>
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<tr>
<td>1.5</td>
<td>315.3</td>
<td>314</td>
</tr>
<tr>
<td>2.0</td>
<td>351.8</td>
<td>351</td>
</tr>
<tr>
<td>2.5</td>
<td>379.8</td>
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<td>399.3</td>
<td>397</td>
</tr>
<tr>
<td>4.0</td>
<td>420.8</td>
<td>416</td>
</tr>
<tr>
<td>5.0</td>
<td>432.3</td>
<td>427</td>
</tr>
<tr>
<td>6.0</td>
<td>437.8</td>
<td>434</td>
</tr>
<tr>
<td>8.0</td>
<td>441.8</td>
<td>440</td>
</tr>
<tr>
<td>10.0</td>
<td>442.7</td>
<td>440</td>
</tr>
</tbody>
</table>
adding the $\Delta t$'s a theoretical heating curve was built up. The assumption of the value of $\alpha$ was done by taking the value of $\alpha$ indicated from the heating curve by the use of the correct value of $n$ and raising it to compensate for the losses from solvent vaporization. Using this assumed absorptivity a theoretical heating curve was built up, and the curve conforming with the observed data was considered to represent the correct value of $\alpha$.

The absorptivities obtained for the various enamels are tabulated in Table XXVI. A comparison of theoretical temperatures and observed temperatures are given in Tables XXVII and XXVIII. It will be noted that the values of $n$ decrease with absorptivity with the exception of the black and the red enamels, which are both out of line. Unfortunately the data had to be collected over a period of several weeks and the room temperature varied. On the day the data were taken for the black enamel, the room temperature was 69°F. This was the lowest temperature encountered and the rate of heat loss (as indicated by the value of $n$) was greater in the baking of the black enamel than for any of the other enamels. During the baking of the red enamel, the enamel darkened markedly as the baking progressed. Toluidine red being an organic compound manifested one of its properties, that of darkening with prolonged heating. The absorptivity probably changed during baking to an appreciable extent. It was therefore hard to determine the correct value of $n$. The values given in Table XXVI represent
### Table XXVI

Absorptivities and Theoretical Heating Curve Constants

<table>
<thead>
<tr>
<th>Receiving Surface</th>
<th>Absorptivity</th>
<th>Heating Curve Constant</th>
<th>Initial Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamp Black in Sodium Silicate</td>
<td>0.96</td>
<td>-0.70</td>
<td>77°F</td>
</tr>
<tr>
<td>Black Enamel (Dry Film)</td>
<td>0.905</td>
<td>-0.76</td>
<td>69°F</td>
</tr>
<tr>
<td>Black Enamel (Wet Film)</td>
<td>0.89</td>
<td>-0.722</td>
<td>69°F</td>
</tr>
<tr>
<td>Green Enamel (Wet Film)</td>
<td>0.73</td>
<td>-0.65</td>
<td>75°F</td>
</tr>
<tr>
<td>Red Enamel (Wet Film)</td>
<td>0.63</td>
<td>-0.61</td>
<td>74°F</td>
</tr>
<tr>
<td>Yellow Enamel (Wet Film)</td>
<td>0.57</td>
<td>-0.625</td>
<td>78°F</td>
</tr>
<tr>
<td>White Enamel (Wet Film)</td>
<td>0.39</td>
<td>-0.50</td>
<td>73°F</td>
</tr>
</tbody>
</table>
**Table XXVII**

**Green Enamel and Red Enamel**

*Theoretical Versus Observed Temperatures*  
*(Vaporization Losses Accounted For)*

<table>
<thead>
<tr>
<th>Green Enamel</th>
<th>Red Enamel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w=7.8$ watts per square inch</td>
<td>$w=7.8$ watts per square inch</td>
</tr>
<tr>
<td>$P=0.73$</td>
<td>$P=0.63$</td>
</tr>
<tr>
<td>$t_o=75^\circ F$</td>
<td>$t_o=74^\circ F$</td>
</tr>
<tr>
<td>$n=0.65$</td>
<td>$n=0.61$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Minutes</th>
<th>Theoretical $t-OF$</th>
<th>Observed $t-OF$</th>
<th>Theoretical $t-OF$</th>
<th>Observed $t-OF$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>170</td>
<td>160</td>
<td>156.5</td>
<td>152</td>
</tr>
<tr>
<td>1.0</td>
<td>238.1</td>
<td>226</td>
<td>216.8</td>
<td>211</td>
</tr>
<tr>
<td>1.5</td>
<td>295.3</td>
<td>277</td>
<td>258.3</td>
<td>256</td>
</tr>
<tr>
<td>2.0</td>
<td>318.4</td>
<td>315</td>
<td>289.3</td>
<td>291</td>
</tr>
<tr>
<td>2.5</td>
<td>344.9</td>
<td>344</td>
<td>316.8</td>
<td>316</td>
</tr>
<tr>
<td>3.0</td>
<td>364</td>
<td>366</td>
<td>333.3</td>
<td>335</td>
</tr>
<tr>
<td>4.0</td>
<td>387.8</td>
<td>392</td>
<td>356.8</td>
<td>358</td>
</tr>
<tr>
<td>5.0</td>
<td>400.2</td>
<td>405</td>
<td>369.8</td>
<td>370.5</td>
</tr>
<tr>
<td>6.0</td>
<td>406.7</td>
<td>412</td>
<td>376.8</td>
<td>378</td>
</tr>
<tr>
<td>8.0</td>
<td>411.8</td>
<td>415</td>
<td>381.3</td>
<td>384.5</td>
</tr>
<tr>
<td>10.0</td>
<td>413.3</td>
<td>415</td>
<td>382.5</td>
<td>387</td>
</tr>
</tbody>
</table>
Table XXVIII

Yellow Enamel and White Enamel

Theoretical Versus Observed Temperature
(Vaporization Losses Accounted For)

<table>
<thead>
<tr>
<th>Minutes</th>
<th>Yellow Enamel</th>
<th></th>
<th>White Enamel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Theoretical ( t_{\Phi} )</td>
<td>Observed ( t_{\Phi} )</td>
<td>Theoretical ( t_{\Phi} )</td>
</tr>
<tr>
<td>0.5</td>
<td>151</td>
<td>148</td>
<td>124.3</td>
</tr>
<tr>
<td>1.0</td>
<td>206.5</td>
<td>203</td>
<td>164</td>
</tr>
<tr>
<td>1.5</td>
<td>245.3</td>
<td>243</td>
<td>195</td>
</tr>
<tr>
<td>2.0</td>
<td>274</td>
<td>274</td>
<td>219</td>
</tr>
<tr>
<td>2.5</td>
<td>295</td>
<td>297</td>
<td>237.5</td>
</tr>
<tr>
<td>3.0</td>
<td>311</td>
<td>314</td>
<td>252.5</td>
</tr>
<tr>
<td>4.0</td>
<td>330</td>
<td>333</td>
<td>273</td>
</tr>
<tr>
<td>8.0</td>
<td>351</td>
<td>353</td>
<td>292.5</td>
</tr>
</tbody>
</table>
an average, and it can be seen that the variation between theoretical and observed temperatures are greater for the red enamel than for any of the others.

A series of calculations was made to determine the distribution of energy in the baking of the five colored enamels starting with a wet film. From the calculated value of \( w \) it is known that 7.8 watts per square inch were received from the lamp. Of this amount a fraction equal in value to \((1 - p)\) is reflected. A portion is used in heating and vaporizing the volatile solvents. The amount consumed in heating the mass to the temperature attained may be considered as useful energy employed. The remaining portion of the energy was lost by convection and low temperature radiation.

In Table XXIX is shown an analysis of the energy distribution over regular, equal time intervals for the five enamels. Four classifications were set up for the distribution of energy:

1. Reflected energy
2. Energy used in vaporizing solvents.
3. Useful energy employed.

Reflection losses were considered constant for each enamel over the entire heating period. This was based on the premise that the total absorptivity of a gray body is unaffected by temperature and that many solids approximate the gray body state for infra red radiation (15). The loss from heating and vaporizing solvents did not vary much
**Table XXIX**

**Analysis of Energy Distribution**

**Distribution of Energy in %**

<table>
<thead>
<tr>
<th>Color</th>
<th>Time Interval</th>
<th>( \Delta T ) - ( \Delta F )</th>
<th>Reflection</th>
<th>Vaporization</th>
<th>Useful Energy</th>
<th>Convection and Radiation Losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black</td>
<td>0 to 1</td>
<td>189</td>
<td>11</td>
<td>1.1</td>
<td>60.6</td>
<td>27.2</td>
</tr>
<tr>
<td>Green</td>
<td></td>
<td>151</td>
<td>27</td>
<td>1.0</td>
<td>18.4</td>
<td>23.6</td>
</tr>
<tr>
<td>Red</td>
<td></td>
<td>131</td>
<td>27</td>
<td>0.8</td>
<td>12.6</td>
<td>19.6</td>
</tr>
<tr>
<td>Yellow</td>
<td></td>
<td>122</td>
<td>13</td>
<td>0.8</td>
<td>16.8</td>
<td></td>
</tr>
<tr>
<td>White</td>
<td></td>
<td>92</td>
<td>61</td>
<td>0.6</td>
<td>28.6</td>
<td>9.6</td>
</tr>
<tr>
<td>Black</td>
<td>1 to 2</td>
<td>83</td>
<td>11</td>
<td>2.5</td>
<td>29.2</td>
<td>56.7</td>
</tr>
<tr>
<td>Green</td>
<td></td>
<td>89</td>
<td>27</td>
<td>2.6</td>
<td>28.5</td>
<td>41.9</td>
</tr>
<tr>
<td>Red</td>
<td></td>
<td>85</td>
<td>27</td>
<td>2.8</td>
<td>27.2</td>
<td>33.0</td>
</tr>
<tr>
<td>Yellow</td>
<td></td>
<td>73</td>
<td>43</td>
<td>0.5</td>
<td>23.4</td>
<td>33.1</td>
</tr>
<tr>
<td>White</td>
<td></td>
<td>55</td>
<td>61</td>
<td>0.3</td>
<td>17.6</td>
<td>21.1</td>
</tr>
<tr>
<td>Black</td>
<td>2 to 3</td>
<td>45</td>
<td>11</td>
<td>2.5</td>
<td>14.4</td>
<td>74.6</td>
</tr>
<tr>
<td>Green</td>
<td></td>
<td>51</td>
<td>27</td>
<td>2.6</td>
<td>16.35</td>
<td>56.65</td>
</tr>
<tr>
<td>Red</td>
<td></td>
<td>45</td>
<td>27</td>
<td>2.8</td>
<td>14.4</td>
<td>41.6</td>
</tr>
<tr>
<td>Yellow</td>
<td></td>
<td>41</td>
<td>43</td>
<td>2.3</td>
<td>13.3</td>
<td>28.2</td>
</tr>
<tr>
<td>White</td>
<td></td>
<td>33</td>
<td>61</td>
<td>0.2</td>
<td>10.6</td>
<td></td>
</tr>
<tr>
<td>Black</td>
<td>3 to 4</td>
<td>20</td>
<td>11</td>
<td>2.5</td>
<td>6.4</td>
<td>82.6</td>
</tr>
<tr>
<td>Green</td>
<td></td>
<td>26</td>
<td>27</td>
<td>8.3</td>
<td>41.7</td>
<td></td>
</tr>
<tr>
<td>Red</td>
<td></td>
<td>23</td>
<td>27</td>
<td>7.4</td>
<td>55.6</td>
<td></td>
</tr>
<tr>
<td>Yellow</td>
<td></td>
<td>19</td>
<td>43</td>
<td>6.1</td>
<td>50.1</td>
<td></td>
</tr>
<tr>
<td>White</td>
<td></td>
<td>18</td>
<td>61</td>
<td>0.1</td>
<td>5.8</td>
<td>53.1</td>
</tr>
<tr>
<td>Black</td>
<td>4 to 5</td>
<td>11</td>
<td>11</td>
<td>3.52</td>
<td>85.18</td>
<td></td>
</tr>
<tr>
<td>Green</td>
<td></td>
<td>13</td>
<td>27</td>
<td>4.16</td>
<td>68.31</td>
<td></td>
</tr>
<tr>
<td>Red</td>
<td></td>
<td>12</td>
<td>27</td>
<td>3.95</td>
<td>59.13</td>
<td></td>
</tr>
<tr>
<td>Yellow</td>
<td></td>
<td>10</td>
<td>43</td>
<td>3.20</td>
<td>53.36</td>
<td></td>
</tr>
<tr>
<td>White</td>
<td></td>
<td>13</td>
<td>61</td>
<td>2.3</td>
<td>4.16</td>
<td>32.54</td>
</tr>
</tbody>
</table>

*Calculated for 1 minute heating periods from \( \Theta=0 \) to \( \Theta=5 \).*
for the different enamels since the volatile content was about equal in each case. These losses were, however, distributed differently for the various enamels. They represented a very small percentage of the energy. It will be noted that the per cent useful energy employed was greatest in the earliest stage of heating for each enamel and decreased proportionately with each increment of $\theta$ and $t$. Conversely the convection and radiation losses were lowest in the earliest stage of heating and increased with each increment of $\theta$ and $t$. The heat loss by convection and radiation increases with $t$, and at $t$ maximum would be equal in value to the energy received minus energy reflected. Thus for the black enamel which has a reflectivity of 0.11 (11% reflected), 89% of the energy received is lost by convection and radiation when $t$ maximum is reached ($\Delta t = 0$). Thus when equilibrium is established at $t$ maximum, the energy lost is equal to the energy received. For any given energy output the temperature which an object will ultimately reach is determined by its reflectivity and the losses by convection and radiation. Since the reflectivity may be considered fairly constant, any decreases in the other losses will result in higher working temperatures.

In Table XXX is shown an analysis of energy required to heat the five enamels to 300° F. These percentages were based on the total energy received from the lamp in the time required to reach this temperature, and the
Table XXX

Distribution of Energy in Heating to 300°F
7.8 Watts Per Square Inch

(Based on Total Energy Received For Each Color in Attaining This Temperature)

<table>
<thead>
<tr>
<th>Color</th>
<th>Total Time</th>
<th>Distribution of Energy in %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reflection</td>
<td>Vaporization</td>
</tr>
<tr>
<td>Black</td>
<td>1.33 Min.</td>
<td>11%</td>
</tr>
<tr>
<td>Green</td>
<td>1.78</td>
<td>27%</td>
</tr>
<tr>
<td>Red</td>
<td>2.15</td>
<td>37%</td>
</tr>
<tr>
<td>Yellow</td>
<td>2.57</td>
<td>43%</td>
</tr>
<tr>
<td>White</td>
<td>8.0</td>
<td>61%</td>
</tr>
</tbody>
</table>
total energy received was different for each enamel. The reflection losses were equal to those given in the previous table. The useful energy percentage decreased with the increase in reflection losses, while the percentage lost by convection and radiation was almost constant for the five enamels. Although the losses by convection and radiation were found to be approximately equal for the white and black enamels, for instance, the white required six times more lamp energy than the black to reach the same temperature. The actual total loss by convection and radiation was therefore six times greater for the white enamel than for the black. These calculations are based on equal energy received.

Goodall (3) gives data for a black surface having a reflectivity of 0.10 showing the effect of heat density on the rate of convection and radiation losses in heating to 300°F. His data show that these losses decrease with an increase in heat density.

The estimation of heat loss by free convection is quite complicated. Since the data obtained in this experimental work represented operating conditions on a laboratory scale, the experimental results must be considered relative. The performance principles, however, may be considered significant. Strong (13) reviews work done by Langmuir in evaluating heat losses by convection from a vertical surface by calculating heat conduction through a postulated stagnant air film thickness of 0.45cm. While the equations given are of no significance for the evaluation of losses in this particular series, the findings of
Langmuir concerning relative heat loss by convection by objects in various positions probably are. Langmuir found that heat losses by free convection from a horizontal surface facing upward are 10% greater than they are from a vertical surface, and they are 50% less from a surface facing downward than they are from a vertical surface. This would indicate that the customary procedure of constructing radiant heat ovens in tunnel form would require variations in heat density on the different sides to attain equal temperature rise for the heating of equal mass.

The losses by convection in this experimental work were probably greater than those encountered in the usual industrial apparatus. In this work the panel was heated on one side only by a lamp facing vertically downward. The conditions were most favorable for high convection losses. In industrial tunnels, the object is such that only the surface facing the lamp is subject to great convection losses. Surface area as well as the surrounding temperature influence these losses.

Under the experimental conditions existing in this work, the distance from the lamp had a great effect on the losses by convection. In Figure X are shown time-temperature curves for heating a black panel at a distance of six inches and also twelve inches from the lamp. The lower rate of temperature rise may not be entirely due to convection losses, for if the heat rays leaving the lamp are divergent, the heat density per square inch at the receiving plane will decrease as the distance from the lamp increases. Shape factors and
Figure X  Time-Temperature Heating Curves For Black Enamels Baked at Different Distances From Lamp

- Panel 6 inches from lamp
- Panel 12 inches from lamp
voids because of shape would greatly influence convection losses.

In several articles on infrared baking mention was made that the difficulties occasioned by the low absorptivity of white enamels could be overcome by baking the object on the reverse side. This would of course be limited by the nature of the object, but would also be markedly influenced by the metal of which the object is composed and the condition of the metal. In Figure XI are shown curves obtained upon heating the same panel three times, using various methods to change the type surface facing the lamp. The panel was originally uniformly brown with a very thin rust scale. Heating data were obtained for this condition. The panel was sanded and the data were again collected. The panel was free of rust scale but still had a brown stained appearance. The same panel was then treated with acid and a dull but definitely metallic surface resulted. The heating data for the last treatment showed a lower rate of heat rise than that obtained for the white enamel given above. The calculated absorptivity for the etched surface was 0.33. It can be seen from the curves that the absorptivity of a metallic surface may vary, and improvement in the rate of baking of white enamels will not always result from making the bare metal the absorbing surface. The normal emissivities given in the literature for polished metallic surfaces are quite low.

The equations developed for mass heating by radiant
Figure XI: Time-Temperature Heating Curves for Uncoated Steel Panels

- O Rust Scaled Panel
- △ Same Panel Sanded
- × Same Panel Etched With Acid
heat baking are strictly applicable only to relatively thin objects of high thermal conductivity. For the heating of objects of increasing thickness or decreasing thermal conductivity the equations must be modified. Such changes result in a complicated problem of thermal conduction in unsteady state.

The basic equation for heat conduction is that of Fourier:

\[ \frac{dq}{d\theta} = kA \frac{dt}{dL} \]

Here \( dq \) is the amount of heat flowing in differential time \( d\theta \), \( k \) is the coefficient of thermal conductivity for the material being heated, \( A \) is the area at right angles to the flow of heat, \( dt \) is the temperature gradient or the rate of change of temperature \( t \) with respect to the length of the path \( L \). This equation applies to thermal conduction in steady state. Fourier's equation is the basis for the development of the equations of unsteady state. It may be used to explain the effect of increasing thickness and decreasing thermal conductivity in radiant heat baking. From Fourier's equation it can be shown that as an object being heated on one side increases in thickness, there is an increasing tendency for a temperature differential to exist between the heated face and the opposite face. The magnitude of this differential would depend largely on \( k \), the thermal conductivity of the material being heated.

In the baking of a paint film by radiant heat the temperature
maintained at the paint film surface largely determines the rate of baking. The highest working temperature for the lowest energy input would in general be the desired ideal. Where the thermal conductivity of a material is high, the temperature gradient in the baked object would be small, and the rate of temperature rise would closely follow the equations for mass heating. In such a case the increase of thickness with respect to the energy receiving surface would result in increased mass and would therefore require increased heat density to maintain the required heating rate. Where the thermal conductivity is low, as is the case with wood, the equations for mass heating would not be applicable. For such a surface the temperature difference between the surface facing the lamp and the opposite face would be fairly great. A temperature gradient would exist all along the path of L. This condition is reflected somewhat in the values recorded for the relaxation time for certain materials by Strong (14). For an object surrounded by air at a different temperature the relaxation time may be defined as the time required for a heat pulse to travel to the center of the object. For an object two centimeters thick, Strong gives a relaxation time of 2.3 seconds for steel as against 34.0 seconds across grain and 122 seconds with the grain for pine wood. Because of the low rate of thermal conductivity of wood, the rate of temperature rise would be greater at a given heat density for a given mass of material than would be that of a material such as steel. (Considering only surface temperature) This would
result in operating economy. One handicap would exist, however. Since the radiant energy at the receiving plane is not always uniformly distributed, the beneficial effect of radial distribution by conduction within the object would not be great, and overheated spots could result. The development of equations for the heating of materials of low thermal conductivity would be as complex as any problem of heat transfer in unsteady state. It will suffice here to point out the potential heat economy indicated for the radiant heat baking of such materials.
CONCLUSIONS
The mathematical development from thermodynamic principles of mass heating and cooling equations by Goodell give a clear picture of the fundamentals underlying the results obtained in radiant heat baking. In general the experimental curves obtained in heating and cooling the five enamels used in this series of tests agreed in form with the equations developed. However since loss by convection is a major factor in the development, and since the evaluation of convection losses is at best a complicated problem, and is dependent on several factors, reservations must be made with respect to the absoluteness of the convection constants in such equations. The degree of air movement about the object, the surface area exposed, and the position of the surface with respect to the air movement will influence the rate of cooling.

In the analysis of the experimental data it was necessary to consider the heating and cooling curves as entities, with no apparent relationship between the cooling constants obtained for either of them. That this should be so may be deduced from the equations themselves, for in the development of the cooling equation, the rate of heat loss per given surface area was said to be a function of the difference in temperature between the object and the surrounding medium and was expressed as \( t - t_a \), while in the development of the theoretical heating equation \( t_a \) was considered to be equal to the initial temperature of the object or the prevailing room temperatures. It would have been very
difficult to obtain the temperature of the surrounding medium, but it was quite evident during the heating and cooling processes that the temperature of the surrounding air medium was definitely higher than the initial temperature, i.e., the prevailing room temperature. Calculations of $t_a$ using the cooling data in the cooling equations yielded values appreciably higher than the prevailing room temperature. The construction of the experimental apparatus was such that rapid air motion was not possible. This reduced air motion was in keeping with industrial practice, and the losses by convection in this set up were probably greater than would exist in the average industrial installation. The calculated air temperature was not found constant for any one cooling curve, a condition which may again be attributed to limited air movement. It is advantageous, because of lowered convection losses, to have a higher surrounding air temperature.

The calculations were all made using Goodell's derived form of the heating equation. This equation applies for the condition that the initial temperature of the object is equal to the surrounding air medium. The observed heating data for the five enamels conformed quite closely to the form of the theoretical heating equation. The cooling constant was, however, determined directly from the heating data, using increments of $\Delta t$ with respect to $\theta$. Absorptivities were determined for the five enamels. Black had the highest absorptivity, and the green, red, yellow, and white were found to be lower in the order named. An unpolished clean steel
panel was found to have a lower absorptivity than the white enamel. The baking of metals coated with white enamel with the bare metal receiving the energy will not always be an improvement.

The distribution of energy in heating an object was also determined. The energy was considered to be distributed four ways: Reflection, vaporization of solvents, useful energy employed, and losses by convection and radiation.

The reflection losses depend on the absorptivity of the receiving surface and are equal to \( (1 - p) \) times the energy received.

The vaporization losses consist of the energy required to heat and vaporize the volatile solvents present. They are quite small in comparison to the total energy received.

The useful energy is that portion of energy devoted solely to heating the object to the attained temperature. The temperature rise attained for a given amount of available energy is dependent on the mass and specific heat of the object being heated. In the heating of objects it is found that the useful energy maintained decreases with increments of \( \Theta \) and \( t \) because of convection and radiation losses.

The losses by convection and radiation were found to be smallest in the earliest stage of heating and increased
as $\Theta$ and $t$ increased. In all cases these losses approached a limiting value equal to the total energy received minus the losses by reflection. When $t$ maximum is reached the energy received from the lamp is equal to the sum of the reflection, convection, and radiation losses. In heating the five enamels to $300^\circ F$, it was found that the percentage of energy lost by convection and radiation was almost constant. The energy required to reach $300^\circ F$, naturally increased with the lower absorptivities. Increasing the distance between the object and the lamp increases the loss by convection. Depending on the construction of the lamp, the increased distance from the lamp will reduce the heat density at the receiving plane.

The equations of mass heating and cooling apply strictly only to thin objects of high thermal conductivity. In the heating of objects of extremely low thermal conductivity, the conduction of heat through the object would be low, and the temperature at the receiving plane would rise more rapidly than indicated by the mass heating equation. This would be an advantage in that high surface temperatures can be obtained rapidly. It would have the disadvantage that equalization of temperature in the work by radial conduction would not be possible in cases where the energy received is not uniformly spread.
Part III

Theory and Experimental
THEORY

The principles governing the behavior of radiant heat lamps being known, the types of products and materials baked should be chosen for their adaptability to this baking. The outstanding feature of radiant heat baking is that a great amount of energy may be directed upon a body, causing instantaneous response and producing a rapid rise in temperature. This rise in temperature, as shown before, is a function of energy absorbed, mass to be heated, density of energy supplied, and losses by convection and radiation. In the baking of a protective coating, the fundamental objective is to convert the film from its liquid or wet state to a hard, tack-free film. To do this, the volatile solvents must be driven off and the necessary chemical change involved in the hardening of a film brought about.

The hardening of a paint film is usually attributed to either or both of two types of chemical reaction: oxidation and polymerization. Oxidation is the taking on of oxygen by the unsaturated bonds in the oil molecule, usually with the aid of a catalytic metal (drier). Polymerization is the interreaction of molecules to form larger molecules. The rate of conversion in oxidation reactions is generally much lower than in polymerizing reactions. The application of heat results in more rapid film hardening.

The vehicles used in baking enamels have in recent years narrowed down to a group of synthetic resins with prop-
erties especially adapted to baking processes. The best baking enamels today are being made from alkyd, urea-formaldehyde, and melamine resins or combinations thereof. In this study only these resins will be considered.

Alkyd resins are essentially reaction products of polybasic acids with polyhydric alcohols. The alkyd resins used in the protective coatings industry today have many modifications and consequently diversified features. Of the alkyd resins, glycerol phthalate resins are most frequently used. This type of resin is strictly a reaction product of glycerine and phthalic anhydride. To make it usable in protective coatings and soluble in hydrocarbons, modifications are made with drying, semi-drying, and in some cases non-drying oil fatty acids or glycerides. Phenolic resin modifications are also made. The properties of the modified resin are largely dependent on the degree of modification and the properties of the modifying agent. The use of a drying oil as a modifying agent will contribute properties normally possessed by the oil to the alkyd resin. The drying of alkyd resins is usually considered to be either an oxidation process or a combination of oxidation and polymerization processes. The extent to which the drying is dependent on one or the other would again be related to the degree of modification and the type modifying agent used. Glycerol phthalate resins have found their way into many types of baking products, for they are quite adaptable to forced drying when so designed.
Urea-formaldehyde resins have in more recent times become commercially available and have added some new and desirable features to baking enamels. The urea-formaldehyde resins are fundamentally condensation products of urea and formaldehyde. Urea-formaldehyde resins harden by polymerization (5), the conversion being brought about in most instances by heating to fairly high baking temperatures. Acidic catalysts hasten conversion, and the acidity of the resin or the resin system influences the rate of conversion. The use of a percentage of urea resin with an oxidizing alkyd resin contributes greater hardness to the film, and increases mar proofness, print resistance, and color retention. The advent of urea resins was soon found extremely advantageous in the manufacture of white refrigerator enamels and other similar heavy duty finishes. As with all new developments, much research was required to adapt this resin to industrial usage, for several problems are encountered in using this type material in protective coatings. One major problem is that of compatibility with alkyd resin solutions. Another is that of stability in enamel form, for the acidity or alkalinity of a composite enamel as measured by pH has a marked influence on the package stability of the enamel. (5) As mentioned before the pH also is a factor in the rate of conversion or film hardening. Fairly high baking temperatures are recommended for the hardening of urea-formaldehyde resins,
above 260°F. being recommended for a neutral system to obtain maximum hardness from a minimum of urea. Temperature has a marked influence on the rate of hardening of urea resins, greater hardness being obtained in shorter times with the increase of temperature. (5) and (11). An increase in the percentage of urea resin is accompanied by an increase in hardness.

Melamine resins are still more recent commercial developments than the urea-formaldehyde resins. Melamine, the chief raw material was discovered by Liebig in 1834, and its recent availability on a commercial scale has created a new and remarkable series of baking resins. Chemically melamine is 2,4,6-triamino-1,3,5-triazine and is also known as cyanuric acid amide, and as cyanuric triamide (6).

A variety of resins may be made starting with melamine. The ramifications in types of reactions, and reactants are discussed in "Melamine-Formaldehyde Film-Forming Compositions" (6). The hydrocarbon-soluble condensation products are those of interest for enamel work. Like urea-formaldehyde resins they are converted by heat or catalysts or both to hard films. Melamine resins have several distinct advantages over urea resins. One advantage is that they may be baked at lower temperature (10). Baked at the same temperature as a urea resin, they will attain equal hardness in shorter periods of
time. Sanderson (11) gives interesting curves showing comparison in hardness between melamine and urea resins baked at equal temperatures for equal periods of time. Melamine resins are more heat-resistant than urea resins and may be heated to temperatures above 500°F without discoloration. They are said to maintain gloss better at higher temperatures than will urea resins.

The rate of hardening of oxidizing films is always slower than that of polymerizing films. The addition of urea or melamine resins to an alkyd system is accompanied by an increase in the rate of film hardening. The rate of film hardening is dependent also upon the temperature at which the film is baked, the rate of hardening increasing with the rise in baking temperature. From the standpoint of composition a film containing a portion of urea or melamine resin would seem ideally adaptable to radiant heat baking, for depending on the amount of energy supplied from a lamp source, rapid rise in temperature may be attained and fairly high temperature maintained with a radiant heat system. A series of baking tests was therefore undertaken to measure the effect of a polymerizing type material on the rate of film hardening using the radiant heat baking equipment.
Experimental Work

A series of baking tests was made using enamels varying in non-volatile composition. Two basic enamels were made up using c.p. chrome green medium as the pigment. In one case the vehicle non-volatile consisted of 100% melamine-urea type resin, while the other was made using 100% alkyd resin. To make enamels varying in composition from one extreme to the other, blends were made from the two enamels. The melamine-urea resin used was not a straight derivative of either type resin, but was a condensation product involving both urea-formaldehyde and melamine derivatives. The alkyd resin used consisted of 50% semi-drying alkyd and 50% non-drying alkyd. The enamels used for the test were as follows:

<table>
<thead>
<tr>
<th>Name</th>
<th>% Alkyd</th>
<th>% Melamine-Urea (By Weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green #1</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Green #2</td>
<td>37.5</td>
<td>12.5</td>
</tr>
<tr>
<td>Green #3</td>
<td>75</td>
<td>25</td>
</tr>
<tr>
<td>Green #4</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Green #5</td>
<td>0</td>
<td>100</td>
</tr>
</tbody>
</table>

The drying progress was measured in terms of Sward hardness. The method used in Part I for applying films and determining hardness was used for this work also. Here again it must be mentioned that the surface receiving radiant energy consisted of a film of green enamel flanked by bare metal. The average absorptivity of this surface would be lower than that of a surface completely coated with the green enamel.
The panels selected for the hardness tests in Part I were used in this series also. The experimental procedure was as follows: A 0.003 inch film was applied by means of a Bird applicator upon a clean panel. After the panel had stood for two minutes, it was placed under the lamp and allowed to bake a definite period of time. The panel was quickly removed at the end of the specified time, allowed to cool to room temperature, and its rocker hardness then determined. Three to five readings were taken and an average value computed. Readings were made for baking periods of 3, 6, 9, 15, and 24 minutes. The baked films were removed with paint and varnish remover and the panel used again. A panel equipped with a thermocouple was used to determine a time-temperature curve for the baking schedule. All panels were baked at a distance of six inches from the lamp. In Table XXXI are shown the average hardness readings obtained in this experimental work. Figure XII shows the plotting of Sward hardness versus baking time for the five enamels. The dotted lines indicate panel temperature at various times.

From the curves in Figure XII, it can be seen that as the percentage of melamine resin content is increased the ultimate hardness as well as the rate of hardening is increased. The rate of film hardening was found to rise sharply when the composition reaches 50% melamine-urea. In a series of tests such as this, all factors cannot be kept on a comparable basis. This group
Table XXXI

Sward Hardness Versus Composition

Green Enamels

Average Sward Hardness

<table>
<thead>
<tr>
<th>Total Baking Time</th>
<th>Green #1</th>
<th>Green #2</th>
<th>Green #3</th>
<th>Green #4</th>
<th>Green #5</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Min.</td>
<td>1</td>
<td>5.2</td>
<td>8.6</td>
<td>21.8</td>
<td>34</td>
</tr>
<tr>
<td>6 Min.</td>
<td>4</td>
<td>12</td>
<td>26</td>
<td>50.8</td>
<td>60</td>
</tr>
<tr>
<td>9 Min.</td>
<td>5</td>
<td>16.7</td>
<td>31.3</td>
<td>53</td>
<td>62.7</td>
</tr>
<tr>
<td>15 Min.</td>
<td>8</td>
<td>26</td>
<td>38.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24 Min.</td>
<td>25</td>
<td>33.7</td>
<td>44.7</td>
<td>54.5</td>
<td>67</td>
</tr>
</tbody>
</table>
Figure XII. Sward Hardness for Green Enamels Varying in Composition.
of curves shows the effect of the melamine or urea resins on the rate of film hardening as the percentage of melamine - urea is increased from 0 to 100. The alkyd resin combination used in conjunction with it is not representative of the type alkyd or the combination used in a straight alkyd formulation. These curves should therefore be viewed as a demonstration of the effect of increasing amounts of polymerizing resin in a given system. To make a comparison with a straight alkyd baking formula, an enamel made with a representative oxidizing baking alkyd should have been used. The inclusion of such an enamel would perhaps have given a clearer picture of the effect of polymerizing material in high temperature short schedule baking.

In Figure XIII the experimental data are shown plotted a different way. Here Sward hardness is plotted against composition, the curves showing hardness at total baking periods of 3, 6, 9, and 24 minutes. These curves show clearly that as the melamine-urea resin content increases the ultimate hardness is approached more rapidly. At the 50% composition the difference in hardness reading between total baking times of 6, 9, and 24 minutes is not great and the advantage of baking 24 minutes would be very little over baking only 6 minutes. There is, however, a difference of $\frac{1}{4}$ to 1 in electrical energy consumed. For this group of enamels and time-temperature conditions, it would seem that beginning at a point equivalent to 30%
melamine-urea resin content there would be diminishing value in baking for more than a six minute period.

Table XXXII shows rocker readings obtained in the baking of three 100% melamine-urea resin enamels made with titanium dioxide, c.p. chrome yellow light, and c.p. chrome green medium respectively. These determinations were made on films applied on panels as previously described. These data show the effect of increasing temperatures instigated by differences in absorptivity.

A few baking tests were made using a black enamel consisting of carbon black ground in straight urea-formaldehyde resin. No temperature or Sward hardness determinations were made, but this enamel was found to bake very hard in two or three minutes. Being a black enamel, the final panel temperature attained was probably quite high.
Table XXXII

100% Melamine-Urea Enamels

Average Sward Hardness

<table>
<thead>
<tr>
<th>Color</th>
<th>3 Minutes</th>
<th>6 Minutes</th>
<th>9 Minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>White</td>
<td>6</td>
<td>41</td>
<td>42.5</td>
</tr>
<tr>
<td>Yellow</td>
<td>20</td>
<td>49.5</td>
<td>52.3</td>
</tr>
<tr>
<td>Green</td>
<td>34</td>
<td>59.5</td>
<td>60.5</td>
</tr>
</tbody>
</table>
CONCLUSIONS
These findings indicate that the use of polymerizing resins in the formulation of baking enamels offers the possibility of using to the best advantage the rapid temperature rise attainable with radiant heat baking. Judicious formulation would then facilitate the securing of short baking schedules and the attendant economy and increased production which is possible with a properly designed heat tunnel.
CONCLUSIONS AND RECOMMENDATIONS
To use radiant heat to its best advantage, consideration must be given to the thermal laws governing its behavior. Likewise the materials to be baked with it should be chosen for their adaptability to the advantages offered by radiant heat.

For baking at the same temperature level, there is no significant difference between baking with radiant heat or in the convection oven. However, because the transfer of radiant energy to the work is direct, independent of transfer by any medium, a rapid rate of temperature rise may be obtained with radiant heat. The absorptivity of the receiving surface will determine the amount of energy received which may be converted into useful energy. The dark colors are therefore best suited for radiant heat baking. The reflection of energy becomes the major loss in the heating of materials having a low absorptivity. As the temperature of an object increases, the losses by convection and radiation increase. However because of the rapid rate of temperature rise, higher temperatures are obtained in much shorter time periods, and the baking operation is accomplished much quicker.

The decrease of losses by convection would result in higher working temperatures. The prevailing air temperature naturally affects this rate of heat loss. The degree of air movement about the object would influence the losses. Whether the surface subjected to convection cooling is facing horizontally upward or downward or is
standing in a vertical position would influence these losses. The objects used in this experimental work were of ideal form from the standpoint of shape. In industrial baking, objects of various shapes and form are encountered. Available surface area for receipt of radiant energy would be an important factor. The greater the surface area with respect to mass being heated, the higher will be the efficiency of operation. Voids or open air spaces will increase losses by convection.

Since the effectiveness of radiant heat baking lies largely in the ability to reach a high temperature very rapidly, the protective coatings which harden quickly at elevated temperatures would be best suited for this method of baking. The tests conducted showing the rate of hardening as influenced by the percentage of polymerizing material in the surface coating, showed clearly the advantage of choosing those materials best adapted to radiant heat baking. Since the losses in heat are great when the maximum temperature is reached, prolonged heating schedules could become costly with radiant heat baking. There would probably be a point in the baking schedule beyond which it would be more costly to use radiant heat baking. The determination of this point would have to be performed for individual cases. The formulator of protective coatings, could, however, design products which use the splendid advantages offered by radiant heat baking to their fullest extent.
LITERATURE CITED

(1) Bennett and Haynes, Chemical and Metallurgical Engineering, February 1940.


(3) Goodell, AIEE Technical Paper 40-156 September 1940.


(5) Hodgins, Hovey, Ryan, Industrial and Engineering Chemistry 32, 334 (1940)

(6) Hodgins, Hovey, Hewett, Barrett, Neaske, Industrial and Engineering Chemistry 32, 769 (1941)

(7) Ickis and Haynes, "Drying with Near Infra-Red Radiation." General Electric Review 42, pp 145-149 (1939)


(9) Ibid, pp 45-49

(10) Sanderson, Paint, Oil, and Chemical Review 102, No.6, April (1940).

(11) Sanderson, Paint, Oil, and Chemical Review 102, No.12, June (1940).


(13) Ibid, pp 505-507

(14) Ibid, pp 500-502

REFERENCE BOOKS


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