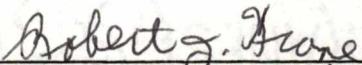
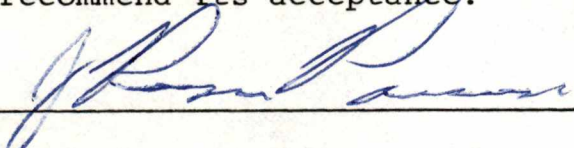


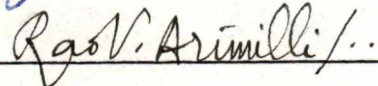
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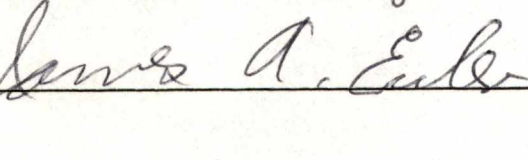

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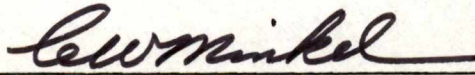








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NATURAL CONVECTION HEAT TRANSFER ABOVE
SQUARE UPWARD-FACING HORIZONTAL
SURFACES OF CONSTANT HEAT FLUX
IN AIR

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Thomas J. Phillips

June 1985

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ABSTRACT

Experiments were carried out to examine the natural convective flow above square upward-facing horizontal surfaces of constant heat flux in air. Of particular interest to this study was the determination of the surface temperature as a function of the modified Rayleigh number as well as to obtain a qualitative understanding of the flow for this geometry.

The results indicated that the flow was unsteady but laminar over the range of modified Rayleigh numbers tested. The correlations obtained indicated that the Nusselt number varied with the $1/5$ power of the modified Rayleigh number as predicted by similarity solutions for the 2-dimensional case.

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CHAPTER I

INTRODUCTION

Motivation for the Present Research

Previous free convection studies have primarily dealt with isothermal, vertically-oriented surfaces. Despite their numerous applications, horizontally-oriented surfaces have received much less attention. These applications vary from micro-meteorology, where natural convection flows parallel to the earth's surface are set up as a result of solar heating, to electronics, where natural convection is primarily responsible for the cooling of many parts such as rectifiers and component boards.

This thesis is concerned with the study of natural convective heat transfer from upward-facing, horizontal square surfaces with constant surface heat fluxes. The surfaces were all immersed in air at standard atmospheric conditions. The project was motivated by a study performed for the IBM Corporation[1], which examined the effect of natural convection on a horizontally-oriented component card mounted in a low aspect ratio enclosure. The horizontally-oriented card, which was modeled as a constant heat flux surface, was used to simulate an electronic component card inside a small keyboard-operated computer console. Typically, in

this type of device a large amount of power is dissipated on a relatively small component card resulting in undesirably high component temperatures. Complicating this problem are design specifications that severely limit the hole size on the top and bottom of the enclosure and that eliminate the possibility of using a fan for forced convection cooling.

A literature search conducted for this study revealed that no experimental investigations have been reported in the open literature for the horizontally-oriented-constant heat flux case. As a result of this surprising gap in the literature, the completion of two main objectives was sought in the present study. The first was to obtain a physical understanding of the natural convection flow for this geometry. The second was to obtain a non-dimensional relationship between the surface temperature and the modified Rayleigh number.

Literature Review

Previous studies, although concentrating more on vertical plates in general, have given a fair amount of attention to isothermal horizontal surfaces.

Rich [2] was the first to perform a study of free convection phenomena from surfaces inclined to the vertical. In this study, it was found that, for

inclination angles of 0 to 40 degrees from the vertical, the vertical plate relations could be used when modified by the cosine of the angle of inclination. Beyond 40 degrees, it was postulated that the data was affected either by the velocity component normal to the plate becoming large or from three dimensional effects.

Croft [3] conducted the first optical experimental observation of the temperature distribution and natural convection flow above a horizontal flat plate. Using a shadowgraph method of flow visualization, Croft observed cellular convection patterns similar to the Benard cell for values of the Rayleigh number between 2000 and 15000.

Husar and Sparrow [4] used an electro-chemical visualization technique to study horizontal surfaces in water. In this method, a PH change brings about the flow visualization. The results of this testing show that in flows adjacent to surfaces with corners the flow field is partitioned. These partitions arise when streamlines from adjacent sides meet along lines corresponding to the bisectors of the respective corner angles. This forces the flow upward, away from the heated surface, creating plumes which separate the flow field.

Another experimental study of isothermal flat plates was conducted by Hassan and Mohamed [5] for inclinations varying from the horizontal upward-facing case to the horizontal downward-facing case in 15 degree increments. The results are presented as plots of Nusselt number versus the tangential component of the Grashof number. For the horizontal upward-facing case, the Nusselt number was reported to vary with the $1/3$ power of the Grashof number.

Fuji and Imura [6] performed an experimental study of heat transfer from rectangular plates with acrylic plate extensions on two opposite sides designed to restrict the flow to two dimensions. The boundary condition for this experiment was neither isothermal nor constant heat flux, but rather an intermediate condition between the two. For the upward-facing horizontal surfaces, no laminar flow was observed. The Nusselt number was again correlated with the $1/3$ power of the Rayleigh number.

Al-Arabi and El-Riedy [7] performed an investigation of heat transfer from square, circular, and rectangular isothermal horizontal surfaces. They suggested that there will be three distinct areas where the heat transfer coefficients will vary: 1) the corner regions, 2) the edge regions, and 3) in the central region of the plate. For square surfaces, it was

reported that the Nusselt number could be correlated with the $1/4$ power of the Rayleigh number for values of the Rayleigh number less than 4×10^7 . For values above this, a $1/3$ power relationship was observed indicating a transition to turbulence at this point.

Ishiguro et al. [8] have studied heat transfer and periodical changes in the flow field above horizontal isothermal surfaces in water. Both a numerical study and a supporting experimental study were performed for this case. They reported that the experiments matched the analysis well to a Rayleigh number of 2×10^5 . Above this value, a $1/3$ power relationship was used to correlate the Nusselt number with the Rayleigh number. This was attributed to three-dimensional disturbances within the experimental flowfield.

Yousef, Tarasuk, and McKeen [9] recently performed experiments using an interferometer to measure heat transfer coefficients and the temperature field above a horizontal isothermal surface. Fluctuations in the local Nusselt number ranging from +45% to -35% were reported in both the laminar and turbulent regimes. In the laminar region, the Nusselt number was correlated to the $1/4$ power of the Rayleigh number; whereas, the turbulent region was fitted to a $1/3$ power relationship. It was concluded that because of the unstable nature of the flow a correlation yielding a single value for Nu

or Nu was unrealistic. These authors suggested that expected deviations from the correlated value be presented along with correlation to provide a more accurate assessment of the heat transfer from horizontal surfaces.

Although the present study is experimental, some of the analytical and numerical solutions available in the literature will be mentioned briefly.

Stewartson [10] presented an analysis of natural convection flows from semi-infinite horizontal surfaces. A sign mistake in Stewartson's analysis was corrected by Gill, Zeh, and Del Casal [11], who showed that boundary layer flow can exist only in the case of a heated plate facing upwards or a cooled plate facing downwards. The Nusselt number was seen to vary with the $1/5$ power of the Rayleigh number for the laminar case.

Suriano and Yang [12] presented a numerical finite-difference solution of the temperature and velocity fields above horizontal isothermal heated surfaces (as well as about heated vertical surfaces). It was shown that conduction effects dominate in the low Grashof number ranges; while, convection dominates for higher Grashof number flows.

Rotem and Claassen [13,14] performed a similarity solution for natural convection flows above horizontal plates and discs with both isothermal and constant heat

flux boundary conditions. The effects of very small and very large Prandtl numbers were investigated; and, temperature and velocity profiles were given for different Prandtl numbers. These studies also predicted that the Nusselt number would vary with the $1/5$ power of the Rayleigh number for laminar flow.

Pera and Gebhart [15,16] conducted a numerical study of horizontal and slightly inclined surfaces. Velocity and temperature fields were solved for and presented for a wide range of Prandtl numbers.

An integral method was used by Fussey and Warneford [17] to obtain the governing equations for upward-facing inclined plates of constant heat flux. The angles of inclination ranged from 0° to 90° from the vertical. These equations were then solved numerically to provide a correlation of Nusselt number as a function of the modified Rayleigh number.

Goldstein and Lau [18] performed a numerical analysis of horizontal isothermal surfaces. Mass transfer experiments, which are mathematically similar to the isothermal heat transfer case, were also conducted to support the analysis. It was found that a $1/5$ power relationship between the Nusselt and Rayleigh numbers described the numerical results and was further justified by the mass transfer experiments.

It should be emphasized that all the analytical studies done to date have assumed a two-dimensional flow field. Experimental studies mentioned previously (such as Yousef, Tarasuk, and McKeen) have indicated, however, that three-dimensional effects can be quite large. For this reason, the two-dimensional assumption has been cited most often as the probable cause for discrepancies between the analytical and experimental results. Summaries of the experimental and analytical studies mentioned above have been presented in Tables 1 and 2, respectively.

Table 1 - Summary of Experimental Studies

Reference	Fluid	Config.	Correl.	Valid Ra	Comments
Rich (1953)	air	vert. and slightly inclined	$Nu=f(Gr, Pr, \cos\theta)$	$Gr < 1 \times 10^3$	isothermal surfaces
Croft (1958)	air	horiz. facing up	$0 \ln(t/t_a) = 3.1(z/z_0)^{-0.5}$	$z/z_0 < 2.2$	isothermal surfaces temperature field was examined optically
Huear and Sparrow (1968)	water	horiz. facing up	---	---	flow visualization study
Hasan and Mohamed (1970)	air	horiz. facing up	$Nu = .12 Gr^{1/3}$	$1.1 \times 10^3 < Gr < 3 \times 10^8$	isothermal surfaces
Puji and Imura (1972)	water	horiz. facing up	$Nu = .13 (Gr Pr)^{1/3}$ $Nu = .16 (Gr Pr)^{1/3}$	$Ra > 5 \times 10^8$ $Ra < 2 \times 10^9$	no laminar flow observed, plate neither isothermal nor constant heat flux
Al-Arabi and El-Riedy (1976)	air	horiz. facing up	$Nu = .70 (Gr Pr)^{1/4}$ $Nu = .155 (Gr Pr)^{1/3}$	$2 \times 10^5 < Ra < 4 \times 10^7$ $Ra > 4 \times 10^7$	laminar flow noted isothermal surfaces
Yousef, Tarasuk, and McKeen (1982)	air	horiz. facing up	$Nu = .622 (Gr Pr)^{1/4}$ $Nu = .162 (Gr Pr)^{1/3}$	$3 \times 10^6 < Ra < 4 \times 10^7$	noted considerable fluctuations in Nu_x isothermal surfaces
Ishiguro, et al. (1978)	water	horiz. facing up	$Nu = .2 (Gr Pr)^{1/3}$	$Ra > 2 \times 10^5$	isothermal periodic variations of Nu noted in transition range (2-D flow)

Table 2 - Summary of Analytical Studies

Reference	Method	Config.	Correl.	Comments
Stewartson (1958)	Similarity Solution	horiz. surfaces isothermal	$Nu=cRa^{1/5}$	sign error led to erroneous conclusions regarding boundary layer on horizontal surfaces
Gill, Zeh, and Del Casal (1965)	Similarity Solution	horiz. surfaces isothermal	$Nu=cRa^{1/5}$	corrected sign error of Stewartson, showed correct boundary layer configuration, 2-D flow
Suriano and Yang (1967)	Numerical finite difference approach	vertical and horiz. plates at small and moderate Grashof	---	temperature and velocity flow field studied isothermal, 2-D flow
Rotem and Claassen (1969)	Similarity Solution	horiz. plates and disks, constant heat flux and isothermal cases	$Nu=cGr^{1/5}$ (air)	temp., veloc., and press. fields studied for differing Pr, 2-D flow
Rotem and Claassen (1969)	Similarity Solution	horiz. surfaces large and small Pr for const. heat flux and isothermal case	$Nu=cRa^{1/5}$	mentions constant heat flux experiments but presents no results from these
Pera and Gebhart (1973)	Linear stability theory with numerical integration	horiz. and slightly inclined, isothermal	---	stability of flow studied analytically and experimentally, 2-D flow
Pera and Gebhart (1973)	Numerical	same as above also const. heat flux	---	vel., temp., and press. fields studied, 2-d flow
Fussey and Warneford (1976)	Integral-Method	upward-facing inclined plates	$Nu_x=.434Ra_x^{1/5}$ $Pr=.10$ $Nu_x=.550Ra_x^{1/5}$ $Pr=1.0$ $Nu_x=.590Ra_x^{1/5}$ $Pr=10.0$	constant heat flux plate, laminar flow 2-D flow
Goldstein and Iau (1983)	Finite difference method	horiz. facing up and down, plate edge extension effects examined	$Nu=cRa^{1/5}$	mass transfer exper. justify $1/5$ power law 2-D flow

CHAPTER II

THE EXPERIMENTAL INVESTIGATION

Statement of Objectives

There were two objectives sought in the completion of this thesis study. The first objective was to obtain a qualitative understanding of the natural convection flows on square, upward-facing, constant heat flux surfaces in air.

The second objective was to determine a non-dimensional correlation of surface temperature as a function of the modified Grashof number and Prandtl number. The magnitude and location of the maximum surface temperature on the plate are of particular interest.

Design of the Constant Heat Flux Surfaces

The first step was to design an appropriate experimental apparatus. Three heater "cards" (6, 8, and 12 inch square) were tested, each with the same design. Each card consisted of an Inconel foil resistance heater (.018 in. thick), which acted as the constant heat flux surface, stretched taut by means of tensioning devices over a square phenolic board (as shown in Figure 1). Both tensioning devices, located on the underside of the heater card, consisted of two copper bars which clamped

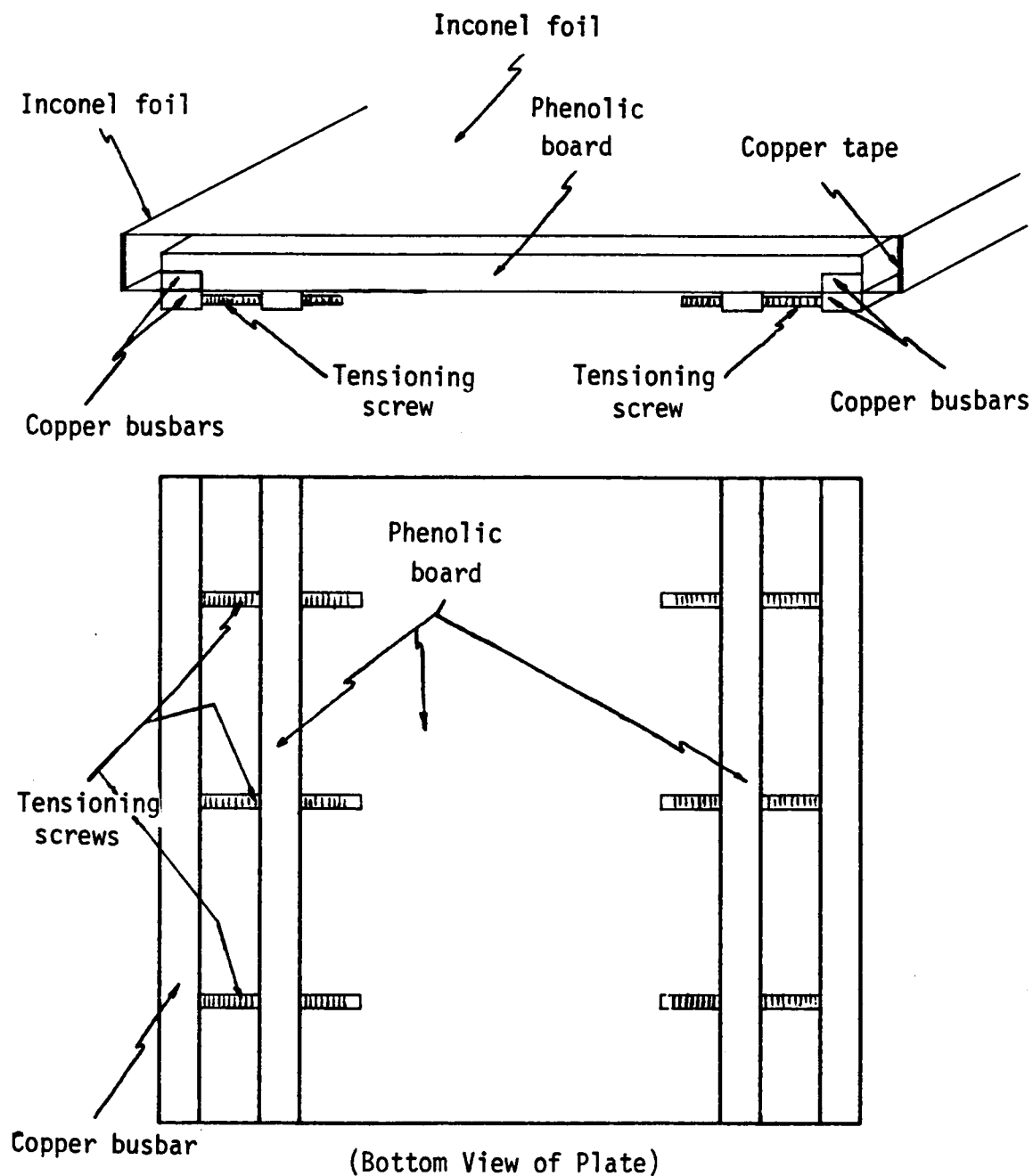


Figure 1. Flat Plate Design Details

around the foil and were allowed to slide out away from the phenolic board. This slide adjustment was made by means of three tensioning screws also located on the underside of the plate.

The low resistance of the copper bars compared to the Inconel foil served to ensure that the current was spread uniformly over the width of the foil. To further aid in the accomplishment of this goal, an electrical lead was connected to each end of the bar, thereby minimizing the voltage drop along its length. To minimize contact resistance between the foil and copper busbars, several clamping screws were employed to tightly secure the copper bars around the foil.

It was desired to have only the square surface of the foil above the phenolic board heated; however, with the copper busbars located on the bottom of the phenolic board there was an undesired length of heated foil. To eliminate this, electrically conductive copper tape (Scotch 1181) was placed along this length and clamped with the foil between the copper bars. This served to keep the entire length at the same potential and thus eliminated any internal heat generation on this portion of the foil.

To provide for temperature measurement on the foil surface, 36 gauge copper-constantan thermocouples were brought through .043 inch diameter holes at the back of

the bakelite board and soldered to the underside of the Inconel. Shallow holes, approximately $1/4$ inch in diameter, were countersunk in the top surface of the bakelite to keep the solder beads from causing any irregularities on the foil surface. Detailed sketches of the thermocouple positions for each of the three heater cards tested are presented in Figures 2,3, and 4.

Insulation was added to reduce the heat transfer out of the back and sides of the heater card assemblies. Balsa wood was used for this purpose with a four inch layer on the bottom and a one-half inch layer around the sides of the plates. Sawdust was used as a filler to eliminate any air spaces left between the balsa wood and the bakelite in preliminary tests of the 6 inch card. However, it was found that the presence of the sawdust had a negligible effect on the results ;and thus, the sawdust was not used in the actual experiments. All surface thermocouples were brought out a single hole in the center of the insulation which was just big enough to accomodate the thermocouple bundle. This hole was then sealed with duct tape at both ends to prevent convection currents from arising.

Radiation heat transfer was minimized by ensuring that the foil surfaces were clean and highly polished.

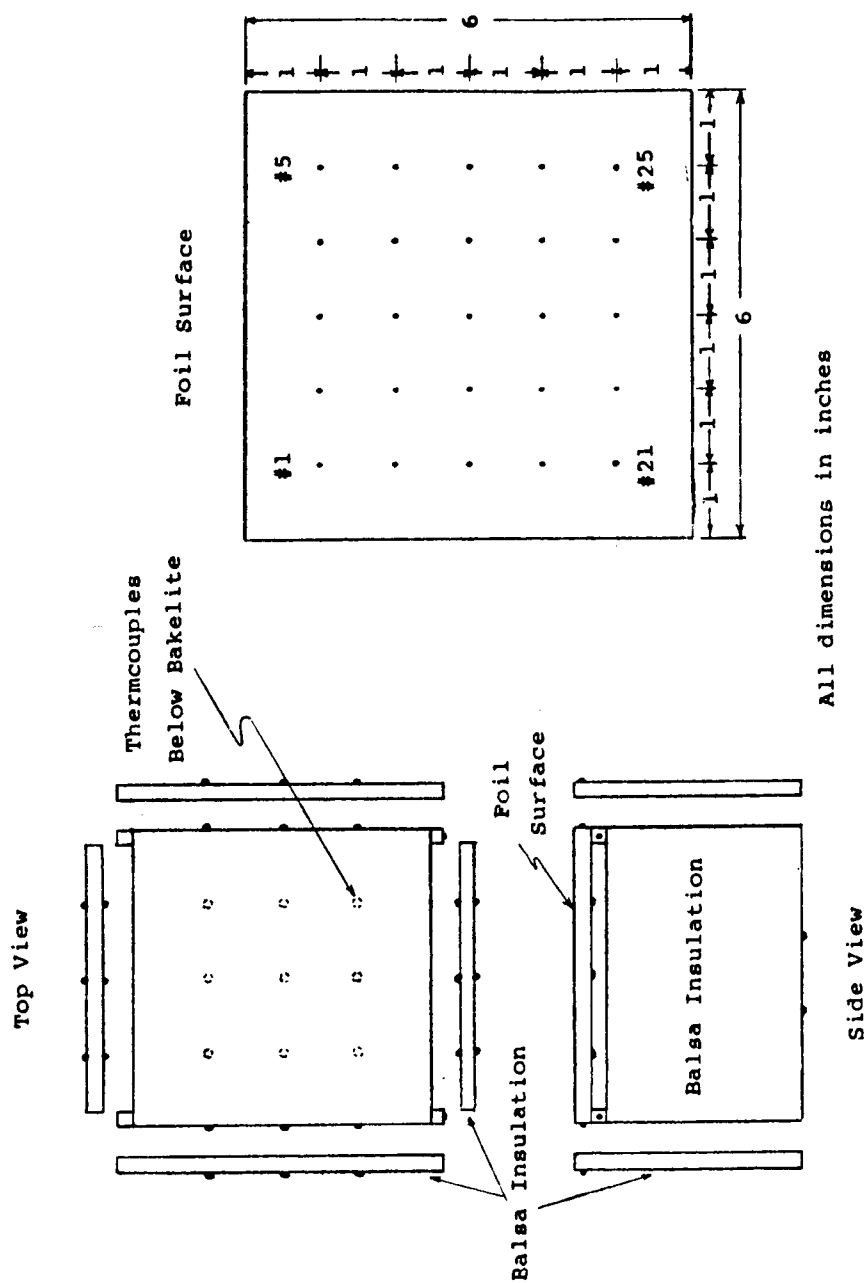


Figure 2. Thermocouple Positioning for the 6 inch Plate

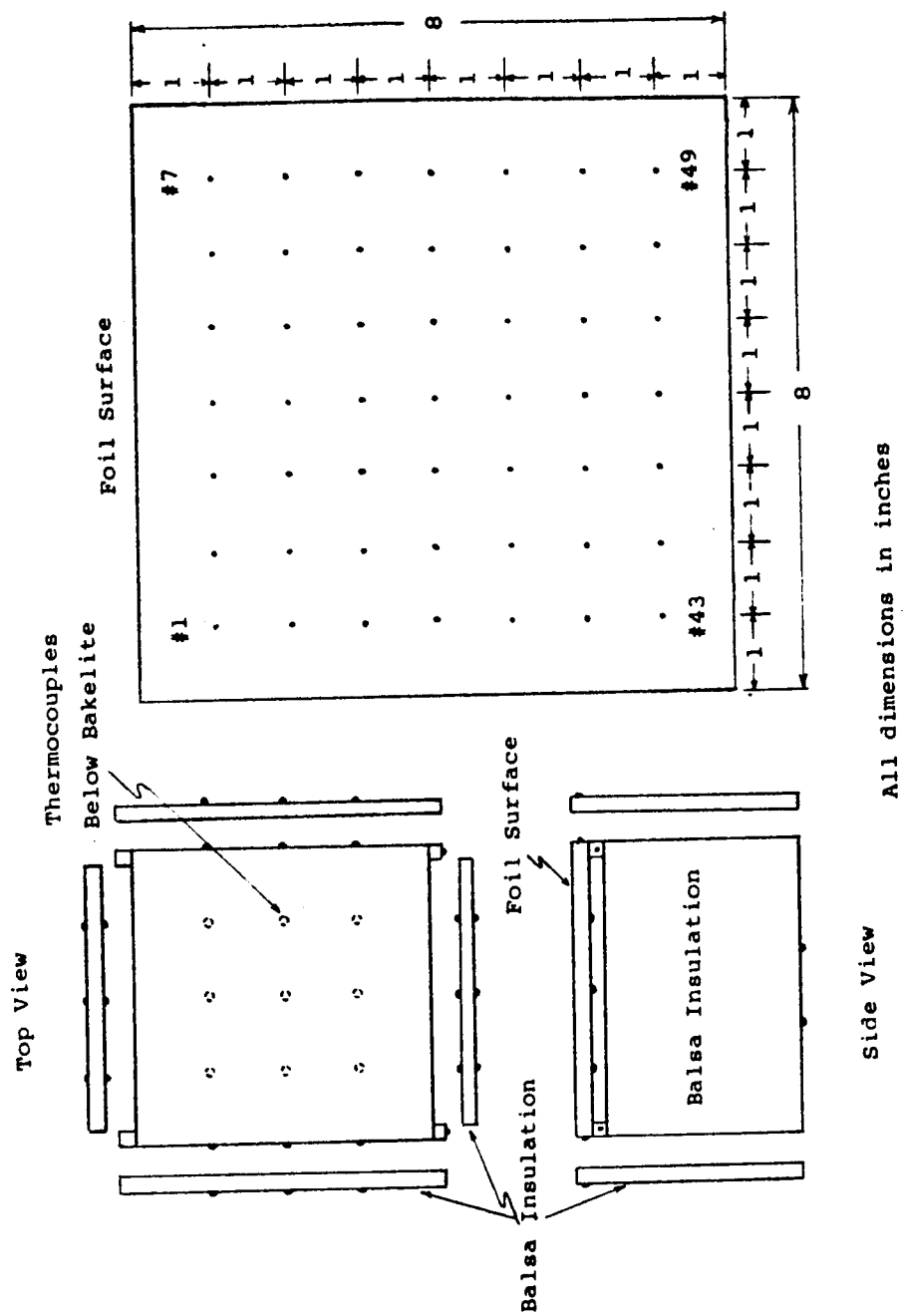


Figure 3. Thermocouple Positioning for the 8 inch Plate

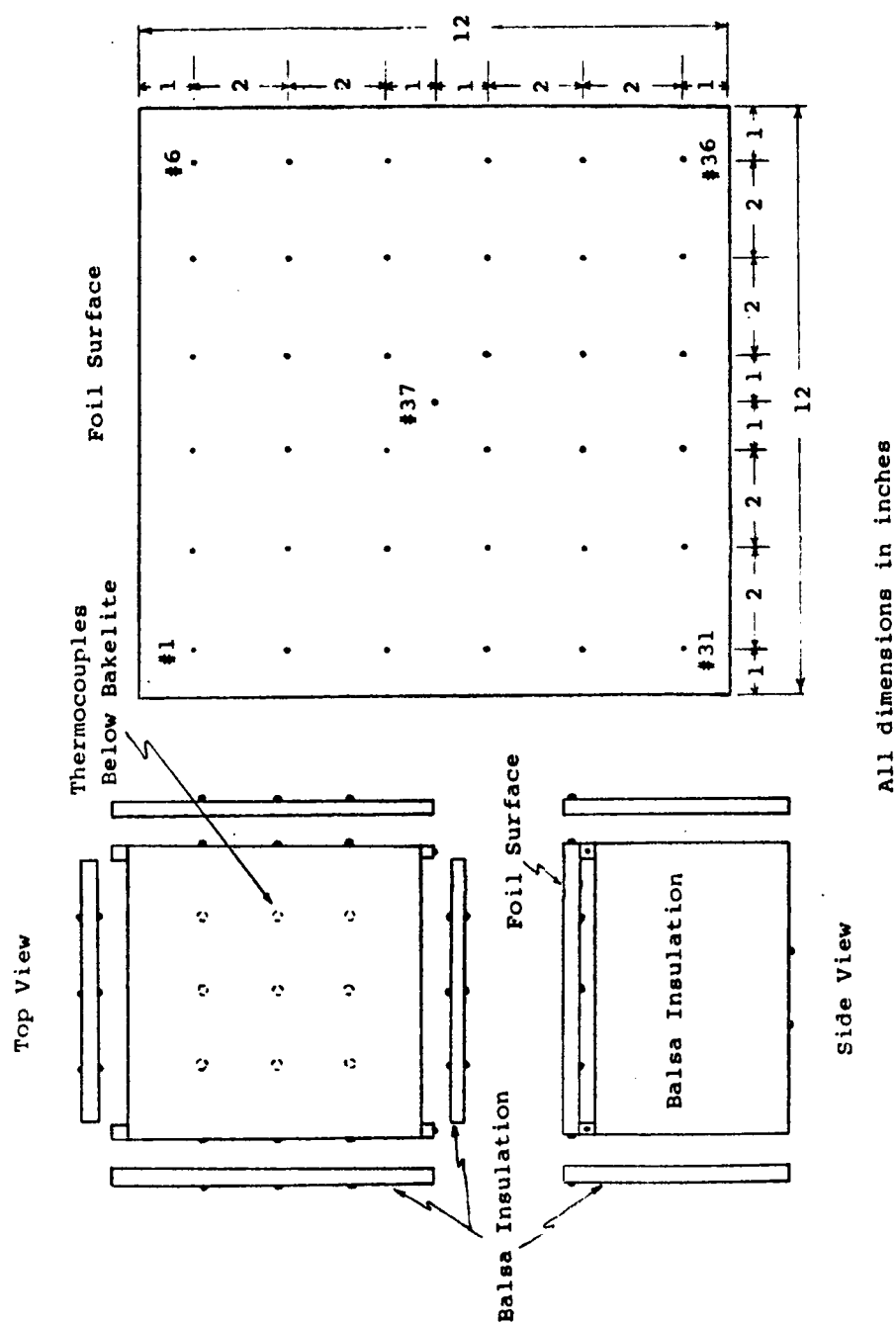


Figure 4. Thermocouple Positioning for the 12 inch Plate

In order to prevent disturbances in the room from affecting the delicate free convection flow, the plates were placed inside a sealed 3 x 3 x 5 foot enclosure. The enclosure was equipped with four leveling screws in the bottom of the chamber to allow the heater assemblies to be leveled accurately. Two sides of the enclosure were made of plexiglass to allow the flow visualization studies to be conducted in the chamber. To minimize enclosure effects on the flow, the experimental setup was placed on a stand, centered in the chamber, which positioned the heat transfer surface approximately two feet above the bottom of the enclosure. A photograph of a flat plate assembly in the enclosure is presented in Figure 5.

Instrumentation and Data Acquisition System

The instrumentation used in this experiment may be divided into three categories. The first group included the instruments used to determine the electrical power input to the heater card assemblies. The second group consisted of instruments used to measure and record the data taken, while the third group was used for the flow visualization experiments. General information on the wiring and configuration of this equipment will be presented in this section. For detailed descriptions of all hardware used in the experiment, see Appendix A.

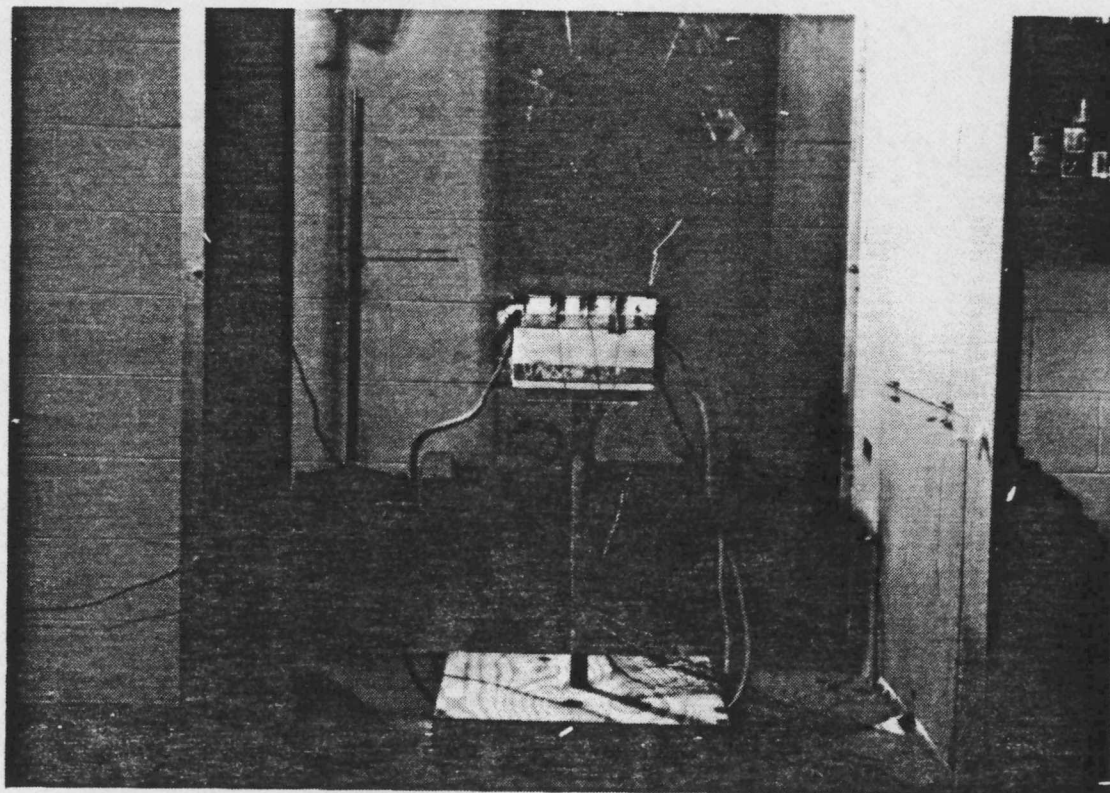
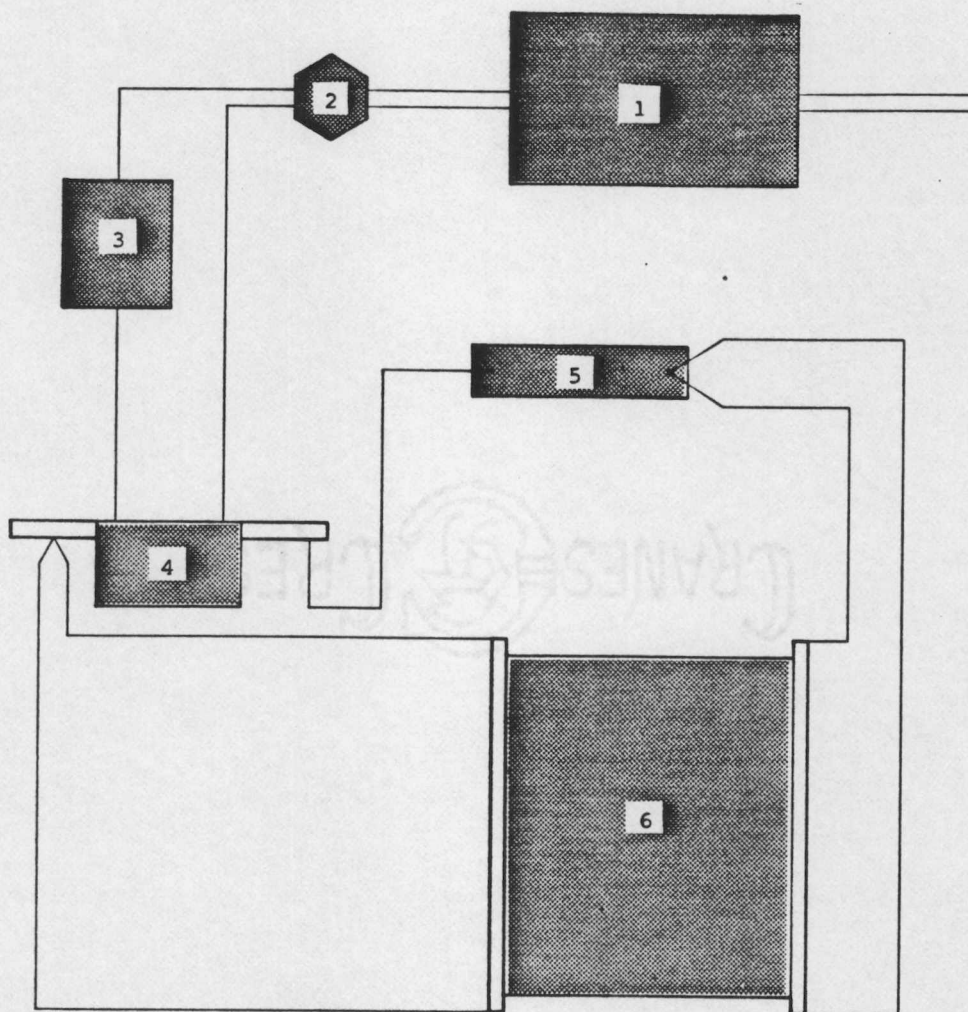


Figure 5. Flat Plate Assembly in the Test Enclosure

A schematic showing the power loop is presented in Figure 6. A constant voltage transformer (item 1) was connected between the line source and the experimental apparatus. This served to minimize the affect of line voltage fluctuations on the experimental results. Observations of measured voltage indicated that this worked very well, limiting the maximum voltage fluctuations to approximately $\pm .5$ milivolts. The constant voltage transformer provided the input to a Variac (item 2), which was in turn connected to a high current transformer (item 4). The Variac provided a variable voltage input to the high current transformer which in turn provided for variation in the power input to the heater surface (item 6). The high current transformer converted a high voltage-low current input into a low voltage-high current output. This high current output was needed to provide sufficient power input to the heater card due to the low resistance of the Inconel foil (.0254 ohms/square).

In order to accurately determine the current provided to the heated plate, a high precision current shunt (item 5) was placed in series with the transformer and flat plate assembly. The voltage drop across the current shunt was measured using a high impedance Data Precision digital voltmeter. The same voltmeter was used to directly measure the voltage drop across the



1. Constant Voltage Transformer
2. Variac
3. Ammeter
4. High Current Transformer
5. High Precision Current Shunt
6. Heater Surface

Figure 6. Electrical Wiring Schematic of Power Input Loop

heated foil surface. An ammeter (item 3) was placed in series between the Variac and the high current transformer. This was not used to take data but, rather, was used to insure that the current specifications of the transformer were not exceeded.

The second group of instruments consisted of those used to measure and record data. Copper-constantan thermocouples (36 gauge), manufactured by Omega Engineering Corporation, were used for temperature measurement. Figures 2,3, and 4 (pp.15-17) present detailed thermocouple locations for all three heater card assemblies. Along the surfaces of the 6 inch and 8 inch plates, thermocouples were placed 1 inch from each edge and at 1 inch intervals for a total of 25 and 49 thermocouples respectively. The 12 inch plate was instrumented with thermocouples located 1 inch from each edge and spaced 2 inch apart. An additional thermocouple was placed at the center of the surface, which brought the total to 37. This allowed for a detailed surface temperature measurement of each plate. All three cards were also instrumented with 6 thermocouples along each side. Three were located between the plate and the insulation, with the remaining three located on the outside of the insulation. This allowed for calculation of the heat losses from the sides. To measure the heat transfer lost through the back surface,

nine thermocouples were placed along the bottom of the phenolic board as well as 2 more located on the underside of the balsa insulation.

In addition to the thermocouples located on the flat plate assemblies, an array of 3 thermocouples were placed at varying heights (1,3, and 5 feet) inside the test chamber. These served to measure the far field temperature around the test setup and to check for thermal stratification in the enclosure.

Two methods were used to provide good thermal contact between the thermocouples and surfaces to be measured. To insure adequate contact on all thermocouples used to measure the foil surface temperature, the thermocouple leads were soldered, directly to the foil surface, with the smallest possible beads. On all other surface temperature measurements, a small amount of thermally conductive paste (Omegatherm 201) was smeared around the leads before taping them to the surface to be measured. An electronic ice point reference cell (Omega model RC-340) was used to provide an ice point reference voltage for all thermocouples.

A Hewlett-Packard 9826 micro-computer was used in conjunction with a Hewlett-Packard 3497-A Data Acquisition/Control Unit to read all thermocouple voltages. Some electronic noise was detected in the preliminary experiments and caused an apparent periodic

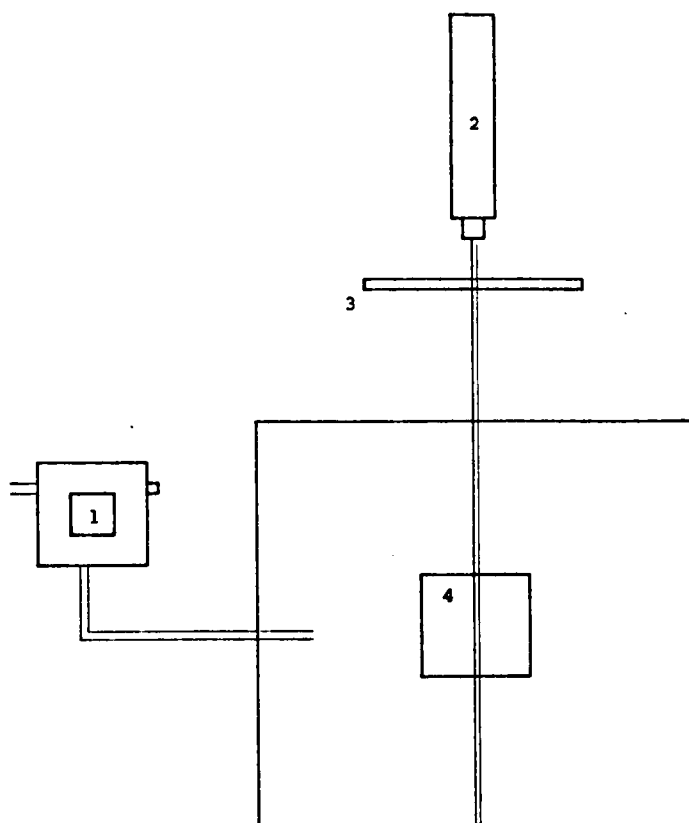
oscillation of the temperatures on the foil surface. In order to eliminate the noise effects, a wire was run from a copper busbar to the guard terminal of the acquisition center and served to keep both at a zero relative potential. A detailed description of the data acquisition methods are given in the Data Acquisition and Reduction section of this thesis. In addition, data acquisition program listings are presented in Appendix B.

The Data Acquisition Unit as presently equipped could handle only 79 thermocouples. The 8 inch card, however, was instrumented with 97 thermocouples so that a manually read thermocouple board was needed to read the 18 additional thermocouples. An Omega (model 200) digital meter with a built-in ice reference was used with this board so that these temperatures were read directly and used as inputs to the computer.

A high impedance Precision Digital Voltmeter (model 3500) was used to measure the voltage drop across both the current shunt (giving a measurement of the current through the foil surface) and the heater card. The high impedance of this instrument served to eliminate any effects of lead wire resistance, thereby avoiding problems of additional voltage drop through the lead wires.

The laboratory air temperature (outside the test chamber) was measured with an accurate mercury-in-glass thermometer. This measurement was made to ensure that the test chamber was in equilibrium with its surroundings.

The flow visualization experiments were conducted using the setup shown in Figure 7. A smoke generator(item 1) was used to inject smoke into the top of the test chamber. This was done at a low flow rate to prevent disturbance of the delicate flow over the flat plate. A schematic of the smoke generator used is given in Figure 8. A 15 mW helium-neon laser(item 2) was then used to illuminate the enclosure. The laser beam was passed through a small diameter (3/16 inch) glass rod(item 3), positioned immediately in front of the laser, which created a sheet of light in a plane perpendicular to the test surface(item 4). The laser source could be positioned in any fashion, so that visualization along virtually any plane (including diagonals) was possible. This provided excellent visualization of the smoke particle pathlines above the entire surface of the plate.



1. Smoke Generator
2. Laser Light Source
3. Glass Rod
4. Test Surface

Figure 7. Flow Visualization Equipment Schematic

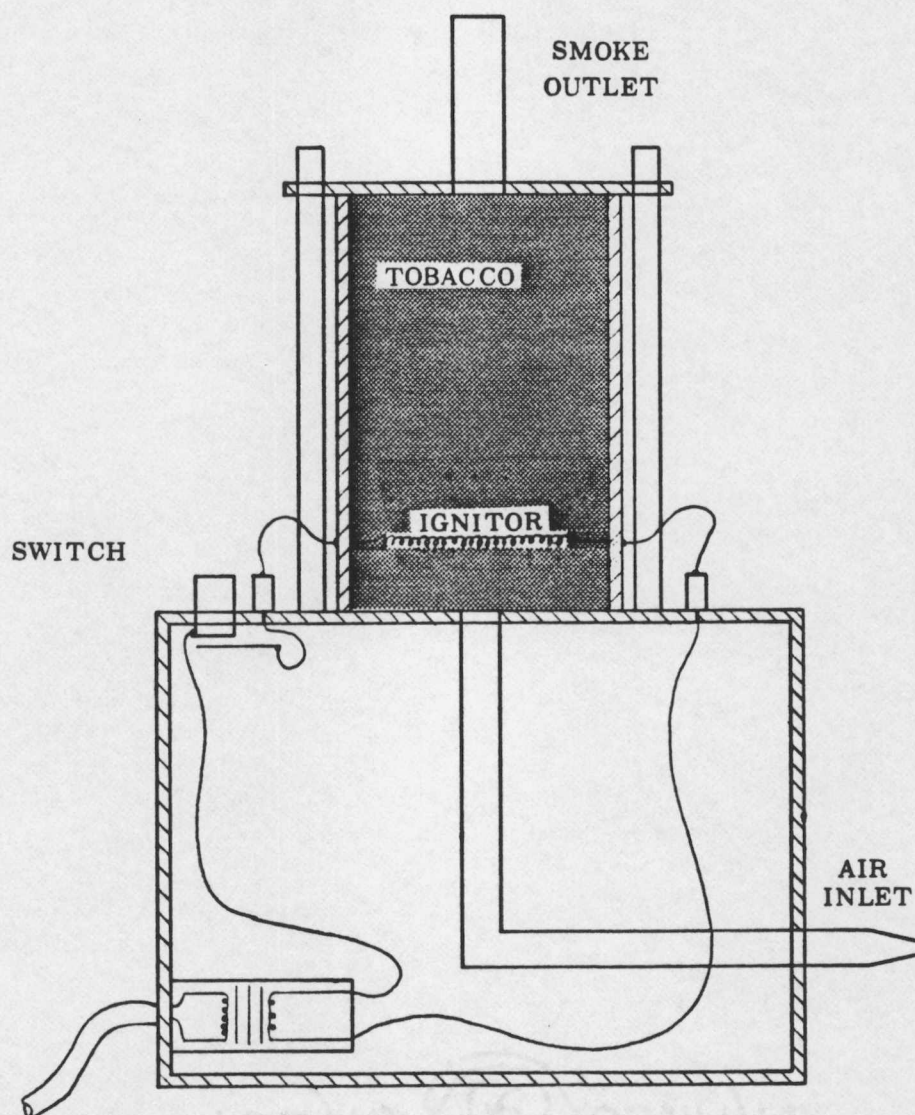


Figure 8. Schematic of Smoke Generator

Test Program

Two types of tests were performed on each of the three plates used in this experiment. The first type of test consisted of determining the temperature distribution on the surface of the foil for different power input levels. These tests were conducted by starting with a power input of 5 Watts (for all three cards) and increasing this input in increments of 5 Watts until the surface temperature approached the melting point of the solder used to attach the surface thermocouples. For a detailed description of the procedure followed in these tests see Appendix C.

The non-dimensional temperature (proportional to the reciprocal of the Nusselt number) was to be correlated as a function of the modified Rayleigh number; so, it was desired to obtain as much overlap as possible between the Rayleigh numbers of the three test surfaces. Figure 9 shows the test matrix for all three test surfaces. Some overlap was present, although not to the desired degree due to the high surface temperatures reached at relatively low power inputs (and consequently low modified Rayleigh number) on the smaller cards.

The second type of test performed were flow visualization studies. These were run to visually determine the physical characteristics of the free

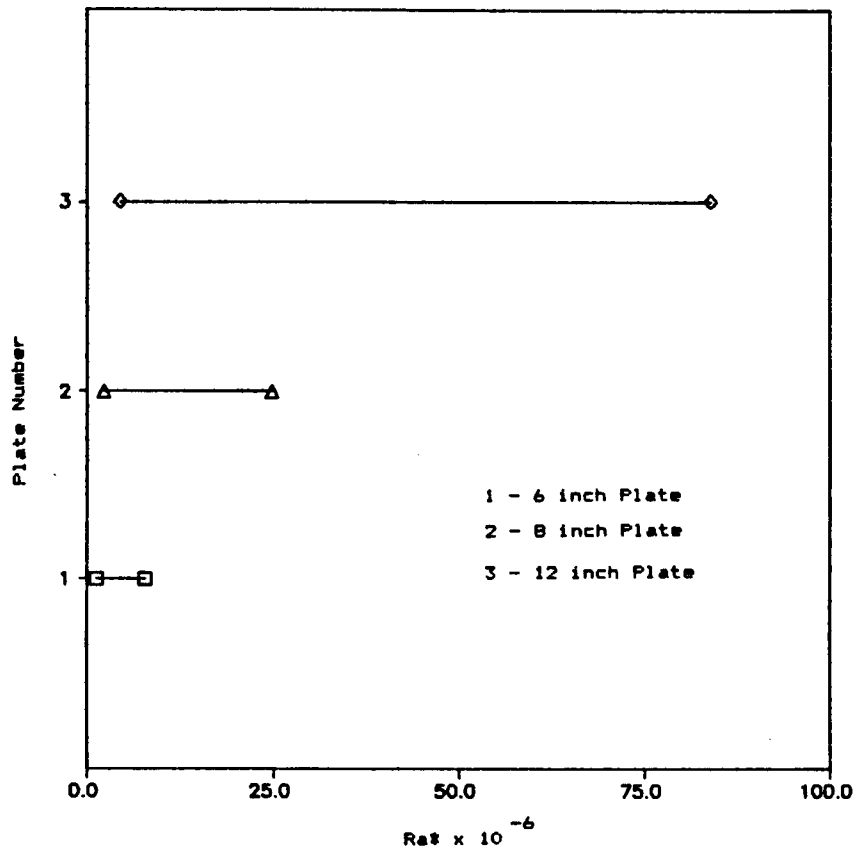


Figure 9. Test Matrix

convective flow over these surfaces. Two tests were performed for each plate at different Rayleigh numbers and were video-taped to provide permanent records of these flows. In addition to the limited amount of video-taping that was done, a considerable amount of time was spent observing the flow phenomena for these experiments.

Data Acquisition and Reduction Procedures

This section is intended to describe the software used to obtain, reduce, and record the data taken in this experiment. In addition to these descriptions, complete program listings are presented in Appendix B.

Measurement of thermocouple outputs was initiated by measuring all of the foil surface thermocouple voltages. These were read sequentially, starting with thermocouple position 1 and proceeding through the last surface thermocouple. This process was then repeated ten times to provide a sufficient number of readings to obtain a representative average temperature at each location. Each measurement cycle took approximately 2.5 seconds for the 6 inch plate, 7.9 for the 8 inch plate, and 5.4 for the 12 inch plate. This averaging process was necessary due to fluctuations of surface temperature caused by the unsteady nature of the flow.

The Data Acquisition Unit thermocouple junction temperatures were free to vary both from card to card and with time. Because of this, it was necessary to include an ice reference thermocouple in each card, and to measure these reference voltages in the same loop (i.e. at approximately the same time) as the surface thermocouples. These reference voltages were then immediately subtracted from the surface voltages to obtain the voltage corresponding to the surface temperature.

In addition to voltage measurements, the computer's internal clock was used to record elapsed time between each successive group of foil surface temperature measurements. This enabled temperature versus time data to be examined and was helpful in detecting "noise" problems in the preliminary tests.

The remaining thermocouples on the second and third cards (the Acquisition Unit could only handle three cards at once) were then read ;and as before, this process was repeated ten times to provide a representative average voltage reading for each thermocouple. The fourth card was then inserted and read in a similar manner, so that all thermocouples were read ten times.

All voltages were then averaged and by means of a lookup table and linear interpolation, this value was converted to its corresponding temperature. At this point, the program paused to allow values such as current, voltage, elapsed time between tests, room temperature, test number, and date to be entered as inputs to the computer.

All pertinent information was then stored on floppy diskettes to provide a permanent record of each test. Due to the differing number of thermocouples, and differing positions of correspondingly numbered thermocouples, a separate program was used for each of the three heater cards tested. However, all three programs used the procedure described above for the measurement and recording of data.

The data reduction was performed in two steps, each step utilizing a separate program. The first step consisted of performing a heat balance on the test setup to determine the amount of heat transferred by free convection.

To perform the heat balance, the plate temperatures, voltage drop, and current flow were read from the file created by the data acquisition program. Next, the Prandtl number, Grashof term ($g\beta/\gamma^2$), and the thermal conductivity of the air were determined at the desired property evaluation temperature (either the

ambient air temperature, average plate surface temperature, or the average film temperature). A tabulation of these properties, using NBS 564, was obtained from Dyer and Wolf[19].

The amount of heat transferred by radiation was determined next. The hemispherical total emittance of the Inconel foil surface was accurately determined using the facilities at the Oak Ridge National Laboratory. A description of the method used is given in Appendix D. Each thermocouple was assumed to represent an average temperature over the small area on which it was centered. The radiation heat transfer was determined by summing the radiative contributions from each of these area elements.

Next, the heat transferred by conduction from the sides and back of the plate was calculated. This was done assuming one-dimensional heat transfer in each case. The thermal conductivity of the balsa wood was determined from Lienhard[20]. To determine the conduction losses from the sides, the temperature was measured on both faces of the balsa insulation placed around the sides of the plate. Three pairs of these thermocouples were placed per side; and, by assuming that each one represented an average surface temperature over the area in which it was centered, the heat transferred by conduction through each of these area

elements could be calculated. The total conductive loss through the sides was then obtained by summing the individual losses.

The conduction losses from the back surface was determined in the following manner. An effective thermal conductivity of the bakelite, air gap, and balsa was calculated, using the previously determined thermal conductivities of the air and the balsa and the manufacturer's listed value for the thermal conductivity of the bakelite. The temperature drop across these surfaces was determined by averaging the balsa surface temperature on the underside of the test setup and subtracting it from the average plate surface temperature. The amount of heat transferred through the back could then be calculated.

Finally, the amount of heat conducted axially along the electrical leads was sought. To accomplish this, the leads were instrumented with thermocouples and tests performed to determine the axial temperature distribution. Once this temperature distribution was known, the heat transferred could be calculated. It was found that this amount was a constant percentage of the input power. A discussion of the tests performed is presented in Appendix E.

The natural convection heat transfer from the top surface of the plate was then calculated by subtracting these "losses" from the power input. It should be noted that the "losses" were quite high (approximately 30% of the power input). Due to this fact, a validation of the heat balance method was sought using a Wollaston Prism Schlieren Interferometer. The procedure and results of this test are discussed in Appendix G. An uncertainty analysis of both the heat balance and the WPI test was performed. The uncertainty analysis of the heat balance was performed in the program; however, details of both these analyses are presented in Appendix H of this thesis.

Once the heat balance was performed, the modified Rayleigh number was calculated and stored on a floppy diskette to be used in the second data reduction step. This second step consisted of calculating Nusselt numbers and correlating them as a function of the modified Rayleigh number. In order to calculate the Nusselt number, it was necessary to determine the average convection coefficient, h_c , for the plate surface. The average convection coefficient is defined by,

$$(2-1) \quad h_c = q / (1/L^2 \int_0^L \int_0^L [T_s(x,y) - T_a] dx dy).$$

The integration was performed numerically using the trapezoidal method. Once the Nusselt numbers were determined, they were correlated using a least square fit to a function of the form,

$$(2-2) \quad Nu = c_1 Ra^{*c_2}.$$

The constant, c_2 , could either be determined as part of the least square fit process or chosen in advance.

This same program was used to correlate non-dimensional maximum surface as a function of the modified Rayleigh number. The non-dimensional maximum surface temperature was defined by,

$$(2-3) \quad T_{max} = (T_{s_{max}} - T_a) / (qL_c/k).$$

The results of these correlations are presented and discussed in Chapter III of this thesis. A listing of each of the data reduction programs appears in Appendix B; and, a copy of the data taken is presented in Appendix I.

CHAPTER III

PRESENTATION AND INTERPRETATION OF RESULTS

The Governing Equations

Utilizing the Boussinesq Approximation, the dimensional form of the governing equations for natural convection flow over a horizontal surface (steady-state flow) may be expressed as:

$$(3-1) \quad \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 ,$$

$$(3-2) \quad u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{1}{\rho} \frac{\partial P_d}{\partial x} + \nu \frac{\partial^2 u}{\partial y^2} ,$$

$$(3-3) \quad g\beta(T - T_\infty) = \frac{1}{\rho} \frac{\partial P_d}{\partial y} ,$$

$$(3-4) \quad \rho C_p \left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) = K \frac{\partial^2 T}{\partial y^2} + Q' + \mu \left(\frac{\partial u}{\partial y} \right)^2 .$$

Examination of the momentum equations reveals that the flow is driven by the motion pressure gradient parallel to the plate. This gradient is set up as a result of the buoyancy force which is directed outward and perpendicular to the surface of the plate. Physically, the fluid adjacent to the surface is heated and rises creating a low pressure region at the plate center. This pressure gradient pulls fluid inward, thus

establishing the flow field. Additional details of the analytical aspects of this flow may be found in Jaluria[21].

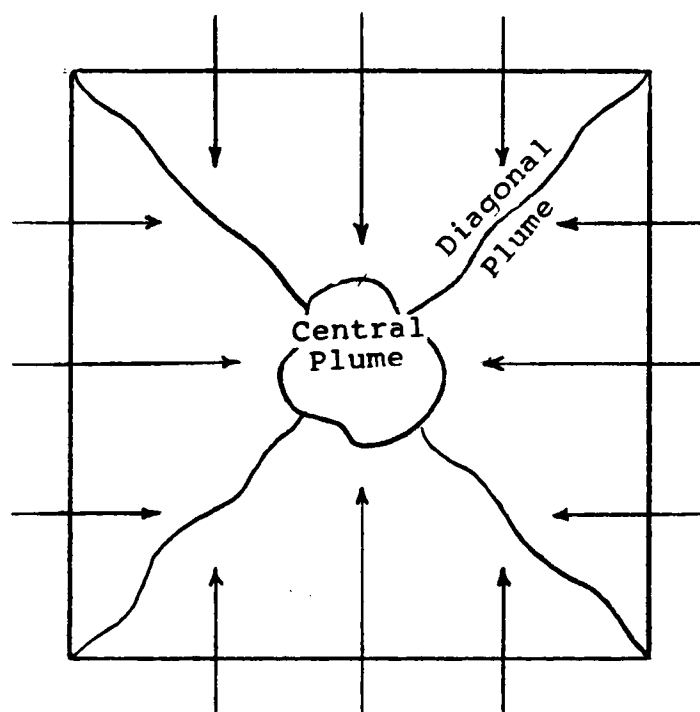
The characteristic non-dimensional parameter for this flow is the Rayleigh number. When the heat flux at the surface is specified, Sparrow and Gregg[22] have shown that the "modified" Rayleigh number should replace the conventional Rayleigh number as the characteristic dimensionless group. This is due to the fact that the temperature difference which appears in the conventional term is no longer known in advance, but must somehow be determined. The "modified" Rayleigh number may be obtained by replacing the temperature difference with qL/k in the conventional term to obtain,

$$Ra^* = (g\beta qL^4/\gamma^2 k)(C_p\mu/k).$$

Flow Visualization Results

As was stated previously, flow visualization tests were performed on each of the three surfaces studied. The results of these tests suggest very similar behavior with the horizontal isothermal flows as presented by Husar and Sparrow[4].

As shown in Figure 10, the fluid flows along a path approximately perpendicular to the plate edges. As the fluid from one edge approaches that from the adjacent (or opposite) edge, the flow turns upward to form a



Central Plume

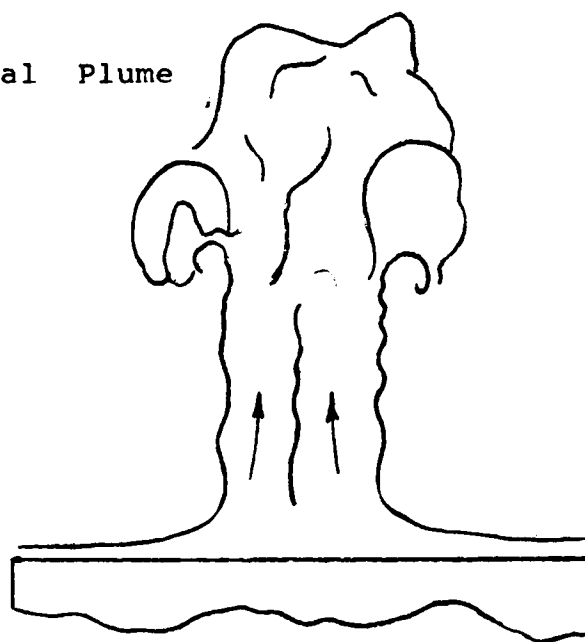


Figure 10. Sketch of the Flow Field for a Typical Test

plume. These plumes rise along the bisectors of the corner angles. The central plume seems to be the strongest plume rising from the surface, as could be deduced from the fact that all four edges are "feeding" fluid to this region.

For the lowest Ra^* tested, ($Ra^* = 1.33 \times 10^6$), the flow was very steady and symmetrical with very few disturbances occurring before the flow rose off the surface of the plate in plumes. The "boundary layer" in the laminar region of the surface was very thick ($\sim 3/4$ inch). Once the flow separated from the surface, a transition to turbulence began. For higher Ra^* , the transition length was quite short. This appeared to be caused by erratic flow separations from the plate surface. As the Ra^* decreased, these erratic separations became less frequent or completely disappeared; and, the transition progressed in a much smoother fashion.

The effect of Ra^* was also evident in the position of the plumes along the surface. As the Ra^* was increased, the plumes began to wander with increasing vigor along the plate surfaces. The average position of the plumes, however, appeared to be along the diagonals. It should be stressed that all tests appeared to have a laminar boundary layer region which then separated from the surface and underwent a transition to turbulence.

The data from each of the three plates was correlated using a least square fit to a function of the form,

$$(3-6) \quad Nu = c_1 Ra^* c_2,$$

where,

Nu average Nusselt number = $h_c L_c / k$,

Ra^* modified Rayleigh number =

$$(g \beta q L^4 / \nu^2 k) (C_p \mu / k),$$

c_1, c_2 constants.

The average convection coefficient, h_c , is defined by the relationship,

$$(3-7) \quad h_c = (q L^2) (1 / \int_0^L \int_0^L (T_s(x, y) - T_a) dx dy),$$

The integration was performed numerically and is discussed in Chapter II of this thesis.

The characteristic length used was that recommended by Goldstein, Sparrow, and Jones[23] and by Lloyd and Moran[24], which is the surface area divided by the perimeter. For square surfaces, this length is,

$$L_c = L/4.$$

As previously mentioned, a problem that involves a constant heat flux boundary condition requires one to somehow determine the surface temperature distribution. For this reason, it is desirable to avoid the use of a property if its evaluation requires the use of the surface temperature or film temperature as commonly used

for isothermal surfaces. Therefore, all properties in the following correlation are to be evaluated at the ambient air temperature. The resulting correlation is,

$$(3-8) \quad Nu = .9536 Ra^{*.1683},$$

(standard deviation = 0.74)

for the range $1 \times 10^6 < Ra^* < 8.5 \times 10^7$. A $1/5$ power was then forced to the points and the leading coefficient found by a least square analysis. The resulting correlation,

$$(3-9) \quad Nu = .556 Ra^{*.2},$$

(standard deviation = 0.90)

was found to fit the data well over the entire range of Ra^* .

A $1/4$ power was also forced to the data, with the resulting correlation,

$$(3-10) \quad Nu = .236 Ra^{*.25},$$

(standard deviation = 1.5)

A significant increase in the standard deviation was obtained for this correlation and was determined to be unacceptably high. A comparison of the three correlations is presented in Figure 11.

Since the $1/5$ power correlation agrees with the analytical results and does not increase the error associated with the fit appreciably, it is recommended that this correlation be used. Further justification of this choice for the curve fit is presented below.

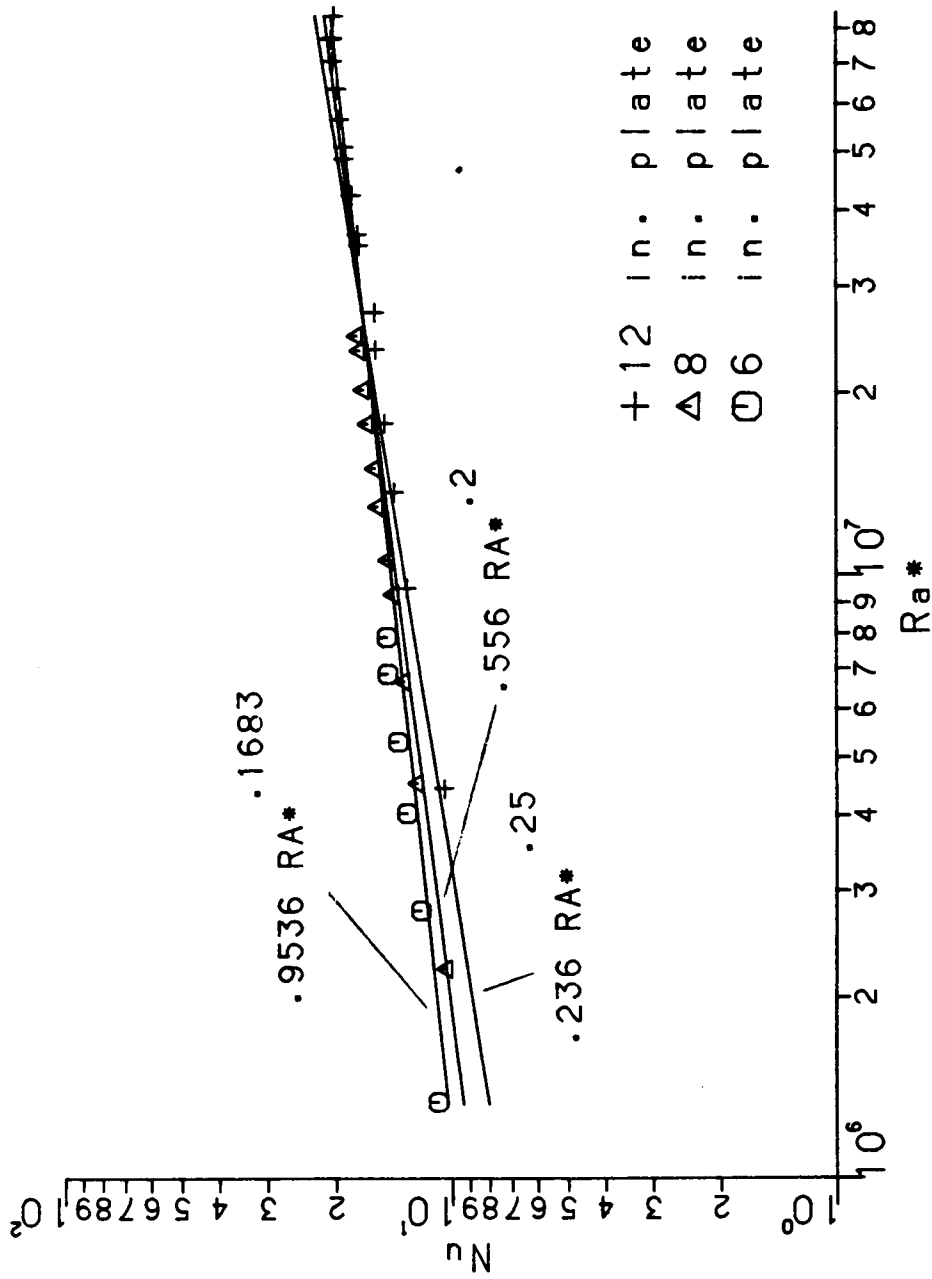


Figure 11. Comparison of Least Square Curve Fits

Comparison of the experimentally determined Nu with those obtained from equation (3-9) reveal agreement to within 14% for the worst case. The average error associated with the fit is approximately 5.3% (for all 34 cases). The correlated and experimental results are listed in Table 3. It can be seen that the error of fit is significantly higher (an average error of 11.0%) for the 6 inch surface than for either the 8 inch or 12 inch surface (with errors of 3.8 and 4.3%).

If the data from the 8 inch and 12 inch plates are correlated together, the following result is obtained:

$$(3-11) \quad Nu = .632 Ra^{*.192} .$$

$$(\text{standard deviation} = .668)$$

When a $1/5$ power is forced to this data, one obtains:

$$(3-12) \quad Nu = .549 Ra^{*.2} .$$

$$(\text{standard deviation} = .6925)$$

This correlation differs from equation (3-9) by only 1.3%; however, the standard deviation has decreased by approximately 30%. The average error associated with this fit is 3.7%, with one data point off by 11.9% and the rest within 6.5% of the values predicted from this correlation. A plot of the 8 inch and 12 inch data together with this correlation is presented in Figure 12.

Table 3 - Comparison of Experimental Nusselt Numbers
with Nusselt Numbers Calculated
from the Correlation

Plate Length (in.)	Ra* $\times 10^{-6}$	Experimental Nu	Correlated Nu	Percent Difference
6	1.33	10.85	9.34	13.97
6	2.77	12.03	10.82	10.08
6	4.02	13.06	11.65	10.82
6	5.28	13.77	12.30	10.67
6	6.84	14.61	12.95	11.37
6	7.87	14.68	13.32	9.23
8	2.23	10.34	10.35	0.10
8	4.52	12.31	11.93	3.13
8	6.66	13.27	12.88	2.93
8	9.27	14.17	13.77	2.83
8	10.56	14.63	14.13	3.42
8	12.94	15.54	14.72	5.31
8	14.98	15.83	15.15	4.24
8	17.75	16.54	15.68	5.21
8	20.23	16.94	16.09	4.98
8	23.48	17.34	16.58	4.39
8	24.85	17.65	16.77	4.96
12	4.44	10.48	11.88	13.38
12	9.50	13.06	13.84	5.92
12	13.69	14.10	14.88	5.58
12	17.80	14.93	15.69	5.04
12	23.61	15.77	16.60	5.40
12	27.17	15.85	17.07	7.69
12	34.99	17.36	17.96	3.42
12	36.47	17.53	18.11	3.31
12	42.31	18.14	18.65	2.20
12	48.62	18.94	19.18	1.23
12	50.84	18.99	19.35	1.88
12	56.53	19.45	19.76	1.62
12	63.51	19.78	20.23	2.26
12	70.59	20.32	20.66	1.69
12	76.74	20.51	21.01	2.45
12	77.00	20.33	21.02	3.42
12	83.80	20.21	21.38	5.81

Although the previous correlation does not differ significantly from that given by equation (3-12), equation (3-11) provides a much better justification for correlating the data with a $1/5$ power correlation than equation (3-8).

The fact that the correlation predicts Nu for the 6 inch surface which is consistently in greater error than for either of the other two surfaces indicates that some systematic error was present for this surface that was not for the others. An explanation for this may lie in the fact that the 6 inch surface was made from the foil used for the 12 inch surface; whereas, the 8 inch and 12 inch foil surfaces were both constructed from "new" pieces of foil. The emittance of a foil surface is very sensitive to surface conditions; and, could have been altered by the presence of smoke residue (from smoke visualization testing) and by additional handling.

The $1/5$ power correlation is an indication that the flow was laminar over the entire range of Ra^* . This is supported by the smoke visualization tests discussed previously.

Rotem and Claassen[13,14] have presented a similarity solution for constant heat flux, horizontal surfaces. A comparison of their solution to the results obtained from the present study is presented in Figure 13. It should be emphasized that this solution assumes

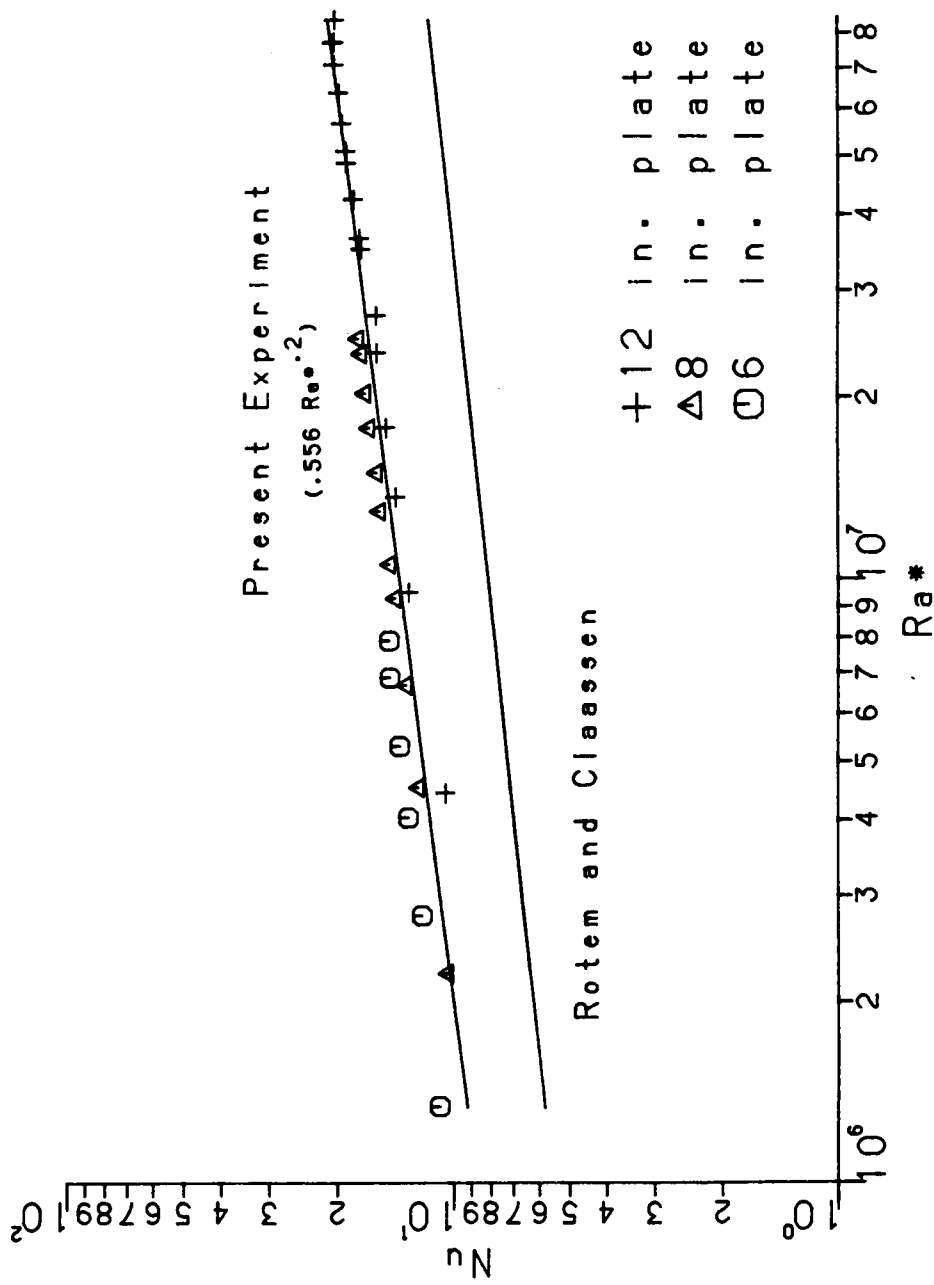


Figure 13. Comparison of the Nusselt Number Correlations

a 2 dimensional flow field. The experimentally determined correlation predicts Nusselt numbers which are significantly higher than those obtained from the similarity solution. The fact that the experimental results lie above the analytical results is consistent with the findings of Yousef, Tarasuk, and McKeen [9] for isothermal surfaces. They reported values of local Nusselt numbers consistently higher than those predicted by the similarity solution of Pera and Gebhart [16]. An explanation for this seems to lie in the fact that this flow is fully three-dimensional, while the similarity solutions performed to date have assumed a two-dimensional flow field.

Surface Temperature Results

As was stated earlier, the magnitude of the maximum surface temperature was also of interest. If one replaces the convection coefficient, h_c , with $q/\Delta T$ in the expression for Nu the following is obtained:

$$(3-13) \quad Nu = h_c L_c / k = q L_c / \Delta T k .$$

Substituting this expression in equation 3-6,

$$(3-14) \quad q L_c / \Delta T k = c_1 Ra^{*c} ,$$

which yields,

$$(3-15) \quad k(\Delta T)/q L_c = c' Ra^{*(-c)} ,$$

The non-dimensional temperature, $k(\Delta T)/qL_c$, is thus recognized as being equal to the reciprocal of the Nusselt number for the constant heat flux case. Based on this fact, a correlation of maximum surface temperature was sought which varied with the $-1/5$ power of the Rayleigh number. The non-dimensional maximum temperature difference is defined as follows,

$$(3-16) \quad T_{\max} = (T_{s_{\max}} - T_a) / (qL/k).$$

A correlation was sought of the form,

$$(3-17) \quad T_{\max} = c Ra^{*(-1/5)},$$

and as before, a least square fit was used to obtain the fit. Again, the ambient temperature was used to evaluate all properties and the $1/4$ plate length was used as the characteristic length. The following correlation was determined to fit the data,

$$(3-18) \quad T_{\max} = (1.927) Ra^{*(-1/5)}.$$

$$(\text{standard deviation} = 0.006)$$

The experimental and calculated values of $T_{\max}$ are presented in Table 4 and Figure 14. All experimental points lie within 15.6% of the correlated points, with the average fit error being 6.6% for all 34 points. Again the 6 inch plate data has a somewhat higher error (11.1%) associated with the fit than the other two plates (2.1 and 7.9%). Correlating the 8 inch and 12 inch plates alone, one obtains:

Table 4 - Comparison of Experimental Maximum Surface
Temperatures with Those Calculated
from the Correlation

Plate Length (in.)	Ra* $\times 10^{-6}$	Correlated $T_{\max}$	Experimental $T_{\max}$	Percent Difference
6	1.33	.1148	.0993	15.62
6	2.77	.0991	.0898	10.35
6	4.02	.0920	.0825	11.53
6	5.28	.0872	.0791	10.18
6	6.84	.0828	.0747	10.77
6	7.87	.0805	.0744	8.13
8	2.23	.1036	.1060	2.26
8	4.52	.0899	.0896	.34
8	6.66	.0832	.0819	1.60
8	9.27	.0779	.0776	.35
8	10.56	.0759	.0749	1.24
8	12.94	.0728	.0705	3.39
8	14.98	.0707	.0690	2.54
8	17.75	.0684	.0665	2.82
8	20.23	.0666	.0643	3.55
8	23.48	.0647	.0635	1.77
8	24.85	.0639	.0621	2.87
12	4.44	.0902	.1062	15.04
12	9.50	.0775	.0846	8.45
12	13.69	.0720	.0788	8.58
12	17.80	.0683	.0748	8.59
12	23.61	.0646	.0714	9.00
12	27.17	.0628	.0707	11.18
12	34.99	.0597	.0642	6.97
12	36.47	.0592	.0639	7.40
12	42.31	.0575	.0615	6.51
12	48.62	.0559	.0590	5.29
12	50.84	.0554	.0593	6.53
12	56.53	.0542	.0571	5.06
12	63.51	.0530	.0560	5.37
12	70.59	.0519	.0550	5.63
12	76.74	.0510	.0549	7.13
12	77.00	.0510	.0555	8.18
12	83.80	.0501	.0551	9.04

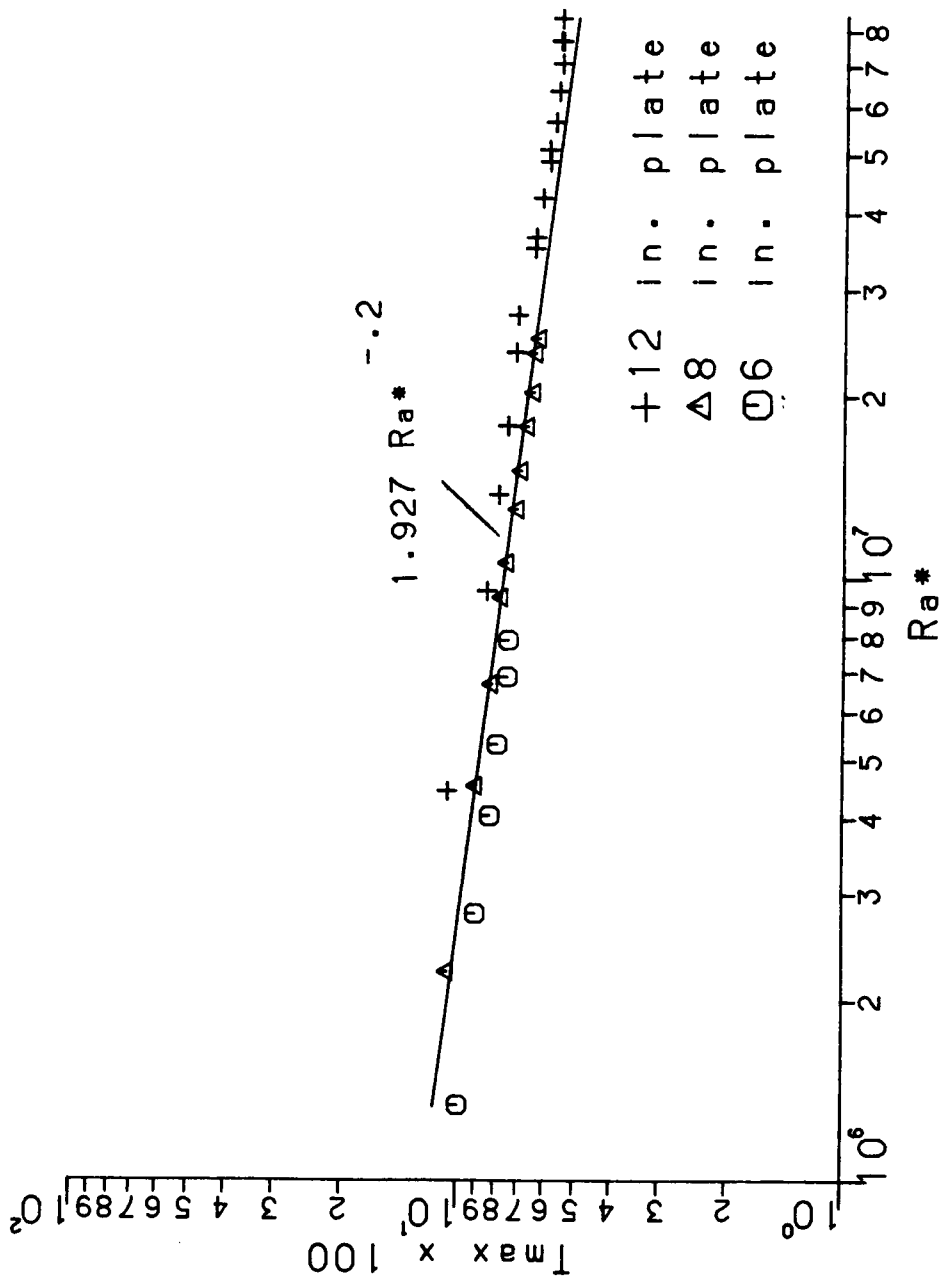


Figure 14. Maximum Surface Temperature Correlation

$$(3-19) \quad T_{\max} = 2.000 \text{ Ra}^*(-1/5),$$

(standard deviation = .0042)

This correlation predicts values of $T_{\max}$ approximately 3.7% higher than those of equation 3-18. The standard deviation, however, has decreased by 48.7%. This again reflects the fact that a systematic error exists for the 6 inch plate results as discussed earlier. The average error associated with the fit was 5.9% for the 8 inch surface and 4.1% for the 12 inch surface.

The flow over the surface of a horizontal plate is very unsteady, and results in a varying location of the maximum surface temperature. For all except 3 tests, however, the maximum surface temperature was recorded either from the center thermocouple or from an adjacent thermocouple (thermocouples were spaced 1 inch apart in the center region for all three plates). In the 3 tests where this did not occur, the magnitude of the maximum surface temperature was very close to that occurring in the center region. The differences were .6, .21, and .13 °F.

A plot of the surface temperature distribution for $\text{Ra}^* = 1 \times 10^6$ is presented in Figures 15 and 16.

From these plots, one can see that the highest temperatures occur in the center region, the lowest temperatures occur in the corners, and intermediate

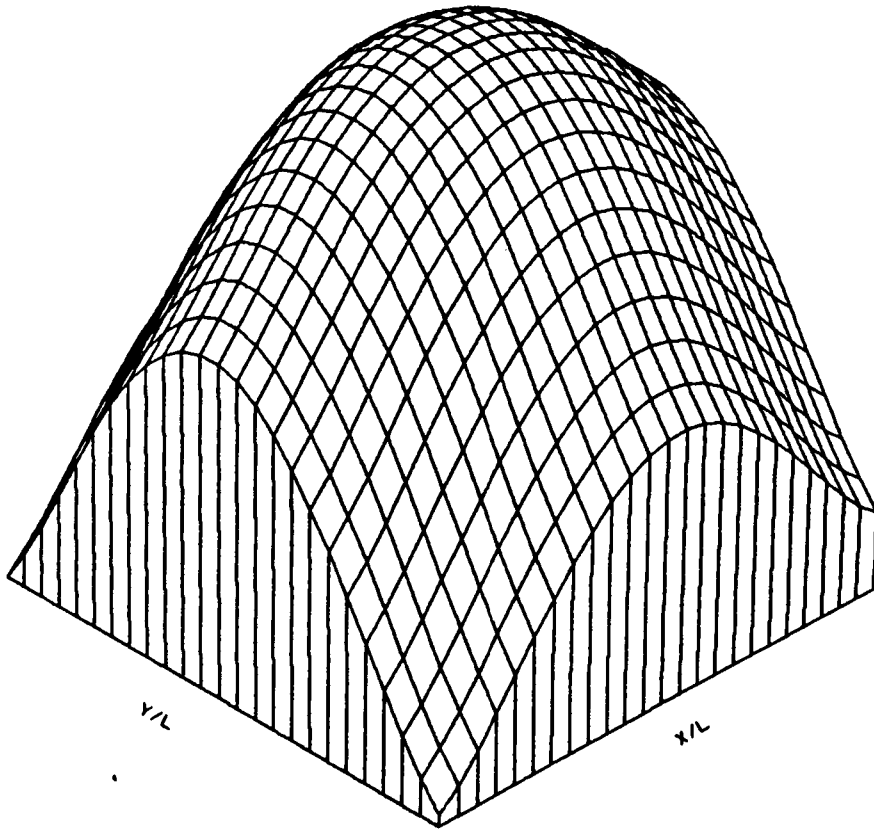


Figure 15. Three Dimensional Plot of the Surface Temperature Distribution on the Plate Surface

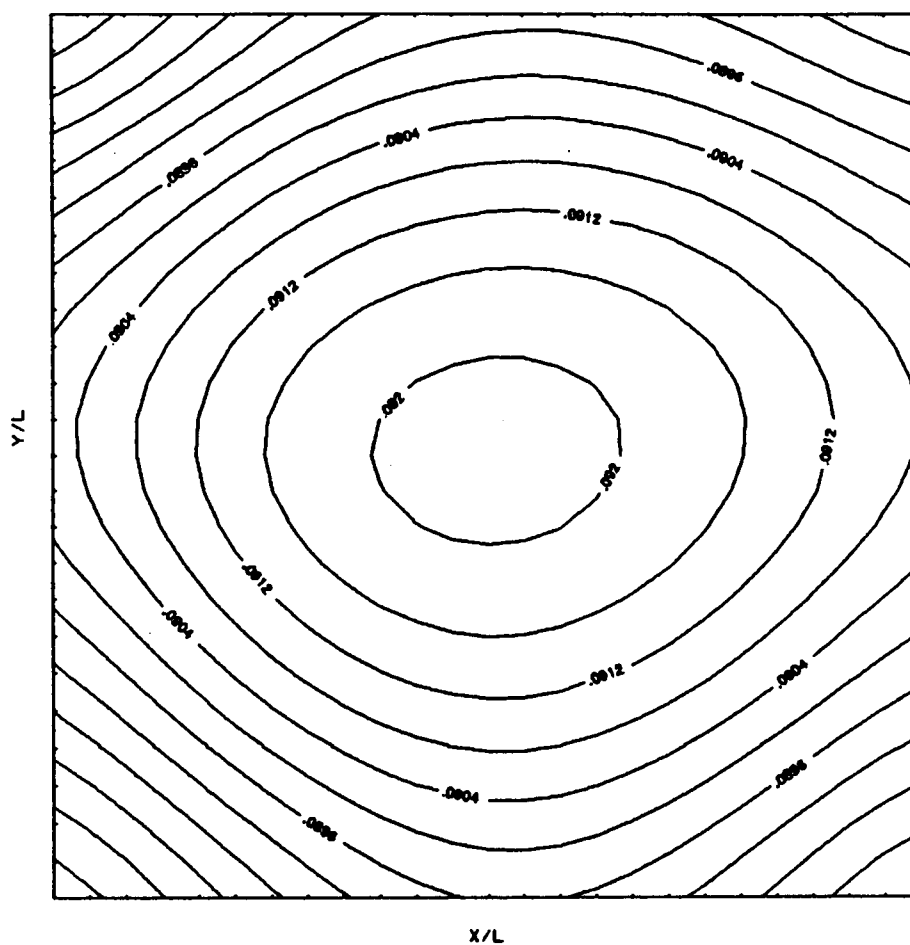


Figure 16. Contour Plot of the Surface Temperature Distribution on the Plate Surface

temperatures occur along the edges. Thus, the plates may be subdivided as shown in Figure 17. It should be noted that this is similar to the observation of Al-Arabi and El-Riedy[7] for heat transfer coefficients along isothermal surfaces.

Physically, the existence of these three distinct regions may be explained by the way in which fluid flows over the surface. As previously mentioned, the fluid is drawn in toward the center of the plate in paths perpendicular to the edges. As the fluid flows inward, it is heated until it either meets the flow from an adjoining side or picks up enough energy to separate from the surface of the plate. Thus, the fluid temperature above the central region is higher than the other regions; and, to maintain the constant heat flux boundary condition the surface temperature in this region must rise correspondingly. Conversely, the corner regions are exposed to "cool" fluid flowing in from two perpendicular edges. Thus, the surface temperature in these regions must drop enough to meet the imposed boundary condition, resulting in lower temperatures than the other regions. Over the edge regions, the fluid is heated to a temperature between the corner and central regions, resulting in a surface temperature intermediate between these two regions.

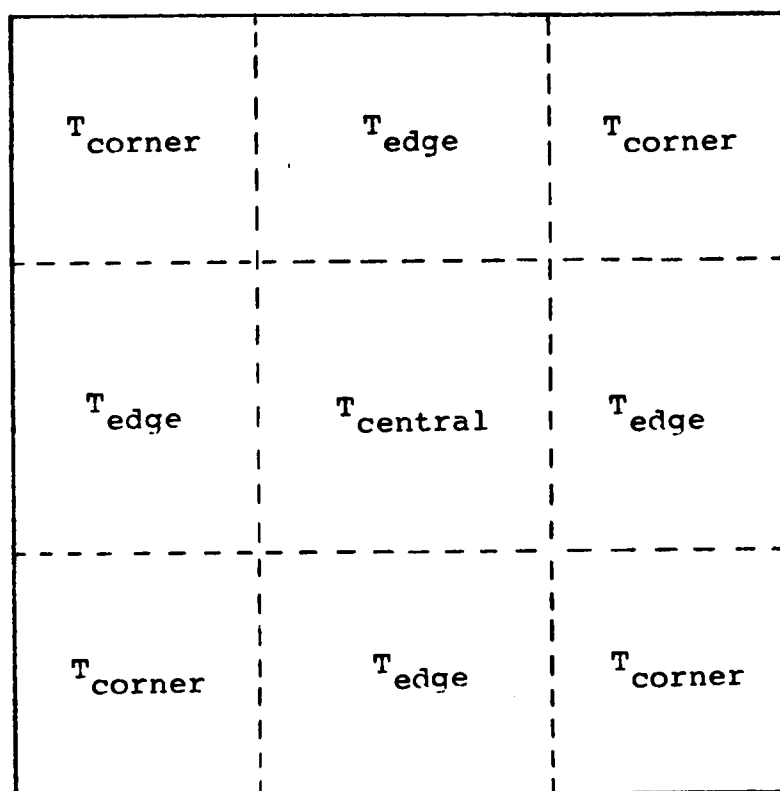


Figure 17. Subdivision of the Plate According to Surface Temperature

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS

For the entire range of Rayleigh numbers, $(1.33 \times 10^6 < Ra^* < 8.38 \times 10^7)$, the flow remained laminar over the surface of the plates. Over this range, the average Nusselt number may be correlated by equation (3-9),

$$Nu = .556 Ra^{*.2}.$$

All air properties should be evaluated at the ambient temperature; and, the Nusselt and Rayleigh numbers based on a characteristic length, $L_c = L/4$. The uncertainty in the experimentally determined Nu is 17%.

The maximum surface temperature was correlated by equation (3-18),
 $T_{max} = 1.927 Ra^{*(-.2)}.$

Again all air properties should be evaluated at the ambient air temperature and the characteristic length, $L_c = L/4$, should be used for this correlation. This correlation fits the experimentally determined points with a maximum error of 16%. The uncertainty associated with the maximum surface temperature is 6%. The maximum surface temperature was found to always occur in a small region surrounding the center of the plate.

As was stated above, the flow was laminar over the entire range of modified Rayleigh numbers tested. The flow was; however, unsteady in nature which resulted in the base of the plumes meandering somewhat on the test surfaces. The average position of the plumes appeared to be along the diagonals; and, the existence of a very strong central plume was always observed. In general, the flow behaved quite similarly to that reported by Husar and Sparrow[4] for horizontal isothermal surfaces.

Due to the lack of experimental results for constant heat flux horizontal surfaces, several recommendations can be made for future studies. These studies should include:

1. Determination of the onset to turbulence and a correlation of turbulent heat transfer results
2. Effects of Prandtl number variation
3. Effects of surface shape
4. Determination of the velocity and temperature profiles within the flow.

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BIBLIOGRAPHY

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APPENDIXES

APPENDIX A

DESCRIPTION OF INSTRUMENTATION

Electrical Instrumentation

The following is a description of the equipment used to provide the electrical power input to the heater surfaces.

1. Sola Harmonic Neutralized Constant Voltage Transformer
Sola Electric Company, Type no. CVH-1
Pri Volts 95-130/190-260
Rate V.A. 500
SEC 118 v @4.24 amps
P.F. 100%
2. Variac
General Radio Company
Range: 0-260 volts
Least Count: 4 volts
3. A-C Ammeter
General Radio Company, Type AD-7
Range: 0-5 amps
Least Count: .1 amps
4. Current Transformer
General Electric Company, Type JKR2
Ratio 100:5 amps
5. Precision Current Shunt
Sensitive Research Company, No. 912566
1 amp - 2 millivolts
Accuracy: .05 of 1%

Measurements Instrumentation

The following instruments were used in the measurement of all physical quantities in this experiment.

1. 36 gauge Copper-Constantan Thermocouples
Omega Engineering Incorporated

2. Data Acquisition/Control Center
Hewlett Packard, Model 3497-A
Range: 0-160 volts
Least Count: 1 microvolt
Accuracy: ± 2 microvolts

3. Digital Voltmeter
Data Precision Incorporated, Model 3500
Range: 0-.10 volts
Least Count: 1 microvolt
Accuracy: $\pm .005\%$ of reading

4. Mercury Thermometer
D.B.P. Company
Range: $-38 - 100^{\circ} \text{C}$
Least Count: 1°C

5. Digital Thermocouple Reader
Omega Engineering Incorporated, Model 200
Range: $0-400^{\circ} \text{C}$
Least Count: $.2^{\circ} \text{C}$
Accuracy: $.2\% \pm .1^{\circ} \text{C}$

Microcomputer

The following computer was used to record and reduce all data taken.

Hewlett Packard Company
Model 9826 micro-computer

Smoke Visualization Apparatus

The following laser was used in the smoke visualization experiments.

15 mW Helium-Neon Laser
Spectra-Physics Incorporated

APPENDIX B

PROGRAM LISTINGS

Data Acquisition Program (6 inch plate)

The following program was used in conjunction with the HP 9826 microcomputer and the HP 3497-A Data Acquisition/Control Center to read the thermocouple voltages of the 6 inch square surface. It was also used to store all pertinent information for these temperature measurement experiments on floppy diskettes.

This program will prompt the user for the following information:

1. Voltage drop across current shunt (volts)
2. Voltage drop across foil surface (volts)
3. Time required for setup to reach steady state (hours)
4. Room temperature ($^{\circ}\text{C}$)
5. Test number
6. Date

The output to the storage disk includes the following information:

1. Temperature versus time data ($^{\circ}\text{C}$ vs. sec.)
2. Average temperature ($^{\circ}\text{C}$)
3. Minimum, maximum, and average thermocouple voltages (volts)

4. Electrical power input (W)
5. Room temperature ($^{\circ}\text{C}$)
6. Time required to reach steady-state (hours)
7. Current through plate (amps)
8. Voltage drop across plate (volts)
9. Elapsed time between successive thermocouple readings (sec.)

```

10  |*****
20  |*
30  |*  THERMOCOUPLE READING PROGRAM
40  |*  FOR USE ON THESIS PROJECT-- 6in. card
50  |*
60  |*****
70  |
80  |
90  OPTION BASE 1
100 DIM
V(71,10),Vavg(71),Tavg(71),Vi(131),Td(131),Vmin(71),Vmax(
71),Te(10),Tl(10),Tt(26,10)
110 DIM Date$(10)
120 INTEGER N,I,Back,Ii,K
130 CLEAR 709      !709 is Acquisition Center
140 OUTPUT 709;"AFOAL39VR1SO0" !.....FIRST 25
150      !.....      T.C.'S ARE ON SURFACE
160      !.....      ICE REF. CHNL. 19
170 N=1 !.....AND CHNL. 39
180 Back=0
190 Test$="P6"
200 Pest$="T6"
210 BEEP
220 PRINT ".....Insert Data Disk Now....."
230 PRINT "...Press Continue Key When Ready..."
240 PAUSE
250 FOR A=1 TO 71
260 Vmin(A)=999
270 NEXT A
280 |
290 |
300 | Read voltages over entire surface 10
310 | times (include ice baths-- t.c. 20 and
320 | t.c. 40)
330 |

```

```

340 Tf=TIMEDATE
350 FOR B=1 TO 10
360 PRINT "GROUP- ";B
370 FOR C=1 TO 40
380 IF C<=26 OR C=40 THEN
390 OUTPUT 709;"AS"
400 ENTER 709;V(C,B)
410 ELSE
420 OUTPUT 709;"AS"
430 END IF
440 NEXT C
450 FOR C=1 TO 26
460 IF C<=20 THEN
470 V(C,B)=V(C,B)-V(20,B)
480 !
490 !
500 !subtract appropriate ice bath ref.
510 !voltages
520 !
530 ELSE
540 IF C>20 AND C<=26 THEN
550 V(C,B)=V(C,B)-V(40,B)
560 END IF
570 END IF
580 NEXT C
590 T1(B)=TIMEDATE
600 Te(B)=T1(B)-Tf !record approximate
610 WAIT .1 !elapsed time
620 NEXT B
630 !
640 !
650 ! scan remaining t.c.'s on cards 2 and 3
660 !
670 CLEAR 709
680 OUTPUT 709;"AF26AL59VR1SO0"
690 FOR E=1 TO 10
700 FOR D=27 TO 60
710 OUTPUT 709;"AS"
720 ENTER 709;V(D,E)
730 WAIT .1
740 NEXT D
750 FOR D=27 TO 60
760 IF D<=40 THEN
770 V(D,E)=V(D,E)-V(40,E)
780 ELSE
790 V(D,E)=V(D,E)-V(60,E)
800 END IF
810 NEXT D
820 NEXT E
830 !
840 !
850 !allow for insertion of 4th card

```

```

860      !
870      BEEP
880      BEEP
890      PRINT "Program Paused to Allow"
900      PRINT "  Thermocouple Change"
910      PRINT "...Press Continue Key When Ready..."
920      PAUSE
930      CLEAR 709
940      !
950      !
960      !Read all t.c.'s on 4th card
970      !
980      OUTPUT 709;"AF0AL10VR1SO0"
990      FOR J=1 TO 10
1000     FOR I=61 TO 71
1010         OUTPUT 709;"AS"
1020         ENTER 709;V(I,J)
1030     NEXT I
1040     FOR B=61 TO 71
1050         V(B,J)=V(B,J)-V(71,J)
1060     NEXT B
1070     NEXT J
1080     !
1090     !Read in voltage and temperature tables
1100     !
1110     DATA
1120     DATA
1130     DATA
1140     DATA
1150     DATA
1160     DATA 147,148,149,150
1170     FOR F=1 TO 131
1180         READ Td(F)
1190     NEXT F
1200     DATA
1210     DATA
1220     DATA

```

20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37,38,
 39,40,41,42,43,44,45,46,47,48,
 49,50,51,52,53,54,55,56,57,58,59,60,61,62,63,64,65,66,67,
 68,69,70,71,72,73,74,75,76,77
 78,79,80,81,82,83,84,85,86,87,88,89,90,91,92,93,94,95,96,
 97,98,99,100,101,102,103,104
 105,106,107,108,109,110,111,112,113,114,115,116,117,118,1
 19,120,121,122,123,124,125
 126,127,128,129,130,131,132,133,134,135,136,137,138,139,1
 40,141,142,143,144,145,146
 .789,.83,.87,.911,.951,.992,1.032,1.073,1.114,1.155,1.196
 ,1.237,1.279,1.32,1.361,1.403
 1.444,1.486,1.528,1.569,1.611,1.653,1.695,1.738,1.780,1.8
 22,1.865,1.907,1.95,1.992
 2.035,2.078,2.121,2.164,2.207,2.25,2.294,2.337,2.38,2.424

```

,2.467,2.511,2.555,2.599,2.643
1230 DATA
2.687,2.731,2.775,2.819,2.864,2.908,2.953,2.997,3.042,3.0
87,3.131,3.176,3.221,3.266
1240 DATA
3.312,3.357,3.402,3.447,3.493,3.538,3.584,3.63,3.676,3.72
1,3.767,3.813,3.859,3.906
1250 DATA
3.952,3.998,4.044,4.091,4.137,4.184,4.231,4.277,4.324,4.3
71,4.418,4.465,4.512,4.559
1260 DATA
4.607,4.654,4.701,4.749,4.796,4.844,4.891,4.939,4.987,5.0
35,5.083,5.131,5.179,5.227
1270 DATA
5.275,5.324,5.372,5.42,5.469,5.517,5.566,5.615,5.663,5.71
2,5.712,5.761,5.81,5.859
1280 DATA
5.908,5.957,6.007,6.056,6.105,6.155,6.204,6.254,6.303,6.3
53,6.403,6.452,6.502,6.552
1290 DATA 6.602,6.652,6.702
1300 FOR G=1 TO 131
1310 READ Vi(G)
1320 NEXT G
1330 A=1
1340 !
1350 !
1360 !Calculate Avg. Voltage for each T.C.
1370 !
1380 !
1390 FOR H=1 TO 71
1400 FOR I=1 TO 10
1410 Vavg(H)=Vavg(H)+V(H,I)
1420 NEXT I
1430 Vavg(H)=Vavg(H)/10
1440 NEXT H
1450 !
1460 !
1470 !Uses linear interpolation between
1480 !table values to compute temperature
1490 !from average measured voltage
1500 !
1510 FOR J=1 TO 71
1520 FOR K=2 TO 131
1530 IF Vavg(J)*1000.0>=Vi(K) THEN GOTO 1600
1540 IF Vavg(J)*1000.0<Vi(K) THEN
1550 Nn=K-1
1560 Pp=K
1570
Tavg(J)=Td(Nn)+(Vavg(J)*1000.0-Vi(Nn))*((Td(Pp)-Td(Nn))/(
Vi(Pp)-Vi(Nn)))
1580 GOTO 1610
1590 END IF

```

```

1600     NEXT K
1610 NEXT J
1620     !
1630     !
1640     !Compute max. and min. voltage measured
1650     ! for each thermocouple
1660     !
1670     FOR L=1 TO 71
1680         FOR I=1 TO 10
1690             IF Vmin(L)<=V(L,I) THEN
1700                 ELSE
1710                     Vmin(L)=V(L,I)
1720             END IF
1730         NEXT I
1740         FOR I=1 TO 10
1750             IF Vmax(L)>=V(L,I) THEN
1760                 ELSE
1770                     Vmax(L)=V(L,I)
1780             END IF
1790         NEXT I
1800     NEXT L
1810     !
1820     !
1830     ! Obtain Temp. vs. Time data
1840     ! for each t.c. on surface
1850     !
1860     !
1870     FOR I=1 TO 26
1880     FOR J=1 TO 10
1890     FOR K=2 TO 131
1900         IF V(I,J)*1000.0>=Vi(K) THEN GOTO 1970
1910         IF V(I,J)*1000.0<Vi(K) THEN
1920             Nn=K-1
1930             Pp=K
1940

$$T_t(I,J)=T_d(Nn)+(V(I,J)*1000-V_i(Nn))*((T_d(Pp)-T_d(Nn))/(V_i(Pp)-V_i(Nn)))$$

1950             GOTO 1980
1960         END IF
1970     NEXT K
1980     NEXT J
1990     NEXT I
2000     !
2010     !
2020     !Store data in 'T65,P65,...'
2030     ! (T6 corresponds to temp. vs time data
2040     !   for 6in. card, power of 5 watts)
2050     ! (Rest of data stored in P65, etc.)
2060     !   and read in current and voltage
2070     !
2080     !
2090     BEEP

```

```

2100      BEEP
2110      BEEP
2120      INPUT "Current thru plate (volts from
shunt).....",Cv
2130      INPUT "VOLTAGE ACROSS PLATE (volts).....",Vp
2140      Cv=Cv*500.0
2150      P=Vp*Cv
2160      INPUT "Time between power on and test
start.....",Ta
2170      INPUT "Room Temperature.....",Tr
2180      LINPUT "Current Test No.....",W$
2190      LINPUT "Date.....",Date$
2200      Name$=Test$&W$
2210      Name2$=Pest$&W$
2220      CREATE BDAT Name$,300,8
2230      CREATE BDAT Name2$,270,8
2240      ASSIGN @Path1 TO Name$
2250      ASSIGN @Path2 TO Name2$
2260      OUTPUT @Path2;Tt(*),Te(*)
2270      OUTPUT
@Path1;Tavg(*),Vmin(*),Vmax(*),Vavg(*),P,Tr,Ta,Cv,Vp,Te(1
0),Date$
2280      IF Back=0 THEN
2290      INPUT "Do you desire a backup copy of data?
Y=Yes",Aaa$
2300      IF Aaa$="Y" THEN
2310      PRINT ".....Insert new disk now....."
2320      PRINT
2330      PRINT ".....Press Continue Key When
Ready....."
2340      Back=1
2350      PAUSE
2360      GOTO 2210
2370      END IF
2380      END IF
2390      !
2400      !
2410      !Thermocouple Channels:
2420      !
2430      !Surface of foil: .....0-18, 20-25
2440      !Side of plate (inside): ...26 thru 37
2450      !Bottom of plate (inside): .38, 40-47
2460      !Side of plate (outside):...48-58, 0
2470      !Bottom of plate (outside): 1-2
2480      !Inside testbox:.....3-7
2490      !Copper Busbars:.....8-9
2500      !Ice Baths.....19,39,59,10
2510      !
2520      !
2530      !Thermocouple Markings:
2540      !
2550      !Surface of foil: .....1 thru 25

```

```

2560      !Side of plate (inside): ...1s thru 12s
2570      !Bottom of plate (inside): .1x,3x,5x,11x,
2580      !      13x,15x,21x,23x,25x
2590      !Side of plate (outside): ..1o thru 12o
2600      !Bottom of plate (outside) .1xo thru 2xo
2610      !Inside textbox.....1' thru 5'
2620      !Copper Busbars:.....CX - CXII
2630      STOP

```

Data Acquisition Program (8 inch plate)

The following program was used to record thermocouple voltages and store pertinent information for the 8 inch square surface temperature tests.

In addition to the inputs required of the program used for the 6 inch surface, this program requires the input of 18 additional thermocouples. All outputs remained the same.

```

10 !*****
20 !*
30 !*   THERMOCOUPLE READING PROGRAM
40 !*   FOR USE ON THESIS PROJECT-- 8in. card
50 !*
60 !*****
70 !
80 !
90 !
100  OPTION BASE 1
110  DIM
V(79,20),Vavg(79),Tavg(97),Vi(131),Td(131),Vmin(79),Vmax(
79),Te(20),Tl(20),Tt(49,20)
120  DIM Date$(10)
130  INTEGER N,I,Back,Ii,K
140  CLEAR 709
150  OUTPUT 709;"AF0AL59VR1SO0" !.....FIRST 49
160      !..... T.C.'S ARE ON SURFACE
170      !.....ICE REF. CHNL. 19
180  N=1 !.....39, AND 59
190  Back=0
200  Test$="P8"
210  Pest$="T8"
220  BEEP
230  PRINT "INSERT DATA DISK NOW"
240  PRINT "PRESS CONTINUE KEY WHEN READY"

```

```

250 PAUSE
260 FOR A=1 TO 79
270   Vmin(A)=999
280 NEXT A
290 !
300 !
310 ! Read voltages over entire surface 20
320 ! times (include ice baths-- t.c.'s 20,40,
    and 60)
330 !
340 !
350 Tf=TIMEDATE
360 FOR B=1 TO 20
370   PRINT "GROUP- ";B
380   FOR C=1 TO 60
390     IF C<=49 OR C=60 THEN
400       OUTPUT 709;"AS"
410       ENTER 709;V(C,B)
420     ELSE
430       OUTPUT 709;"AS"
440     END IF
450   NEXT C
460   Tl(B)=TIMEDATE ! Record approximate
470   Te(B)=Tl(B)-Tf ! elapsed time
480   FOR C=1 TO 49
490     IF C<=20 THEN
500       V(C,B)=V(C,B)-V(20,B)
510       !
520       !
530       !subtract appropriate ice bath ref.
540       !voltages
550       !
560     ELSE
570       IF C>20 AND C<=40 THEN
580         V(C,B)=V(C,B)-V(40,B)
590       ELSE
600         V(C,B)=V(C,B)-V(60,B)
610       END IF
620     END IF
630   NEXT C
640   WAIT .1
650 NEXT B
660 !
670 !
680 ! scan remaining t.c.'s on cards 2,3 and 4
690 !
700 CLEAR 709
710 OUTPUT 709;"AF49AL59VR1SO0"
720 FOR E=1 TO 20
730   FOR D=50 TO 60
740     OUTPUT 709;"AS"
750     ENTER 709;V(D,E)

```

```

760         WAIT .1
770         V(D,E)=V(D,E)-V(60,E)
780     NEXT D
790     PRINT "2nd AND 3rd CARD...GROUP";E
800 NEXT E
810     !
820     !
830     !allow for insertion of 4th card
840     !
850     BEEP
860     BEEP
870     PRINT "PROGRAM PAUSED TO ALLOW"
880     PRINT "  THERMOCOUPLE CHANGE"
890     PRINT "PRESS CONTINUE KEY WHEN READY"
900     PAUSE
910     CLEAR 709
920     !
930     !
940     !read all t.c.'s on 4th card
950     !
960     OUTPUT 709;"AFOAL18VR1SO0"
970     FOR J=1 TO 20
980         FOR I=61 TO 79
990             OUTPUT 709;"AS"
1000             ENTER 709;V(I,J)
1010         NEXT I
1020         FOR B=61 TO 79
1030             V(B,J)=V(B,J)-V(79,J)
1040         NEXT B
1050     NEXT J
1060     !
1070     !Read in voltage and temperature tables
1080     !
1090     DATA
20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37,38,
39,40,41,42,43,44,45,46,47,48,
1100     DATA
49,50,51,52,53,54,55,56,57,58,59,60,61,62,63,64,65,66,67,
68,69,70,71,72,73,74,75,76,77
1110     DATA
78,79,80,81,82,83,84,85,86,87,88,89,90,91,92,93,94,95,96,
97,98,99,100,101,102,103,104
1120     DATA
105,106,107,108,109,110,111,112,113,114,115,116,117,118,1
19,120,121,122,123,124,125
1130     DATA
126,127,128,129,130,131,132,133,134,135,136,137,138,139,1
40,141,142,143,144,145,146
1140     DATA 147,148,149,150
1150     FOR F=1 TO 131
1160         READ Td(F)
1170     NEXT F

```

```

1180      DATA
.789,.83,.87,.911,.951,.992,1.032,1.073,1.114,1.155,1.196
,1.237,1.279,1.32,1.361,1.403
1190      DATA
1.444,1.486,1.528,1.569,1.611,1.653,1.695,1.738,1.780,1.8
22,1.865,1.907,1.95,1.992
1200      DATA
2.035,2.078,2.121,2.164,2.207,2.25,2.294,2.337,2.38,2.424
,2.467,2.511,2.555,2.599,2.643
1210      DATA
2.687,2.731,2.775,2.819,2.864,2.908,2.953,2.997,3.042,3.0
87,3.131,3.176,3.221,3.266
1220      DATA
3.312,3.357,3.402,3.447,3.493,3.538,3.584,3.63,3.676,3.72
1,3.767,3.813,3.859,3.906
1230      DATA
3.952,3.998,4.044,4.091,4.137,4.184,4.231,4.277,4.324,4.3
71,4.418,4.465,4.512,4.559
1240      DATA
4.607,4.654,4.701,4.749,4.796,4.844,4.891,4.939,4.987,5.0
35,5.083,5.131,5.179,5.227
1250      DATA
5.275,5.324,5.372,5.42,5.469,5.517,5.566,5.615,5.663,5.71
2,5.712,5.761,5.81,5.859
1260      DATA
5.908,5.957,6.007,6.056,6.105,6.155,6.204,6.254,6.303,6.3
53,6.403,6.452,6.502,6.552
1270      DATA 6.602,6.652,6.702
1280      FOR G=1 TO 131
1290          READ Vi(G)
1300      NEXT G
1310      !
1320      !
1330      ! Allow for input of remaining t.c.'s
1340      !
1350      !
1360      PRINT "Input remaining 18 thermocouple readings"
1370      FOR I=80 TO 97
1380          INPUT Tavg(I)
1390      NEXT I
1400      FOR I=80 TO 97
1410          PRINT "T(";I;")=";Tavg(I)
1420      NEXT I
1430      LINPUT "Are all temperature readings
correct?",Ans$
1440      IF Ans$="Y" OR Ans$="N" THEN
1450          IF Ans$="N" THEN
1460              INPUT "Input t.c. number",I,"Input correct
reading",Valu
1470              Tavg(I)=Valu
1480              GOTO 1400
1490          END IF

```

```

1500     ELSE
1510         BEEP
1520         PRINT "Invalid response....type 'Y'-yes or
'N'-no"
1530         GOTO 1430
1540     END IF
1550     A=1
1560     !
1570     !
1580     !CALCULATE AVG. VOLTAGE FOR EACH T.C.
1590     !
1600     !
1610     FOR H=1 TO 79
1620         FOR I=1 TO 20
1630             Vavg(H)=Vavg(H)+V(H,I)
1640         NEXT I
1650         Vavg(H)=Vavg(H)/20
1660     NEXT H
1670     !
1680     !
1690     !Uses linear interpolation between
1700     !table values to compute temperature
1710     !from average measured voltage
1720     !
1730     FOR J=1 TO 79
1740         IF Vavg(J)*1000>6.702 THEN
1750             BEEP
1760             PRINT "Look-up table range exceeded"
1770             GOTO 1880
1780         END IF
1790         FOR K=2 TO 131
1800             IF Vavg(J)*1000.0>=Vi(K) THEN GOTO 1870
1810             IF Vavg(J)*1000.0<Vi(K) THEN
1820                 Nn=K-1
1830                 Pp=K
1840
Tavg(J)=Td(Nn)+(Vavg(J)*1000.0-Vi(Nn))*((Td(Pp)-Td(Nn))/(
Vi(Pp)-Vi(Nn)))
1850                 GOTO 1880
1860             END IF
1870         NEXT K
1880     NEXT J
1890     !
1900     !
1910     !Compute max. and min. voltage measured
1920     ! for each thermocouple
1930     !
1940     FOR L=1 TO 79
1950         FOR I=1 TO 20
1960             IF Vmin(L)<=V(L,I) THEN
1970                 ELSE
1980                     Vmin(L)=V(L,I)

```

```

1990         END IF
2000     NEXT I
2010     FOR I=1 TO 20
2020         IF Vmax(L)>=V(L,I) THEN
2030             ELSE
2040                 Vmax(L)=V(L,I)
2050             END IF
2060     NEXT I
2070 NEXT L
2080     !
2090     !
2100     ! OBTAIN TEMP. VS. TIME DATA
2110     ! FOR EACH T.C. ON SURFACE
2120     !
2130     !
2140     FOR I=1 TO 49
2150         FOR J=1 TO 20
2160             FOR K=2 TO 131
2170                 IF V(I,J)*1000.0>=Vi(K) THEN GOTO 2240
2180                 IF V(I,J)*1000.0<Vi(K) THEN
2190                     Nn=K-1
2200                     Pp=K
2210

$$Tt(I,J)=Td(Nn)+(V(I,J)*1000-Vi(Nn))*((Td(Pp)-Td(Nn))/(Vi(Pp)-Vi(Nn)))$$

2220                     GOTO 2250
2230                 END IF
2240             NEXT K
2250         NEXT J
2260     NEXT I
2270     !
2280     !
2290     !Store data in 'T85,P85,...'
2300     !(T85 corresponds to temp. vs time data
2310     !   for 8in. card, power of 5 watts)
2320     ! (Rest of data stored in P85, etc.)
2330     !   and read in current and voltage
2340     !
2350     !
2360     BEEP
2370     BEEP
2380     INPUT "CURRENT THRU PLATE (volts from
shunt)",Cv
2390     INPUT "VOLTAGE ACROSS PLATE (volts)",Vp
2400     Cv=Cv*500.0
2410     P=Vp*Cv
2420     INPUT "TIME BETWEEN POWER ON AND TEST
START",Ta
2430     INPUT "ROOM TEMPERATURE",Tr
2440     LINPUT "CURRENT TEST NO.",W$
2450     LINPUT "DATE",Date$
2460     Name$=Test$&W$

```

```

2470      Name2$=Pest$&W$
2480      CREATE BDAT Name$,350,8
2490      CREATE BDAT Name2$,1000,8
2500      ASSIGN @Path1 TO Name$
2510      ASSIGN @Path2 TO Name2$
2520      OUTPUT @Path2;Tt(*),Te(*)
2530      OUTPUT
@Path1;Tavg(*),Vmin(*),Vmax(*),Vavg(*),P,Tr,Ta,Cv,Vp,Te(2
0),Date$
2540      IF Back=0 THEN
2550          INPUT "DO YOU DESIRE A BACKUP COPY OF DATA?
Y=1",Aaa
2560          IF Aaa=1 THEN
2570              PRINT "INSERT NEW DISK NOW"
2580              PRINT
2590              PRINT "PRESS CONTINUE KEY WHEN READY"
2600              Back=1
2610              PAUSE
2620              GOTO 2470
2630          END IF
2640      END IF
2650      !
2660      !
2670      !Thermocouple Channels:
2680      !
2690      !Surface of foil: .....0-18, 20-38, 40-50
2700      !Side of plate (inside): ...51-58, 0-3
2710      !Bottom of plate (inside): ....5-13
2720      !Side of plate (outside):...4, 14-17
2730      !Ice Baths.....19,39,59,18
2740      !
2750      !
2760      !Thermocouple Markings:
2770      !
2780      !Surface of foil: .....1-49
2790      !Side of plate (inside): ...50-61
2800      !Bottom of plate (inside): .62-70
2810      !Side of plate (outside): ..71-82
2820      !Bottom of plate (outside) .83-84
2830      !Inside textbox.....85-87
2840      !Copper Busbars:.....88-89
2850      !Balsa Top.....90-93
2860      !Ice Baths.....94-97
2870      STOP
2880      END

```

Data Acquisition Program (12 inch plate)

This program was used for data acquisition purposes of the 12 inch surface temperature tests. All inputs and outputs were identical to that of the 6 inch surface program except that 2 additional thermocouple voltages were required as input.

```

10  !*****
20  !*
30  !*  THERMOCOUPLE READING PROGRAM
40  !*  FOR USE ON THESIS PROJECT-- 12in. card
50  !*
60  !*****
70  !
80  !
90  !
100  OPTION BASE 1
110  DIM
V(79,20),Vavg(79),Tavg(81),Vi(131),Td(131),Vmin(79),Vmax(
79),Te(20),Tl(20),Tt(37,20)
120  DIM Date$(10)
130  INTEGER N,I,Back,Ii,K
140  CLEAR 709
150  OUTPUT 709;"AFOAL39VR1SOO"  !.....FIRST 37
160          !..... T.C.'S ARE ON SURFACE
170          !.....ICE REF. CHNL. 19
180  N=1  !.....AND CHNL. 39
190  Back=0
200  Test$="P12"
210  Pest$="T12"
220  BEEP
230  PRINT ".....Insert Data Disk Now....."
240  PRINT "...Press Continue Key When Ready..."
250  PAUSE
260  FOR A=1 TO 79
270      Vmin(A)=999
280  NEXT A
290  !
300  !
310  ! Read voltages over entire surface 20
320  ! times (include ice baths-- t.c. 20 and
330  ! t.c. 40)
340  !
350  Tf=TIMEDATE
360  FOR B=1 TO 20
370      PRINT "GROUP- ";B

```

```

380   FOR C=1 TO 40
390     IF C<=37 OR C=40 THEN
400       OUTPUT 709;"AS"
410       ENTER 709;V(C,B)
420     ELSE
430       OUTPUT 709;"AS"
440     END IF
450   NEXT C
460     Tl(B)=TIMEDATE   ! Record approximate
470     Te(B)=Tl(B)-Tf   ! elapsed time
480   FOR C=1 TO 37
490     IF C<=20 THEN
500       V(C,B)=V(C,B)-V(20,B)
510       !
520       !
530       !subtract appropriate ice bath ref.
540       !voltages
550       !
560     ELSE
570       IF C>20 AND C<=37 THEN
580         V(C,B)=V(C,B)-V(40,B)
590       END IF
600     END IF
610   NEXT C
620     WAIT .1
630 NEXT B
640   !
650   !
660   ! scan remaining t.c.'s on cards 2,3 and 4
670   !
680 CLEAR 709
690 OUTPUT 709;"AF37AL59VR1S00"
700 FOR E=1 TO 20
710   FOR D=38 TO 60
720     OUTPUT 709;"AS"
730     ENTER 709;V(D,E)
740     WAIT .1
750   NEXT D
760   FOR D=38 TO 60
770     IF D<=40 THEN
780       V(D,E)=V(D,E)-V(40,E)
790     ELSE
800       V(D,E)=V(D,E)-V(60,E)
810     END IF
820   NEXT D
830   PRINT "2nd AND 3rd CARD...GROUP";E
840 NEXT E
850   !
860   !
870   !Allow for insertion of 4th card
880   !
890 BEEP

```

```

900     BEEP
910     PRINT "PROGRAM PAUSED TO ALLOW"
920     PRINT "  THERMOCOUPLE CHANGE"
930     PRINT "PRESS CONTINUE KEY WHEN READY"
940     PAUSE
950     CLEAR 709
960     !
970     !
980     !Read all t.c.'s on 4th card
990     !
1000    OUTPUT 709;"AFOAL18VR1SO0"
1010    FOR J=1 TO 20
1020      FOR I=61 TO 79
1030        OUTPUT 709;"AS"
1040        ENTER 709;V(I,J)
1050      NEXT I
1060      FOR B=61 TO 79
1070        V(B,J)=V(B,J)-V(79,J)
1080      NEXT B
1090    NEXT J
1100    !
1110    !Read in voltage and temperature tables
1120    !
1130    DATA
20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37,38,
39,40,41,42,43,44,45,46,47,48,
1140    DATA
49,50,51,52,53,54,55,56,57,58,59,60,61,62,63,64,65,66,67,
68,69,70,71,72,73,74,75,76,77
1150    DATA
78,79,80,81,82,83,84,85,86,87,88,89,90,91,92,93,94,95,96,
97,98,99,100,101,102,103,104
1160    DATA
105,106,107,108,109,110,111,112,113,114,115,116,117,118,1
19,120,121,122,123,124,125
1170    DATA
126,127,128,129,130,131,132,133,134,135,136,137,138,139,1
40,141,142,143,144,145,146
1180    DATA 147,148,149,150
1190    FOR F=1 TO 131
1200      READ Td(F)
1210    NEXT F
1220    DATA
.789,.83,.87,.911,.951,.992,1.032,1.073,1.114,1.155,1.196
,1.237,1.279,1.32,1.361,1.403
1230    DATA
1.444,1.486,1.528,1.569,1.611,1.653,1.695,1.738,1.780,1.8
22,1.865,1.907,1.95,1.992
1240    DATA
2.035,2.078,2.121,2.164,2.207,2.25,2.294,2.337,2.38,2.424
,2.467,2.511,2.555,2.599,2.643
1250    DATA

```

```

2.687,2.731,2.775,2.819,2.864,2.908,2.953,2.997,3.042,3.0
87,3.131,3.176,3.221,3.266
1260      DATA
3.312,3.357,3.402,3.447,3.493,3.538,3.584,3.63,3.676,3.72
1,3.767,3.813,3.859,3.906
1270      DATA
3.952,3.998,4.044,4.091,4.137,4.184,4.231,4.277,4.324,4.3
71,4.418,4.465,4.512,4.559
1280      DATA
4.607,4.654,4.701,4.749,4.796,4.844,4.891,4.939,4.987,5.0
35,5.083,5.131,5.179,5.227
1290      DATA
5.275,5.324,5.372,5.42,5.469,5.517,5.566,5.615,5.663,5.71
2,5.712,5.761,5.81,5.859
1300      DATA
5.908,5.957,6.007,6.056,6.105,6.155,6.204,6.254,6.303,6.3
53,6.403,6.452,6.502,6.552
1310      DATA 6.602,6.652,6.702
1320      FOR G=1 TO 131
1330          READ Vi(G)
1340      NEXT G
1350      A=1
1360      !
1370      !
1380      !CALCULATE AVG. VOLTAGE FOR EACH T.C.
1390      !
1400      !
1410      FOR H=1 TO 79
1420          FOR I=1 TO 10
1430              Vavg(H)=Vavg(H)+V(H,I)
1440          NEXT I
1450          Vavg(H)=Vavg(H)/10
1460      NEXT H
1470      !
1480      !
1490      !Uses linear interpolation between
1500      !table values to compute temperature
1510      !from average measured voltage
1520      !
1530      FOR J=1 TO 79
1540          FOR K=2 TO 131
1550              IF Vavg(J)*1000.0>=Vi(K) THEN GOTO 1620
1560              IF Vavg(J)*1000.0<Vi(K) THEN
1570                  Nn=K-1
1580                  Pp=K
1590
Tavg(J)=Td(Nn)+(Vavg(J)*1000.0-Vi(Nn))*((Td(Pp)-Td(Nn))/(
Vi(Pp)-Vi(Nn)))
1600          GOTO 1630
1610      END IF
1620      NEXT K
1630      NEXT J

```

```

1640      !
1650      !
1660      !Compute max. and min. voltage measured
1670      ! for each thermocouple
1680      !
1690      FOR L=1 TO 79
1700          FOR I=1 TO 10
1710              IF Vmin(L)<=V(L,I) THEN
1720                  ELSE
1730                      Vmin(L)=V(L,I)
1740                  END IF
1750          NEXT I
1760          FOR I=1 TO 10
1770              IF Vmax(L)>=V(L,I) THEN
1780                  ELSE
1790                      Vmax(L)=V(L,I)
1800                  END IF
1810          NEXT I
1820      NEXT L
1830      !
1840      !
1850      ! OBTAIN TEMP. VS. TIME DATA
1860      ! FOR EACH T.C. ON SURFACE
1870      !
1880      !
1890      FOR I=1 TO 37
1900          FOR J=1 TO 20
1910              FOR K=2 TO 131
1920                  IF V(I,J)*1000.0>=Vi(K) THEN GOTO 1990
1930                  IF V(I,J)*1000.0<Vi(K) THEN
1940                      Nn=K-1
1950                      Pp=K
1960
1970                      Tt(I,J)=Td(Nn)+(V(I,J)*1000-Vi(Nn))*((Td(Pp)-Td(Nn))/(Vi(
1980                      Pp)-Vi(Nn)))
1990                      GOTO 2000
2000                  END IF
2010              NEXT K
2020          NEXT J
2030      NEXT I
2040      !
2050      !Store data in 'T125,P125,...'
2060      ! (T125 corresponds to temp. vs time data
2070      !   for 12in. card, power of 5 watts)
2080      ! (Rest of data stored in P125, etc.)
2090      ! and read in current and voltage
2100      !
2110      BEEP
2120      BEEP
2130      BEEP

```

```

2140      INPUT "BUSBAR
TEMPERATURES....",Tavg(80),Tavg(81)
2150      INPUT "CURRENT THRU PLATE (volts from
shunt)",Cv
2160      INPUT "VOLTAGE ACROSS PLATE (volts)",Vp
2170      Cv=Cv*500.0
2180      P=Vp*Cv
2190      INPUT "TIME BETWEEN POWER ON AND TEST
START",Ta
2200      INPUT "ROOM TEMPERATURE",Tr
2210      LINPUT "CURRENT TEST NO.",W$
2220      LINPUT "DATE",Date$
2230      Name$=Test$&W$
2240      Name2$=Pest$&W$
2250      CREATE BDAT Name$,334,8
2260      CREATE BDAT Name2$,760,8
2270      ASSIGN @Path1 TO Name$
2280      ASSIGN @Path2 TO Name2$
2290      OUTPUT @Path2;Tt(*),Te(*)
2300      OUTPUT
@Path1;Tavg(*),Vmin(*),Vmax(*),Vavg(*),P,Tr,Ta,Cv,Vp,Te(1
0),Date$
2310      IF Back=0 THEN
2320      INPUT "DO YOU DESIRE A BACKUP COPY OF DATA?
Y=1",Aaa
2330      IF Aaa=1 THEN
2340      PRINT "INSERT NEW DISK NOW"
2350      PRINT
2360      PRINT "PRESS CONTINUE KEY WHEN READY"
2370      Back=1
2380      PAUSE
2390      GOTO 2240
2400      END IF
2410      END IF
2420      !
2430      !
2440      !Thermocouple Channels:
2450      !
2460      !Surface of foil: .....0-18, 20-37
2470      !Side of plate (inside): ...38,40-50
2480      !Bottom of plate (inside): .51-58, 0
2490      !Side of plate (outside):...1-12
2500      !Bottom of plate (outside): 13-14
2510      !Inside testbox:.....15-17
2520      !Ice Baths.....19,39,59,18
2530      !
2540      !
2550      !Thermocouple Markings:
2560      !
2570      !Surface of foil: .....1-37
2580      !Side of plate (inside): ...38-49
2590      !Bottom of plate (inside): .50-58

```

```
2600      !Side of plate (outside): ..59-70
2610      !Bottom of plate (outside) .71-72
2620      !Inside testbox.....73-75
2630      !Copper Busbars:.....76-77
2640      !Ice Baths.....78-81
2650      STOP
2660      END
```

Data Reduction Program

The following program was used to perform the heat balance as well as to evaluate the modified Rayleigh number. This information was then stored on a floppy diskette to be used with the correlation program.

This program will prompt the user for the following information:

1. Plate size (inches)
2. Test number (this corresponds to the power input in watts)
3. Desired property evaluation temperature (either surface temperature, ambient temperature, or average film temperature)

The output to the storage diskette includes the following information:

1. All surface temperatures ($^{\circ}\text{F}$)
2. Ambient temperature ($^{\circ}\text{F}$)
3. Convective heat transfer ($\text{Btu}/\text{ft}^2 \text{ hr}$)
4. Modified Rayleigh number
5. Thermal conductivity of air ($\text{Btu}/\text{hr ft F}$)

```

1  !*****
2  !*
10 !* THIS PROGRAM WILL CALCULATE PROPERTIES
20 !* OF AIR AND EVALUATE PERTINENT DIMENSIONLESS*
30 !* PARAMETERS FOR THIS THESIS PROJECT
40 !* VALID TEMPERATURES ARE FROM 26-260 F
41 !*
42 !*****
43 !
44 !
45 ! Modified 12/29/84
46 ! Program to be used in conjunction with
47 ! "Nuslt" to correlate data
48 !
50 !
60 !PROGRAM WILL CALCULATE HEAT LOSSES FROM
70 !PLATE TO DETERMINE HEAT TRANSFER BY
80 !CONVECTION
90 !
140 !
150 !
160 ! GRP= GRASHOF PROPERTIES TERM
170 ! K= THERMAL CONDUCTIVITY
180 ! PR= PRANDTL NUMBER
190 !
200 !
210 OPTION BASE 1
220 DIM Aa(14),Bb(14),Cc(14),Tp(14),Dat(3,9)
230 INPUT "Card Size",Cs$
231 Cn=VAL(Cs$)
240 LINPUT "CURRENT TEST NUMBER",Tn$
250 Test$="P"Cs$
260 Name$=Test$Tn$
261 FOR I=1 TO 3
262 FOR J=1 TO 9
263 READ Dat(I,J)
264 NEXT J
265 NEXT I
267 IF Cn=6 THEN
268 A=1
270 ELSE
271 IF Cn=8 THEN
272 A=2
273 ELSE
274 A=3
275 END IF
276 END IF
277 !
278 ! Initialize card parameters
279 !
281 I=1
282 N1=Dat(A,I) !no. of t.c.'s total

```

```

283  N2=Dat(A,I+1)
284  N3=Dat(A,I+2)  !no. of t.c.'s in 1 row
285  Nat=Dat(A,I+3) !no. of t.c.'s vert. in chmbr
286  At=Dat(A,I+4)
287  Ad=Dat(A,I+5)  !add factor for 12" plate
288  Bbt=Dat(A,I+6)
289  L=Dat(A,I+7)   !L=1/2 length of plate (ft.)
290  St=Dat(A,I+8)
291  !
292  !
293  !
294  DATA 71,71,5,5,61,0,59,.25,26
295  DATA 97,79,7,3,85,0,83,.3333333,50
296  DATA 81,79,6,3,73,1,71,.5,38
301  Nn3=N3*N3+Ad  !no. of surface t.c.'s
302  ON ERROR GOTO 304
303  GOTO 307
304  N1=93
306  DEALLOCATE
T(*),Vmin(*),Vmax(*),Vavg(*),X(*),Y(*),Al(*),Nu(*),Tr(*)
307  ALLOCATE
T(N1),Vmin(N2),Vmax(N2),Vavg(N2),X(Nn3),Y(Nn3),Al(Nn3),Nu
(Nn3),Tr(Nn3)
308  ASSIGN @Path1 TO Name$
309  ENTER
@Path1;T(*),Vmin(*),Vmax(*),Vavg(*),P,Trr,Taa,Cv,Vp,Tpp
310  OFF ERROR
311  FOR I=1 TO 14
312  READ Aa(I)
313  NEXT I
320  FOR I=1 TO 14
330  READ Bb(I)
340  NEXT I
350  FOR I=1 TO 14
360  READ Cc(I)
370  NEXT I
380  FOR I=1 TO 14
390  READ Tp(I)
400  NEXT I
410  !
420  !
430  ! ELIMINATE ICE BATH TEMP.'S AND CONVERT TO
      FAHRENHEIT
440  !
450  !
460  J=1
470  FOR I=1 TO N1
490  T(J)=DROUND((9/5)*T(I)+32,4)
493  IF T(J)<60 THEN
494  GOTO 510
495  END IF
500  J=J+1
510  NEXT I

```

```

520   Tsa=0
530   FOR I=1 TO Nn3
540     Tsa=T(I)+Tsa
550   NEXT I
560   Tsa=Tsa/Nn3
570   Ta=0
580   FOR I=1 TO Nat
590     Ta=Ta+T(At)
591     At=At+1
600   NEXT I
610   Taa=Ta/Nat
620   !
630   !Ta is computed by averaging surface
640   ! temperature and air temperature and
650   ! then taking the average of these two
660   ! to obtain a suitable temp. for property
670   ! evaluation
680   !
690   !
700   Ta=(Tsa+Taa)/2
701   !
702   !
703   ! Initialize x and y
704   !
705   !
708   J=1
710   Cn2=-((Cn/2)-1)
711   FOR I=1 TO Cn-1
712     X(I)=(Cn2/12)
713     IF Cn=12 THEN
714       Cn2=Cn2+2
715     ELSE
716       Cn2=Cn2+1
717     END IF
718   NEXT I
719   K=1
720   FOR I=1 TO N3
721     FOR J=1 TO N3
722       X(K)=X(J)
723       Y(K)=X(I)
724       K=K+1
725     NEXT J
726   NEXT I
727   IF Cn=12 THEN
728     X(37)=0.
729     Y(37)=0.
730   END IF
731   Ar=L*L*4
732   !
733   ! GRP TERM DATA (ENGLISH UNITS)
734   !
735   !

```

```

940  DATA
    .33976E7,.28761E7,.24522E7,.20977E7,.18069E7,.15654E7,.13
624E7,.11891E7,.10434E7
950  DATA .92288E6,.81560E6,.72191E6,.64523E6,.57621E6
960  !
970  !
980  !  PRANDTL NUMBER
990  !
1000 !
1010 DATA
    .7158,.7129,.7102,.7076,.7052,.7028,.7006,.6985,.6965,.69
47,.6930,.6914,.6899,.6886
1020 !
1030 !
1040 !  THERMAL CONDUCTIVITY (BTU/hr. ft. F)
1050 DATA
    .013802,.014263,.014718,.015169,.015616,.016059,.016497,.
016931,.017360,.017786,.018207
1060 DATA .018625,.019039,.019448
1070 !
1080 !
1090 !  TEMPERATURE (F)
1100 !
1110 !
1120 DATA
    26,44,62,80,98,116,134,152,170,188,206,224,242,260
1130 !
1140 !
1150 !  PROPERTY EVALUATION TEMP. (F)....Ta
1160 !
1170 !
1180 !.....INTERPOLATE FOR PROPERTIES.....
1190 !
1200 I=1
1210 IF Ta>Tp(I) THEN
1220     I=I+1
1230     GOTO 1210
1240 ELSE
1250     IF Ta=Tp(I) THEN
1260         Grp=Aa(I)
1270         Pr=Bb(I)
1280         K=Cc(I)
1290     ELSE
1300         Tvar=(Ta-Tp(I-1))/(Tp(I)-Tp(I-1))
1310         Grp=(Aa(I)-Aa(I-1))*Tvar+Aa(I-1)
1320         Pr=(Bb(I)-Bb(I-1))*Tvar+Bb(I-1)
1330         K=(Cc(I)-Cc(I-1))*Tvar+Cc(I-1)
1340     END IF
1350 END IF
1360 G=0
1370 !
1380 !CONVERT POWER TO ENGLISH UNITS

```

```

1390  !
1400  Qin=P*.05688*60      !Watts to Btu/hr
1410  Wqin=((3.4128*.00005*Cv)2+(3.4128*.05*Cv*Vp)2)*.5
1430  !
1530  !
1540  !
1550  !   Calculate heat transfer losses
1560  !
1570  !       Q = Qin - Qr - Qk
1580  !
1590  !   Compute radiation heat transfer
1600  !
1601  !   Calculate Areas for radiation
1602  !
1603  IF Cn=6 OR Cn=8 THEN
1604      FOR I=1 TO N3
1605          IF I=1 OR I=N3 THEN
1606              Ppp=2.25
1607          ELSE
1608              Ppp=1.5
1609          END IF
1611          A1(I)=Ppp/144
1612          A1(N3*(N3-1)+I)=A1(I)
1613      NEXT I
1614      FOR I=N3+1 TO (N3-2)*N3+1 STEP N3
1615          A1(I)=A1(2)
1616          A1(N3-1+I)=A1(2)
1617      NEXT I
1618      J=2
1620      FOR I=1 TO N3-2
1621          FOR Kk=1 TO N3-2
1622              A1(J+I*N3)=1/144
1623              J=J+1
1625          NEXT Kk
1626          J=2
1628      NEXT I
1629      END IF
1630      IF Cn=12 THEN
1631          FOR I=1 TO N3*N3
1632              A1(I)=4/144
1633          NEXT I
1634          A1(37)=1/144
1635          A1(15)=3.75/144
1636          A1(16)=A1(15)
1637          A1(21)=A1(15)
1638          A1(22)=A1(15)
1639      END IF
1641  !
1642  !
1643  !
1644  Sbc=.1714*10(-8)
1645  Eta=.1383

```

```

1646 Tar=Taa+459.7
1647 Qr=0
1648 FOR I=1 TO Nn3
1649   Tr(I)=T(I)+459.7
1650
1651   Qr2=(Sbc2*Al(I)2*((.01*(Tr(I)4-Tar4))2+(4*Eta*Tr(I)3)2+(4
*Eta*Tar3)2)).5
1651   Wqr=Wqr+Qr2
1653   Qr=Qr+Sbc*Eta*Al(I)*(Tr(I)4-Tar4)
1655 NEXT I
1660 !
1670 !   Compute conduction heat transfer
1680 !
1690 !       (out bottom of plate)
1691 !
1692 !       calculate k equivalent
1693 !
1700 Kbl=.0289   !Btu/hr ft F   (for balsa wood)
1701 Kbak=.1833 !Btu/hr ft F   (for bakelite)
1702 !K=[Btu/hr ft F]   (for air)
1704 Rt=1/(24*Kbak)+1/(3*Kbl)+1/(48*K)
1705 Kb=4.75/(12*Rt)
1710 Tba=(T(Bbt)+T(Bbt+1))/2
1711 IF Cn=8 THEN
1713   Tsa2=0
1716   J=90
1717   Ck=0
1718   FOR I=1 TO 4
1719     IF ABS(T(J)>300) THEN
1720       GOTO 1725
1721     END IF
1722     Tsa2=Tsa2+T(J)
1723     Ck=Ck+1
1725     J=J+1
1726   NEXT I
1727   Tsa2=Tsa2/Ck
1731   Qkbb=Kb*(Tsa2-Tba)*Ar*12/4.75
1733   END IF
1734   Qkb=Kb*(Tsa-Tba)*Ar*12/4.75
1735
1736   Wqb=((.20*Kb*Ar*12/4.75*(Tsa-Tba))2+2*(Kb*Ar*12/4.75)2).5
1740 !
1741 !       (out sides of plate)
1742 !
1743 L=L*12*2
1750 FOR I=1 TO 12
1751   IF I=2 OR I=5 OR I=8 OR I=11 THEN
1753     Ak=(L/6)*(1/2)/144   !area...ft2
1754   ELSE
1755     Ak=(1/2)*5*(L/12)/144   !area ...ft2
1756   END IF
1760   Qks=Qks+Kbl*(T(St)-T(St+21))*24*Ak

```

```

1761
Wqs=Wqs+((.2*Kbl*Ak*24*(T(St)-T(St+21)))^2+2*(Kbl*24*Ak)^2)
.5
1763      !.....1/2 in. thick insulation
1764      !
1765      St=St+1
1767  NEXT I
1768  L=L/48      !Convert to 1/4 length in ft.
1772  !
1780  !total
1790  !
1800  Qk=Qkb+Qks
1810  !
1820  ! Compute convection heat transfer
1830  !
1840  Q=.888*Qin-Qr-Qk      !Lead losses=11.2% Qin
1841  Wq=(Wqin^2+Wqr^2+Wqb^2+Wqs^2).5
1842  Wq=Wq/Q*100
1850  !
1880  !
1881! PRINTER IS 701
1883  PRINT "*****HEAT TRANSFER
RESULTS*****"
1884  PRINT "*"
1885  PRINT "*"
1890  PRINT "*"
Qc=";DROUND(Q,4),"Qin=";DROUND(Qin,4),"      *"
1900  PRINT "*"
Qr=";DROUND(Qr,4),"Qk=";DROUND(Qk,4),"      *"
1901  PRINT "*"
(Qkb=";DROUND(Qkb,4),"Qks=";DROUND(Qks,4);")
1902  PRINT "*"
1903  PRINT "*"      Percent heat
loss.....";DROUND((Qin-Q)*100/Qin,4),"      *"
1904  PRINT "*"
1905  PRINT "*"      Uncertainty in
Qc.....";DROUND(Wq,4),"      *"
1906  PRINT "*"
1908  PRINT
"*****"
1909  PRINT
1910  PRINT
1911  PRINT "Qkbb=";Qkbb
1912  PRINT "Tsa2=";Tsa2,"tsa=";Tsa
1913  PRINT
1914  PRINT

```

```

1921  Q=Q/Ar    !obtain q on per area basis
1922  !    Calculate Ra number
1923  !
1980    Ra=Grp*(L4)*Q*Pr*(1/K)
1981    PRINT
1990    PRINT "Ra=";Ra
1991    PRINT
1992    PRINT
2000    PRINTER IS 1
2030  !
2040  !
2041  !
2250  !
2260  BEEP
2261  PRINT
2262  PRINT
2263  PRINT
2270  PRINT ".....Insert Destination Disk....."
2280  PAUSE
2282  ALLOCATE Ts(Nn3)
2283  FOR I=1 TO Nn3
2284    Ts(I)=T(I)
2285  NEXT I
2290  Dest$="COR"Cs$Tn$
2291  ON ERROR GOTO 2300
2300  CREATE BDAT Dest$,Nn3+4,8
2301  OFF ERROR
2310  ASSIGN @Path2 TO Dest$
2320  OUTPUT @Path2;Ts(*),Q,Ra,K,Taa
2325  PRINT Dest$
2333  STOP
2340  END

```

Correlation Program

The following program takes the results from the data reduction program, calculates Nusselt numbers, and correlates these as a function of the modified Rayleigh number. It will also calculate a non-dimensional maximum surface temperature and correlate this as a function of the modified Rayleigh number.

This program will prompt the user for the following information:

1. Number of surfaces to be correlated (either 1,2, or 3)
2. Size of surfaces to be correlated in inches (if the number of srfaces is less than three)
3. Input file prefix (this indicates what propety evaluation temperature was used)
4. Characteristic length factor (actual plate length divided by this factor determines charateristic length)
5. Power desired for correlation (may be any number; zero indicates that the program is to solve for the power)
6. Indicate if plotting data is desired (if yes, the program will create a file of experimentally determined Nusselt and Rayleigh numbers)
7. Indicate if maximum surface temperature is to be correlated
8. Indicate if power is to be changed and corrleation performed again

The output from this program includes the following information:

1. Correlation constant(s)
2. Standard error of the correlation

3. Experimental value of Nusselt and/or Maximum surface temperature, values of these parameters calculated from the correlation, and the percent difference.

```

10  !This program will use a least square
20  ! fit to correlate data output from
30  ! program "corr". Data will be correlated
40  ! in the form:
50  !           Nu=C1*RaC2
60  ! where C1 and c2 are unknowns.
70  !
80  !
90  ! This program was written 12/28/84
100 !
110 !
120 OPTION BASE 1
130 DIM Hc(34),Tb(34),Ra(34),K(34),Nu(34),Tmax(34)
140 !
150 !
160 INPUT "Number of surfaces to be correlated",Ns
170 A8=55
180 A12=100
190 IF Ns=1 THEN INPUT "Plate size?",Plat
200 IF Ns=2 THEN INPUT "Which two surfaces? (must be
in order of size)",S1,S2
210 IF S1=8 THEN GOTO 660
220 IF Plat=8 THEN GOTO 660
230 IF Plat=12 THEN GOTO 970
240 !
250 !
260 ! Start 6" plate tbar calculation
270 !
280 ALLOCATE Ts(25),Tbx(5)
290 !
300 ! NAM$ DECIDES WHICH PROPERTY EVAL.
310 ! TEMP. TO USE ---
320 ! "CORR"- TAVG "CTA"-TAIR "CTS"-TS
330 !
340 INPUT "NAME PREFIX",Nam$
350 ON ERROR GOTO 610
360 C=0
370 !
380 !
390 FOR I=5 TO 30 STEP 5
400 C=C+1
410 Nam1$=Nam$"6"
420 Nam2$=VAL$(I)

```

```

430  Name$=Nam1$Nam2$
440  ASSIGN @Path TO Name$
450  ENTER @Path;Ts(*),Q,Ra(C),K(C),Tair
460  !
470  !
480  !INTEGRATE BY TRAPEZOIDAL METHOD
490  !
500  F=0
510  FOR J=1 TO 25
520      IF Tmax(C)<Ts(J) THEN Tmax(C)=Ts(J)
530  NEXT J
540  FOR J=1 TO 25 STEP 5
550      F=F+1
560
Tbx(F)=1/8*(Ts(J)+2*(Ts(J+1)+Ts(J+2)+Ts(J+3))+Ts(J+4))
570  NEXT J
580
Tb(C)=1/8*(Tbx(1)+2*(Tbx(2)+Tbx(3)+Tbx(4))+Tbx(5))-Tair
590      Hc(C)=Q/Tb(C)
600      Tmax(C)=(Tmax(C)-Tair)/Tb(C)
610  NEXT I
620  OFF ERROR
630  IF S2=12 THEN GOTO 960
640  IF Ns=1 THEN GOTO 1300
650  DEALLOCATE Ts(*),Tbx(*)
660  ALLOCATE Ts(49),Tbx(7)
670  ASSIGN @Path TO *
680  Nam1$=Nam$_"8"
690  !
700  ON ERROR GOTO 910
710  !
720  !
730  FOR I=5 TO A8 STEP 5
740      C=C+1
750      Nam2$=VAL$(I)
760      Name$=Nam1$Nam2$
770      ASSIGN @Path TO Name$
780      ENTER @Path;Ts(*),Q,Ra(C),K(C),Tair
790      F=0
800      !
810      FOR J=1 TO 49
820          IF Tmax(C)<Ts(J) THEN Tmax(C)=Ts(J)
830      NEXT J
840      FOR J=1 TO 49 STEP 7
850          F=F+1
860
Tbx(F)=1/12*(Ts(J)+2*(Ts(J+1)+Ts(J+2)+Ts(J+3)+Ts(J+4)+Ts(
J+5))+Ts(J+6))
870  NEXT J
880
Tb(C)=1/12*(Tbx(1)+2*(Tbx(2)+Tbx(3)+Tbx(4)+Tbx(5)+Tbx(6))
+Tbx(7))-Tair

```

```

890   Hc(C)=Q/Tb(C)
900   Tmax(C)=(Tmax(C)-Tair)/Tb(C)
910   NEXT I
920   OFF ERROR
930   IF S2=12 THEN GOTO 960
940   IF Ns=2 THEN GOTO 1280
950   IF Ns=1 THEN GOTO 1300
960   DEALLOCATE Ts(*),Tbx(*)
970   ALLOCATE Ts(37),Tbx(6)
980   ASSIGN @Path TO *
990   Nam1$=Nam$_12"
1000  !
1010  ON ERROR GOTO 1220
1020  !
1030  C=C+1
1040  FOR I=5 TO A12 STEP 5
1050  Nam2$=VAL$(I)
1060  Name$=Nam1$Nam2$
1070  ASSIGN @Path TO Name$
1080  ENTER @Path;Ts(*),Q,Ra(C),K(C),Tair
1090  F=0
1100  !
1110  FOR J=1 TO 36
1120      IF Tmax(C)<Ts(J) THEN Tmax(C)=Ts(J)
1130  NEXT J
1140  FOR J=1 TO 36 STEP 6
1150      F=F+1
1160
Tbx(F)=2/20*(Ts(J)+2*(Ts(J+1)+Ts(J+2)+Ts(J+3)+Ts(J+4))+Ts
(J+5))
1170  NEXT J
1180
Tb(C)=2/20*(Tbx(1)+2*(Tbx(2)+Tbx(3)+Tbx(4)+Tbx(5))+Tbx(6)
)-Tair
1190  Hc(C)=Q/Tb(C)
1200  Tmax(C)=(Tmax(C)-Tair)/Tb(C)
1210  C=C+1
1220  NEXT I
1230  OFF ERROR
1240  !
1250  !
1260  !   Calcualte Nu
1270  !
1280  N=C-1
1290  IF Ns=2 AND S2=8 THEN N=C
1300  IF Plat=6 THEN N=6
1310  IF Plat=8 THEN N=11
1320  IF Plat=12 THEN N=17
1330  !
1340  !           Use 1/4 plate length
1350  !           as characteristic length
1360  !

```

```

1370 INPUT "Charact. plate length, L*?",Cpl
1380 Cpl=Cpl*12 !cpl=[in/ft]
1390 L=6/Cpl
1400 PRINT
1410 PRINT
1420 PRINT
1430 FOR I=1 TO N
1440 IF N=11 THEN L=8/Cpl
1450 IF N=17 AND Ns=1 THEN L=12/Cpl
1460 IF N=17 AND Ns=2 AND I>6 THEN L=8/Cpl
1470 IF N=34 AND I>6 THEN L=8/Cpl
1480 IF N=34 AND I>17 THEN L=12/Cpl
1490 IF N=23 AND I>6 THEN L=12/Cpl
1500 IF N=28 AND I<12 THEN L=8/Cpl
1510 IF N=28 AND I>11 THEN L=12/Cpl
1520 Nu(I)=Hc(I)*L/K(I)
1530 Ra(I)=Ra(I)*(48/Cpl)4
1540 NEXT I
1550 !
1560 !
1570 ! Correlate data using least square
1580 ! curve fit
1590 !
1600 !
1610 INPUT "What power is desired for fit?",Pwr
1620 Sx=0
1630 Sxy=0
1640 Sy=0
1650 Sx2=0
1660 Snr=0
1670 Sr2=0
1680 FOR I=1 TO N
1690 Sxy=Sxy+LOG(Ra(I))*LOG(Nu(I))
1700 Sx=Sx+LOG(Ra(I))
1710 Sy=Sy+LOG(Nu(I))
1720 Sx2=Sx2+LOG(Ra(I))*LOG(Ra(I))
1730 Snr=Snr+Nu(I)*Ra(I)Pwr
1740 Sr2=Sr2+Ra(I)(2*Pwr)
1750 NEXT I
1760 !
1770 ! compute coefficients
1780 !
1790 C2=(N*Sxy-Sx*Sy)/(N*Sx2-Sx*Sx)
1800 C1=EXP((Sy*Sx2-Sxy*Sx)/(N*Sx2-Sx*Sx))
1810 C=Snr/Sr2
1820 !
1830 ! Compute error associated with fit
1840 !
1850 IF Pwr<>0 THEN
1860 C1=C
1870 C2=Pwr
1880 END IF

```

```

1890 Sum=0
1900 FOR I=1 TO N
1910     Sum=Sum+(Nu(I)-C1*Ra(I)C2)2
1920 NEXT I
1930 !
1940 Serr=(Sum/(N-1)).5
1950 !
1960 ! Output results
1970 !
1980 INPUT "Is plotting data desired?",Y$
1990 IF Y$="Y" OR Y$="YES" THEN
2000     B$="EXP"
2010     IF Repeat=1 THEN B$="TMAX"
2020     ON ERROR GOTO 2040
2030     PURGE B$
2040     OFF ERROR
2050     ON ERROR GOTO 2070
2060     CREATE BDAT B$,4*N,8
2070     OFF ERROR
2080     ASSIGN @Path2 TO B$
2090     ALLOCATE Ral(N),Nul(N)
2100     FOR J=1 TO N
2110         Nul(J)=Nu(J)
2120         Ral(J)=Ra(J)/1.E+6
2130     NEXT J
2140     OUTPUT @Path2;Ral(*),Nul(*)
2150     DEALLOCATE Ral(*),Nul(*)
2160 END IF
2170 PRINT
2180 PRINT
2190 PRINT "          Correlation Results"
2200 PRINT "          "
2210 PRINT
2220 PRINT
2230 PRINT "c1=";DROUND(C1,6)
2240 PRINT "c2=";DROUND(C2,6)
2250 PRINT
2260 PRINT "Nu=c1*RaC2"
2270 PRINT
2280 PRINT "          Error=";DROUND(Serr,4)
2290 IF Repeat=1 THEN GOTO 2400
2300 INPUT "Correlate surface temperature?",Y$
2310 IF Y$="YES" OR Y$="Y" THEN
2320     FOR I=1 TO N
2330         Nu(I)=Tmax(I)
2340     NEXT I
2350     Repeat=1.0
2360     GOTO 1620
2370 END IF
2380 INPUT "Change length or power?",Y$
2390 IF Y$="Y" OR Y$="YES" THEN GOTO 1370
2400 STOP

```

APPENDIX C

PROCEDURES

Temperature Measurement Experiments

The following procedure was used in obtaining data for each temperature measurement experiment:

1. The flat plate assembly was placed in the test chamber and all electrical connections were made.

2. The plate was levelled using the leveling screws in the bottom of the test chamber.

3. The test chamber was sealed to prevent any disturbances in the room from propagating to the experimental setup.

4. A desired power input to the card was obtained by adjusting the Variac until a desired voltage drop across the card was reached. The set-up was then allowed to reach steady-state.

5. An HP 9826 micro-computer with an HP 3497-A Data Acquisition Center was used to read the thermocouples. (A listing of the programs used is given in Appendix B). All the thermocouples on the surface of the plate were read sequentially; and, this process was

repeated ten times to provide an adequate number of readings to obtain an average value. Once this was completed, the rest of the thermocouples were read sequentially and this was again repeated ten times.

6. The voltage drop across the current shunt was then measured using a Precision Digital Voltmeter to determine the current through the flat-plate, and then entered into the computer.

7. The voltage drop across the plate was measured and also entered into the computer.

8. The temperature in the laboratory was measured and entered into the computer.

9. The time required for the setup to reach steady-state was entered into the computer.

10. The power was turned up to the next desired input level and the experiment allowed to reach steady-state conditions.

11. Steps 5 through 10 were then repeated until the maximum surface temperature of the foil was just below the melting point of the solder (350 F) used to

attach thermocouples to the surface.

12. The flat plate setup was then replaced with the next card to be tested and steps 1 through 12 repeated until all three heater card assemblies were tested.

Flow Visualization Experiments

Flow visualization studies, as previously mentioned, were conducted in a sealed 3 x 3 x 5 foot enclosure. These studies were conducted after the completion of all temperature measurement experiments. This was done to prevent changing the emissivity of the foil as a result of smoke particle deposition. The following procedure was used:

1. The power input to the card was adjusted as before and the flow allowed to reach to steady-state conditions.

2. A 15 mW helium-neon laser was positioned outside the test chamber so that the beam passed just above the foil surface.

3. A cylindrical glass rod was placed in the laser beam in a direction perpendicular to the beam. This spread the beam of light into a verticle plane perpendicular to the heated surface of the card.

4. The inlet hose to the smoke generator was connected to the laboratory air supply. The outlet hose was run into the top of the test chamber; and, the pipe tobacco in the smoke generator was ignited.

5. Smoke was then injected into the top of the test chamber. Care was taken to insure that the flow rate of smoke entering was slow enough to have a minimal effect on the free convective flow in the chamber. The smoke generator is described fully in the instrumentation section of this thesis. (Note: It was found that the amount of smoke in the chamber and position of the laser greatly affected the ability of the experimenter to view and video-tape the flows; thus, some "tinkering" was required to obtain optimum conditions).

6. The room lights were turned off and the flow was studied and video-taped.

7. Steps 1-6 were repeated to provide a minimum of two flow visualization studies per card.

APPENDIX D

EXPERIMENTAL DETERMINATION OF THE TOTAL HEMISPHERICAL EMITTANCE OF THE INCONEL 600 FOIL

In order to accurately assess the radiative heat loss from the foil surfaces, it was necessary to experimentally determine the total hemispherical emissivity of the Inconel foil. This was done using the facilities at the Oak Ridge National Laboratory. The method followed was essentially the same followed by McElroy and Kollie[25] and is briefly described below.

A foil sample was machined to the form of a sheet tensile test specimen. The overall specimen length was 10 inches, with the central 6 inches used for measurement purposes. This central region was machined to a width of 0.2 in. $\pm$ 0.0006 in. The surface finish and thickness (polished Inconel 600, approximately 0.018 in. thick) were as received from the manufacturer, Hamilton Precision Metals.

Foil surface temperature measurement was provided by three 0.005 in. diameter Pt₉₀ Rh₁₀ /Pt thermocouples which were welded to the surface of the foil. These leads were separated laterally by approximately 5 wire diameters. The Pt₉₀ Rh₁₀ leads were also used to determine the voltage drop along the specimen, so that

the length between the leads determined the length of the test section. A translating microscope was used to measure both the length and width of each of the two test sections accurately. During the experiment, the foil sample was placed vertically in the specimen chamber.

This chamber consisted of a 14 in. I.D., 30 in. tall brass cylinder. The wall temperature of the chamber was kept constant to within $\pm 0.05^\circ$ C by circulating water through copper tubing attached to its outer wall. All inside surfaces were blackened with a high emissivity (approximately 1.0) paint.

The chamber was evacuated to a pressure of approximately 7.5×10^{-6} torr.

A direct current power supply (Electronics Research Associates, Inc., model 36-12M) which has $\pm 0.05\%$ load regulation and $\pm 0.0005\%$ rms ripple was used to provide power to the specimen. All voltage measurements were made with an L&N K-3 potentiometer. The current was determined by the voltage drop across a .001 ohm L&N standard resistor, model 4222, in series with the specimen. This measurement was also made with the K-3 potentiometer.

Determination of the emissivity was made in the following manner. Once the specimen was machined, the thermocouples were welded in place and their locations

were accurately determined. The specimen was then placed in the test chamber and the chamber was evacuated. Next, the power was applied to the specimen and the specimen allowed to come to steady-state. The chamber temperature, specimen temperature, voltage drop, and current measurements were then made. The current direction was reversed, and once steady-state was again reached, all measurements were repeated. The power was then adjusted and the same procedure repeated. The forward and reverse current readings were necessary to eliminate a d.c. voltage pickup by the thermocouples. The two thermocouple voltage measurements were thus averaged to obtain the "true" thermocouple EMF.

Systematic error evaluation by McElroy and Kollie showed that this measurement was accurate to within $\pm 2.7\%$ with a reproducibility of $\pm 0.5\%$. A plot of the emissivity versus temperature as determined by this experiment is presented in Figure 18.

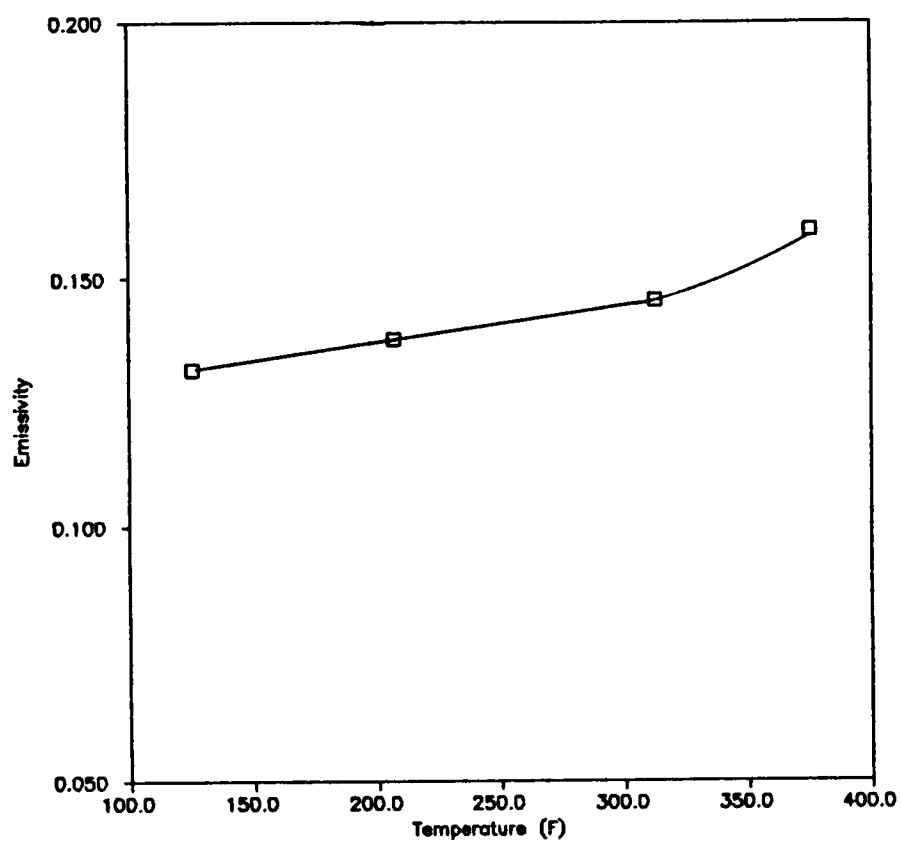


Figure 18. Emissivity as a Function of Temperature for the Inconel 600 Foil

APPENDIX E

EXPERIMENTS TO DETERMINE

LEAD WIRE LOSSES

In order to accurately determine the amount of heat transferred to the air by free convection, a heat balance on the test apparatus was performed. The heat balance required the accurate assessment of all "losses" from the test apparatus. In order to accomplish this goal, the heat conducted away from the plate by the lead wires had to be determined.

Each plate was equipped with four .162 inch diameter (6 gauge) copper leads which supplied current to the foil surface. To determine the conduction losses along these leads, the following experiment was run.

One of the four leads was instrumented with four thermocouples welded to an interior wire strand at distances of 1,2,3, and 6 inches from the plate connection. The wire insulation was replaced and the lead wire-busbar connection made. Power was supplied through the leads and the test setup allowed to achieve thermal equilibrium. The power input and thermocouple voltages were then measured. This allowed for a determination of the axial temperature distribution of the wire at a known power input to the card. This data is presented in Figure 19.

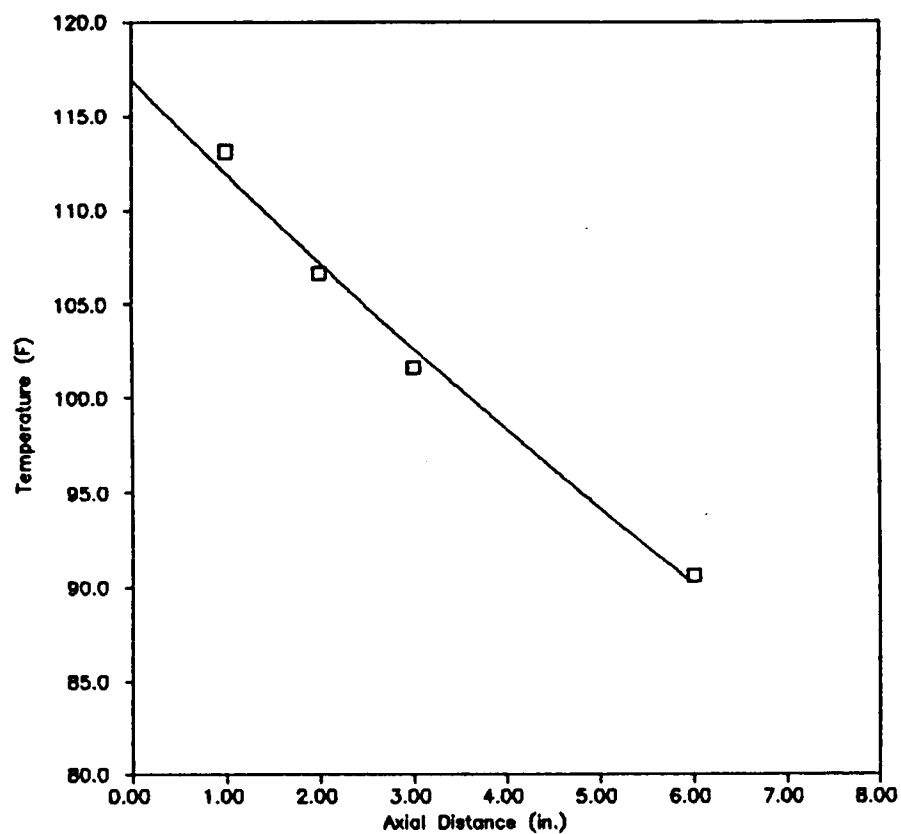


Figure 19. Axial Temperature Distribution of the Electrical Lead Wires

The temperature gradient at the end of the wire lead was extrapolated from the data and the heat transfer lost by conduction calculated. The test was repeated at a different power setting and the losses again calculated. As with the other losses from the test setup, the lead losses were approximately a constant percentage of the input power. That is, lead losses remained at approximately 11.2% of the total power input to the test surface for both tests run.

Losses from plate to plate were also seen to remain relatively constant for all tests. Because of this fact, the lead losses were assumed constant for all three surfaces. This assumption did, however, result in a greater estimated uncertainty in the Nusselt number for the 6 inch and 12 inch surfaces. See Appendix H for details of the uncertainty analysis.

APPENDIX F

MEASUREMENT OF THE SEPARATION

ANGLE OF THE WOLLASTON PRISM

The Wollaston Prism Schlieren Interferometer is an optical device which is used to directly measure the heat flux in a test section. Measurements at the University of Tennessee have in the past relied on accurately measuring several quantities directly from an interferogram. One of these quantities is a distance, h , called the double image distance. This is typically a very small distance, on the order of .01 in. The measured heat flux, q , is inversely proportional to this distance; consequently, a given error in a measurement of h will result in a corresponding error in the heat flux. For example, if the measurement of h is 15% low, the true value of q will be 15% lower than the calculated value.

Since h is typically a very small distance, the uncertainty associated with this measurement can easily become quite large, resulting in a large uncertainty in the heat flux.

An alternative method to measuring this distance is to calculate it using an equation presented by Sernas [26],

$$h = B(f - uW/f + W),$$

where,

B = separation angle of the Wollaston Prism

f = focal length of the spherical mirror

u = distance from the test section to the
real image in the spherical mirror

W = distance from the spherical mirror focal
point to the center of the Wollaston Prism.

All of the quantities except the separation angle are very large compared to the double image distance, and so may be determined with a much lower uncertainty. Thus, if the separation angle of the prism is accurately known, this method may be used to more accurately determine the double image distance. The prism manufacturer, however, does not always accurately measure this angle[27]. Therefore, an experiment was performed to measure this angle for the UTK Wollaston prism.

The separation angle, although very small (typically $.05^\circ$), may be determined accurately provided there is a sufficiently long optical path to allow the beams to achieve an appreciable separation. The following method was used to determine this angle.

A laser and the Wollaston prism were placed on an optical rail in the 3rd floor hallway of the Mechanical Engineering building at the University of Tennessee.

The laser was aimed at the Wollaston prism so that the two resultant beams leaving the prism were directed onto a screen at the opposite end of the hall, approximately 296.4 ft. away. (A Civil Engineering steel tape was used to measure this length) Then, using calipers, the separation distance of the two beams was measured, allowing the separation angle to be calculated.

Some uncertainty was associated with the separation distance measurement due to the fact that the area illuminated was neither circular nor of uniform intensity. This uncertainty was not excessive but could be reduced by using an aperture in combination with the laser. The estimated uncertainty for the measured separation angle was approximately 5%, or $.0026^\circ$.

Data

Hallway length - $S=3556.8 \text{ in.} = 296.40 \text{ ft.}$

Separation Distance - (3 measurements) - $d=3.339 \text{ in.}$
 $d=3.220 \text{ in.}$
 $d=3.261 \text{ in.}$

Average $\overline{d}=3.2733 \text{ in.}$

Experimentally determined separation angle

$$B = \tan [d/2S]$$

$$B = .0527^\circ \pm 5\%$$

Separation angle from manufacturer - $B = .054^\circ$.

Thus, the manufacturer's value for the UTK Wollaston Prism separation angle is within the uncertainty of this measurement. However, this measurement has provided two benefits: 1) the manufacturer's number has been validated; and, 2) the double image distance may now be determined with greater accuracy.

APPENDIX G

VALIDATION OF THE HEAT BALANCE

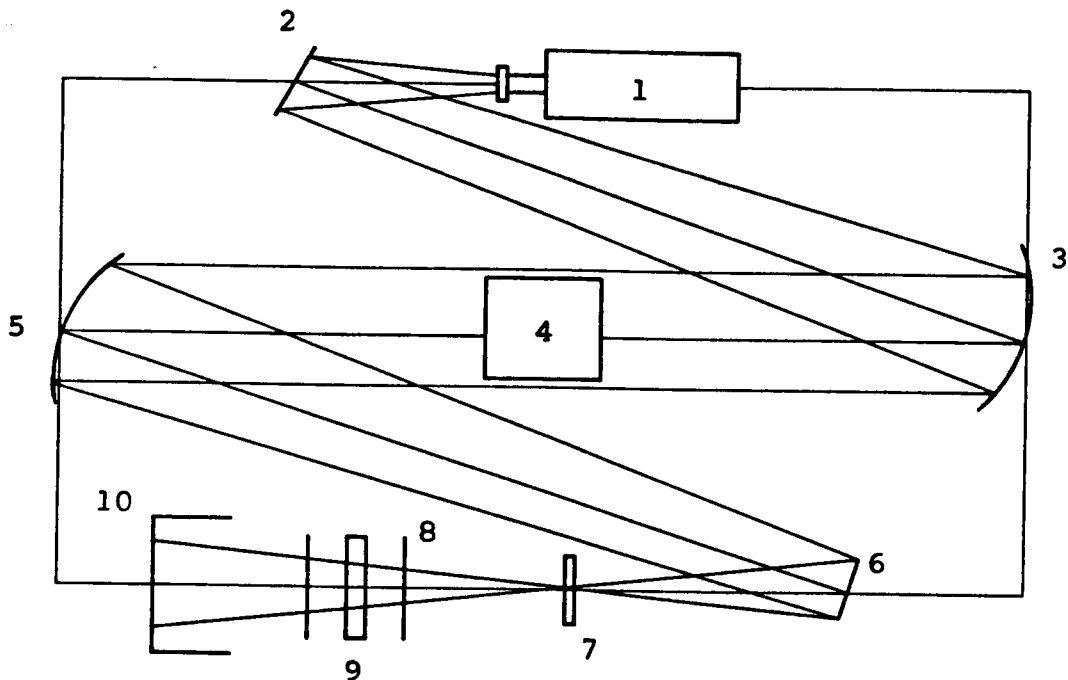
USING THE WOLLASTON PRISM

SCHLIEREN INTERFEROMETER

The determination of the natural convection heat transfer from the test surfaces was accomplished by use of a heat balance method. Since the "losses" from these surfaces were rather large (on the order of 30% of the total input), it was desired to check the heat transfer results independently. A Wollaston Prism Interferometer (WPI) was used for this purpose.

The WPI is an optical device in which the shift in the fringes produced can be shown to be proportional to the density gradient, or heat flux [26]. Thus, the amount of heat transferred from a surface by free convection can be measured directly using this device. A schematic of the University of Tennessee's WPI setup is presented in Figure 20.

It was decided to run the verification test for the 8 inch surface and an electrical power input of approximately 20 Watts. The procedure used was as follows: First, the WPI was set up and the laser beam collimated as described in Irby and Parsons [28]. The test surface was then positioned in the interferometer, power applied, and the setup allowed to reach



- | | |
|---------------------|--------------------|
| 1. Laser | 6. Plane Mirror |
| 2. Plane Mirror | 7. Focusing Lens |
| 3. Spherical Mirror | 8. Polarizer |
| 4. Test Section | 9. Wollaston Prism |
| 5. Spherical Mirror | 10. Camera |

Figure 20. Schematic of the University of Tennessee's Wollaston Prism Schlieren Interferometer

steady-state. Once this was accomplished, the interferograms were recorded on polaroid film. Measurements to determine the magnification factor, boundary layer thickness, fringe spacing, and fringe shift were made directly from the negative, using a translating microscope. The data was then reduced to provide a measure of the average convection coefficient (along the optical path) at desired locations. These coefficients were then integrated along the surface to obtain the average convection coefficient over the entire plate, which, in turn, allowed the heat transfer to be calculated.

A sample interferogram is presented in Figure 21, with points representative of those used in the calculations indicated. Sample calculations are presented below.

Ambient Air Temperature, $T_a = 67.64^{\circ}\text{F}$

Average Plate Temperature, $T_s = 157.62^{\circ}\text{F}$

Overall Temperature Difference, $\Delta T = 89.98^{\circ}\text{F}$

Average Temperature, $T_{avg} = 112.6^{\circ}\text{F}$

Boundary Layer Thickness, $\delta_{photo} = .1398 \text{ in.}$

Length of Test Section, $Z = 8.0 \text{ in.}$

Vertical Magnification Factor, $M_v = .5073$

Horizontal Magnification Factor, $M_h = .5133$

Average Magnification Factor, $M_{avg} = .5097$

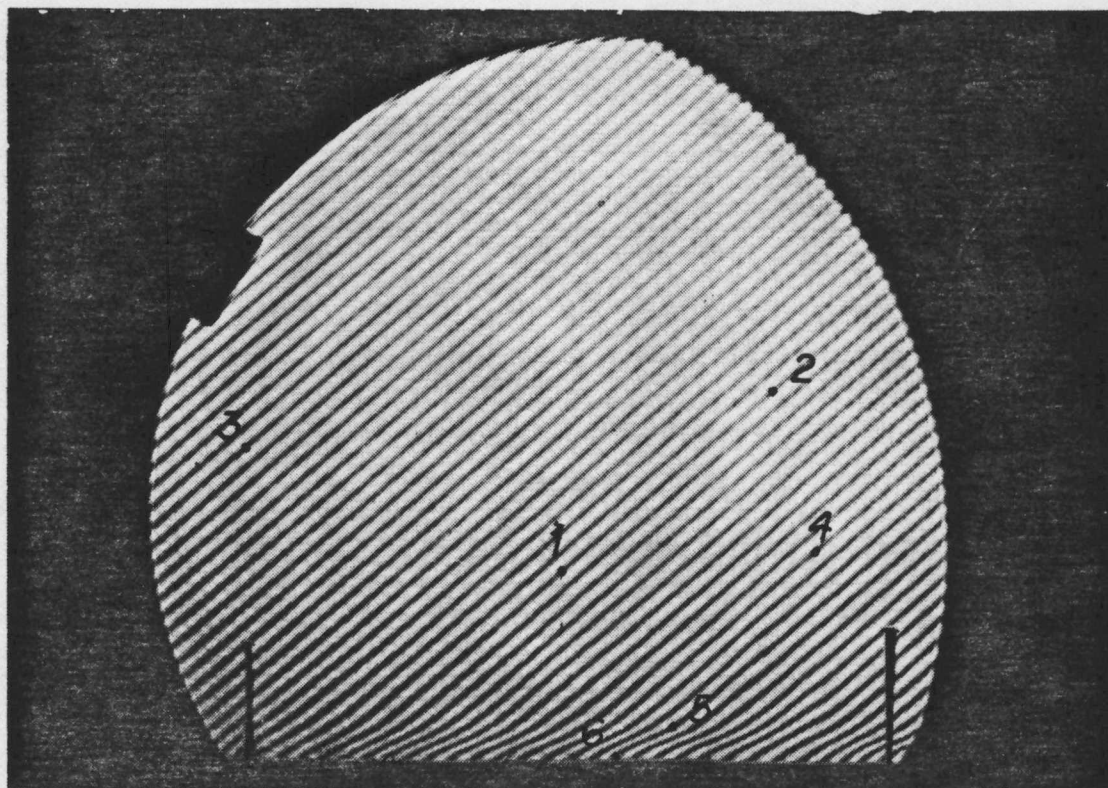


Figure 21. Sample Interferogram

Actual Thermal Boundary Layer Thickness, $\delta =$

$$\delta_{\text{photo}}/M_{\text{avg}} = .2743 \text{ in.}$$

Distance from Spherical Mirror(SM) Focal Point to

Wollaston Prism, $W = 18.5 \text{ in.}$

Distance from Camera to SM, $v = 95.1 \text{ in.}$

Focal Length of Spherical Mirror, $f = 63.0 \text{ in.}$

Separation Angle of Wollaston Prism, $B = .0527^\circ$

Double Image Distance,

$$1/f = 1/u + 1/v$$

$$1/u = 1/f - 1/v = 1/63.0 - 1/95.1$$

$$u = 186.6 \text{ in.}$$

From Sernas[26],

$$h = B(f - uW/f + W)$$

$$h = (.0527)(\pi/180)(63.0 - (186.6)(18.5)/(63.0) + 18.5)$$

$$h = .0246 \text{ in.}$$

$$H = h M_{\text{avg}} = (.0246)(.5097)$$

$$H = .0125 \text{ in.}$$

End Effects,

$$\delta/Z = (.2743) / (8.0) = .0343, \quad H/\delta = .0894 .$$

From Heidari and Parsons[29] Figure 5,

$$\epsilon = .75\%$$

$$Z_{\text{eff}} = Z(1 + .0075) = 8.06 \text{ in.}$$

The following coordinates were taken from an interferogram:

$$\begin{aligned}x_1 &= 1.0135 & y_1 &= .6072 \\x_2 &= .1952 & y_2 &= 1.2994 \\x_3 &= 1.9250 & y_3 &= 1.3537 \\x_4 &= .2081 & y_4 &= 1.5909.\end{aligned}$$

N number of fringes between points 3 and 4

$$N = 20$$

$$\phi = \tan^{-1}[(1.2994 - .6072) / (1.0135 - .1952)] = 40.2^\circ$$

$$\theta = 90 - \phi = 49.8^\circ$$

Fringe spacing,

$$S = .0463 \text{ in.}$$

Two points were also measured from the interferogram to obtain the fringe shift at each thermocouple location (points 5 and 6 in Figure 21).

From Heidari and Parsons [29],

$$\Delta S = \left| \frac{(y_1 - y_2)x_6 + (x_2 - x_1)y_6 + (x_1 - x_2)y_5 + (y_2 - y_1)x_5}{[(y_1 - y_2)^2 + (x_1 - x_2)^2]^{1/2}} \right|$$

$$h_{\text{conv } x} = (19.6895)\Delta S$$

(see Table 5)

ΔS - inches

Table 5 - Fringe Shifts and Convection Coefficients
as Determined from the Interferograms

Location (in. from edge)	ΔS (in.)	$h_{conv} x$ (BTU/hr ft ² F)
1.076	.0449	.8841
2.071	.0479	.9431
3.027	.0501	.9864
3.837	.0467	.9195
4.467	.0491	.9668
5.579	.0532	1.047
6.824	.0354	.6970

By trapezoidal rule,

$$2(x_0 - x_1)h = (x_2 - x_1)(h_1 + h_2) + (x_3 - x_2)(h_2 + h_3) + \\ (x_4 - x_3)(h_3 + h_4) + (x_5 - x_4)(h_4 + h_5) + (x_6 - x_5)(h_5 + h_6) + (x_7 - x_6)(h_6 + h_7),$$

$$h = .940,$$

$$Q = hA \Delta T,$$

$$Q = 37.6 \text{ BTU/hr.}$$

From Heat Balance,

$$Q = 49.6 \text{ BTU/hr.}$$

The estimated uncertainty associated with the two measurements (see Appendix H) are approximately 20% for the WPI experiment and just under 10% for the heat balance method.

The two results, although significantly different, lie within the the range of uncertainty associated with each method. Thus, the heat balance method is verified within the estimated uncertainty.

The uncertainty associated with the WPI results was high for the present test. This was mainly due to the unsteady nature of the flow, which would require the taking of several interferograms to obtain an average value of the heat transfer coefficient. This was not done in the present study because of the large amount of time needed to process the interferograms.

APPENDIX H

UNCERTAINTY ANALYSIS FOR THE SURFACE TEMPERATURE AND WOLLASTON PRISM VALIDATION EXPERIMENTS

An uncertainty analysis was performed, following the method of Kline and McClintock [30], for both the surface temperature experiments and the WPI verification experiment (see Appendix G). The analysis for the surface temperature experiments was performed on the HP 9826 computer and was part of the Data Reduction Program (see Chapter II). The equations and assumptions used as well as the results of these analyses are presented below.

Surface Temperature Experiments

Power Input:

$$P_{in} = V \cdot I ,$$

$$\omega_P = [(\omega_V \frac{\partial P}{\partial V})^2 + (\omega_I \frac{\partial P}{\partial I})^2]^{1/2} ,$$

$$\omega_P = [(\omega_V I)^2 + (\omega_I V)^2]^{1/2} .$$

Assume:

$$\omega_V = .0005 \text{ volts}, \omega_I = .025 \text{ I (2.5\%)} ,$$

$$\omega_P = [(.0005 \text{ I})^2 + (.025 \text{ I V})^2]^{1/2} .$$

Radiation Heat Transfer:

$$q_{r_i} = \sigma A_i \epsilon (T_{s_i}^4 - T_{air}^4) .$$

Assume:

$$\omega_{A_i} \ll \omega_{\epsilon} , \omega_{T_{s_i}} , \omega_{T_{air}} .$$

$$\omega_{q_{r_i}} = \left[\left(\omega_{\epsilon} \frac{\partial q_{r_i}}{\partial \epsilon} \right)^2 + \left(\omega_{T_{s_i}} \frac{\partial q_{r_i}}{\partial T_{s_i}} \right)^2 + \left(\omega_{T_{air}} \frac{\partial q_{r_i}}{\partial T_{air}} \right)^2 \right]^{1/2} .$$

$$\frac{\partial q_{r_i}}{\partial \epsilon} = \sigma A_i (T_{s_i}^4 - T_{air}^4) , \quad \frac{\partial q_{r_i}}{\partial T_{s_i}} = 4\sigma A_i \epsilon T_{s_i}^3 .$$

$$\frac{\partial q_{r_i}}{\partial T_{air}} = -4\sigma A_i \epsilon T_{air}^3 .$$

Assume:

$$\omega_{\epsilon} = .01 , \omega_{T_{s_i}} = 1^{\circ}R , \omega_{T_{air}} = 1^{\circ}R .$$

$$\begin{aligned} \omega_{q_r} &= \sum_{i=1}^N \omega_{q_{r_i}} = \sum_{i=1}^N \{ [(.01) \sigma A_i (T_{s_i}^4 - T_{air}^4)]^2 \\ &\quad + (4\sigma A_i \epsilon T_{s_i}^3)^2 + (4\sigma A_i \epsilon T_{air}^3)^2 \}^{1/2} . \end{aligned}$$

Conduction Heat Transfer:

From the back surface,

$$q_{b_i} = \frac{K_{eff} A_b}{L_b} (T_{s_i} - T_{b_i}) .$$

Assume:

$$\omega_{L_b} \ll \omega_{K_{eff}} , \omega_{T_{s_i}} , \omega_{T_{b_i}}$$

$$\omega_{A_b} \ll \omega_{K_{eff}} , \omega_{T_{s_i}} , \omega_{T_{b_i}} .$$

$$\omega_{q_{b_i}} = (\omega_{K_{eff}} \frac{\partial q_{b_i}}{\partial K_{eff}})^2 + (\omega_{T_s} \frac{\partial q_{b_i}}{\partial T_{s_i}})^2 + (\omega_{T_b} \frac{\partial q_{b_i}}{\partial T_{b_i}})^2^{1/2} .$$

$$\omega_{q_b} = \sum_{i=1}^N \omega_{q_{b_i}} = \sum_{i=1}^N \{ [\omega_{K_{eff}} (\frac{A_b}{L_b} (T_{s_i} - T_{b_i}))]^2$$

$$(\omega_{T_s} \frac{K_{eff} A_b}{L_b})^2 + (\omega_{T_b} \frac{K_{eff} A_b}{L_b})^2 \}^{1/2} .$$

Assume:

$$\omega_{K_{eff}} = 0.20 K_{eff} , \omega_{T_s} = 1^\circ F , \omega_{T_b} = 1^\circ F .$$

$$\omega_{q_b} = \sum_{i=1}^N \{ [(.20 K_{eff}) (\frac{A_b}{L_b} (T_{s_i} - T_{b_i}))]^2 + 2 (\frac{K_{eff} A_b}{L_b})^2 \}^{1/2} .$$

From side surfaces,

$$q_{s_i} = \frac{K_{balsa} A_{s_i}}{L_s} (T_{IN_i} - T_{OUT_i}) .$$

$$\omega_{q_{s_i}} = \left\{ \left[\omega_{K_{balsa}} \left(\frac{A_{s_i}}{L_s} \right) (T_{IN_i} - T_{OUT_i}) \right]^2 + \left(\omega_{T_{IN}} \frac{K_{balsa} A_{s_i}}{L_s} \right)^2 + \left(\omega_{T_{OUT}} \frac{K_{balsa} A_{s_i}}{L_s} \right)^2 \right\}^{1/2} .$$

Assume:

$$\omega_{K_{balsa}} = .20 K_{balsa} , \omega_{T_{IN}} = 1^\circ F , \omega_{T_{OUT}} = 1^\circ F .$$

$$\omega_{q_s} = \sum_{i=1}^N \omega_{q_{s_i}} = \left\{ \left[.20 K_{balsa} \frac{A_{s_i}}{L_s} (T_{IN_i} - T_{OUT_i}) \right]^2 + 2 \left(\frac{K_{balsa} A_{s_i}}{L_s} \right)^2 \right\}^{1/2} .$$

From electrical leads,

$$q_L = .112 q_{IN} .$$

Assume:

$$\omega_{q_L} = .05 q_{IN} .$$

For Convection Heat Transfer,

$$q_c = q_{IN} - q_r - q_b - q_s - q_l .$$

$$\omega_{q_c} = [(\omega_{q_{IN}})^2 + (\omega_{q_r})^2 + (\omega_{q_b})^2 + (\omega_{q_s})^2 + (\omega_{q_l})^2]^{1/2} .$$

$$\omega_{q_c} \sim 9\% .$$

For Integrated Average Temperature,

$$T_{AV} = \frac{1}{L^2} \int_0^L \int_0^L [T_s(x,y) - T_{AIR}] dx dy .$$

Assume:

$$\omega_{T_{AV}} = .15 T_{AV} .$$

For Convection Coefficient,

$$h_c = \frac{q_c}{T_{AV}} .$$

$$\omega_{h_c} = [(\omega_{q_c} \cdot \frac{\partial h_c}{\partial q_c})^2 + (\omega_{T_{AV}} \cdot \frac{\partial h_c}{\partial T_{AV}})^2]^{1/2} .$$

$$\omega_{h_c} = [(.09 q_c \frac{1}{T_{AV}})^2 + (.15 T_{AV} \frac{q_c}{T_{AV}^2})^2]^{1/2} .$$

$$\omega_{h_c} \sim 17\% .$$

For Nusselt Number,

$$Nu = \frac{h_c L_c}{K} .$$

Assume

$$\omega_{L_c} , \omega_K \ll \omega_{h_c} .$$

$$\omega_{Nu} = \omega_{h_c} \sim 17\% .$$

Wollaston Prism Interferometer Experiments

$$h_c = \left[\frac{\lambda}{K_{GD} Z_{eff} h} \right] \left(\frac{\Delta S}{S} \right) \left(\frac{h K_w^2}{P} \right) \frac{K_w}{\sin \theta (\Delta T)} .$$

Assume:

$$\omega_{K_w} , \omega_{\lambda} , \omega_{K_{GD}} , \omega_R \ll \omega_{Z_{eff}} , \omega_h , \omega_{\Delta S} , \omega_S ,$$

$$\omega_{T_w} , \omega_P , \omega_{K_w} , \omega_{\theta} , \omega_{\Delta T} .$$

$$\omega_{Z_{eff}} = 2\% .$$

$$h = \beta \left(f - \frac{uw}{f} + w \right) .$$

$$\frac{\partial h}{\partial \beta} = \left(f - \frac{uw}{f} + w \right) \frac{\partial h}{\partial f} = \beta \left(1 + \frac{uw}{f^2} \right) .$$

$$\frac{\partial h}{\partial u} = -\beta w / f , \frac{\partial h}{\partial w} = \beta \left(1 - \frac{u}{f} \right) .$$

$$\omega_{\beta} = 5\% , \omega_f = 1.5 \text{ in} , \omega_w = .25 \text{ in} , \omega_v = .5 \text{ in} .$$

$$u = \frac{1}{(\frac{1}{f} - \frac{1}{v})} = (\frac{vf}{v - f}) .$$

$$\omega_u = \frac{\partial u}{\partial f} = (\frac{v}{v - f}) + (\frac{1}{v - f})^2 vf .$$

$$\frac{\partial u}{\partial v} = \frac{f}{v - f} - \frac{vf}{(v - f)^2} .$$

$$\omega_u = [(\omega_f \cdot \frac{\partial u}{\partial f})^2 + (\omega_v \cdot \frac{\partial u}{\partial v})^2]^{1/2} .$$

$$\omega_u = [(1.5(\frac{92.06}{92.06 - 63} + (\frac{92.06 (63)}{(92.06 - 63)^2}))^2 + (.5(\frac{92.06}{92.06 - 63} - \frac{92.06 (63)}{(92.06 - 63)^2}))^2]^{1/2} .$$

$$\omega_u = 15.2 \text{ in} = 7.6\% .$$

$$\omega_h = [(\omega_{\beta} \frac{\partial h}{\partial \beta})^2 + (\omega_f \frac{\partial h}{\partial f})^2 + (\omega_u \frac{\partial h}{\partial u})^2 + (\omega_w \frac{\partial h}{\partial w})^2]^{1/2} .$$

$$\omega_h = [(\frac{.0026\pi}{180} (63 - \frac{(199.58) 15.5}{63} + 15.5))^2 + (1.5 \frac{(.0527)\pi}{180} (1 + \frac{199.58 (15.5)}{63^2}))^2 + (15.2 \frac{(.0527)\pi}{180} \frac{15.5}{63})^2 + (.5 \frac{.0527\pi}{180} (1 - \frac{199.58}{63}))^2]^{1/2} .$$

$$\omega_h = .0045 \text{ in} = 16.7\% .$$

Assume:

$$\omega_{\Delta S} = 2\% , \omega_S = 2\% , \omega_T = 4^\circ R , \omega_{\Delta T} = 4^\circ R .$$

$$\omega_\theta = 1\% , \omega_P = 2\% , \omega_{z_{eff}} = 2\% .$$

$$\frac{\partial h_c}{\partial z_{eff}} = \left(\frac{-\lambda}{K_{GD} z_{eff}^2 h} \right) \left(\frac{\Delta S}{S} \right) \left(\frac{RT_v^2}{P} \right) \left(\frac{K_w}{\sin \theta \Delta T} \right) = A \left(\frac{\Delta S}{\Delta T} \right) .$$

$$\frac{\partial h_c}{\partial h} = \left(\frac{-\lambda}{K_{GD} z_{eff}^2 h^2} \right) \left(\frac{\Delta S}{S} \right) \left(\frac{RT_w^2}{P} \right) \left(\frac{K_w}{\sin \theta \Delta T} \right) = B \left(\frac{\Delta S}{\Delta T} \right) .$$

$$\frac{\partial h_c}{\partial \Delta S} = \left(\frac{\lambda}{K_{GD} z_{eff}^2 h} \right) \left(\frac{1}{S} \right) \left(\frac{RT_w^2}{P} \right) \left(\frac{K_w}{\sin \theta \Delta T} \right) = C \left(\frac{1}{\Delta T} \right) .$$

$$\frac{\partial h_c}{\partial S} = \left(\frac{\lambda}{K_{GD} z_{eff}^2 h} \right) \left(\frac{-\Delta S}{S^2} \right) \left(\frac{RT_w^2}{P} \right) \left(\frac{K_w}{\sin \theta \Delta T} \right) = D \left(\frac{\Delta S}{\Delta T} \right) .$$

$$\frac{\partial h_c}{\partial T_w} = \left(\frac{\lambda}{K_{GD} z_{eff}^2 h} \right) \left(\frac{\Delta S}{S} \right) \left(\frac{2RT_w}{P} \right) \left(\frac{K_w}{\sin \theta (\Delta T)} \right) = E \left(\frac{\Delta S}{\Delta T} \right) .$$

$$\frac{\partial h_c}{\partial P} = \left(\frac{\lambda}{K_{GD} z_{eff}^2 h} \right) \left(\frac{\Delta S}{S} \right) \left(\frac{-RT_w^2}{P^2} \right) \left(\frac{K_w}{\sin \theta (\Delta T)} \right) = F \frac{\Delta S}{\Delta T} .$$

$$\frac{\partial h_c}{\partial \theta} = \left(\frac{\lambda}{K_{GD} z_{eff}^2 h} \right) \left(\frac{\Delta S}{S} \right) \left(\frac{RT_w^2}{P} \right) \left(\frac{-K_w \cos \theta}{\sin^2 \theta (\Delta T)} \right) = G \frac{\Delta S}{\Delta T} .$$

$$\frac{\partial h_c}{\partial \Delta P} = \left(\frac{\lambda}{K_{GB}^2 \text{eff}^h} \right) \left(\frac{\Delta S}{S} \right) \left(\frac{RT_w^2}{P} \right) \left(\frac{-K_w}{\sin \theta \Delta T^2} \right) = H \left(\frac{\Delta S}{\Delta T^2} \right) .$$

$$\omega_{h_{c_x}} = \left[\left(\omega_{z_{\text{eff}}} \frac{\partial h_c}{\partial z_{\text{eff}}} \right)^2 + \left(\omega_h \frac{\partial h_c}{\partial h} \right)^2 + \left(\omega_{\Delta S} \frac{\partial h_c}{\partial \Delta S} \right)^2 + \left(\omega_{T_w} \frac{\partial h_c}{\partial T_w} \right)^2 + \left(\omega_P \frac{\partial h_c}{\partial P} \right)^2 + \left(\omega_{\theta} \frac{\partial h_c}{\partial \theta} \right)^2 + \left(\omega_{\Delta T} \frac{\partial h_c}{\partial \Delta T} \right)^2 \right]^{1/2} .$$

$$A = 31,652.478$$

$$E = 68.8814$$

$$B = 10,402,731$$

$$F = 9.8623$$

$$C = 21,259.9142$$

$$G = 17,985.11$$

$$D = 5,498,253.664$$

$$H = 21,259.9142$$

$$\omega_{h_{c_x}} = \left[(4.725 \cdot \Delta S)^2 + (35.406 \cdot \Delta S)^2 + (4.7255 \cdot \Delta S)^2 + (4.725 \cdot \Delta S)^2 + (3.062 \cdot \Delta S)^2 + (4.725 \cdot \Delta S)^2 + (1.736 \cdot \Delta S)^2 + (10.503 \cdot \Delta S)^2 \right]^{1/2} .$$

$$\omega_{h_{c_x}} = \left[(1443.3)(\Delta S)^2 + (22.33)\Delta S^4 \right]^{1/2} .$$

Since

$$\Delta S \ll 1 , \omega_{h_{c_x}} \sim (37.99)\Delta S .$$

Values of these uncertainties for various locations are presented in Table 6.

Table 6. Convection Coefficient Uncertainty

Location (in.)	$\omega_{h_{c_x}}$
1.076	.1421 (16%)
2.071	.1516
3.027	.1586
3.837	.1478
4.457	.1554
5.579	.1684
6.824	.1121

$$h_c = \frac{1}{L} \int_0^L h_{c_x} dx .$$

Assume uncertainty from integration is $(.05) h_c$.

$$\omega_{h_c} \sim 21\% .$$

$$q_c = h_c A (\Delta T) .$$

$$\omega_{q_c} = \left[\left(\omega_{h_c} \frac{\partial q_c}{\partial h_c} \right)^2 + \left(\omega_{\Delta T} \frac{\partial q_c}{\partial \Delta T} \right)^2 \right]^{1/2} .$$

$$\omega_{q_c} = \{ [(.21 h_c) A (\Delta T)]^2 + (4 h_c A)^2 \}^{1/2} .$$

$$\omega_{q_c} = 7.7 = 20.5\% .$$

APPENDIX I

SURFACE TEMPERATURE DATA

The following is the data taken from all surface temperature test performed. The data includes:

1. Data storage file name (this name indicates the plate size and power input level, e.g. P820 indicates the 8 inch plate with a 20 watt power input)
2. Voltage drop across the plate (volts)
3. Current through the plate (amps)
4. Power input (Watts)
5. Room temperature ($^{\circ}\text{C}$)
6. Date test performed
7. Time between tests (hours)
8. Time needed for 10 readings of the thermocouples (sec.)
9. All temperatures from the thermocouples indicated in Figures 2,3, and 4 (pp. 15-17)

DATA STORED IN FILENAME:P65

VOLTAGE= .37 volts
 CURRENT= 13.85 amps
 POWER= 5.1245 watts
 ROOM TEMP.= 22.2 (F)
 DATE.....2/24/84

TIME BETWEEN START UP AND TEST= 36 HRS.
 TIME REQUIRED TO TAKE 100 READINGS= 25.29 sec.

AVERAGE PLATE SURFACE TEMP.

38.89	40.51	41.95	41.09	39.12
40.98	44.01	44	43.58	41.7
42.64	44.42	43.94	43.92	42.91
42.12	43.93	43.98	44.06	42.43
38.13	40.83	41.17	40.76	39.7

TEMP. ALONG PLATE SIDE (INSIDE)

31.31	31.7	31.58	34.16
35.42	35.02	31.22	31.2
31.2	34.65	36.38	34.75

TEMP. ALONG PLATE SIDE (OUTSIDE)

24.57	24.63	24.42	24.56
25.16	24.77	24.49	24.45
24.41	24.57	25.11	24.54

TEMP. UNDER PLATE (INSIDE)

36.29	37.51	35.6
39.69	40.97	39.96
35.28	37.71	35.07

TEMP. UNDER PLATE (OUTSIDE)

21.94	21.92
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TEMP. IN TEST BOX

21.05	21.16	21.23	21.54	21.45
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BUSBAR TEMP.

30.3	30.49
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DATA STORED IN FILENAME:P610

VOLTAGE= .528 volts
 CURRENT= 19.7 amps
 POWER= 10.402 watts
 ROOM TEMP.= 21.1 (F)
 DATE.....2/25/84

TIME BETWEEN START UP AND TEST= 19.5 HRS.
 TIME REQUIRED TO TAKE 100 READINGS= 24.94 sec.

AVERAGE PLATE SURFACE TEMP.

54.29	56.69	59.33	57.59	53.65
58.04	62.99	61.41	60.7	57.99
59.56	63.38	61.72	62.21	59.93
58.61	62.94	61.97	61.89	59.84
52.46	57.42	57.83	56.93	54.84

TEMP. ALONG PLATE SIDE (INSIDE)

39.68	40.41	40.22	44.84
47.07	46.05	39.38	39.39
39.35	45.68	49.03	46.18

TEMP. ALONG PLATE SIDE (OUTSIDE)

26.48	26.58	26.2	26.38
27.37	26.59	26.37	26.33
26.3	26.58	27.66	26.26

TEMP. UNDER PLATE (INSIDE)

49.22	51.46	47.83
55.09	57.18	55.23
47.02	51.45	46.5

TEMP. UNDER PLATE (OUTSIDE)

22.12	22.09
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TEMP. IN TEST BOX

20.22	20.28	20.27	20.72	20.26
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BUSBAR TEMP.

37.78	38.03
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DATA STORED IN FILENAME:P615

VOLTAGE= .634 volts
 CURRENT= 23.6 amps
 POWER= 14.962 watts
 ROOM TEMP.= 20.6 (F)
 DATE.....2/26/84

TIME BETWEEN START UP AND TEST= 22.5 HRS.
 TIME REQUIRED TO TAKE 100 READINGS= 25.29 sec.

AVERAGE PLATE SURFACE TEMP.

66.09	69.38	72.56	70.78	65.88
70.6	76.05	75.92	74.47	71.02
72.4	77.65	74.85	76.11	72.03
72.26	76.4	75.35	76.77	73.01
63.55	70.09	70.55	69.9	67.08

TEMP. ALONG PLATE SIDE (INSIDE)

46.71	47.84	47.49	53.14
55.72	54.95	46.2	46.18
46.1	54.39	58.55	54.76

TEMP. ALONG PLATE SIDE (OUTSIDE)

28.25	28.39	27.89	27.96
29.17	28.37	28.07	28.02
28.07	28.33	29.69	28.09

TEMP. UNDER PLATE (INSIDE)

59.09	62.14	57.32
66.52	69.13	66.55
56.1	61.85	55.45

TEMP. UNDER PLATE (OUTSIDE)

22.51	22.46
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TEMP. IN TEST BOX

20.04	20.21	20.3	20.94	20.43
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BUSBAR TEMP.

44.05	44.59
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DATA STORED IN FILENAME:P625

VOLTAGE= .843 volts
 CURRENT= 31.3 amps
 POWER= 26.386 watts
 ROOM TEMP.= 23.3 (F)
 DATE.....2/27/84

TIME BETWEEN START UP AND TEST= 15.5 HRS.
 TIME REQUIRED TO TAKE 100 READINGS= 25.28 sec.

AVERAGE PLATE SURFACE TEMP.

96.5	100.6	105.6	103	96.01
100.2	111.1	108.8	107.8	101.3
104.4	113.7	107.5	109.6	105.1
102.2	113.4	103.6	108.9	105.1
91.64	102.4	101.5	101.6	97.92

TEMP. ALONG PLATE SIDE (INSIDE)

65.26	67.23	66.6	74.1
77.81	76.78	64.63	64.6
64.44	75.59	81.24	76.25

TEMP. ALONG PLATE SIDE (OUTSIDE)

34.82	35.07	34.29	34.03
35.68	34.68	34.82	34.67
34.77	34.69	36.42	34.27

TEMP. UNDER PLATE (INSIDE)

83.69	88.55	81.36
94.4	98.3	95.01
79.5	88.13	78.78

TEMP. UNDER PLATE (OUTSIDE)

25.92	25.86
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TEMP. IN TEST BOX

21.79	22.16	22.35	23.39	22.68
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BUSBAR TEMP.

61.05	61.88
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DATA STORED IN FILENAME:P630

VOLTAGE= .927 volts
 CURRENT= 34.3 amps
 POWER= 31.796 watts
 ROOM TEMP.= 25 (F)
 DATE.....2/27/84

TIME BETWEEN START UP AND TEST= 7 HRS.
 TIME REQUIRED TO TAKE 100 READINGS= 24.91 sec.

AVERAGE PLATE SURFACE TEMP.

111.2	115.4	121.4	118.2	110.3
116.5	128.6	126.2	124.7	117.2
120.6	132.7	128.2	129	122
118.3	132.5	124.8	127.4	120.6
105.5	119	118.6	117.5	112.5

TEMP. ALONG PLATE SIDE (INSIDE)

75.04	77.42	76.6	85.65
90.22	88.73	74.52	74.49
74.26	87.04	93.88	88.13

TEMP. ALONG PLATE SIDE (OUTSIDE)

38.72	39.02	38.07	37.95
39.83	38.56	38.85	38.62
38.74	38.57	40.57	38.41

TEMP. UNDER PLATE (INSIDE)

96.78	102.2	93.97
109.4	115.2	110.7
91.87	102.6	91.17

TEMP. UNDER PLATE (OUTSIDE)

28.76	28.71
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TEMP. IN TEST BOX

23.65	24.19	24.34	25.62	24.64
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BUSBAR TEMP.

70.2	71.2
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DATA STORED IN FILENAME:P85

VOLTAGE= .3648 volts
 CURRENT= 14.45 amps
 POWER= 5.2714 watts
 ROOM TEMP.= 22.5 (F)
 DATE.....5/16/84
 TIME BETWEEN START UP AND TEST= 48 HRS.
 TIME REQUIRED TO TAKE 100 READINGS= 89.61 sec.

AVERAGE PLATE SURFACE TEMP.

36.42	37.04	37.36	37.1	37.39	36.93	36.95
38.28	39.32	39.49	39.2	39.38	39.19	38.6
39.29	40.84	40.75	40.41	40.52	40.19	40.99
39.8	39.45	41.08	40.83	40.83	40.85	39.9
39.59	40.63	41.02	40.68	40.82	40.82	39.93
38.54	39.41	39.7	39.21	39.43	39.53	38.92
36.65	37.14	37.4	37.22	37.39	37.24	37.25

TEMP. ALONG PLATE SIDE (INSIDE)

31.31	31.27	31.1	34.6
35.46	33.64	31.77	31.63
31.69	34.54	35.32	34.3

TEMP. ALONG PLATE SIDE (OUTSIDE)

26.34	26.61	26.6	26.23
26.31	25.4	25.4	25.8
25.6	25.2	25.4	25.2

TEMP. UNDER PLATE (INSIDE)

37.77	38.38	37.84
39.41	39.33	39.03
38.86	38.74	37.77

TEMP. UNDER PLATE (OUTSIDE)

23.2	23.2
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TEMP. IN TEST BOX

23	23	23.4
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BUSBAR TEMP.
 29.6 30.6

NOTES:

DATA STORED IN FILENAME:P810

VOLTAGE= .51 volts
 CURRENT= 20.2 amps
 POWER= 10.302 watts
 ROOM TEMP.= 21.3 (F)
 DATE.....5/17/84
 TIME BETWEEN START UP AND TEST= 16 HRS.
 TIME REQUIRED TO TAKE 100 READINGS= 89.44 sec.

AVERAGE PLATE SURFACE TEMP.

46.25	45.94	47.28	46.84	47.63	46.92	46.88
48.85	50.3	50.26	50.19	50.67	50.21	49.03
50.48	53.38	51.95	51.61	52.1	52.2	52.61
51.07	50.5	52.78	52.56	52.73	52.99	51.01
50.57	52.59	51.78	51.41	52.44	52.26	51.18
49	49.65	49.79	49.68	50.93	50.48	50.22
45.97	46.9	46.86	46.97	47.49	47.06	47.22

TEMP. ALONG PLATE SIDE (INSIDE)

36.76	36.73	36.43	42.13
43.56	40.85	37.62	37.44
37.02	41.93	43.25	41.71

TEMP. ALONG PLATE SIDE (OUTSIDE)

27.19	27.74	27.65	26.68
26.92	26.2	26.6	27.2
27	26.4	26.6	26.4

TEMP. UNDER PLATE (INSIDE)

47.7	48.54	47.81
50.11	49.92	49.75
49.2	48.88	47.52

TEMP. UNDER PLATE (OUTSIDE)

23.2	23
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TEMP. IN TEST BOX

22.4	22.6	23.2
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BUSBAR TEMP.
 34.2 36

NOTES:

DATA STORED IN FILENAME:P815

VOLTAGE= .619 volts
 CURRENT= 24.55 amps
 POWER= 15.196 watts
 ROOM TEMP.= 21.8 (F)
 DATE.....5/17/84
 TIME BETWEEN START UP AND TEST= 7 HRS.
 TIME REQUIRED TO TAKE 100 READINGS= 89.48 sec.

AVERAGE PLATE SURFACE TEMP.

55.8	55.35	57.03	56.55	57.53	56.4	56.28
59.62	60.97	61.33	60.69	60.97	60.79	59.68
61.59	64.88	63.99	63.45	63.61	63.05	63.66
61.97	61.57	63.63	64.67	64.36	64.34	62.33
61.7	63.78	63.96	63.65	63.85	64	62.59
59.72	60.57	60.99	60.95	62.35	61.44	61.3
55.96	56.95	57.16	57.43	58.01	57.29	57.72

TEMP. ALONG PLATE SIDE (INSIDE)

42.95	42.89	42.43	50.41
52.4	48.36	44.36	43.98
43.24	49.8	51.31	49.33

TEMP. ALONG PLATE SIDE (OUTSIDE)

29.19	30.04	29.88	28.59
28.85	28	28.6	29.4
29.2	28.2	28.4	28.2

TEMP. UNDER PLATE (INSIDE)

57.54	58.74	57.61
60.79	60.77	60.31
59.7	59.48	57.42

TEMP. UNDER PLATE (OUTSIDE)

24	23.8
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TEMP. IN TEST BOX

23	23	23.8
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BUSBAR TEMP.
 39.4 42.2

NOTES:

DATA STORED IN FILENAME:P820

VOLTAGE= .723 volts
 CURRENT= 28.3 amps
 POWER= 20.461 watts
 ROOM TEMP.= 19.8 (F)
 DATE.....5/17/84

TIME BETWEEN START UP AND TEST= 18 HRS.
 TIME REQUIRED TO TAKE 100 READINGS= 89.98 sec.

AVERAGE PLATE SURFACE TEMP.

63.78	62.76	64.65	64.37	66.03	63.44	64.88
68.39	69.69	70.01	68.39	68.93	68.27	68.59
71.11	74.58	73.78	72.17	71.82	73.62	72.15
71.35	71.03	72.57	75.42	74.08	74.07	71.88
71.18	73.27	74.42	73.57	74.71	75.55	72.74
68.58	69.62	69.72	70.02	72.35	69.86	71.22
65.04	65	65.24	66.06	66.65	66	67.06

TEMP. ALONG PLATE SIDE (INSIDE)

47.15	47.12	46.51	56.52
58.61	54.5	49.53	49.08
48.02	56.16	57.84	55.25

TEMP. ALONG PLATE SIDE (OUTSIDE)

29.26	30.41	30.08	28.46
28.8	27.8	28.8	30
29.6	28.2	28.4	28

TEMP. UNDER PLATE (BAKELITE)

65.5	66.56	65.46
69.3	69.8	69.1
68.07	68.31	66.06

TEMP. UNDER PLATE (BALSA)

58.6	59.6
62	62

TEMP. UNDER PLATE (OUTSIDE)

22.6	22.6
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TEMP. IN TEST BOX

21.2	21.6	22.8
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BUSBAR TEMP.

42.6	46.6
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DATA STORED IN FILENAME:P825

VOLTAGE= .791 volts
 CURRENT= 30.9 amps
 POWER= 24.442 watts
 ROOM TEMP.= 23.6 (F)
 DATE.....5/19/84

TIME BETWEEN START UP AND TEST= 24 HRS.
 TIME REQUIRED TO TAKE 100 READINGS= 89.44 sec.

AVERAGE PLATE SURFACE TEMP.

72.24	71.03	74.44	73.28	75.59	72.12	73.53
77.19	79.08	80.56	78.61	79.4	77.67	77.42
80.68	83.65	84.32	83.34	83.21	83.06	84.47
82.02	79.44	85.11	85.97	85.68	84.09	80.87
80.69	82.8	84.53	83.88	85.11	82.17	80.94
79.58	79.76	80.06	80.2	83.02	78.03	79.87
74.09	74.27	74.47	75.23	76.31	74.84	75.87

TEMP. ALONG PLATE SIDE (INSIDE)

53.74	53.73	53.02	64.09
67.01	61.8	56.85	56.39
55.06	64.53	65.99	62.73

TEMP. ALONG PLATE SIDE (OUTSIDE)

32.55	34.08	33.35	31.75
32.17	31.4	32.8	34
33.4	31.8	32	31.4

TEMP. UNDER PLATE (BAKELITE)

74.66	76.53	74.52
79.57	80	78.59
78.22	78.36	74.84

TEMP. UNDER PLATE (BALSA)

67.2	68.4
70.6	71.6

TEMP. UNDER PLATE (OUTSIDE)

25.8	25.6
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TEMP. IN TEST BOX

23.6	24.2	25.4
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BUSBAR TEMP.

49.2	53.6
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DATA STORED IN FILENAME:P830

VOLTAGE= .882 volts
 CURRENT= 34.35 amps
 POWER= 30.297 watts
 ROOM TEMP.= 23.5 (F)
 DATE.....5/21/84

TIME BETWEEN START UP AND TEST= 48 HRS.
 TIME REQUIRED TO TAKE 100 READINGS= 89.45 sec.

AVERAGE PLATE SURFACE TEMP.

79.58	79.73	83.83	82.96	84.88	82.22	82.89
87.92	89.41	91.61	88.94	88.9	88.6	87.31
91.61	93.96	95.57	94.57	94.65	93.63	93.87
92.12	89.54	95.29	97.21	97.11	95.31	91.5
91.89	94.87	95.73	94.38	95.45	91.62	91.2
88.67	90.58	90.67	90.45	93.66	87.71	91.21
84.25	84.37	84.16	85.08	86.43	84.26	85.66

TEMP. ALONG PLATE SIDE (INSIDE)

59.99	60.05	59.2	71.6
75.23	69.3	64.03	63.4
61.63	71.98	73.93	70.47

TEMP. ALONG PLATE SIDE (OUTSIDE)

34.44	36.52	35.12	33.5
34.14	33.2	35.2	36.6
35.8	33.8	34.2	33.6

TEMP. UNDER PLATE (BAKELITE)

84.25	86.36	84.08
89.73	90.42	88.62
88.35	88.3	84.04

TEMP. UNDER PLATE (BALSA)

75.8	77
79.6	81

TEMP. UNDER PLATE (OUTSIDE)

27	27
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TEMP. IN TEST BOX

24.6	24.6	26.6
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BUSBAR TEMP.

54.4	60.4
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DATA STORED IN FILENAME:P835

VOLTAGE= .9536 volts
 CURRENT= 36.95 amps
 POWER= 35.236 watts
 ROOM TEMP.= 22.8 (F)
 DATE.....5/21/84

TIME BETWEEN START UP AND TEST= 9 HRS.
 TIME REQUIRED TO TAKE 100 READINGS= 89.47 sec.

AVERAGE PLATE SURFACE TEMP.

88.72	88.5	91.36	90.92	93.17	88.69	91.56
96.72	97.71	100.9	98.94	98.34	97.05	96.58
101.1	104.5	105.8	104.8	105	104.1	102.7
100.9	100.1	104.6	107.1	105.8	104.8	101.1
100.5	102.8	105.6	103.9	104.3	104	102
97.16	99.33	100.2	99.95	102	97.9	99.97
92.44	93.05	92.74	93.68	94.8	93.07	93.67

TEMP. ALONG PLATE SIDE (INSIDE)

65.14	65.18	64.16	78.58
81.78	75.78	69.65	68.91
67.14	78.54	80.72	77.11

TEMP. ALONG PLATE SIDE (OUTSIDE)

35.88	38.25	36.57	34.81
35.32	34.2	36.6	38.2
37.2	35	35.4	34.6

TEMP. UNDER PLATE (BAKELITE)

92.62	95.77	92.93
98.55	99.56	97.93
97.42	97.22	92.89

TEMP. UNDER PLATE (BALSA)

83.2	84.6
88	89

TEMP. UNDER PLATE (OUTSIDE)

27.2	27
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TEMP. IN TEST BOX

24.4	24.8	27
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BUSBAR TEMP.
 59 65.6

DATA STORED IN FILENAME:P840

VOLTAGE= 1.027 volts
 CURRENT= 39.5 amps
 POWER= 40.566 watts
 ROOM TEMP.= 21 (F)
 DATE.....5/23/84
 TIME BETWEEN START UP AND TEST= 54 HRS.
 TIME REQUIRED TO TAKE 100 READINGS= 89.45 sec.

AVERAGE PLATE SURFACE TEMP.

94.8	94.4	98.15	97.28	99.15	95.11	98.17
104.6	104.7	108.8	104.3	103.1	103.7	103.5
108.8	110.9	113.7	111.5	111.3	111	109.2
108.4	106.9	111.7	115.6	112.6	112.7	108.1
108.6	110.5	114.2	110.7	111.8	111.7	108.2
104.4	106.6	108.2	106	110.1	102.7	106.3
99.31	100.6	99.75	100.1	102.3	98.78	101.4

TEMP. ALONG PLATE SIDE (INSIDE)

69.47	69.42	68.26	83.18
86.32	80.03	74.64	73.59
71.67	83.74	85.78	82.08

TEMP. ALONG PLATE SIDE (OUTSIDE)

35.74	38.61	36.53	34.46
35	34	36.8	38.8
37.4	35	35.2	34.6

TEMP. UNDER PLATE (INSIDE)

98.95	101.4	98.55
105.2	106.3	104.4
103.8	103.7	98.9

TEMP. UNDER PLATE (OUTSIDE)

26.2	26
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TEMP. IN TEST BOX

23	23.4	26
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BUSBAR TEMP.
 62.6 70.2

NOTES:

DATA STORED IN FILENAME:P845

VOLTAGE= 1.084 volts
 CURRENT= 41.25 amps
 POWER= 44.715 watts
 ROOM TEMP.= 19.8 (F)
 DATE.....5/28/84
 TIME BETWEEN START UP AND TEST= 96 HRS.
 TIME REQUIRED TO TAKE 100 READINGS= 89.46 sec.

AVERAGE PLATE SURFACE TEMP.

101.4	99.8	102.5	101.2	103.8	99.57	102.2
110.9	110.2	113.3	110.2	110.1	109.8	108.7
116	116.1	118.2	117.1	117.3	116.5	116.2
115.7	112	119.1	120.5	117.3	115.2	112.1
114.4	115	119.2	115.1	117.9	117.6	113.9
109.3	112.1	114.2	110.3	114.4	108.1	110.1
103.4	105.7	104.9	104.4	107.1	103	105.7

TEMP. ALONG PLATE SIDE (INSIDE)

73	72.82	71.66	86.55
89.34	82.8	77.78	76.5
74.57	86.38	88.83	85.45

TEMP. ALONG PLATE SIDE (OUTSIDE)

35.28	38.76	36.07	34.01
34.29	33.2	36.4	38.8
36.8	34.2	34.6	34

TEMP. UNDER PLATE (INSIDE)

104	106.5	103.4
110.2	110.6	108.7
108.7	108.3	103.2

TEMP. UNDER PLATE (OUTSIDE)

25	24.8
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TEMP. IN TEST BOX

21.4	21.8	24.2
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BUSBAR TEMP.
 65 72.8

NOTES:

DATA STORED IN FILENAME:P850

VOLTAGE= 1.1611 volts
 CURRENT= 43.95 amps
 POWER= 51.03 watts
 ROOM TEMP.= 18.5 (F)
 DATE.....5/30/84

TIME BETWEEN START UP AND TEST= 48 HRS.
 TIME REQUIRED TO TAKE 100 READINGS= 89.46 sec.

AVERAGE PLATE SURFACE TEMP.

108.2	107.6	111.4	109.2	116.3	110.2	110.9
119.9	118.9	124.4	119.1	122.2	119.3	117
125.5	124.7	131.3	127.5	128.2	126	123.6
124.3	120.2	129.1	132.1	127.8	126.6	120.3
123.9	124.9	129	125.8	125.8	125.6	120.9
118	121.2	122.9	119.5	122.9	116.6	117.4
111.8	114.1	112.9	112.4	115.7	110.5	113.5

TEMP. ALONG PLATE SIDE (INSIDE)

78.85	78.86	77.6	92.32
95.21	87.96	83.42	82.01
79.77	92.54	95.08	91.85

TEMP. ALONG PLATE SIDE (OUTSIDE)

35.48	39.86	20.99	34
34.41	33.2	37	39.6
37.2	34.4	34.8	34.2

TEMP. UNDER PLATE (BAKELITE)

112.3	115.5	112.2
118.6	119.7	117.3
117.7	116.8	110.6

TEMP. UNDER PLATE (BALSA)

999	103.4
106	108.6

TEMP. UNDER PLATE (OUTSIDE)

23.8	23.8
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TEMP. IN TEST BOX

20.2	20.8	23.4
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BUSBAR TEMP.

70.2	77.6
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DATA STORED IN FILENAME:P855

VOLTAGE= 1.201 volts
 CURRENT= 45.65 amps
 POWER= 54.826 watts
 ROOM TEMP.= 19 (F)
 DATE.....5/31/84

TIME BETWEEN START UP AND TEST= 29 HRS.
 TIME REQUIRED TO TAKE 100 READINGS= 89.48 sec.

AVERAGE PLATE SURFACE TEMP.

114.2	113.8	117.8	115.1	119.3	112.8	116.7
128.8	128.9	131.9	125.1	125.9	122.8	122.9
133.6	133.3	137.9	134.8	135.2	134.1	128.3
131.2	126.5	136.4	138.5	133.9	134.1	126.9
131.2	131	136.2	132.1	132.9	133.7	128.2
124.1	126.9	128.4	125.1	128	121.8	123.7
119.2	117.9	118.6	118.4	121.3	116	119.8

TEMP. ALONG PLATE SIDE (INSIDE)

83.88	83.38	81.84	97.04
99.87	92.78	87.89	86.51
83.87	97.25	99.8	97

TEMP. ALONG PLATE SIDE (OUTSIDE)

39.48	41.53	41.16	35.41
35.53	35	39	41.8
41.4	36.2	36.6	36.6

TEMP. UNDER PLATE (BAKELITE)

118.8	121.3	117.3
124.2	125.4	123.4
123.7	122.1	116.1

TEMP. UNDER PLATE (BALSA)

999	109.4
111.8	114.4

TEMP. UNDER PLATE (OUTSIDE)

24.8	24.6
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TEMP. IN TEST BOX

21	21.6	24.4
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BUSBAR TEMP.

74	82.2
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DATA STORED IN FILENAME:P125

VOLTAGE= .351 volts
 CURRENT= 14.6 amps
 POWER= 5.1246 watts
 ROOM TEMP.= 24.1 (F)
 DATE.....3/28/84

TIME BETWEEN START UP AND TEST= 13.5 HRS.
 TIME REQ'D TO TAKE 1 GROUP OF SURFACE READINGS= 33.81 sec.

AVERAGE PLATE SURFACE TEMP.

31.04	31.46	31.82	31.6	31.34	30.9
32.54	33.46	33.77	33.75	33.3	32.14
33.07	34.12	34.26	34.18	33.88	32.72
			33.91		
33.09	34.01	33.96	34.23	34.28	32.73
32.35	33.38	33.66	33.51	33.56	32.36
31.03	31.78	32.05	31.92	31.85	31.32

TEMP. ALONG PLATE SIDE (INSIDE)

28.98	28.89	28.84	29.9
30.35	30.1	28.8	28.83
28.99	30.43	30.69	30.2

TEMP. ALONG PLATE SIDE (OUTSIDE)

24.9	24.89	24.86	25.12
25.29	25.21	25.02	24.99
24.92	25.03	25.19	25.08

TEMP. UNDER PLATE (INSIDE)

30.74	30.44	33.5
33.43	33.57	33.5
30.98	31.15	33.42

TEMP. UNDER PLATE (OUTSIDE)

24.47	24.37
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TEMP. IN TEST BOX

23.48	23.58	23.62
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BUSBAR TEMP.

28.8	28.8
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DATA STORED IN FILENAME:P1210

VOLTAGE= .499 volts
 CURRENT= 20.75 amps
 POWER= 10.354 watts
 ROOM TEMP.= 23.3 (F)
 DATE.....3/18/84

TIME BETWEEN START UP AND TEST= 21 HRS.
 TIME REQ'D TO TAKE 1 GROUP OF SURFACE READINGS= 33.84 sec.

AVERAGE PLATE SURFACE TEMP.

36.35	36.82	37.12	36.64	36.33	35.83
38.37	39.6	39.8	39.83	39.04	37.64
39.25	40.91	40.82	40.64	40.4	38.75
		40.89			
39.55	41.18	40.62	41.19	41.04	38.9
38.5	40.28	40.61	40.12	39.87	38.18
36.96	37.93	37.88	37.66	37.48	36.74

TEMP. ALONG PLATE SIDE (INSIDE)

32.81	32.58	32.45	34.17
34.62	34.25	32.74	32.59
33.08	34.95	35.49	34.6

TEMP. ALONG PLATE SIDE (OUTSIDE)

25.42	25.39	25.17	25.61
25.91	25.71	25.63	25.61
25.49	25.54	25.71	25.54

TEMP. UNDER PLATE (INSIDE)

35.77	35.16	40.29
39.87	40.44	39.89
36.65	36.47	39.95

TEMP. UNDER PLATE (OUTSIDE)

23.8	23.09
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TEMP. IN TEST BOX

22.72	23.08	23.32
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BUSBAR TEMP.

32.8	32.8
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DATA STORED IN FILENAME:P1215

VOLTAGE= .6 volts
 CURRENT= 25 amps
 POWER= 15 watts
 ROOM TEMP.= 24.4 (F)
 DATE.....3/19/84

TIME BETWEEN START UP AND TEST= 19 HRS.
 TIME REQ'D TO TAKE 1 GROUP OF SURFACE READINGS= 33.81 sec.

AVERAGE PLATE SURFACE TEMP.

42.62	43.11	43.34	42.84	42.37	42.05
44.94	46.66	47.21	47.05	45.99	44.32
45.96	48.15	48.39	47.88	47.74	45.23
		48.05			
46.38	48.25	47.6	48.46	48.72	45.1
44.88	47.27	47.37	46.58	46.39	44.52
42.79	44.03	44.1	43.67	43.62	42.68

TEMP. ALONG PLATE SIDE (INSIDE)

37.16	37.01	36.8	38.97
39.49	39.12	37.12	36.92
37.56	39.79	40.54	39.55

TEMP. ALONG PLATE SIDE (OUTSIDE)

27.07	27	26.73	27.24
27.63	27.41	27.3	27.31
27.16	27.11	27.33	27.15

TEMP. UNDER PLATE (INSIDE)

41.31	40.49	46.97
46.54	47.31	46.7
42.59	42.46	46.79

TEMP. UNDER PLATE (OUTSIDE)

24.97	23.79
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TEMP. IN TEST BOX

23.41	24.19	24.44
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BUSBAR TEMP.

37.2	37.2
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DATA STORED IN FILENAME:P1220

VOLTAGE= .684 volts
 CURRENT= 28.45 amps
 POWER= 19.46 watts
 ROOM TEMP.= 24.4 (F)
 DATE.....3/19/84

TIME BETWEEN START UP AND TEST= 11.5 HRS.
 TIME REQ'D TO TAKE 1 GROUP OF SURFACE READINGS= 33.8 sec.

AVERAGE PLATE SURFACE TEMP.

47.91	48.35	48.71	47.87	47.24	46.86
50.28	52.16	52.48	52.45	51.42	49.37
51.74	53.84	54.01	53.97	53.39	50.88
54.6					
52.52	54.52	53.98	54.45	55.23	51.07
51.12	53.78	53.7	52.25	52.19	50.01
48.21	49.93	49.87	49.49	49.43	47.98

TEMP. ALONG PLATE SIDE (INSIDE)

41.19	40.13	39.84	42.54
43.12	42.71	40.25	40.02
40.78	43.59	44.68	43.38

TEMP. ALONG PLATE SIDE (OUTSIDE)

28.34	28.2	27.9	28.5
28.95	28.7	28.7	28.69
28.52	28.33	28.64	28.4

TEMP. UNDER PLATE (INSIDE)

45.4	44.35	52.09
51.64	52.52	51.76
46.86	46.57	52.94

TEMP. UNDER PLATE (OUTSIDE)

25.89	24.3
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TEMP. IN TEST BOX

23.85	24.66	24.99
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BUSBAR TEMP.

40.8	40.8
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DATA STORED IN FILENAME:P1225

VOLTAGE= .784 volts
 CURRENT= 32.65 amps
 POWER= 25.598 watts
 ROOM TEMP.= 23.9 (F)
 DATE.....3/20/84

TIME BETWEEN START UP AND TEST= 11 HRS.
 TIME REQ'D TO TAKE 1 GROUP OF SURFACE READINGS= 33.8 sec.

AVERAGE PLATE SURFACE TEMP.

53.77	54.52	55.13	54.09	53.04	53.03
57.46	58.82	59.96	59.25	57.89	55.44
58.76	61.61	61.67	60.72	60.65	57.07
		62.08			
58.92	60.48	61.29	62.57	63.21	57.18
57.69	60.41	60.69	59.49	59.81	56.58
54.74	56.36	56.49	55.49	55.4	53.47

TEMP. ALONG PLATE SIDE (INSIDE)

45.34	44.88	44.64	47.69
48.44	48.05	45.23	44.94
45.82	49.41	50.46	48.9

TEMP. ALONG PLATE SIDE (OUTSIDE)

29.24	29.06	28.76	29.4
29.95	29.69	29.62	29.62
29.35	29.2	29.52	29.21

TEMP. UNDER PLATE (INSIDE)

51.32	49.97	59.55
58.99	59.71	59.36
53.18	52.85	59.77

TEMP. UNDER PLATE (OUTSIDE)

26.14	24
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TEMP. IN TEST BOX

23.56	24.61	24.98
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BUSBAR TEMP.

44.4	44.4
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DATA STORED IN FILENAME:P1230

VOLTAGE= .853 volts
 CURRENT= 35 amps
 POWER= 29.855 watts
 ROOM TEMP.= 24.2 (F)
 DATE.....3/20/84

TIME BETWEEN START UP AND TEST= 12.5 HRS.
 TIME REQ'D TO TAKE 1 GROUP OF SURFACE READINGS= 33.79 sec.

AVERAGE PLATE SURFACE TEMP.

58.98	59.5	59.99	59.34	57.71	57.75
62.93	65.14	65.2	65.02	62.92	60.52
64.74	67.65	68.19	66.72	66.98	62.18
		68.36			
64.82	67.6	67.67	69.56	69.57	62.54
62.97	66	67.26	66.02	66.15	62.14
59.88	61.65	61.61	60.68	60.7	58.85

TEMP. ALONG PLATE SIDE (INSIDE)

49.25	48.79	48.5	51.79
52.62	52.32	49.23	48.88
49.92	53.83	55.11	53.23

TEMP. ALONG PLATE SIDE (OUTSIDE)

30.35	30.18	29.79	30.44
31.09	30.85	30.77	30.85
30.5	30.16	30.57	30.29

TEMP. UNDER PLATE (INSIDE)

56.16	54.49	65.67
64.97	65.88	65.62
58.2	57.91	65.78

TEMP. UNDER PLATE (OUTSIDE)

26.94	24.32
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TEMP. IN TEST BDX

23.79	25.18	25.72
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BUSBAR TEMP.

47.7	47.7
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DATA STORED IN FILENAME:P1235

VOLTAGE= .938 volts
 CURRENT= 39 amps
 POWER= 36.582 watts
 ROOM TEMP.= 22.2 (F)
 DATE.....3/21/84

TIME BETWEEN START UP AND TEST= 11.5 HRS.
 TIME REQ'D TO TAKE 1 GROUP OF SURFACE READINGS= 33.84 sec.

AVERAGE PLATE SURFACE TEMP.

62.69	62.97	63.97	62.99	61.38	61.08
66.48	68.6	68.96	69.18	67.39	64.46
69.08	72.02	71.82	71.73	71.2	66.55

73.38

69.53	72.68	72.11	74.07	74.07	66.75
67.66	70.18	70.64	69.32	69.8	66
64.29	65.74	65.98	65.12	64.95	62.61

TEMP. ALONG PLATE SIDE (INSIDE)

51.78	50.74	50.42	53.92
54.96	54.51	51.12	50.77
52.05	56.32	58.09	55.91

TEMP. ALONG PLATE SIDE (OUTSIDE)

29.58	29.39	28.96	29.64
30.42	30.04	29.96	30.03
29.7	29.37	29.83	29.42

TEMP. UNDER PLATE (INSIDE)

59.1	57.43	70.09
69.03	70.48	69.65
61.61	61.23	70.42

TEMP. UNDER PLATE (OUTSIDE)

25.38	22.51
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TEMP. IN TEST BOX

21.97	23.6	24.21
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BUSBAR TEMP.

50.4	50.4
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DATA STORED IN FILENAME:P1240

VOLTAGE= .981 volts
 CURRENT= 40.5 amps
 POWER= 39.731 watts
 ROOM TEMP.= 25 (F)
 DATE.....3/21/84

TIME BETWEEN START UP AND TEST= 9 HRS.
 TIME REQ'D TO TAKE 1 GROUP OF SURFACE READINGS= 33.78 sec.

AVERAGE PLATE SURFACE TEMP.

67.6	67.93	69.45	68.2	66.48	66.06
72.2	73.9	74.6	73.91	72.83	69.5
75.1	77.76	77.87	76.74	76.98	71.6
		78.44			
74.97	77.24	76.92	79.54	80.02	71.73
72.59	75.82	75.8	74.11	74.7	71.37
69.26	70.85	71.01	70.3	70.01	67.04

TEMP. ALONG PLATE SIDE (INSIDE)

55.48	54.57	54.25	58.03
58.62	58.31	55.05	54.67
55.87	60.83	62.75	60.11

TEMP. ALONG PLATE SIDE (OUTSIDE)

32.31	32.07	31.62	32.32
32.99	32.72	32.66	32.74
32.36	31.97	32.53	32.04

TEMP. UNDER PLATE (INSIDE)

63.34	61.63	74.98
73.82	75.1	73.96
65.8	65.44	75.38

TEMP. UNDER PLATE (OUTSIDE)

27.14	26.69
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TEMP. IN TEST BOX

23.84	25.87	26.38
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BUSBAR TEMP.

54	54
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DATA STORED IN FILENAME:P1245

VOLTAGE= 1.067 volts
 CURRENT= 44 amps
 POWER= 46.948 watts
 ROOM TEMP.= 26.1 (F)
 DATE.....3/22/84

TIME BETWEEN START UP AND TEST= 12 HRS.
 TIME REQ'D TO TAKE 1 GROUP OF SURFACE READINGS= 33.78 sec.

AVERAGE PLATE SURFACE TEMP.

75.23	75.26	76.76	75.85	74.13	73.26
80.08	81.01	80.92	81.56	80.82	77.31
83.11	86.32	85.49	85.51	84.17	79.07
87.55					
82.99	86.23	85.02	87.89	88.34	79.53
80.44	83.8	83.41	82.39	83.23	79.24
76.86	77.83	78.27	77.6	77.5	74.5

TEMP. ALONG PLATE SIDE (INSIDE)

61.64	60.37	60.12	63.37
64.76	64.33	60.83	60.42
61.82	67.2	69.5	66.35

TEMP. ALONG PLATE SIDE (OUTSIDE)

34.09	33.87	33.45	34.13
34.93	34.59	34.5	34.62
34.22	33.73	34.4	33.85

TEMP. UNDER PLATE (INSIDE)

70.14	68.45	83.2
81.54	83.42	81.9
72.8	72.54	83.13

TEMP. UNDER PLATE (OUTSIDE)

28.31	27.72
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TEMP. IN TEST BOX

24.53	27.1	27.43
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BUSBAR TEMP.

59.4	59.4
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DATA STORED IN FILENAME:P1250

VOLTAGE= 1.121 volts
 CURRENT= 46.05 amps
 POWER= 51.622 watts
 ROOM TEMP.= 23.2 (F)
 DATE.....3/23/84

TIME BETWEEN START UP AND TEST= 12 HRS.
 TIME REQ'D TO TAKE 1 GROUP OF SURFACE READINGS= 33.81 sec.

AVERAGE PLATE SURFACE TEMP.

76.73	77.02	78.2	77.24	74.87	74.16
81.29	83.88	82.54	83.27	82.58	78.35
84.39	88.89	88.13	87.76	86.55	80.61
		89.78			
85.48	88.55	87.3	90.11	90.87	80.47
81.89	85.68	84.52	84.8	85.86	80.32
78.62	79.94	80	79.22	79.29	76.41

TEMP. ALONG PLATE SIDE (INSIDE)

62.6	61.07	60.89	64.32
65.62	65.24	61.83	61.42
62.97	68.48	71.02	67.62

TEMP. ALONG PLATE SIDE (OUTSIDE)

32.74	32.52	32.07	32.65
33.53	33.2	33.26	33.45
33	32.42	33.19	32.56

TEMP. UNDER PLATE (INSIDE)

71.69	69.92	85.59
84	85.99	84.56
74.58	74.22	85.74

TEMP. UNDER PLATE (OUTSIDE)

26.99	26.33
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TEMP. IN TEST BOX

22.68	25.2	25.8
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BUSBAR TEMP.

60.6	60.6
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DATA STORED IN FILENAME:P1255

VOLTAGE= 1.18 volts
 CURRENT= 48 amps
 POWER= 56.64 watts
 ROOM TEMP.= 25.1 (F)
 DATE.....3/24/84

TIME BETWEEN START UP AND TEST= 20 HRS.
 TIME REQ'D TO TAKE 1 GROUP OF SURFACE READINGS= 33.82 sec.

AVERAGE PLATE SURFACE TEMP.

83.56	82.84	84.88	84.12	81.55	80.53
88.3	90.11	90.18	91.14	89.53	85.12
91.98	95.74	95.51	94.96	94.11	87.18
		97.33			
91.61	95.3	94.87	97.89	99	87.77
88.34	92.59	91.32	91.09	93.07	87.52
84.89	86.32	87.34	86.51	86.06	83.41

TEMP. ALONG PLATE SIDE (INSIDE)

68.31	67.09	67.01	70.58
71.92	71.31	67.82	67.38
68.98	75.02	77.59	73.51

TEMP. ALONG PLATE SIDE (OUTSIDE)

35.49	35.27	34.94	35.36
36.39	36.04	36.06	36.34
35.85	35.06	35.97	35.27

TEMP. UNDER PLATE (INSIDE)

78.33	76.49	92.86
91.54	93.17	91.86
81.22	81.17	92.26

TEMP. UNDER PLATE (OUTSIDE)

28.98	28.33
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TEMP. IN TEST BOX

24.64	27.49	28.1
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BUSBAR TEMP.
 66 66

DATA STORED IN FILENAME:P1260

VOLTAGE= 1.245 volts
 CURRENT= 51 amps
 POWER= 63.495 watts
 ROOM TEMP.= 25.6 (F)
 DATE.....3/25/84

TIME BETWEEN START UP AND TEST= 14 HRS.
 TIME REQ'D TO TAKE 1 GROUP OF SURFACE READINGS= 33.81 sec.

AVERAGE PLATE SURFACE TEMP.

89.23	89.95	90.73	90.26	87.37	86.34
94.52	96.64	96.21	97.2	96.06	91.01
98.61	102.8	101.8	102.5	101	93.6
			103.5		
98.25	102.7	101.7	105	105.3	94.26
94.86	99.05	99.54	98.37	99.12	93.35
91.45	92.74	93.75	92.8	91.82	88.94

TEMP. ALONG PLATE SIDE (INSIDE)

72.52	71.47	71.56	75.06
76.55	75.92	72.59	72.19
73.92	80.05	82.9	78.58

TEMP. ALONG PLATE SIDE (OUTSIDE)

36.95	36.75	36.48	36.67
37.85	37.47	37.54	37.9
37.35	36.42	37.4	36.61

TEMP. UNDER PLATE (INSIDE)

83.74	81.67	99.17
98.19	99.58	98.41
86.93	86.72	98.63

TEMP. UNDER PLATE (OUTSIDE)

29.82	29.08
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TEMP. IN TEST BOX

25	28.2	28.66
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BUSBAR TEMP.

70.6	70.6
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DATA STORED IN FILENAME:P1270

VOLTAGE= 1.329 volts
 CURRENT= 54.25 amps
 POWER= 72.098 watts
 ROOM TEMP.= 25.3 (F)
 DATE.....3/25/84

TIME BETWEEN START UP AND TEST= 5.5 HRS.
 TIME REQ'D TO TAKE 1 GROUP OF SURFACE READINGS= 33.79 sec.

AVERAGE PLATE SURFACE TEMP.

97.99	97.2	98.97	98.64	95.41	95.04
103.4	105.6	104.1	105.2	104.6	99.8
107.5	111.1	110.6	110.8	109.1	101.7
		114			
106.2	112	110.1	114.2	114.3	102.2
102.8	108.9	107.6	105.8	107.7	101.2
98.52	100.9	101.4	100.9	99.91	96.14

TEMP. ALONG PLATE SIDE (INSIDE)

79.87	77.81	77.97	80.88
82.89	82.02	78.73	78.32
80.32	86.44	89.91	85.07

TEMP. ALONG PLATE SIDE (OUTSIDE)

38.72	38.53	38.34	38.6
39.65	39.27	39.36	39.86
39.13	38	39.11	38.15

TEMP. UNDER PLATE (INSIDE)

90.9	88.75	107.5
106	108	106.3
94.1	93.8	106.9

TEMP. UNDER PLATE (OUTSIDE)

30.59	29.77
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TEMP. IN TEST BOX

25.09	28.76	29.47
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BUSBAR TEMP.

76.4	76.4
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DATA STORED IN FILENAME:P1275

VOLTAGE= 1.393 volts
 CURRENT= 56.6 amps
 POWER= 78.844 watts
 ROOM TEMP.= 24.2 (F)
 DATE.....3/26/84

TIME BETWEEN START UP AND TEST= 21 HRS.
 TIME REQ'D TO TAKE 1 GROUP OF SURFACE READINGS= 33.81 sec.

AVERAGE PLATE SURFACE TEMP.

100.7	101.5	104.1	102.8	98.6	97.61
107.9	110.5	110	108.7	108.8	102.8
111.6	116.4	117	115.5	114.1	105.8
		118.8			
111.1	117.5	115.5	118.8	120.5	106.1
106.6	112.8	112.4	112.3	112.4	105.7
103.8	105.1	106	105.2	103.9	100.8

TEMP. ALONG PLATE SIDE (INSIDE)

82.56	80.52	80.63	83.68
85.97	85.14	82.11	81.72
83.84	89.47	93.23	88.43

TEMP. ALONG PLATE SIDE (OUTSIDE)

38.67	38.5	38.28	38.38
39.62	39.22	39.43	40.03
39.32	37.9	39.06	37.99

TEMP. UNDER PLATE (INSIDE)

94.49	92.08	112.3
110.7	113.3	111.4
98.18	97.72	111.9

TEMP. UNDER PLATE (OUTSIDE)

30.19	29.23
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TEMP. IN TEST BOX

24.19	28.08	28.77
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BUSBAR TEMP.

79.6	79.6
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DATA STORED IN FILENAME:P1285

VOLTAGE= 1.476 volts
 CURRENT= 59.85 amps
 POWER= 88.339 watts
 ROOM TEMP.= 24.8 (F)
 DATE.....3/26/84

TIME BETWEEN START UP AND TEST= 10.5 HRS.
 TIME REQ'D TO TAKE 1 GROUP OF SURFACE READINGS= 33.81 sec.

AVERAGE PLATE SURFACE TEMP.

109.1	110.1	113.9	112.2	107	106.3
116.8	120.2	119.3	118.4	117.7	112.2
121.4	127.2	127.2	125.7	124.2	114.7
		128.8			
120.4	127.9	125.8	131.2	132.2	115
115.7	123.2	121	121.7	122.8	115.7
112.5	114.9	115.9	114.9	113.9	110.1

TEMP. ALONG PLATE SIDE (INSIDE)

89.51	87.26	87.59	90.66
93.56	93.06	89.49	89.21
91.42	97.45	101.6	96.36

TEMP. ALONG PLATE SIDE (OUTSIDE)

41	40.86	40.58	40.72
42.08	41.79	41.88	42.68
41.85	40.29	41.55	40.35

TEMP. UNDER PLATE (INSIDE)

102.5	99.95	122.2
120.5	123.1	121.1
106.4	106.1	121.5

TEMP. UNDER PLATE (OUTSIDE)

31.74	30.67
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TEMP. IN TEST BOX

25.11	29.69	30.66
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BUSBAR TEMP.
 86 86

DATA STORED IN FILENAME:P1290

VOLTAGE= 1.475 volts
 CURRENT= 60 amps
 POWER= 88.5 watts
 ROOM TEMP.= 25.1 (F)
 DATE.....3/27/84

TIME BETWEEN START UP AND TEST= 20 HRS.
 TIME REQ'D TO TAKE 1 GROUP OF SURFACE READINGS= 33.81 sec.

AVERAGE PLATE SURFACE TEMP.

108	110.4	114.9	112.9	106.5	106
116.4	121.6	120.2	119.1	118.8	112.7
122.2	127.6	128.1	127.4	125.5	116
		129.9			
121.1	127.5	127.3	132.4	133.2	116.7
117.9	124	121.9	119.9	123.8	116.5
112.5	115.3	116.6	114.8	113.5	111.5

TEMP. ALONG PLATE SIDE (INSIDE)

88.37	85.62	86.4	90.78
94.19	93.68	88.49	88.4
90.61	97.19	102.3	96.74

TEMP. ALONG PLATE SIDE (OUTSIDE)

40.73	40.6	40.45	40.75
42.23	41.89	41.68	42.43
41.62	40.25	41.59	40.22

TEMP. UNDER PLATE (INSIDE)

102.4	99.43	122.8
121.3	123.6	121.9
106.2	105.9	122.3

TEMP. UNDER PLATE (OUTSIDE)

31.68	30.58
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TEMP. IN TEST BOX

24.89	29.61	30.42
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BUSBAR TEMP.

85.8	85.8
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DATA STORED IN FILENAME:P12100

VOLTAGE= 1.567 volts
 CURRENT= 63.65 amps
 POWER= 99.74 watts
 ROOM TEMP.= 26.1 (F)
 DATE.....3/27/84

TIME BETWEEN START UP AND TEST= 7.5 HRS.
 TIME REQ'D TO TAKE 1 GROUP OF SURFACE READINGS= 33.79 sec.

AVERAGE PLATE SURFACE TEMP.

118.2	120.9	125.5	124.1	117.9	115.7
127.7	133.3	133.3	132.2	131.6	123.2
135.8	140.4	141.5	140.6	138.6	126.6
		143.3			
134.7	141.8	140.4	144.7	145.5	127.2
128.2	137.6	135.6	135.6	137.2	128.7
124.5	126.5	127.2	125.9	124.6	120.7

TEMP. ALONG PLATE SIDE (INSIDE)

96.31	93.16	94.28	98.83
102.9	102.7	97.53	97.5
99.99	106.3	111.9	105.9

TEMP. ALONG PLATE SIDE (OUTSIDE)

43.45	43.28	43.13	43.68
45.06	44.85	44.58	45.63
44.78	43.01	44.45	42.88

TEMP. UNDER PLATE (INSIDE)

111.5	108.3	135
133.5	135.9	134.1
115.9	115.6	134.5

TEMP. UNDER PLATE (OUTSIDE)

33.25	32.04
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TEMP. IN TEST BOX

26.12	31.14	32.05
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BUSBAR TEMP.

94	94
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VITA

Thomas J. Phillips was born in Frankfurt, Germany on October 8, 1958. He graduated from Ooltewah High School in Ooltewah, Tennessee in June of 1976.

In September of 1976, he entered The Georgia Institute of Technology. He attended this institution for two years in the cooperative education program, working off-quarters at Combustion Engineering Inc. in Chattanooga, Tennessee.

In January of 1979, he was admitted to the University of Tennessee, Knoxville. He was awarded the Bachelor of Science Degree in Mechanical Engineering in June of 1982.

He accepted a research assistantship in the summer of 1982 at the University of Tennessee, Knoxville, and began work on his Master's Degree. This degree was awarded in June 1985.