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NATURAL CONVECTION HEAT TRANSFER STUDIES OF SIMULATED AND ACTUAL ELECTRONIC COMPONENTS USING DIELECTRIC LIQUIDS FOR IMMERSION COOLING

by

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Two experimental studies of the natural convection characteristics of heated protrusions immersed in dielectric liquids were conducted. The first study used a three by three array of simulated 20 pin dual-in-line chips which were made from aluminum blocks with foil heaters. The second set of experiments used a three by three array of thermal evaluation devices mounted on an alumina substrate. The devices were 8.9 mm square chips which contained resistors and a type of temperature sensing transistor. Both studies used an insulated Plexiglas enclosure with a top mounted heat exchanger maintained at a constant 10 degrees C. Each array was mounted on a Plexiglas substrate, and spacers were used to vary the horizontal distance from the components to the enclosure wall. Five separate enclosure widths were used, with a maximum spacing of 40 mm.

The vertically oriented aluminum blocks were tested with FC-71 and power levels ranging from 0.115 W/chip to 2.9 W/chip. The non-dimensional data obtained was used to develop an empirical correlation which predicts Nusselt number as a function of Rayleigh number and enclosure width. The correlation was accurate to within 4% of the array averaged data, and the maximum uncertainty in the Nusselt number was 7.4%.

The actual electronic components were tested with FC-71, FC-43, and FC-75. Power levels ranged from 0.34 W/chip to 1.48 W/chip. Again, the data obtained was used to develop a Nusselt number correlation. In this case a better correlation of the data was achieved using Grashof number and enclosure width. The correlation is accurate to within 2% of the array averaged data. The maximum Nu uncertainty was 4.7%.

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Natural Convection Heat Transfer Studies of Simulated and Actual Electronic Components Using Dielectric Liquids for Immersion Cooling

by

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Lieutenant Commander, United States Navy
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Submitted in partial fulfillment
of the requirements for the degree of

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ABSTRACT

Two experimental studies of the natural convection characteristics of heated protrusions immersed in dielectric liquids were conducted. The first study used a three by three array of simulated 20 pin dual-in-line chips which were made from aluminum blocks with foil heaters. The second set of experiments used a three by three array of thermal evaluation devices mounted on an alumina substrate. The devices were 8.9 mm square chips which contained resistors and a type of temperature sensing transistor. Both studies used an insulated Plexiglas enclosure with a top mounted heat exchanger maintained at a constant 10 °C. Each array was mounted on a Plexiglas substrate, and spacers were used to vary the horizontal distance from the components to the enclosure wall. Five separate enclosure widths were used, with a maximum spacing of 40 mm.

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The actual electronic components were tested with FC-71, FC-43, and FC-75. Power levels ranged from 0.34 W/chip to 1.48 W/chip. Again, the data obtained was used to develop a Nusselt number correlation. In this case a better correlation of the data was achieved using Grashof number and enclosure width. The correlation is accurate to within 2% of the array averaged data. The maximum Nusselt number uncertainty was 4.7%.

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NOMENCLATURE

Symbol	Description	Units
A_{tot}	Total surface area for convection	m^2
c_p	Dielectric liquid specific heat	J/kg °C
g	Acceleration due to gravity	m/s^2
Gr	Grashof number	dimensionless
h	Average heat transfer coefficient	W/m^2 °C
k	Dielectric fluid thermal conductivity	W/m °C
L	Chip length in vertical direction	m
Nu	Nusselt number	dimensionless
Power	Calculated power supplied to a chip	W
Pr	Prandtl number	dimensionless
Q_{loss}	Average heat loss by conduction through circuit board assembly	W
Q_{net}	Net power dissipated by a chip	W
R_c	Thermal resistance for conduction loss	°C/W
R_r	Precision resistor resistance	Ω
Ra	Rayleigh number	dimensionless
Ra_f	Flux based Rayleigh number	dimensionless
T_{avg}	Average temperature of the five chips	°C
T_{chip}	Indicated chip temperature from transistor voltage measurement	°C
T_{film}	Dielectric liquid film temperature	°C
T_{lid}	Chip lid temperature	°C
T_s	Circuit board assembly back temperature	°C
T_{side}	Chip side temperature	°C
T_{sink}	Average heat exchanger (sink) temperature	°C
V_{htr}	Voltage drop across chip resistor	V
V_{rr}	Voltage drop across precision resistor	V
X	Non-dimensional enclosure width	dimensionless

α	Dielectric liquid thermal diffusivity	m^2/s
β	Dielectric liquid thermal expansion coefficient	1/ °C
δ	Uncertainty	various
ΔT	Area-based temperature difference between chip surface and sink	°C
ΔT_c	Temperature difference for conduction loss	°C
ν	Dielectric liquid kinematic viscosity	m^2/s
ρ	Dielectric liquid density	kg/m^3

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I. INTRODUCTION

A. THE ELECTRONICS COOLING PROBLEM

Computer silicon chips continue to become more powerful and smaller year after year. However, the surface heat flux produced continues to increase, and the removal of this heat plays a major role in large computer design. For example, Hitachi's recent M-880 general purpose computer uses a 100 cm^2 water cooled module which dissipates almost 850 W, and it is predicted that heat fluxes of nearly 10^6 W/m^2 will be reached by the year 2000 (Bar-Cohen, 1991).

The challenge of removing this eleven-fold increase in surface heat flux is formidable. Forced convection air cooling methods are limited to heat fluxes of 10^4 W/m^2 (Bergles, 1991). Conduction cooling with a cold plate and direct immersion dielectric liquid cooling are the cooling methods currently employed in large mainframe computers. However, with the exception of the Cray series of supercomputers, major computer companies have opted for various types of generally complex cold plate assemblies.

Extensive research into direct liquid cooling is being conducted for a number of reasons. First, potential cooling schemes using dielectric fluid would be much simpler than their conduction/cold plate counterparts. Second, the advantages and disadvantages of single phase natural convection, nucleate boiling, and forced convection methods for a wide variety of available dielectric liquids needs to be studied to determine their basic heat transfer characteristics in a simulated computer circuit board environment. Finally, the results of the research should point the way for the optimum dielectric cooling method, which can then be refined in order to make it a competitive means of cooling for the next generation of computers.

B. RELATED RESEARCH

Park and Bergles (1987) conducted natural convection experiments using foil heaters mounted both flush and protruding from a circuit board. The heat transfer coefficient was measured for a single flush heater with two heater heights of 5 mm and 10 mm. Heater widths varied from 2 mm to 70 mm. Additional experiments used a vertical array of two or three heaters with various distances between them. Combinations of heaters included two or three flush in-line, two flush staggered, and two protruding in-line. Distilled water and R-113 were the fluids used.

For the single flush heater, the heat transfer coefficient was found to increase as the heater width decreases, with this effect more pronounced in the R-113. For the in-line flush heaters, the heat transfer coefficient was higher for the bottom heater, while the opposite was true for the in-line protruding heaters.

Kelleher et al. (1987) conducted a natural convection study of a long horizontal protruding heater mounted on a vertical wall in a water filled enclosure. Heat exchangers on the bottom and top of the enclosure maintained a constant temperature. Results for three separate heater positions indicated that the Nusselt number decreased as the heater position was raised. Additionally, a flow visualization study revealed that the flow was divided into two regions. The more active upper buoyancy driven region accounted for most of the heat transfer, while the more sluggish lower region was driven by shear interaction with the upper region.

Joshi et al. (1990) performed a detailed natural convection study of a vertically mounted three by three array of heated protrusions in an enclosure filled with dielectric liquid FC-75. The protrusions were horizontally oriented rectangular aluminum blocks sized to simulate 20 pin dual-in-line (DIP) packages. The top and bottom enclosure boundaries were heat exchangers set to maintain a constant temperature for various heater power levels. Enclosure width was fixed at 30 mm.

Extensive flow visualization revealed three-dimensional transport which varied with power level. As the power level was raised, the upward flow increased in intensity and complexity. Flow away from the components varied with time, and this was confirmed by time history temperature measurement. Embedded thermocouples were also used to calculate heat transfer characteristics. A correlation was developed to compute component temperature from the dissipated power.

A follow-on investigation by Joshi et al. (1991) utilized a vertically mounted three by three array of vertically oriented heated protrusions in an enclosure filled with three different fluorinert type dielectric liquids. Again, the upper and lower boundaries were constant temperature heat exchangers. Enclosure widths of 13 mm and 30 mm were used with varying power levels in this study.

It was found that the top and bottom enclosure conditions affected the component temperatures to a greater degree for the lower power levels. The effect of enclosure width was minimal on the resultant calculations of Nusselt and modified Rayleigh numbers. These non-dimensional heat transfer characteristics were correlated in a similar manner to the previous investigation.

A similar set of experiments using ethylene glycol as the fluid was conducted by Keyhani et al. (1991). Five heated protrusions were uniformly spaced on a vertical wall inside an enclosure equipped with a top mounted heat exchanger. Six different enclosure widths varying from 13.5 mm to 45 mm were tested at power levels ranging from 2 W to 12 W per heater.

Flow visualization of the experiments revealed primary flows along the vertical walls separated by a narrow core flow consisting of secondary flow cells. The heat transfer coefficient of the top and bottom heaters was influenced markedly by the power level and enclosure width. A single correlation for Nusselt number versus modified Rayleigh number was developed that was independent of heater location and enclosure width.

Thesis experiments accomplished by Aytar (1991) and Matthews (1991) further established the heat transfer abilities of dielectric liquids on simulated electronic components. They both used a three by three array of 20 pin DIP sized aluminum blocks mounted vertically in an enclosure with a top mounted heat exchanger. Aytar studied the effects of enclosure width, power level, and Prandtl number on horizontally oriented protrusions. Matthews performed similar experiments with the protrusions oriented vertically.

C. OBJECTIVES

The objectives of this thesis were as follows:

1. Complete collecting data on Matthews' vertically oriented experimental setup. The component power level and enclosure width were varied using FC-71 as the dielectric liquid.

2. Reduce the above data into useful dimensional and non-dimensional parameters.

3. Utilize the non-dimensional data in developing an empirical correlation for the Nusselt number which takes into account the effects of enclosure width and Rayleigh number.

4. Using a circuit board assembly provided by NSWC, Crane, fabricate an actual three by three electronic component array experiment.

5. Collect natural convection heat transfer data on this circuit board assembly using dielectric liquids FC-71, FC-43, and FC-75. The power level and enclosure width were varied for each liquid similar to the previous study.

6. Reduce the above data into useful dimensional and non-dimensional parameters.

7. Utilize the non-dimensional data in developing a single correlation for the Nusselt number which takes into account the effects of enclosure width and Grashof number.

8. Based on the above findings, make a recommendation for the best dielectric liquid to use for natural convection cooling. Additionally, recommend additional areas for future research using the selected liquid.

II. EXPERIMENTAL APPARATUS

A. TEST CHAMBER ASSEMBLY

The test chamber assembly consisted of the rectangular enclosure and heat exchanger used by Matthews. The enclosure was constructed of 25.4 mm and 12.7 mm thick Plexiglas. A 3.2 mm O-ring sealed the boundary between the enclosure walls and the bottom of the heat exchanger. The two were assembled together with 12 threaded studs, washers, and nuts. Plexiglas inserts of various widths were used in order to vary the spacing between the circuit board assembly and the wall. Details of the enclosure are shown in Figure 1.

The top mounted heat exchanger was a Plexiglas and aluminum single-pass type with five rectangular channels for cooling water flow. Heat transferred from the dielectric liquid was conducted to the coolant across the 3 mm thick aluminum plate which formed the bottom of the heat exchanger. Three thermocouples embedded in the aluminum plate were used for temperature measurement. A drawing of the heat exchanger is shown in Figure 2.

B. SIMULATED CIRCUIT BOARD

The first set of experiments utilized the same component board used by Matthews. Nine aluminum blocks arranged in a three-by-three array were mounted on a 12.7 mm thick Plexiglas substrate. The numbering system for the components was unchanged: bottom to top, right column to left column. Small 10.6 Ω foil heaters were located between the blocks and the substrate. Temperatures were measured using six thermocouples per block. Nine thermocouples were also mounted on the back of the substrate for conduction loss calculations. Details of the heater, thermocouple, and block mounting procedures are described by Aytar (1991). A drawing of the circuit board is shown in Figure 3.

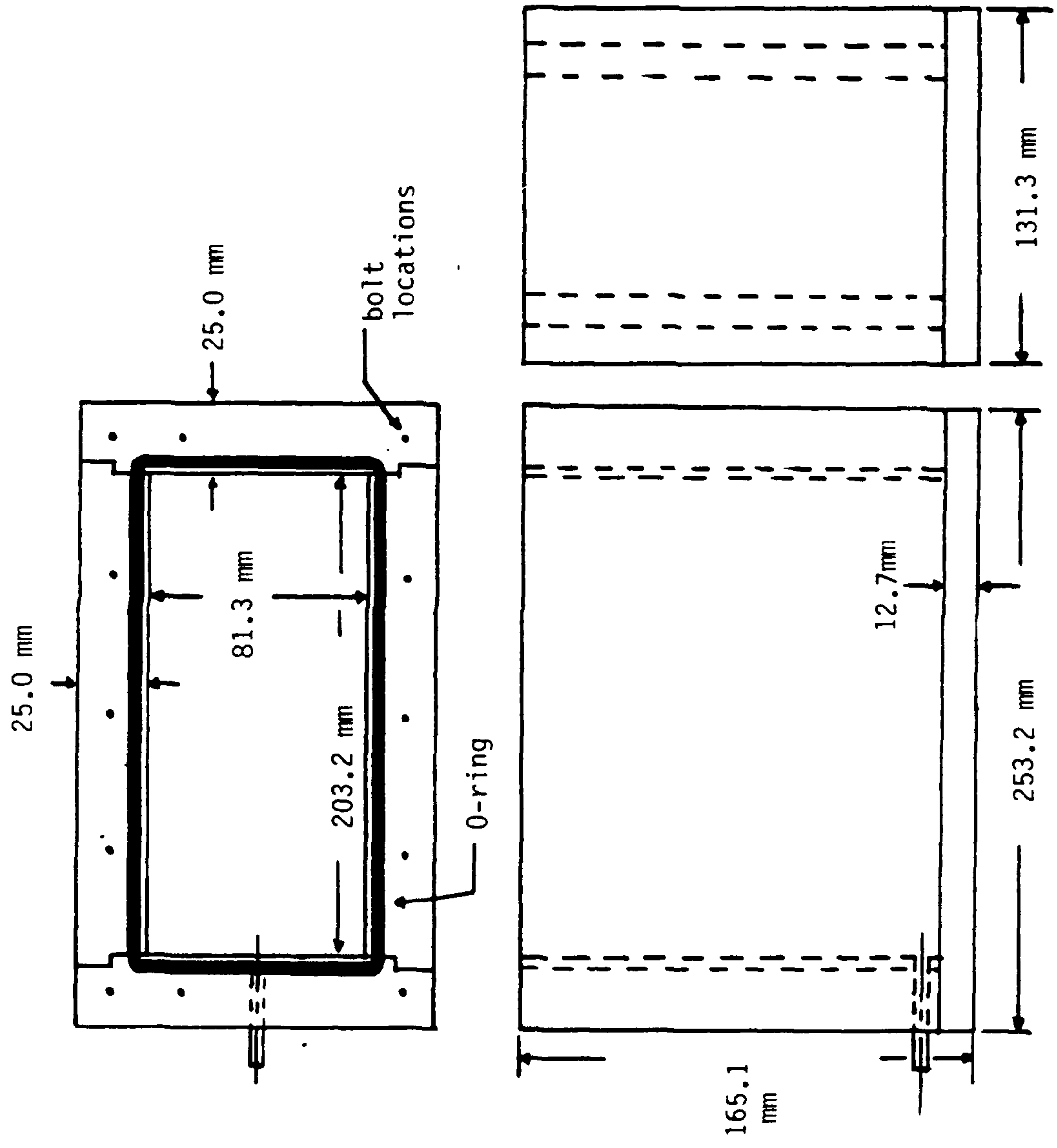

Figure 1. Enclosure

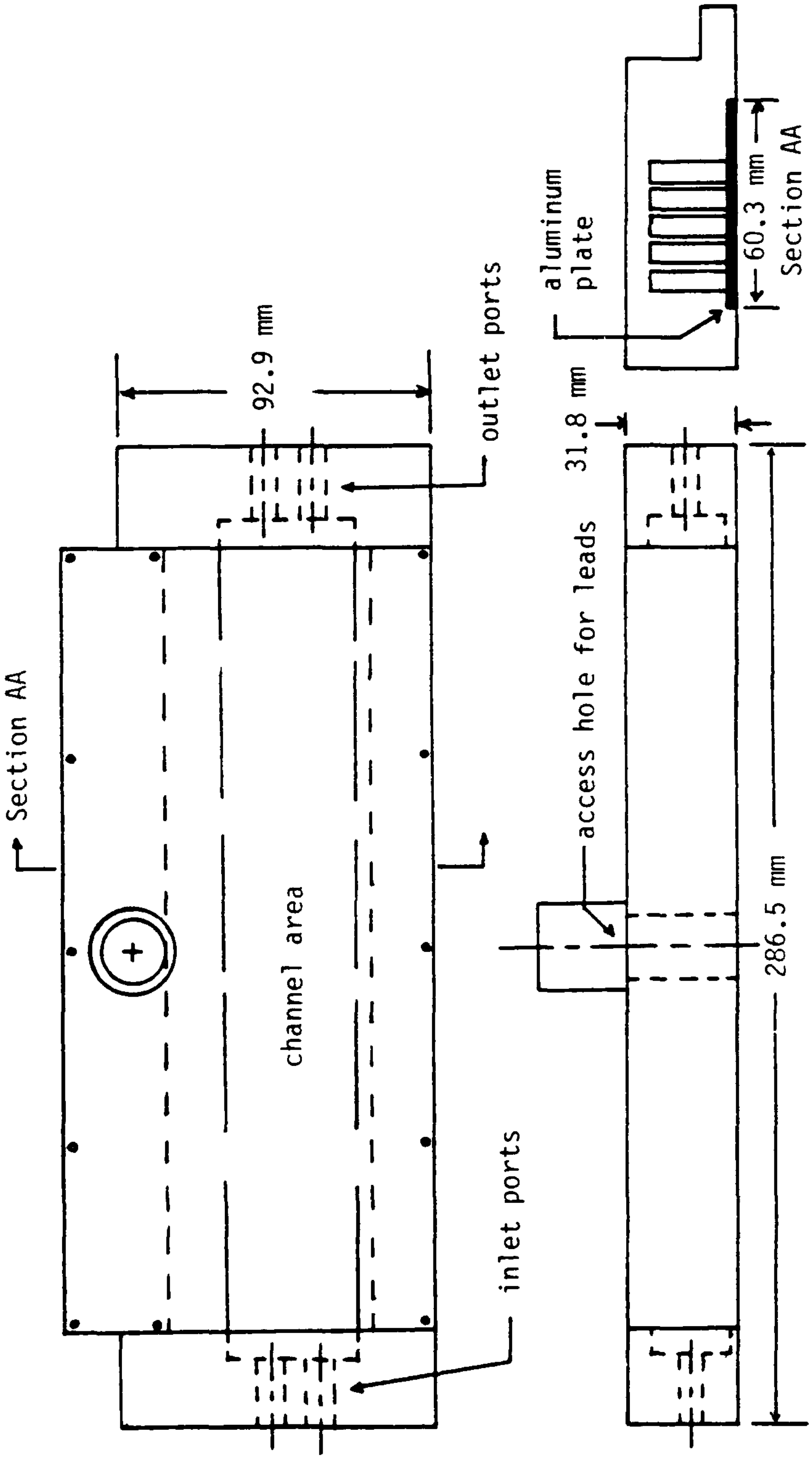

Figure 2. Heat Exchanger

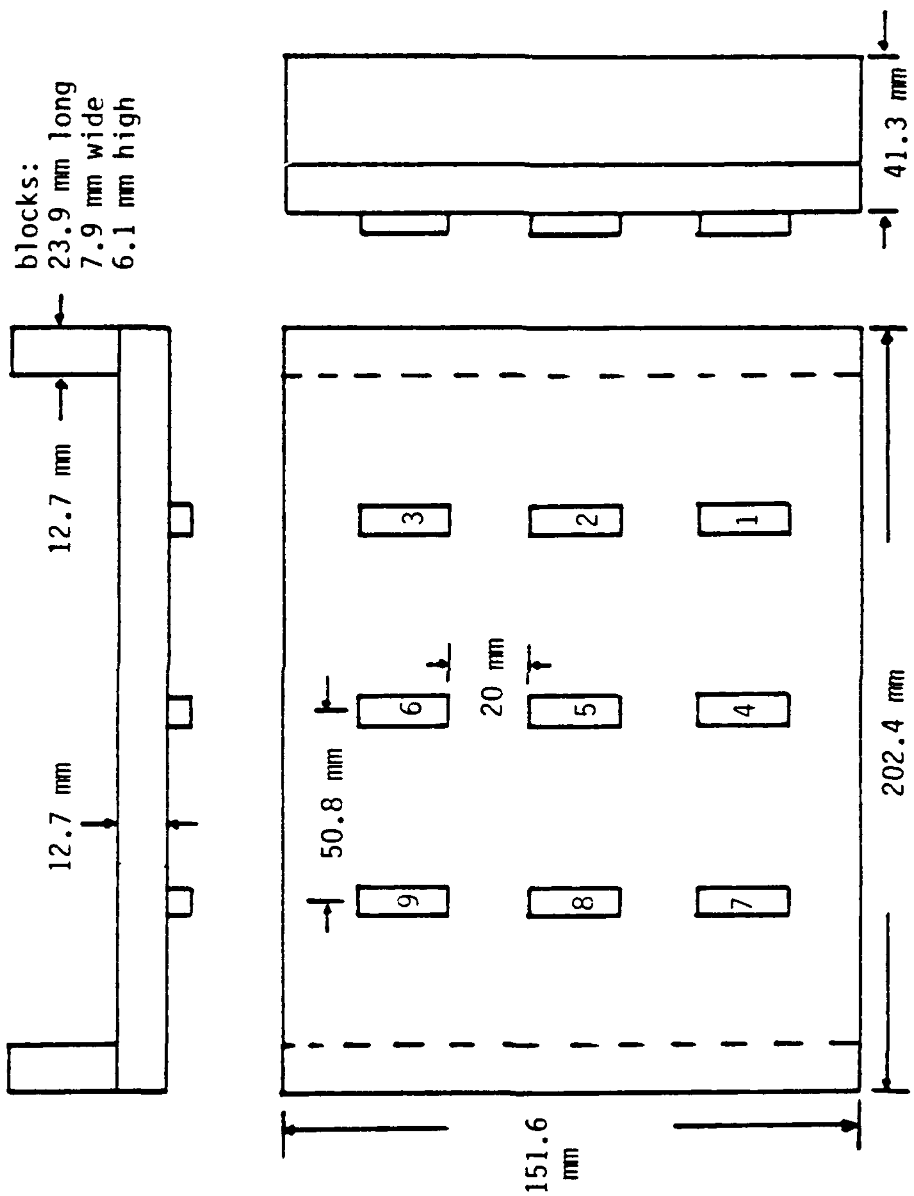

Figure 3. Circuit Board

C. NSWC CIRCUIT BOARD

The remainder of the experiments used a three by three array of Texas Instruments thermal evaluation devices which were assembled on a 50.8 mm square alumina substrate board by Naval Surface Warfare Center (NSWC), Crane, Indiana. Each device is an 8.9 mm square chip which contains four resistors and a Temperature Sensing Element (TSE). Again, the same component numbering system is used for consistency. The resistors, when connected in series, have a resistance of approximately 165 ohms. The TSE is a solid state temperature measuring device, or a type of transistor. Figure 4 is a photograph of the circuit board, and a schematic diagram of the chip internals is shown in Figure 5.

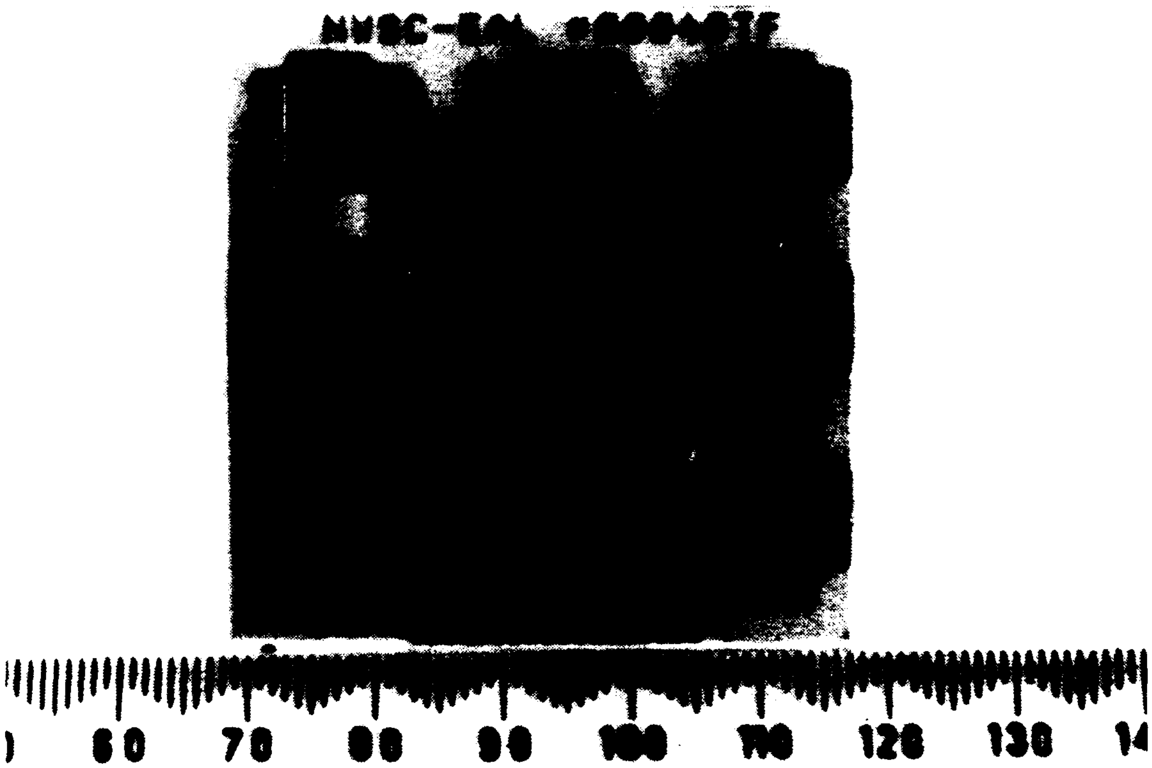

Figure 4. NSWC Circuit Board

To simulate actual electronic chips, power is provided to the resistors for heating purposes. Using a constant 1 mA current source, the voltage across the transistor base to emitter, V_{BE}, is measured. Component temperature is then obtained from a previously plotted calibration curve of temperature versus V_{BE}. The complete circuit board is mounted in the center of a Plexiglas substrate board with essentially the same dimensions as in Figure 3. 18 thermocouples were added as follows:

- Five on the chip lid surfaces. Located on chip #2, 4, 5, 6 and 9.
- Four on the substrate face. Located diagonally between chip #1 and 5, #3 and 5, #7 and 5, and #9 and 5.
- Nine on the circuit board assembly back. Located directly behind the chips.

The complete circuit board is shown in Figure 6.

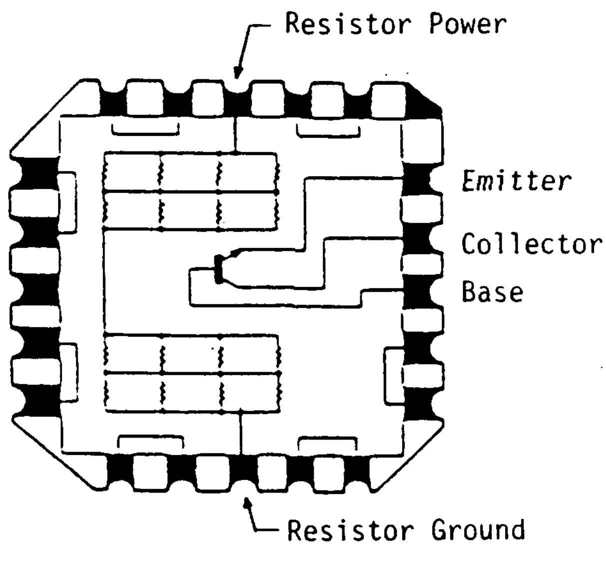

Figure 5. Thermal Evaluation Device Circuitry

D. SYSTEM HARDWARE

1. Simulated Circuit Board

Copper-constantan thermocouples, 0.010 inch diameter, were used for temperature measurement on the simulated circuit board assembly. Each foil heater was connected in series to a 2.0 Ω ± 2.5% resistor. These resistors, in turn, were connected in parallel to a 0-100 V, 0-5 A direct current power supply. This arrangement allowed for a simple calculation of heater power from measured voltages. Details of this simple calculation can be found in Matthews' thesis. The thermocouples and heaters were connected to a Hewlett-Packard HP-3497A Data Acquisition System (DAS). The input and output to the DAS was via an HP-9826 microcomputer. The data channels were unchanged from Matthews' experiments, and they are repeated below:

- Channels 0-53 Aluminum block temperatures
- Channels 54-56 Heat exchanger temperatures
- Channels 57-60 Back of board assembly temperatures
- Channel 61 DC power supply voltage
- Channels 62-70 Foil heater voltages
- Channels 71-75 Back of board assembly temperatures
- Channel 76 Ambient temperature

2. NSWC Circuit Board

As before, identically sized copper-constantan thermocouples were used with two HP-3497A units. One HP-3497A with two, twenty channel cards was used to measure thermocouple and voltage data. The other HP-3497A was used only as a current source. It had one, twenty channel card modified to supply the constant 1 mA current to the TSEs. Power supplied to each chip was easily calculated by multiplying the chip resistor voltage by its current. The current was equal to the precision resistor voltage divided by its resistance.

The chip resistors were powered from the same direct current power supply. However, all nine chips could not be powered individually. This was due to the circuit board layout employed by NSWC. The center column, chip #4, 5, and 6, could be powered individually, but the chip resistors in the two outer columns were each wired in parallel.

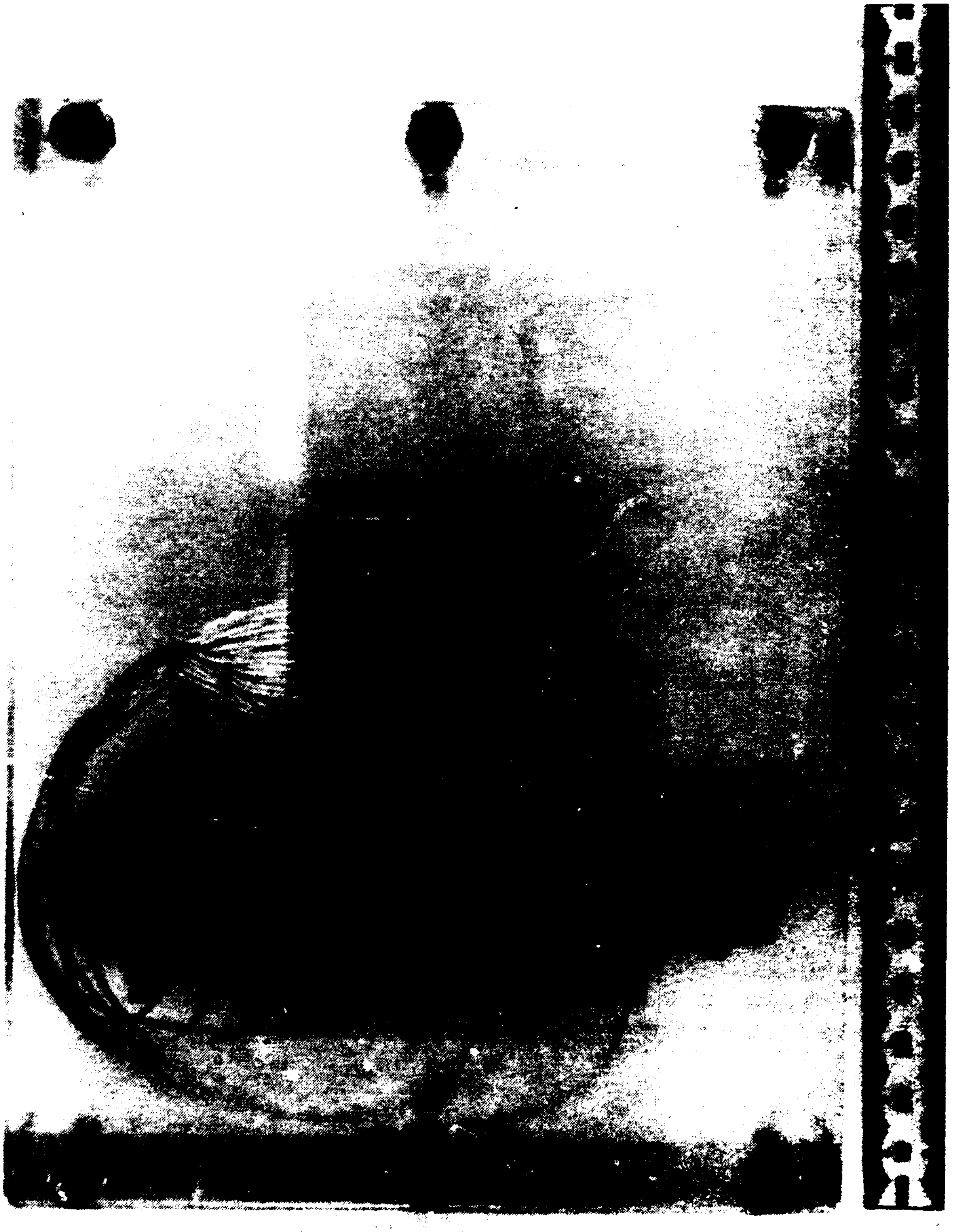

Figure 6. NSWC Circuit Board Assembly

Additionally, due to circuit board constraints, TSE junction temperatures could not be measured for the four corner chips. The channels were numbered as follows:

- Channels 0-4 Chip resistor voltages
- Channels 5-9 Precision resistor voltages
- Channel 10 DC power supply voltage
- Channels 11-13 Heat exchanger temperatures
- Channels 41-44 Substrate surface temperatures
- Channels 45-49 Chip lid temperatures
- Channel 50 Ambient temperature
- Channels 51-59 Circuit board assembly back temperatures
- Channels 60-64 Chip V_{BE} voltages

III. EXPERIMENTAL PROCEDURE

A. HARDWARE PREPARATION

Similar preparations were made for both sets of experiments. Once the component assembly was in place, the proper sized spacer was inserted for the particular run. Careful measurements of assembly to enclosure wall spacing were performed to ensure accuracy. Frequently a small amount of silicone RTV was applied to the corners of both the component assembly and the spacer to correct for any small warpage. The remaining steps were as follows:

1. The enclosure was filled nearly to the top with the proper dielectric liquid.

2. The heat exchanger was bolted to the enclosure, with the O-ring providing a seal.

3. The circulating bath supply and return lines were attached to the heat exchanger. The bath unit was set to 6-9 °C (indicated) and energized. It was found that this temperature setting was required in order for the heat exchanger temperature to be 10 °C during the runs. The system was checked for leaks.

4. The foil heaters or chip resistors were energized with the DC power supply.

5. The HP-3497A was energized. All channels were scanned to insure continuity.

6. Foam insulation was attached to the enclosure walls and bottom.

7. Additional dielectric liquid was siphoned into the enclosure via the vent hole. The air bubbles trapped directly under the heat exchanger were manipulated to the lead access hole via a small slot in the tops of the component assemblies.

B. EXPERIMENTAL PROCEDURE

After the above preparations were completed, the proper voltage was set on the DC power supply. Data was taken after steady state conditions were reached. For the FC-71, this took at least eight hours from ambient conditions. Subsequent runs took two to six hours to reach steady state, depending on power level and spacing. Steady state was achieved when two to three data runs taken approximately 10 minutes apart indicated a ±0.1 °C random temperature difference between the thermocouple readings. This criterion was changed to conform with Matthews' work for other dielectric liquids. It was ±1 °C and ±0.4 °C, respectively, for FC-75 and FC-43. As a rule, steady state conditions were achieved sooner with FC-75 and FC-43.

For the simulated circuit board, data acquisition was accomplished with the software program ACQUIRE. Calculations were then performed with the program CALCDIEL. Both of these programs were originally written and modified by Pamuk, Benedict, Torres, Powell, Aytar, and Matthews. They are included in Appendices A and B.

For the NSWC circuit board, two new programs were written. The program ACQ2 was used for data acquisition, and calculations were performed by the program CALC2. Major improvements in the new software are as follows:

- Since the TSEs had to be calibrated, the thermocouples were calibrated at the same time. Calibration was performed using a constant temperature oven and a platinum resistance thermometer. The equations for the resulting calibration curves were used in the programs to convert voltages to temperature. Temperature uncertainty was calculated to be 0.275 °C for the TSEs, and it was 0.3 °C for the thermocouples.
- To promote understanding and facilitate future modifications, extensive documentation and explanations are included in the programs, where appropriate.

The programs ACQ2 and CALC2 are included in Appendices C and D.

IV. DATA ANALYSIS

A. SIMULATED CIRCUIT BOARD

The experiments using the FC-71 were virtually identical in nature to the experiments previously completed with FC-75 and FC-43. A detailed explanation of the methodology used for data analysis can be found in Matthews' thesis.

B. NSWC CIRCUIT BOARD

The program CALC2 was used to obtain the Nusselt, Rayleigh, and Grashof numbers for the NSWC circuit board. These non-dimensional parameters were calculated on a single chip, horizontal row, and array basis for three dielectric liquids (FC-75, FC-43, and FC-71) and five enclosure spacings. Various power levels ranging from approximately 0.34 W/chip to 1.48 W/chip were tested. Assumptions used in the CALC2 program were as follows:

- The chip was modeled as a square wafer.
- Chip and lid temperatures of the four corner chips were assumed identical to the horizontally adjacent chip in their respective row.
- Chip side temperature was the average of the TSE and the lid temperatures.
- Conduction was assumed one dimensional from the chip to the back of the Plexiglas substrate. The heat was conducted from the chip, through the alumina circuit board and a very thin layer of silicone rubber, to the Plexiglas.
- Thermophysical properties of the above materials were assumed constant at a reference temperature.
- Thermophysical properties of the dielectric liquids were assumed constant. They were evaluated at T_{film}.
- The temperature difference used for the calculation of the heat transfer coefficient was area weighted. The lid accounted for about 55% of the convection area, so the surface temperature was 55% of T_{lid} plus 45% of T_{side}.
- All contact resistances were assumed negligible.

Calibration curve equations for the thermocouples and the TSEs were entered into the program. All thermocouple temperatures were obtained from the following equation:

$$T\ (^\circ C) = 0.24977483 + 24.896088V - 0.079219169V^2$$

where V is the thermocouple voltage in millivolts. For accuracy, each TSE had its own calibration curve. A representative equation for chip #2 is as follows:

$$T\ (^\circ C) = 577.58074 - 575.54353V_{BE}$$

Similar equations were obtained for the other TSEs. The calibration curve for the thermocouples is shown in Figure 7, and a TSE calibration curve is shown in Figure 8. The calibration data for the five TSEs is included in

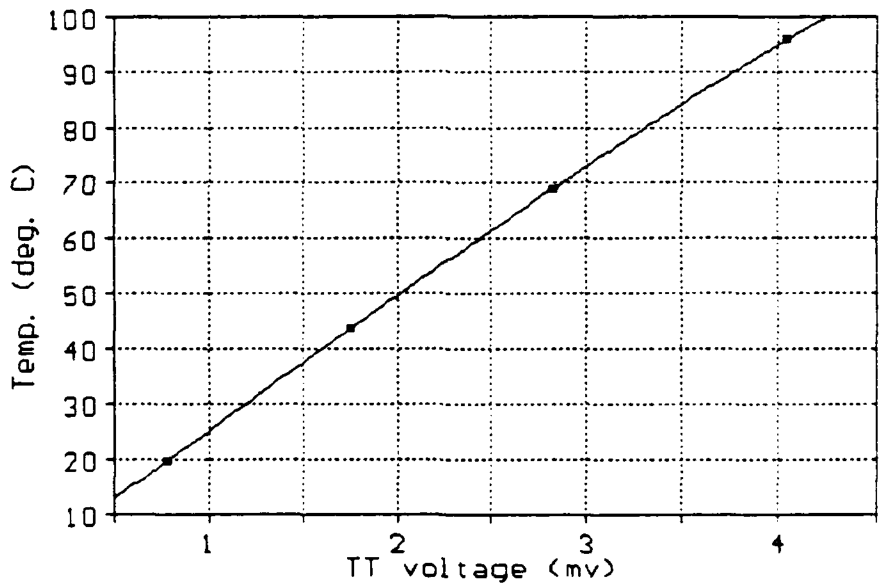

Figure 7. Thermocouple Calibration Curve

Appendix F.

Due to the wiring scheme of the NSWC circuit board, the power supplied to the TSEs had to be calculated two different ways. The power for the individually wired TSEs in the center column (chip #4, 5, and 6) was defined as follows:

$$Power = \frac{V_{htr} V_{rp}}{R_p}$$

where

V_{htr} = voltage drop across chip resistor

V_{rp} = voltage drop across precision resistor

R_p = precision resistor resistance

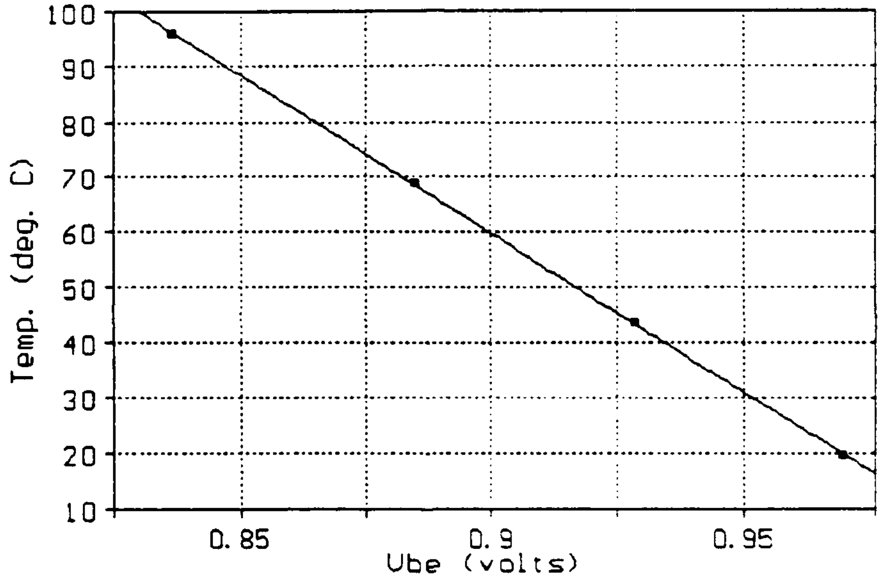

Figure 8. TSE #2 Calibration Curve

The remainder of the TSEs were wired in two parallel sets (chip #1, 2, and 3 and chip #7, 8, and 9), but only chip #2 and 8 could be read directly. Therefore, the power was modified as follows:

$$Power = \frac{V_{htr}V_{rp}}{3R_p}$$

with the correct V_{htr} (chip #2 or 8) substituted in the equation.

The heat loss by conduction involved several materials. The thermal resistance for conduction loss, R_c, was represented as:

$$R_c = \frac{1}{A}\sum \frac{L_i}{k_i}$$

where

A = cross-sectional area for conduction

L_i = material thickness

k_i = material thermal conductivity

The equation for Q_{loss}, calculated for each chip, was therefore:

$$Q_{loss} = \frac{\Delta T_c}{R_c}$$

where ΔT_c was the difference in temperature between the TSE derived temperature, T_{chip}, and the circuit board assembly back temperature, T_s.

The net heat transferred from the chip to the dielectric liquid could then be calculated from the following equation:

$$Q_{net} = Power - Q_{loss}$$

The average heat transfer coefficient, h, was calculated from:

$$h = \frac{Q_{net}}{A_{tot}\Delta T}$$

where

A_{tot} = total surface area for convection

ΔT = area based temperature difference between the chip surface and the heat exchanger, or sink

In equation form,

$$\Delta T = (0.55T_{lid} + 0.45T_{side}) - T_{sink}$$

T_{sink} is the average of the three heat exchanger temperatures.

The program then calculates the thermophysical properties for the particular dielectric liquid under investigation. The properties were evaluated at the film temperature, T_{film}, which was:

$$T_{film} = \frac{T_{avg} + T_{sink}}{2}$$

where T_{avg} was the average of the five chip TSE temperatures. The corresponding equations for the properties are outlined below:

Thermal conductivity, k (W/m °C)

$$FC\text{-}75: \quad k = \frac{(0.65 - 7.89474\times10^{-4} \times T_{film})}{10}$$

$$FC\text{-}43: \quad k = 0.0666 - 9.864\times10^{-6} \times T_{film}$$

$$FC\text{-}71: \quad k = 0.071$$

Density, ρ (kg/m^3)

$$FC\text{-}75: \quad \rho = (1.825 - 0.00246\times T_{film}) \times 1000$$

$$FC\text{-}43: \quad \rho = (1.913 - 0.00218\times T_{film}) \times 1000$$

$$FC\text{-}71: \quad \rho = (2.002 - 0.00224\times T_{film}) \times 1000$$

Specific heat, c_p (J/kg °C)

$$FC\text{-}75,43,71: \quad c_p = (0.241111 + 3.7037\times10^{-4} \times T_{film}) \times 4187$$

Kinematic viscosity, ν (m^2/s)

$$FC\text{-}75: \quad \nu = (1.4074 - 2.964\times10^{-2} \times T_{film} + 3.8018\times10^{-4} \times T_{film}^2 - 2.7308\times10^{-6} \times T_{film}^3 + 8.1679\times10^{-9} \times T_{film}^4) \times 10^{-6}$$

$$FC\text{-}43: \quad \nu = (8.875 - 0.47007 \times T_{film} + 1.387 \times 10^{-2} \times T_{film}^2 - 2.1469 \times 10^{-4} \times T_{film}^3 + 1.3139 \times 10^{-6} \times T_{film}^4) \times 10^{-6}$$

$$FC\text{-}71: \quad \nu = 10^{-6} \times \exp(6.8976 - 0.1388 \times T_{film} + 1.331 \times 10^{-3} \times T_{film}^2 - 7.041 \times 10^{-6} \times T_{film}^3 + 1.523 \times 10^{-8} \times T_{film}^4)$$

Coefficient of thermal expansion, β (1/°C)

$$FC\text{-}75: \quad \beta = \frac{0.00246}{1.825 - 0.00246 \times T_{film}}$$

$$FC\text{-}43: \quad \beta = \frac{0.00218}{1.913 - 0.00218 \times T_{film}}$$

$$FC\text{-}71: \quad \beta = \frac{0.00224}{2.002 - 0.00224 \times T_{film}}$$

Now the various dimensionless numbers which characterize the heat transfer can be calculated. First, the ratio of thermal energy conduction to storage, or thermal diffusivity, was found from:

$$\alpha = \frac{k}{\rho c_p}$$

Then the Prandtl number could be calculated from:

$$Pr = \frac{\nu}{\alpha}$$

A primary measure of convective heat transfer, the Nusselt number, was defined as:

$$Nu = \frac{hL}{k}$$

where L was the vertical length of an individual chip. Natural convection effectiveness is measured by the Grashof number, which can be calculated from:

$$Gr = \frac{g\beta L^3 (T_{avg} - T_{sink})}{\nu^2}$$

Finally, the Rayleigh number is defined as:

$$Ra = GrPr$$

V. SIMULATED CIRCUIT BOARD RESULTS

A. GENERAL

The natural convection heat transfer characteristics of a vertically oriented array of simulated electronic components were studied using the dielectric liquid FC-71 as the coolant. The experiments were performed on the same equipment used by Matthews. The enclosure widths used, after careful measurement, were determined to be 7, 9, 16, 28, and 40 mm. The 2 mm difference between these widths and those reported by Matthews is due to the actual enclosure width, with no spacers, being 40 mm wide instead of 42 mm. The same Plexiglas spacers were used for the FC-71 runs. Additionally, the same approximate power levels of 0.115, 0.34, 0.8, 1.3, 1.7, 2.25, and 2.9 W/component were used for the FC-71 study.

The non-dimensional data obtained with the FC-71 was combined with Matthews' results with the FC-75 and FC-43. An empirical correlation for the Nusselt number, Nu, was then derived in a similar manner for the third liquid, FC-71. As defined in Matthews' thesis, this correlation accounted for variations in Rayleigh number and chamber width. Conspicuously absent is the variation due to Prandtl number, Pr. After reviewing Matthews' results, it was determined that the effect of Pr was accounted for in the Rayleigh number. The correlation is of the form:

$$Nu = a\ Ra^{b1}\ X^{b2}$$

where Nu is based on the component dimension in the direction of gravity, X is a non-dimensional enclosure width, and a, b1, and b2 are constants.

B. DIMENSIONAL RESULTS

The array average temperature, $T_{avg} - T_{sink}$, is plotted against net power, Q_{net}, in Figure 9. Figure 10 through Figure 14 show the same plot for all three liquids, with each figure representing a different spacing.

The general shape of the curves in Figure 9 are identical to similar graphs of FC-43 and FC-75 data taken by Matthews (vertical orientation) and Aytar (horizontal orientation). However, the aluminum block temperatures are much hotter when using FC-71. Matthews took the maximum increase in the array average temperatures, which occurred at 2.86 W, and calculated the average of the five spacings. He reported this temperature to be 34.9 °C for FC-75 and 48.3 °C for FC-43. For FC-71, this temperature is 67.2 °C.

The maximum component temperature for FC-71 cooling was 76.5 °C, and it occurred at a power level of 2.9 W and an enclosure width of 7 mm. Corresponding values for FC-75 and FC-43 were 52 °C and 68 °C, respectively.

To be consistent with previous work, all FC-71 component temperature data was averaged. The temperatures of the three blocks on any row were averaged to facilitate a row-by-row comparison. For all power levels and spacings, the order of average row temperatures were always top > middle > bottom. This pattern indicated that the buoyancy forces overcame the viscous forces in the fluid. The boundary layers emerging from each component were definitely affected by the natural convection flow below them. This pattern for FC-71 compares to middle > top > bottom for FC-75 and top > middle > bottom for FC-43.

Specific component and row temperature extremes for the FC-71 data were as follows:

- Maximum block temperature occurred on chip #3 60% of the time and chip #6 or 9 34% of the time.
- Minimum block temperature occurred on chip #7 97% of the time.
- Maximum temperature difference between the top and middle rows was 1.7 °C. For the middle and bottom rows, it was 6.0 °C. These differences were noted at a power level of 2.9 W and a spacing of 7 mm.

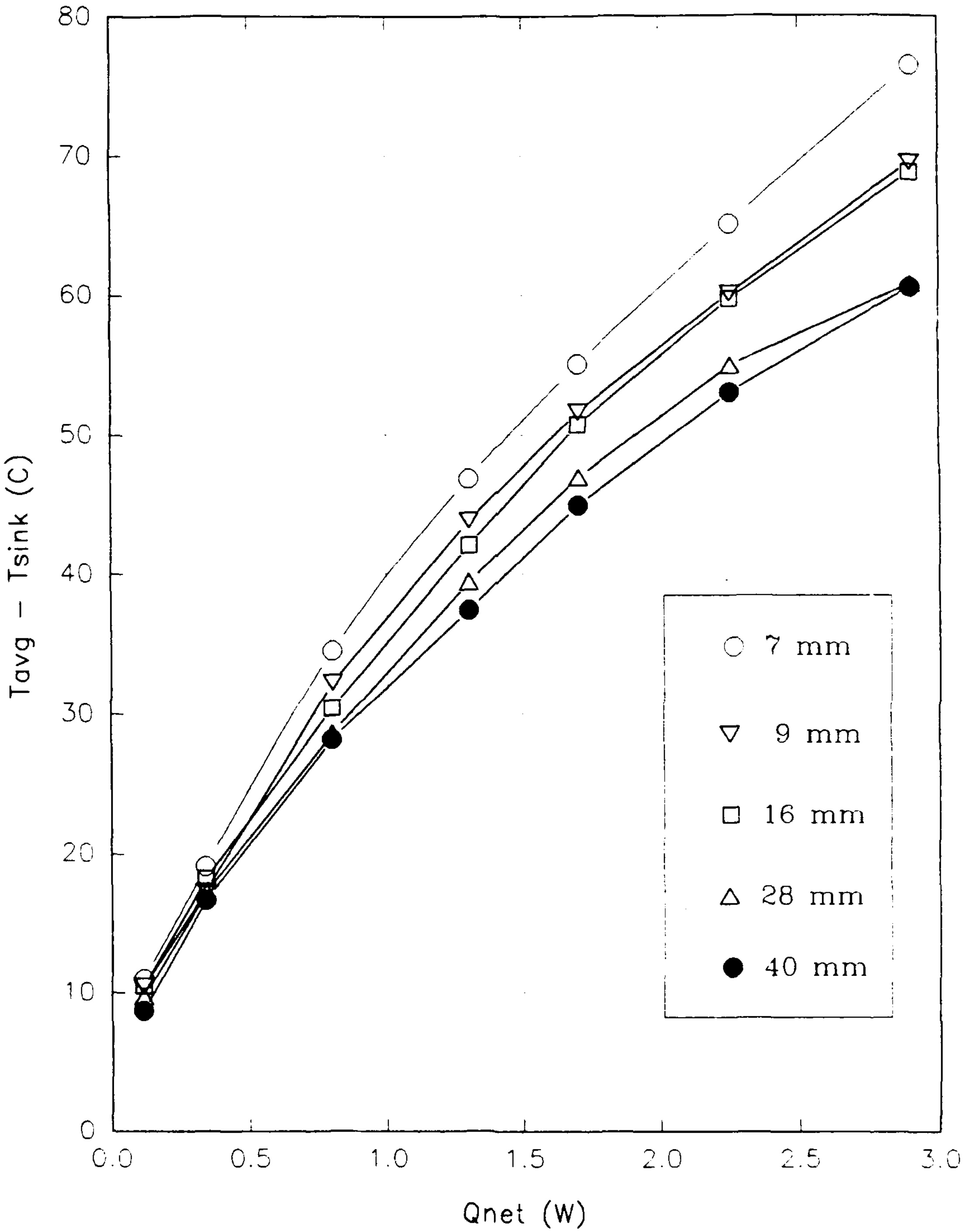

Figure 9. Array Average Temperature vs. Net Power for FC-71, Vertical Orientation

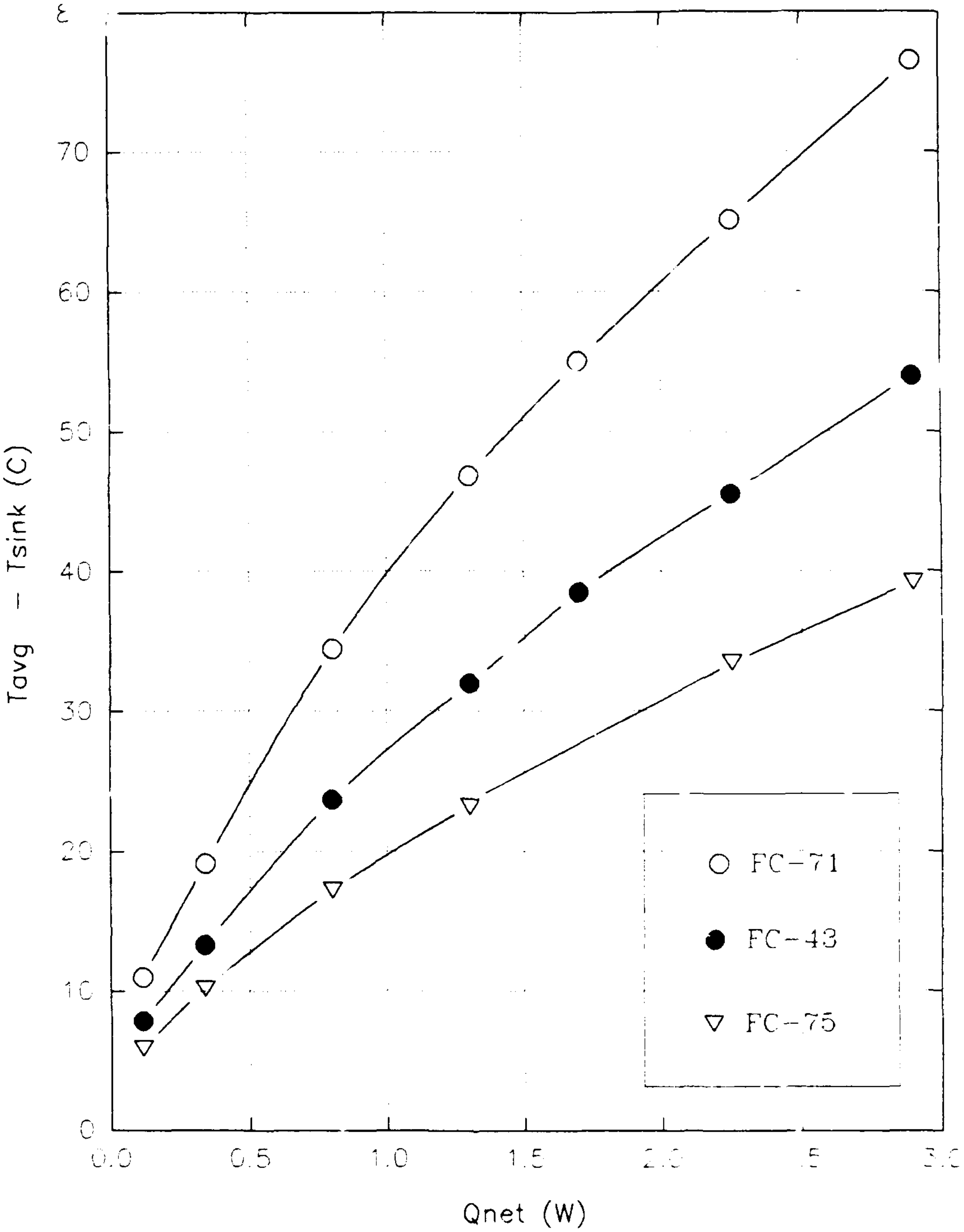

Figure 10. Array Average Temperature vs. Net Power for FC-71, 43, and 75, 7 mm Spacing, Vertical Orientation

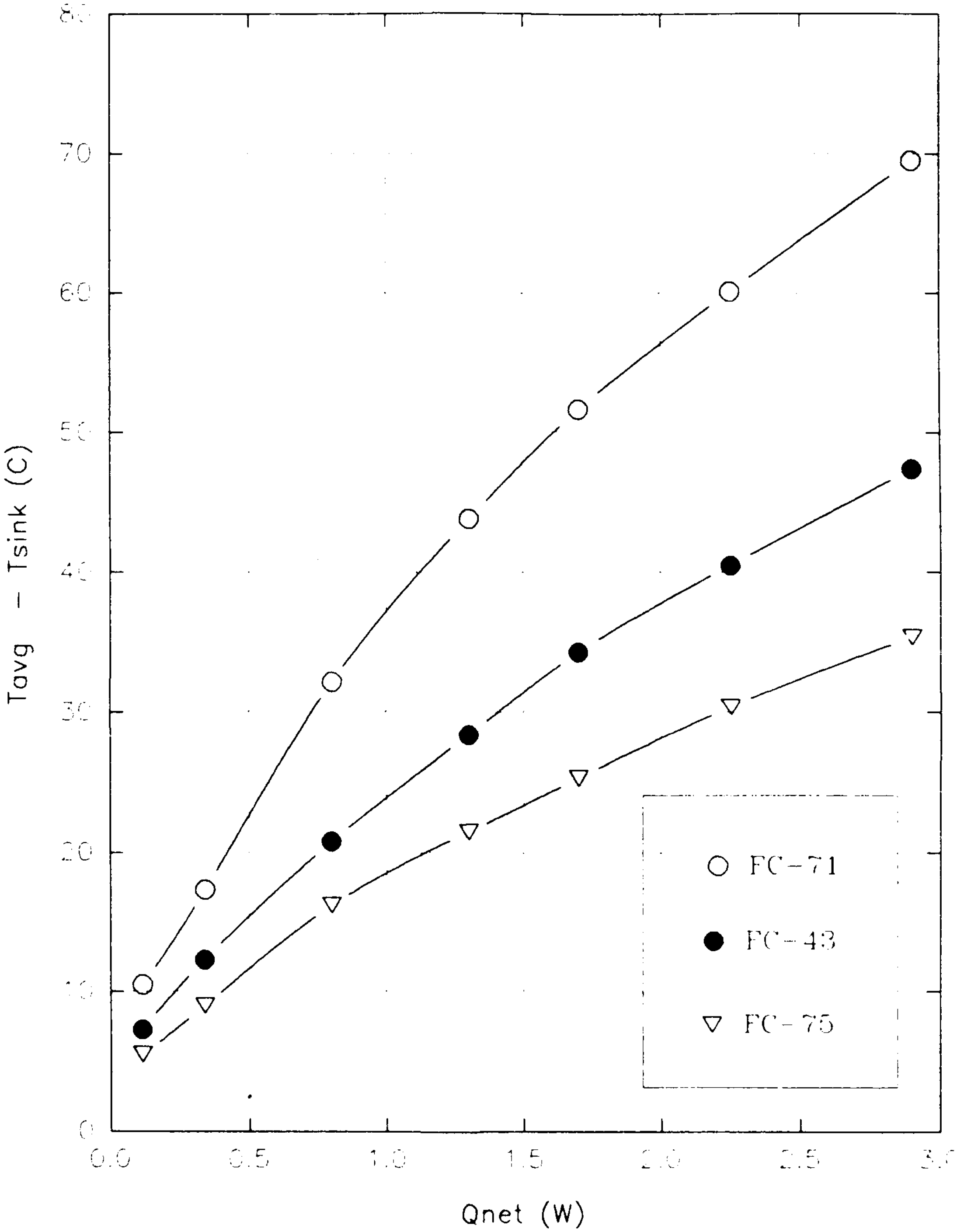

Figure 11. Array Average Temperature vs. Net Power for FC-71, 43, and 75, 9 mm Spacing, Vertical Orientation

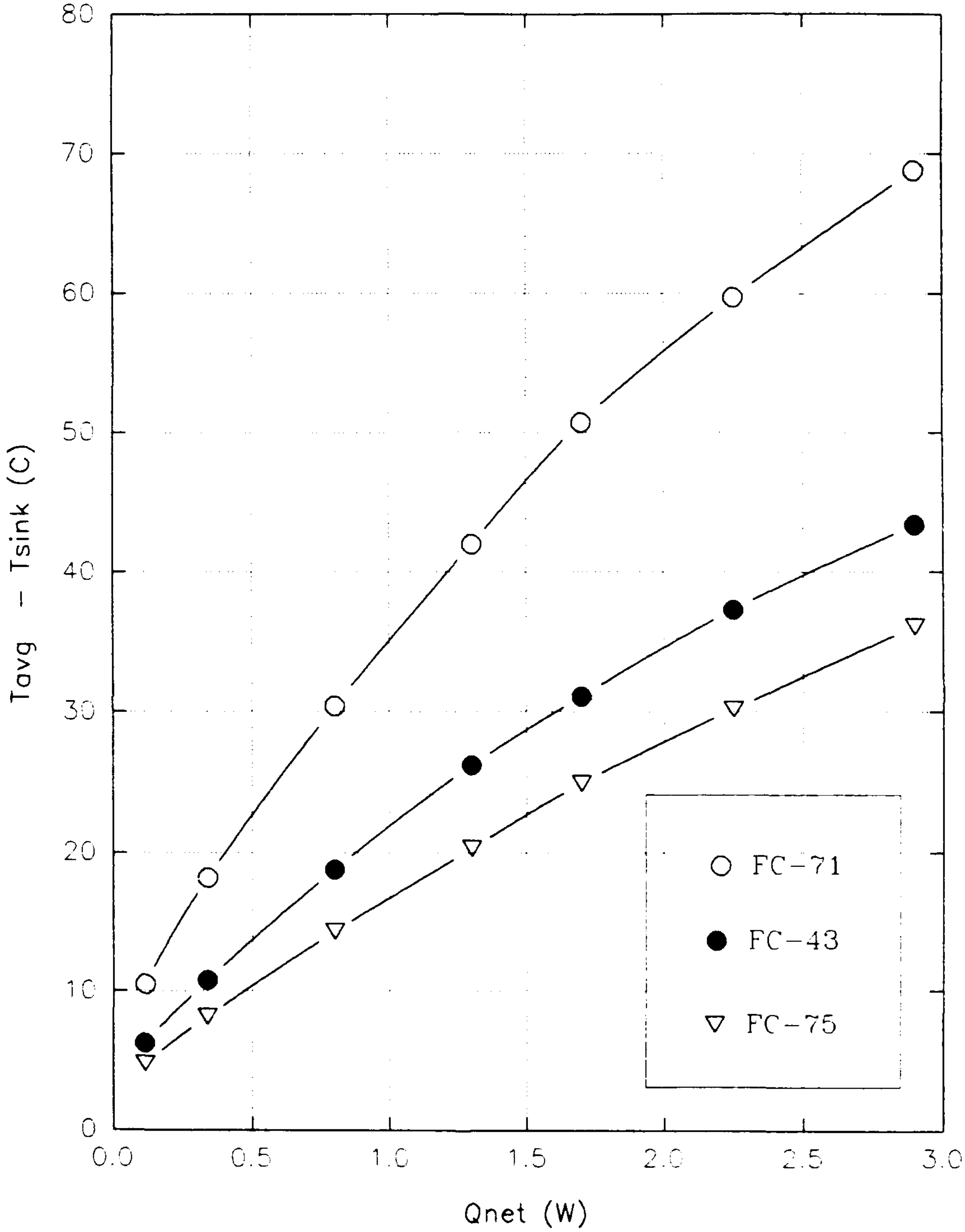

Figure 12. Array Average Temperature vs. Net Power for FC-71, 43, and 75, 16 mm Spacing, Vertical Orientation

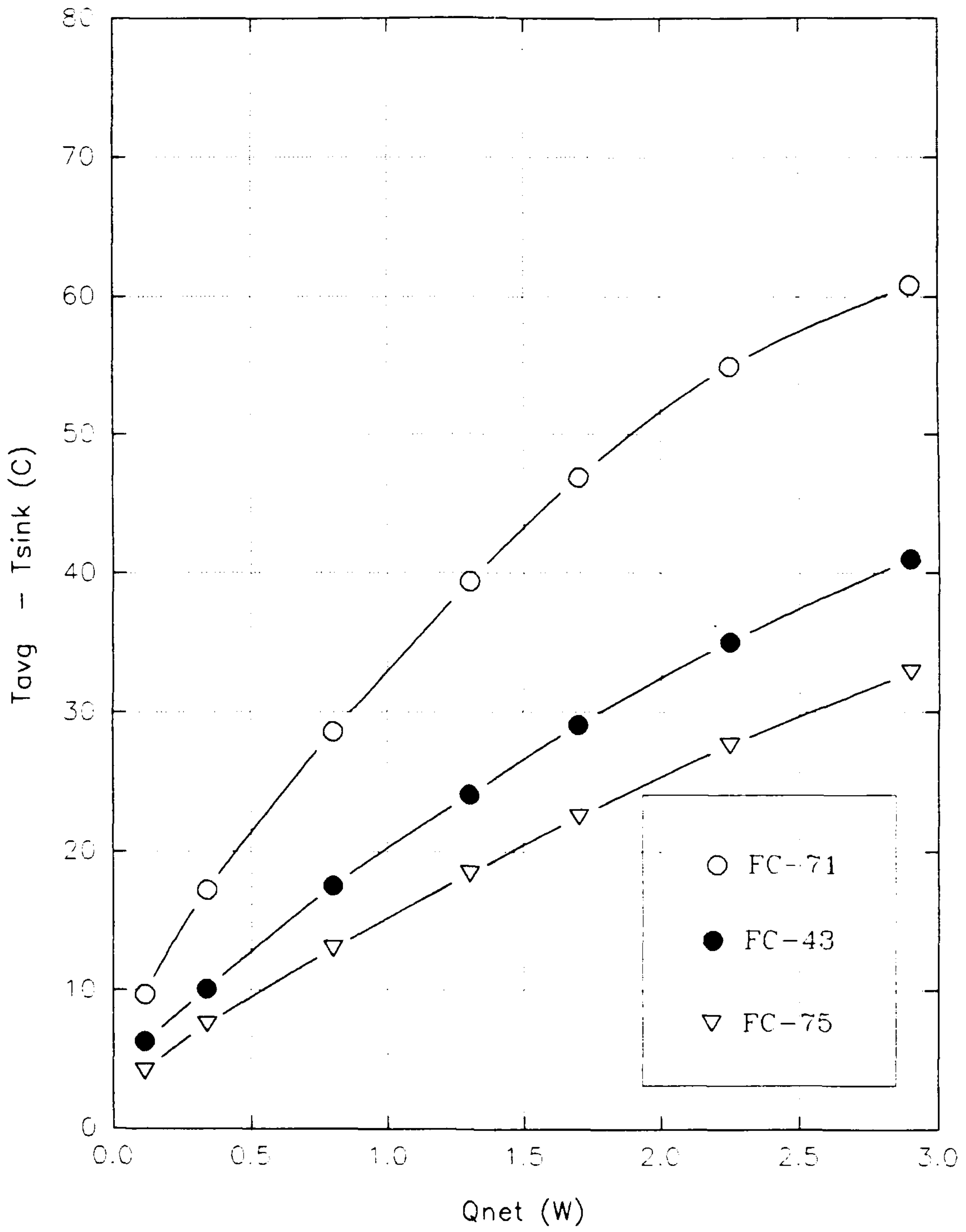

Figure 13. Array Average Temperature vs. Net Power for FC-71, 43, and 75, 28 mm Spacing, Vertical Orientation

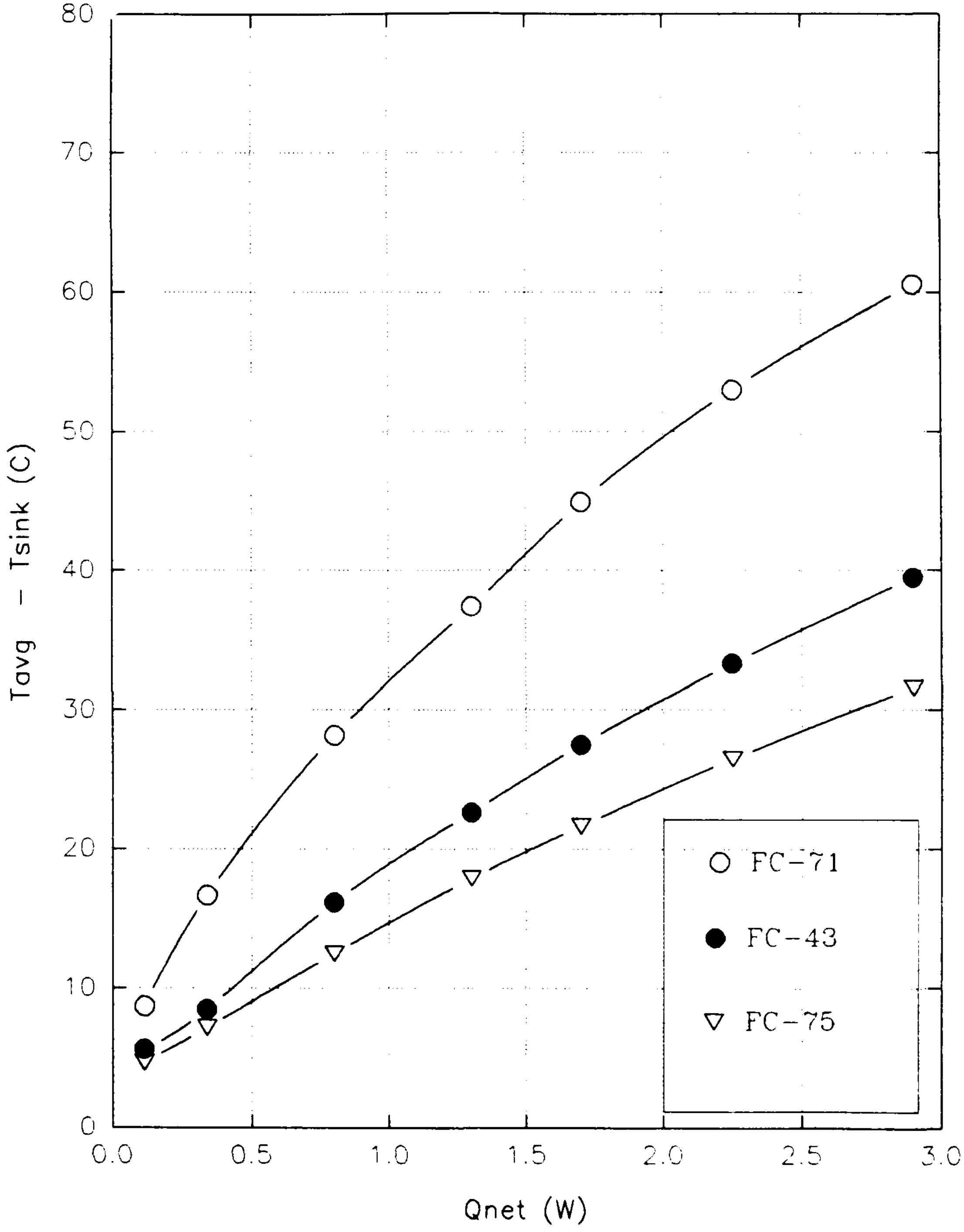

Figure 14. Array Average Temperature vs. Net Power for FC-71, 43, and 75, 40 mm Spacing, Vertical Orientation

For the 0.115 W power level, only 0.5 °C or less separated all chip temperatures for the 7, 9, and 16 mm spacings. This is within the uncertainty of the thermocouple measurement.

C. NON-DIMENSIONAL RESULTS

1. General

The following maximums and minimums for all power levels and enclosure widths were noted:

- The maximum value of the flux based Rayleigh number, Ra_f, was 616.4×10^6. It occurred on chip #3 at a 2.9 W power level and 7 mm spacing. The minimum Ra_f was 1.417×10^6 on chip #7 at 0.115 W and a 40 mm spacing.
- The maximum temperature based Rayleigh number, Ra, was 31.11×10[illegible]. It occurred on chip #3 under the same conditions as the Ra_f maximum listed above. The minimum Ra was 190,000 on chip #7 at 0.115 W and a 40 mm spacing.
- The maximum Nu was 28.88 on chip #4 at 2.9 W and a 28 mm spacing. The minimum Nu of 5.40 was noted on chip #7 at 0.115 W and a 7 mm spacing.
- The maximum uncertainty in Ra and Nu were 6.90% and 7.39%, respectively. Both values were calculated on chip #7 at a power of 0.115 W and a spacing of 9 mm.

Both Aytar and Matthews plotted the array averaged Nu as a function of either the array averaged Ra_f or Ra. When the data taken at 0.115 W was omitted, it was found that these plots were straight lines, independent of enclosure width. This was done since the uncertainty was highest at this power level, and the resulting chip temperatures were less than or equal to the ambient temperature. Figure 15 is a similar plot for FC-71. For comparison, Nu versus Ra for all three dielectric liquids have been plotted for each enclosure width in Figure 16 through Figure 20. In these figures, it is noted that the slopes of any particular dielectric liquid are virtually identical in nature.

2. Effect of Rayleigh Number

Matthews and Aytar both observed a linear relationship when log Nu was plotted against log Ra. This relationship was of the following form:

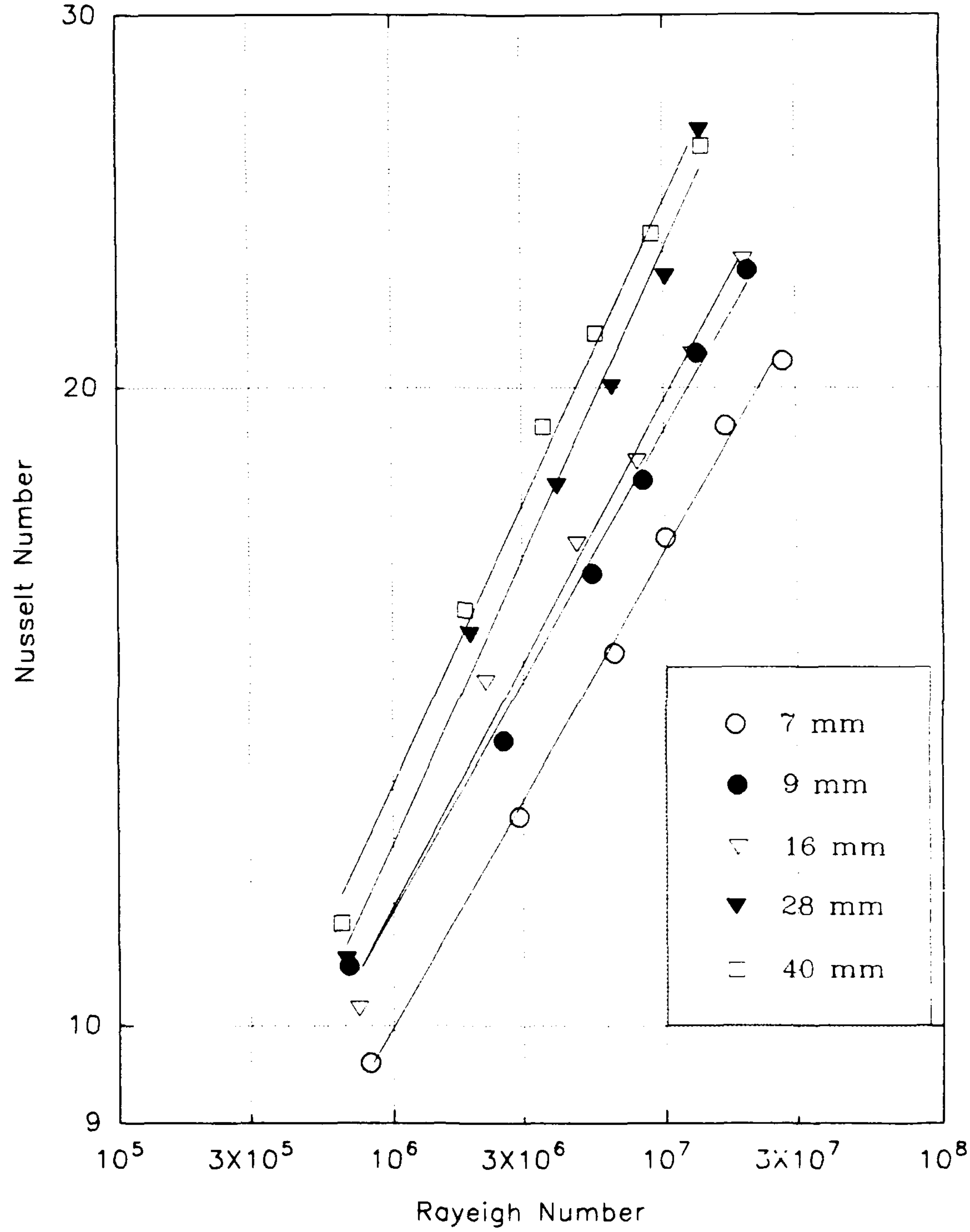

Figure 15. Nu vs. Ra for FC-71, Array Averaged, Vertical Orientation, and all Enclosure Widths

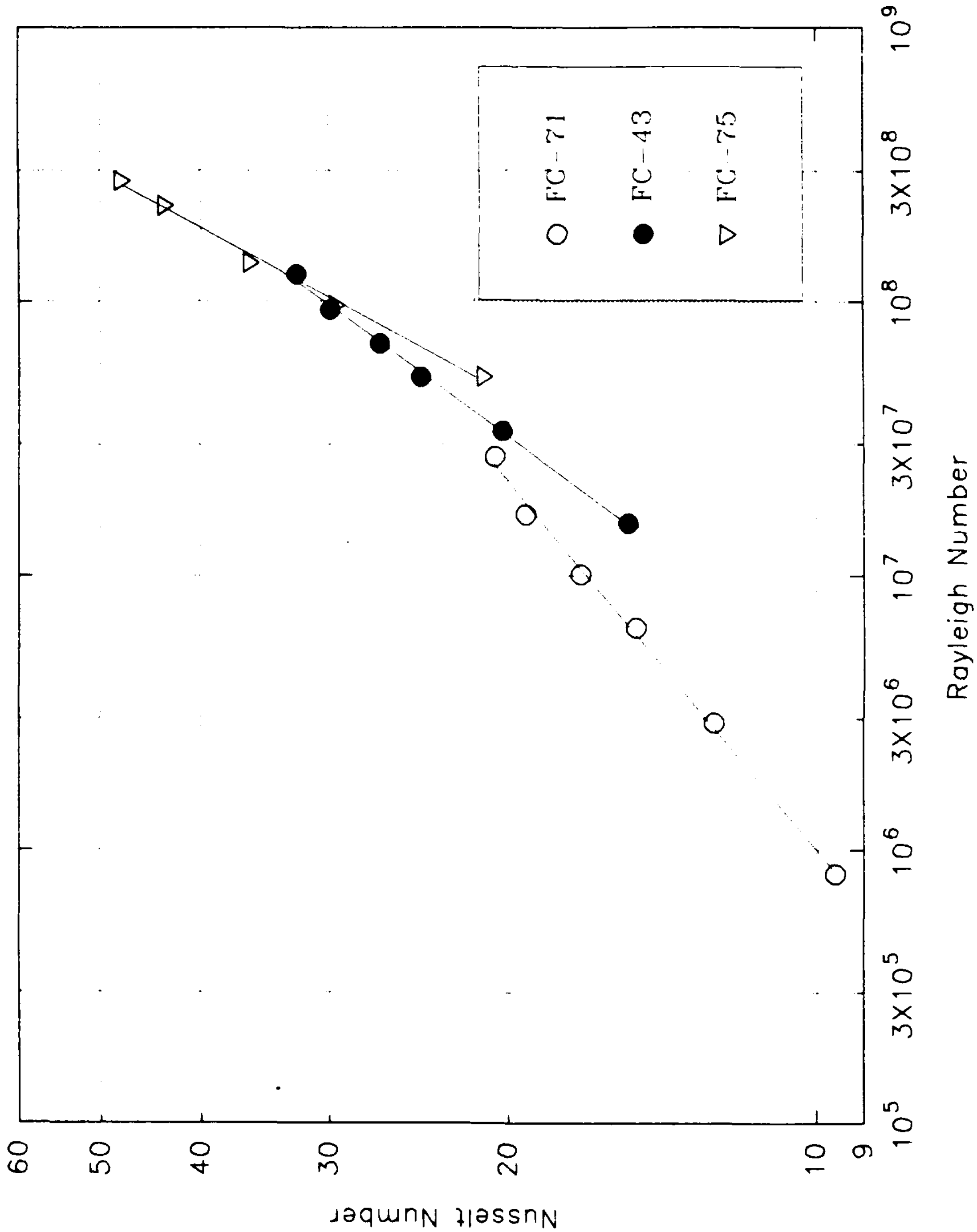

Figure 16. Nu vs. Ra for FC-71, 43, and 75, Array Averaged, Vertical Orientation, and 7 mm Enclosure Width

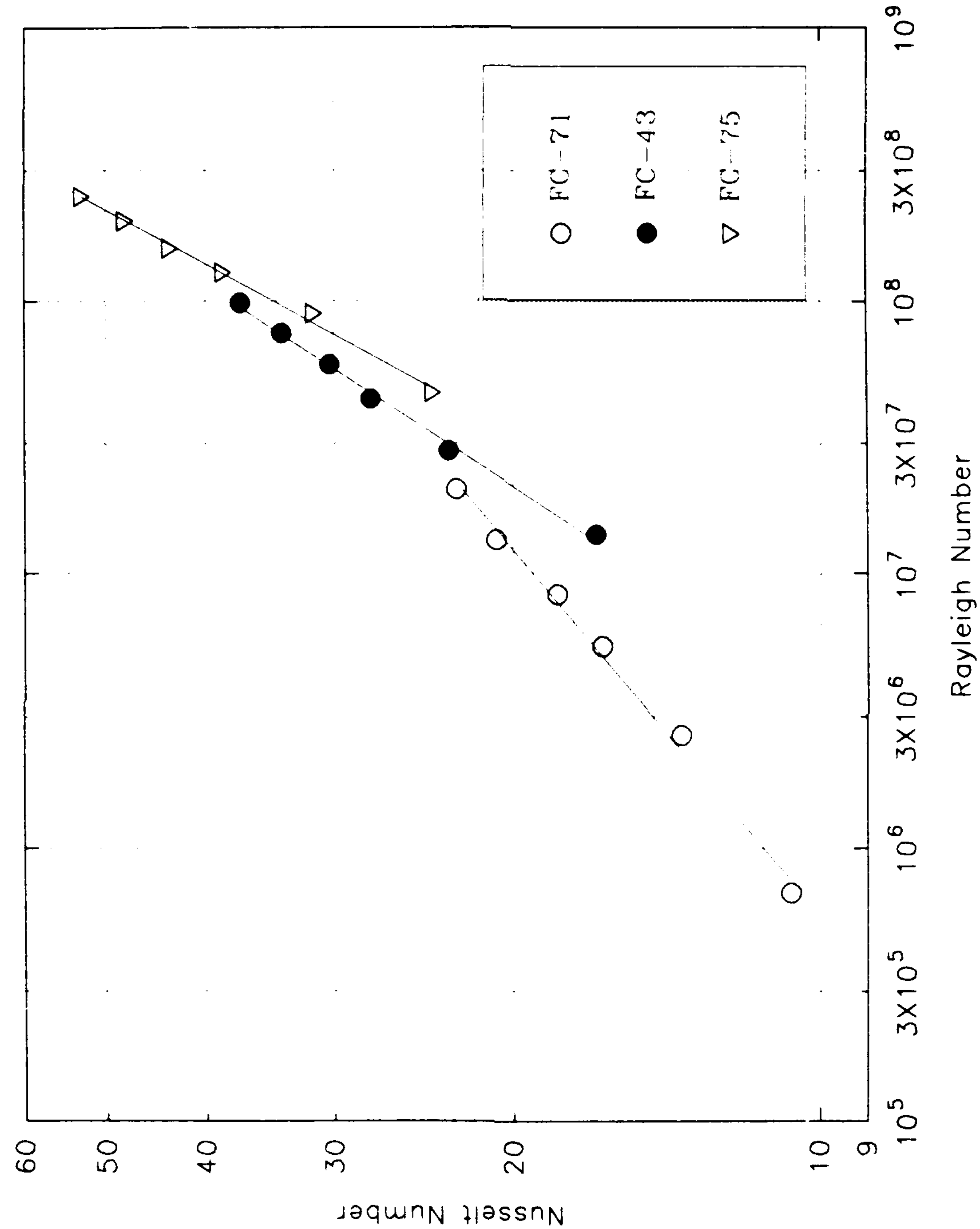

Figure 17. Nu vs. Ra for FC-71, 43, and 75, Array Averaged, Vertical Orientation, and 9 mm Enclosure Width

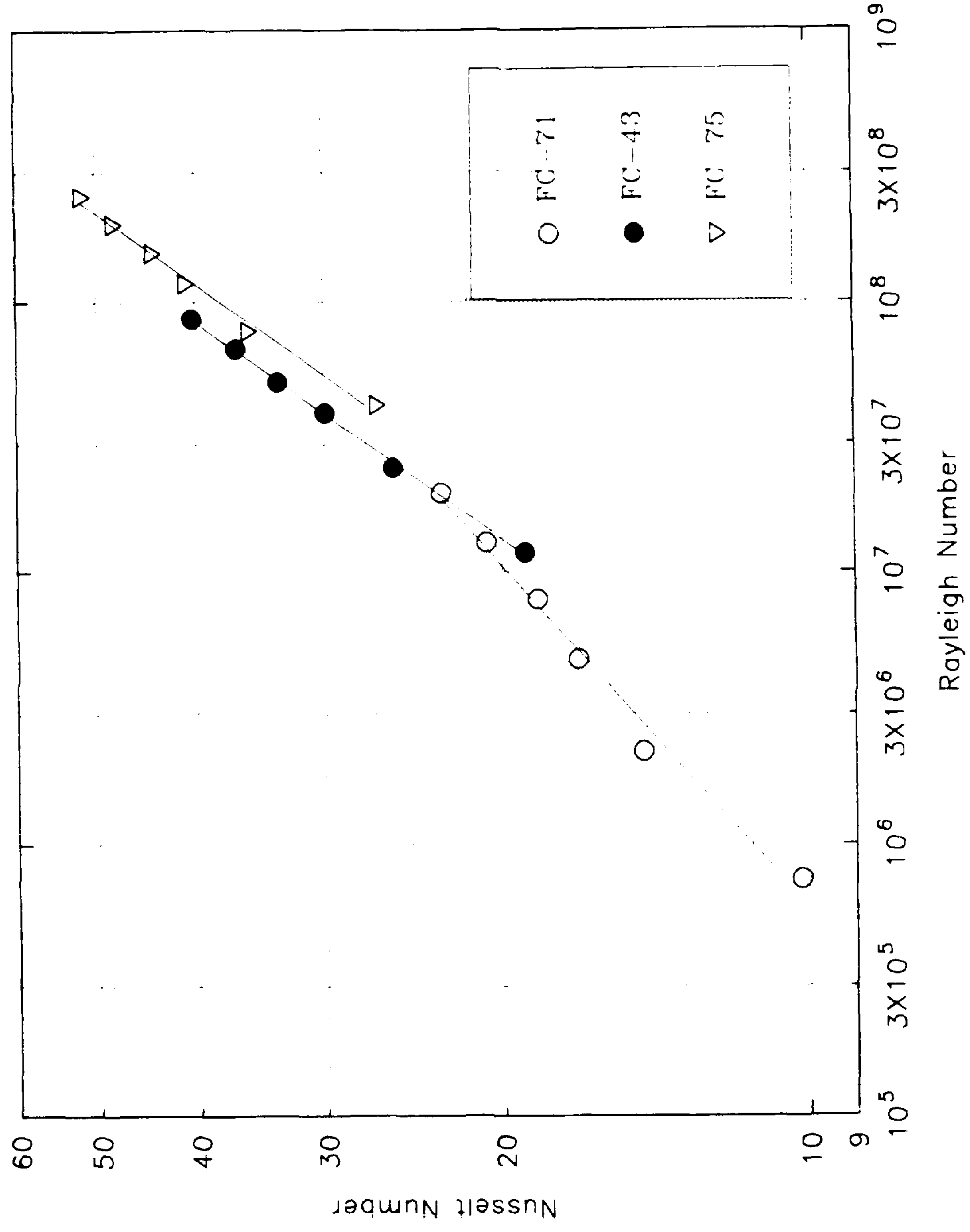

Figure 18. Nu vs. Ra for FC-71, 43, and 75, Array Averaged, Vertical Orientation, and 16 mm Enclosure Width

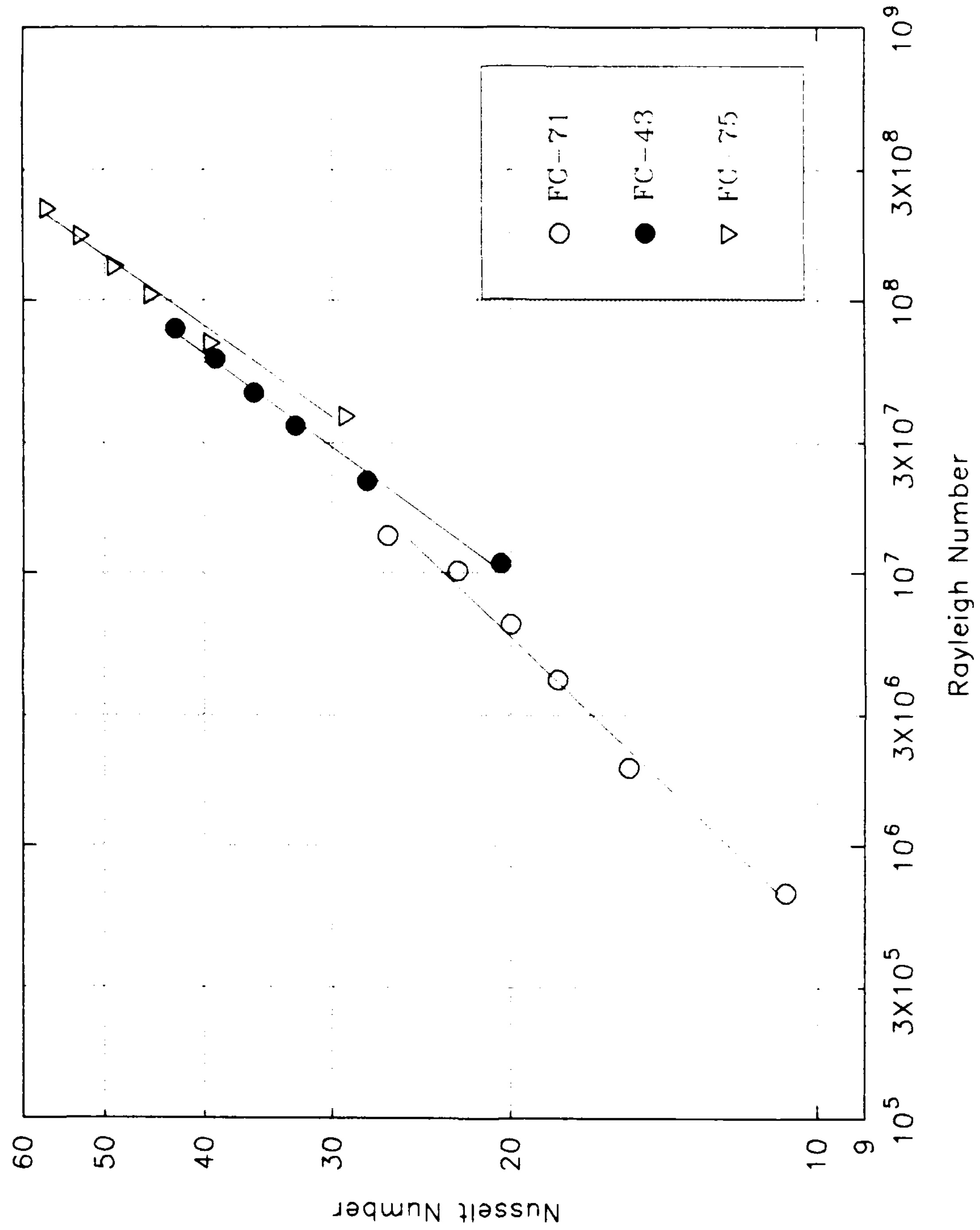

Figure 19. Nu vs. Ra for FC-71, 43, and 75, Array Averaged, Vertical Orientation, and 28 mm Enclosure Width

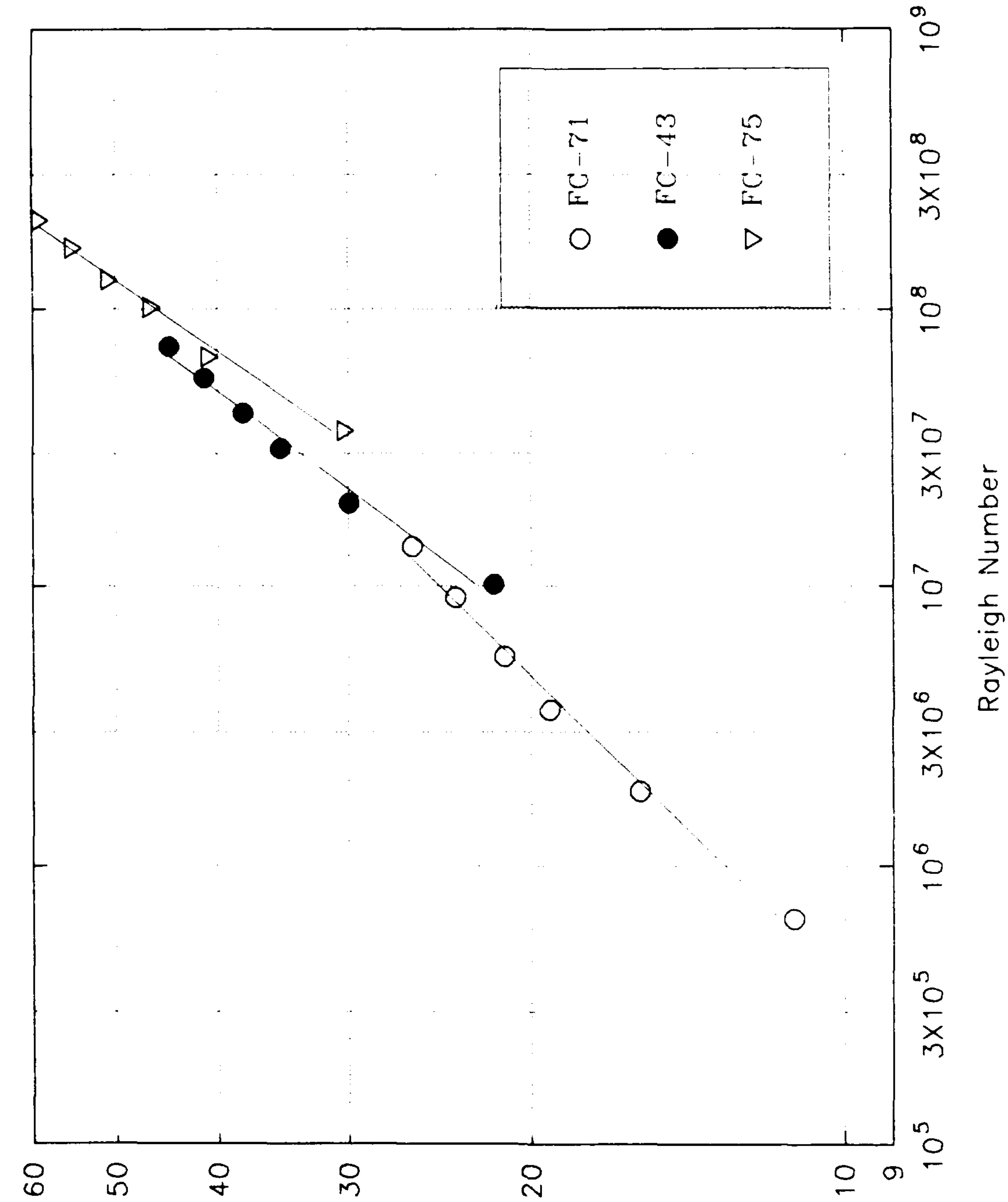

Figure 20. Nu vs. Ra for FC-71, 43, and 75, Array Averaged, Vertical Orientation, and 40 mm Enclosure Width

$$Nu = c_1 Ra^{b1}$$

where c_1 and b1 are constants. Both row averaged and array averaged values were calculated and plotted for each spacing. The curve fit software TABLECURVE (1990) was used to find the coefficients of the above equation, and the software package SIGMAPLOT (1989) was used to produce the graphs. Again, for consistency and correlation accuracy, the data taken at 0.115 W was omitted.

Figure 21 through Figure 25 are the FC-71 data array averaged Nu versus Ra plots for the five spacings. The corresponding curve fit equation is also included. For completeness, Figure 26 through 40 are similar plots for the spacings using row averaged data. The value of the constant b1 was found to vary from 0.225 to 0.280 for the array averaged data. The average value of b1 was 0.249. Corresponding values of 0.381 and 0.371 were reported by Matthews for FC-75 and FC-43, respectively. The constant c_1 varied from 0.255 to 0.514 for the same array averaged data, and the average value of c_1 was 0.383.

3. Effect of Enclosure Width

Enclosure width effects on Nu were accounted for in the following equation:

$$Nu = c_2 X^{b2}$$

where b2 is a constant and c_2 is the Ra dependence. X is the non-dimensional enclosure width, which is the ratio of the actual spacing to the maximum spacing of 40 mm. The constant c_2 can be represented by:

$$c_2 = c_1 Ra^{b1}$$

The constant b2 was derived from a plot of Nu vs. X for the five spacings, which is shown in Figure 41. The values for Nu were taken from the curve fit equations for each spacing's array averaged data using an average Ra of 4×10^6. The resulting value for the exponent b2 was 0.165.

Combining the above results gives the following general correlation for FC-71:

$$Nu = 0.383 Ra^{0.249} X^{0.165}$$

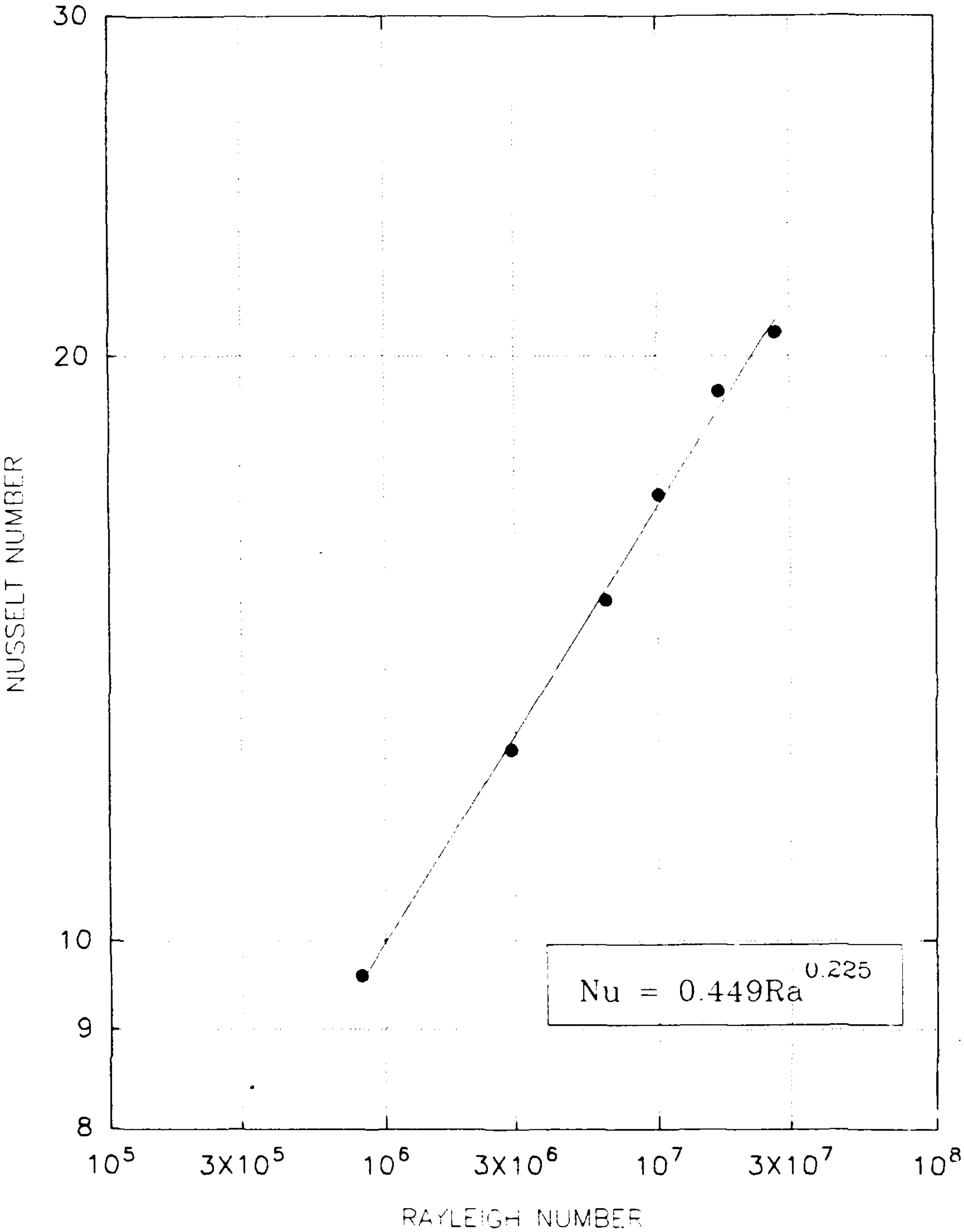

Figure 21. Nu vs. Ra for FC-71, Array Averaged, Vertical Orientation, and 7 mm Spacing

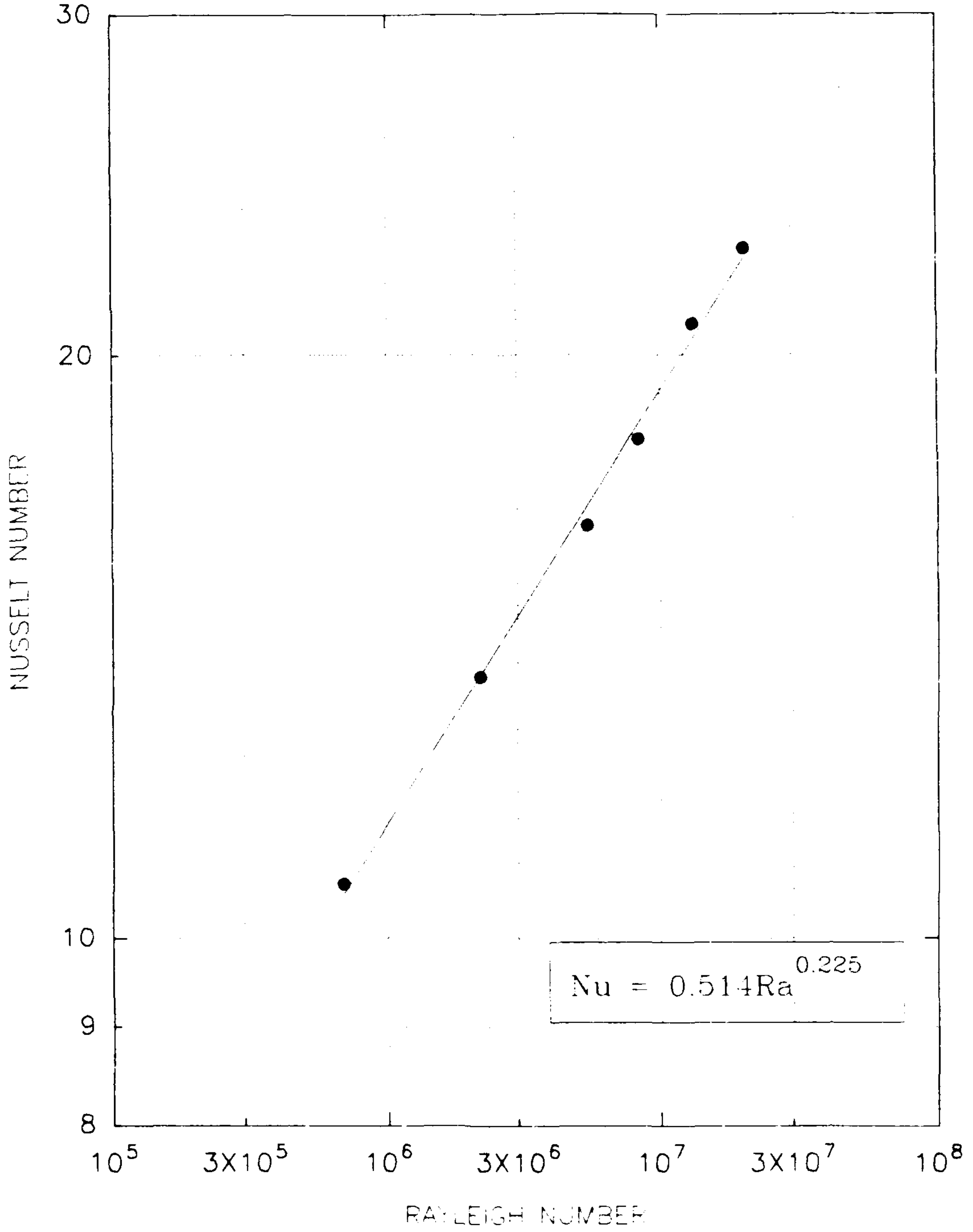

Figure 22. Nu vs. Ra for FC-71, Array A eraged, Vertical Orientation, and 9 mm Spacing

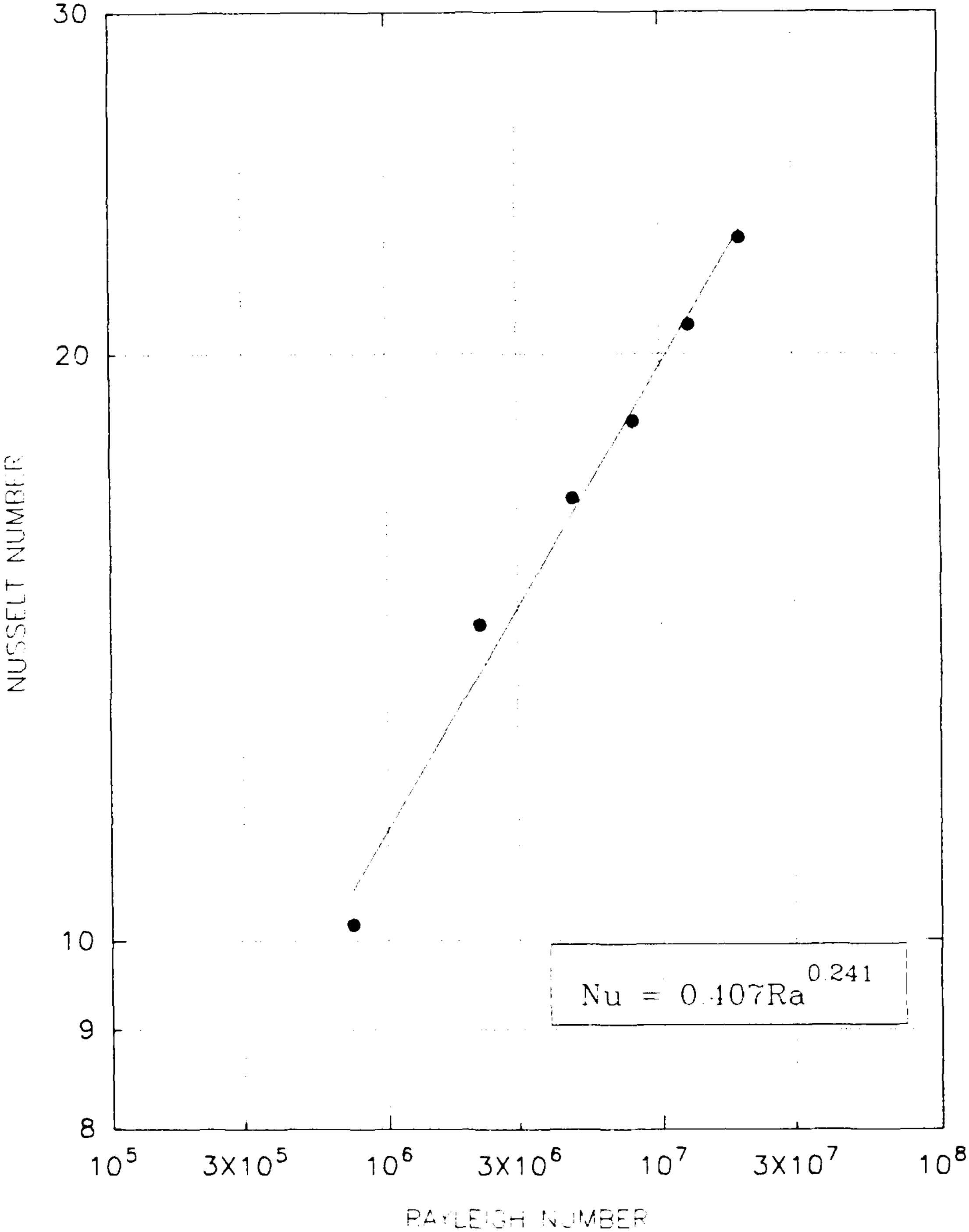

Figure 23. Nu vs. Ra for FC-71, Array Averaged, Vertical Orientation, and 16 mm Spacing

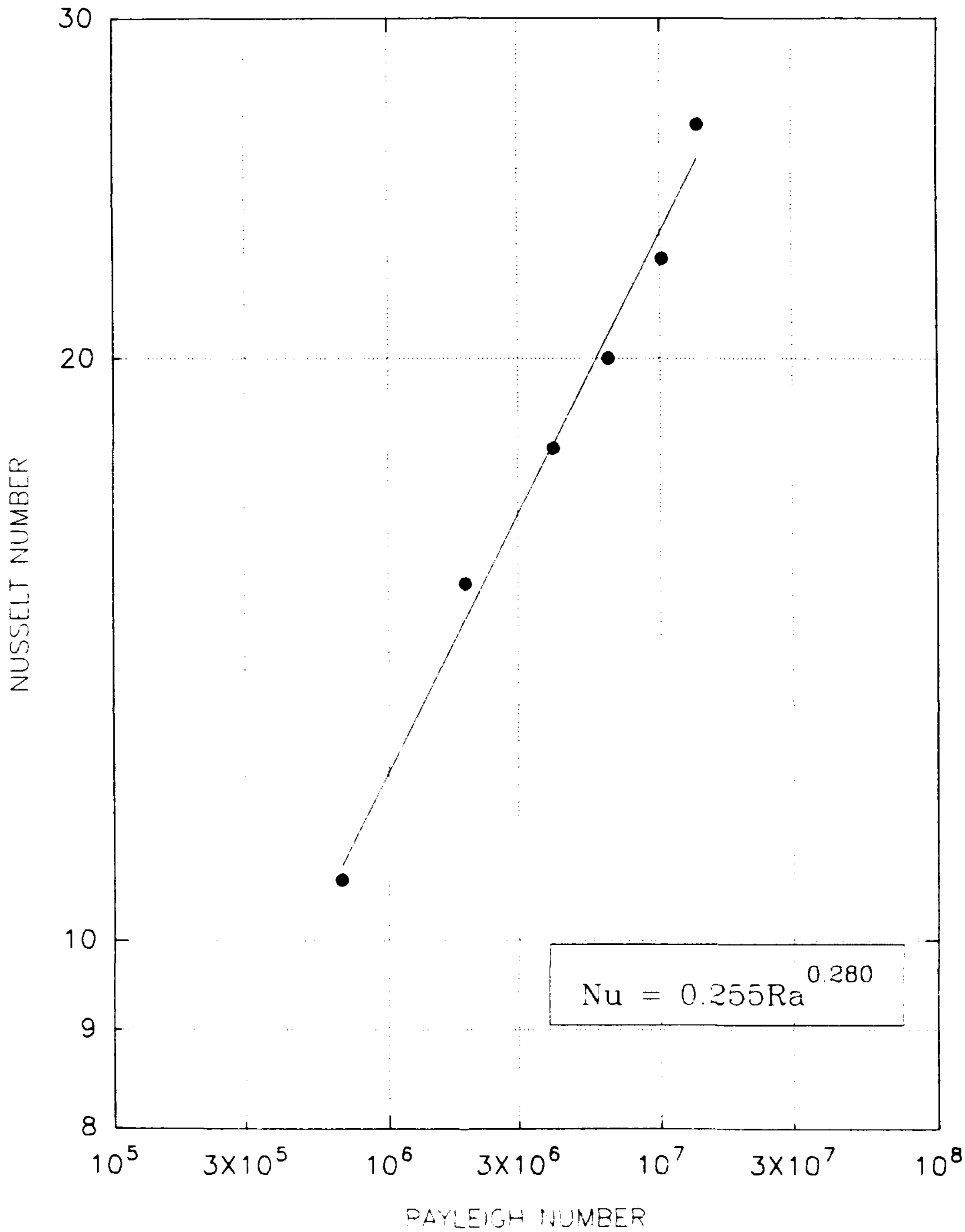

Figure 24. Nu vs. Ra for FC-71, Array Averaged, Vertical Orientation, and 28 mm Spacing

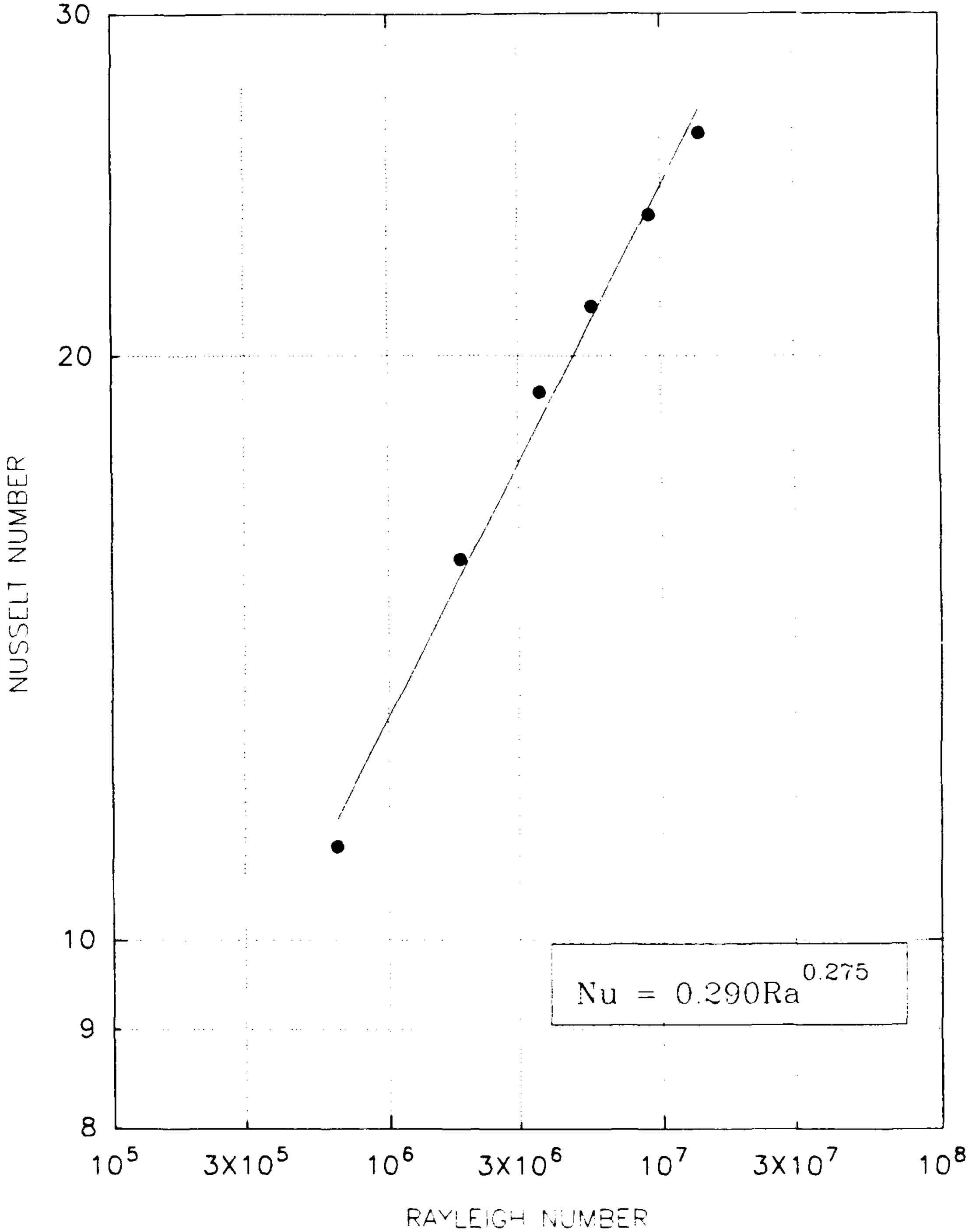

Figure 25. Nu vs. Ra for FC-71, Array Averaged, Vertical Orientation, and 40 mm Spacing

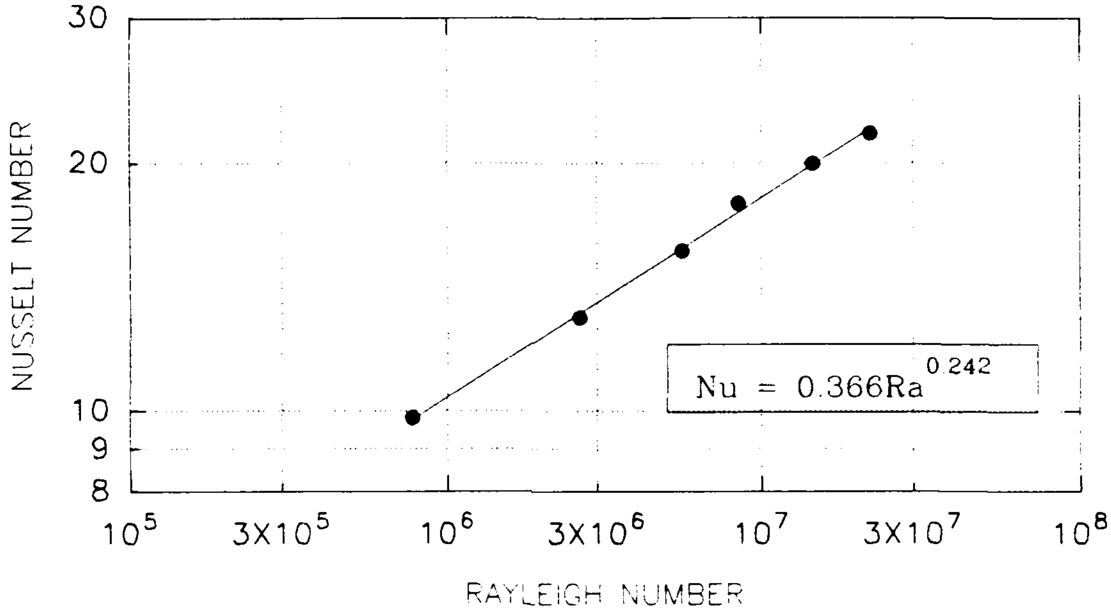

Figure 26. Nu vs. Ra for FC-71, Bottom Row Averaged, Vertical Orientation, and 7 mm Spacing

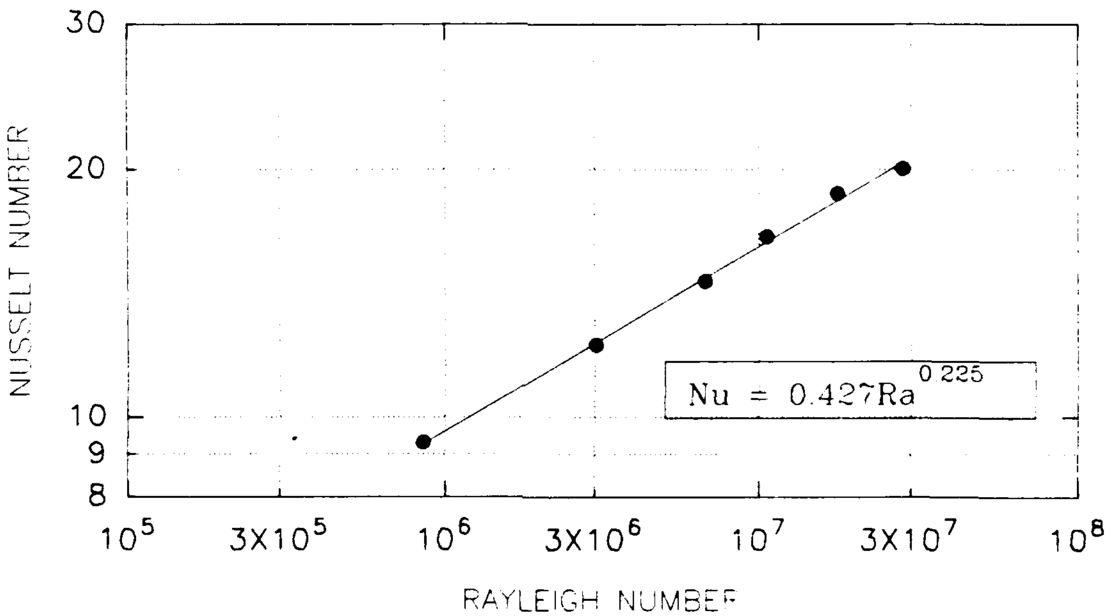

Figure 27. Nu vs. Ra for FC-71, Middle Row Averaged, Vertical Orientation, and 7 mm Spacing

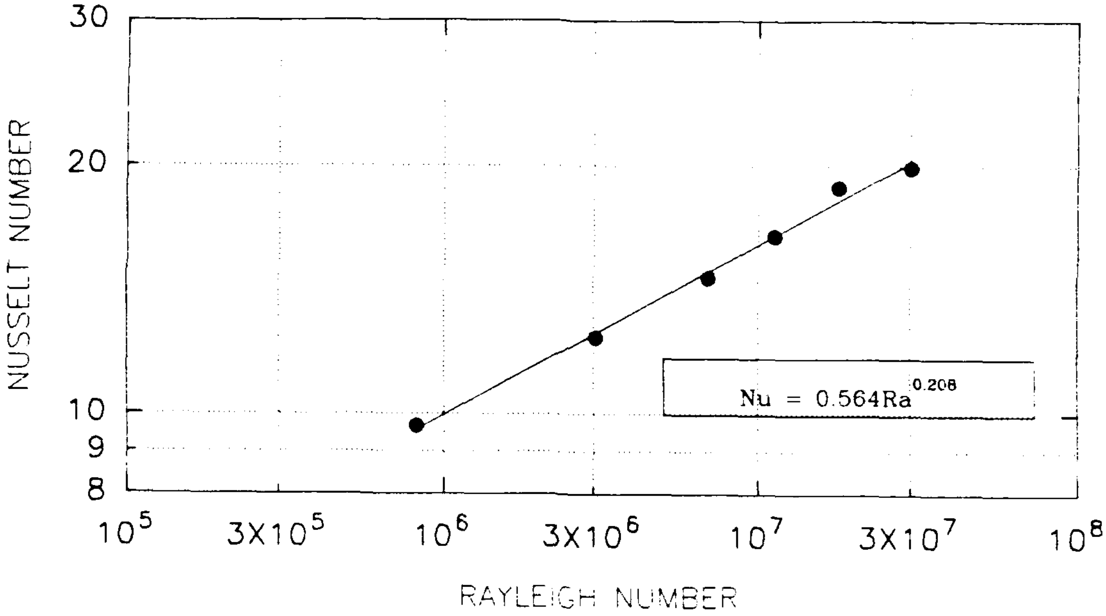

Figure 28. Nu vs. Ra for FC-71, Top Row Averaged, Vertical Orientation, and 7 mm Spacing

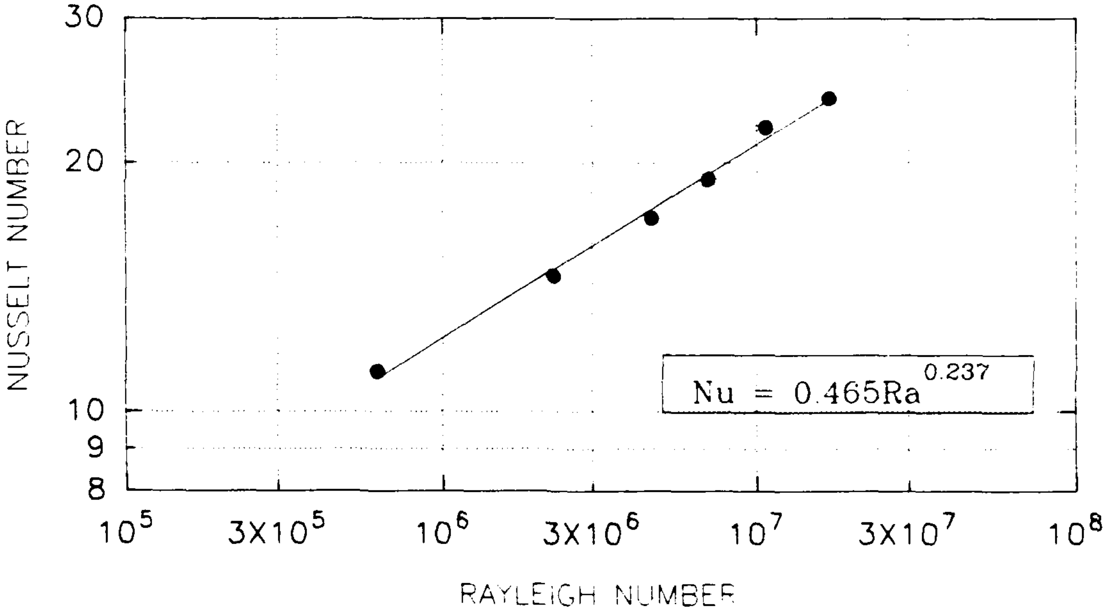

Figure 29. Nu vs. Ra for FC-71, Bottom Row Averaged, Vertical Orientation, and 9 mm Spacing

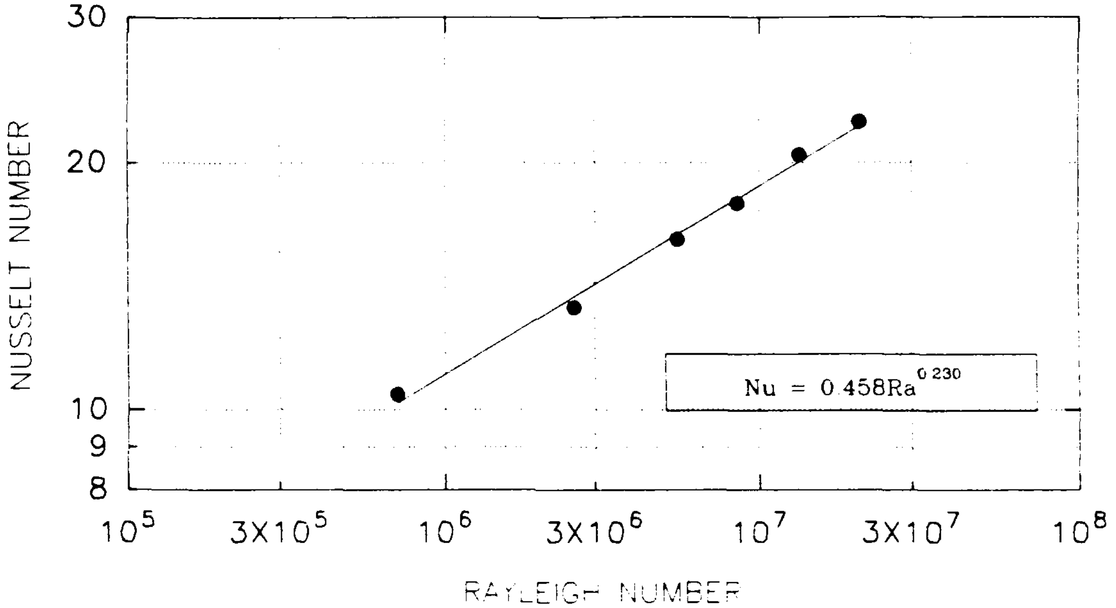

Figure 30. Nu vs. Ra for FC-71, Middle Row Averaged, Vertical Orientation, and 9 mm Spacing

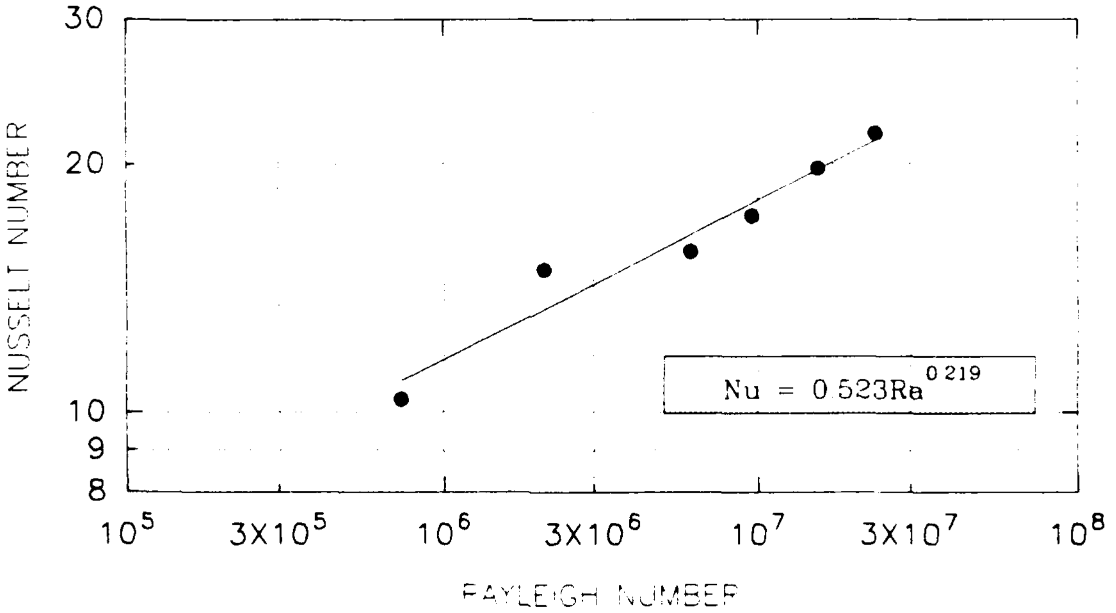

Figure 31. Nu vs. Ra for FC-71, Top Row Averaged, Vertical Orientation, and 9 mm Spacing

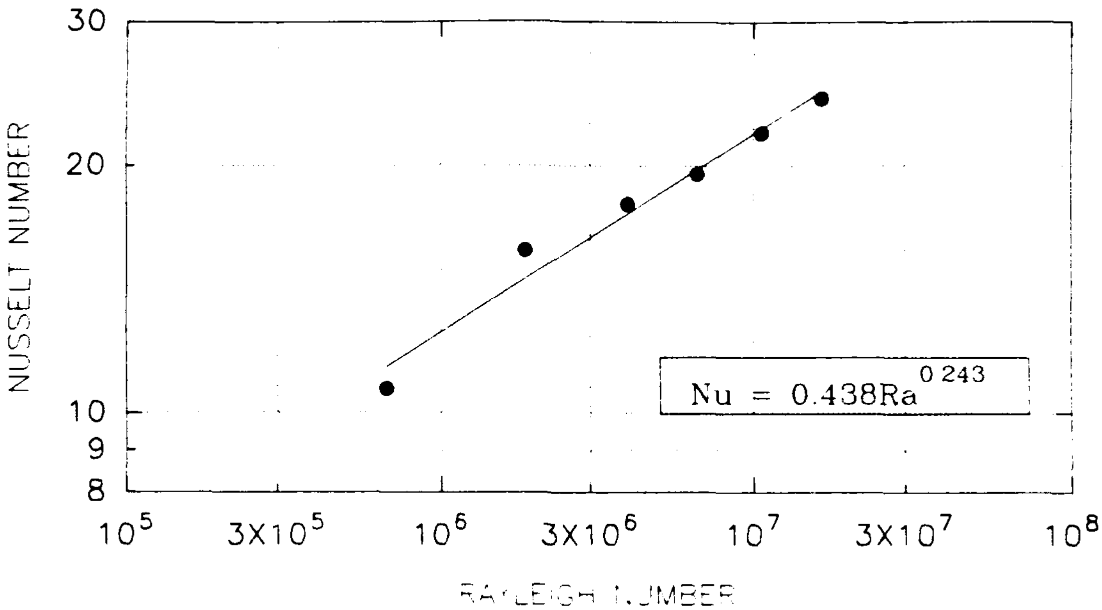

Figure 32. Nu vs. Ra for FC-71, Bottom Row Averaged, Vertical Orientation, and 16 mm Spacing

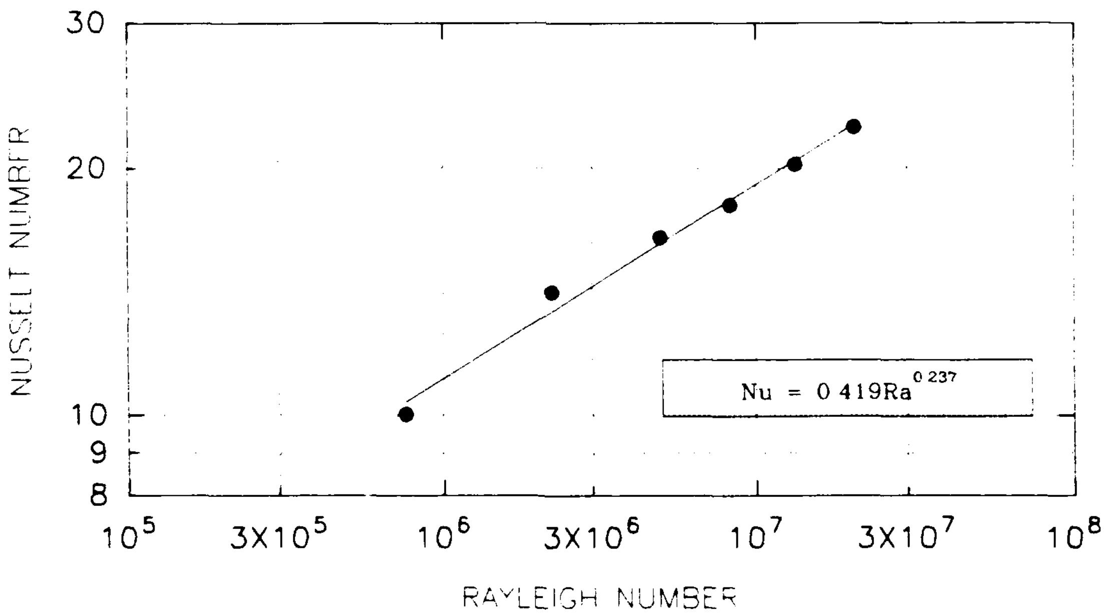

Figure 33. Nu vs. Ra for FC-71, Middle Row Averaged, Vertical Orientation, and 16 mm Spacing

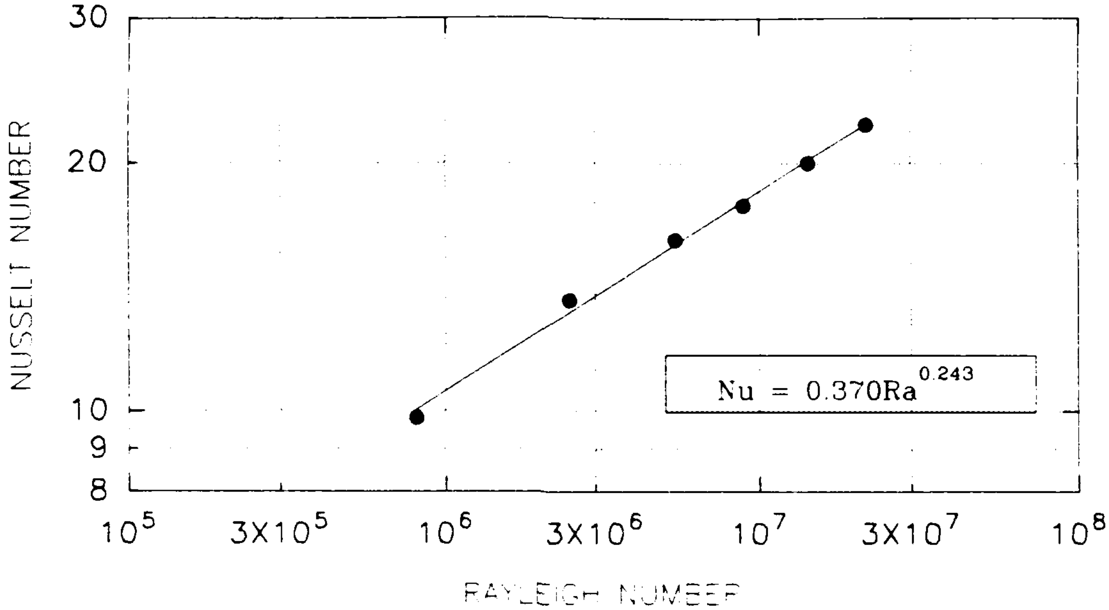

Figure 34. Nu vs. Ra for FC-71, Top Row Averaged, Vertical Orientation, and 16 mm Spacing

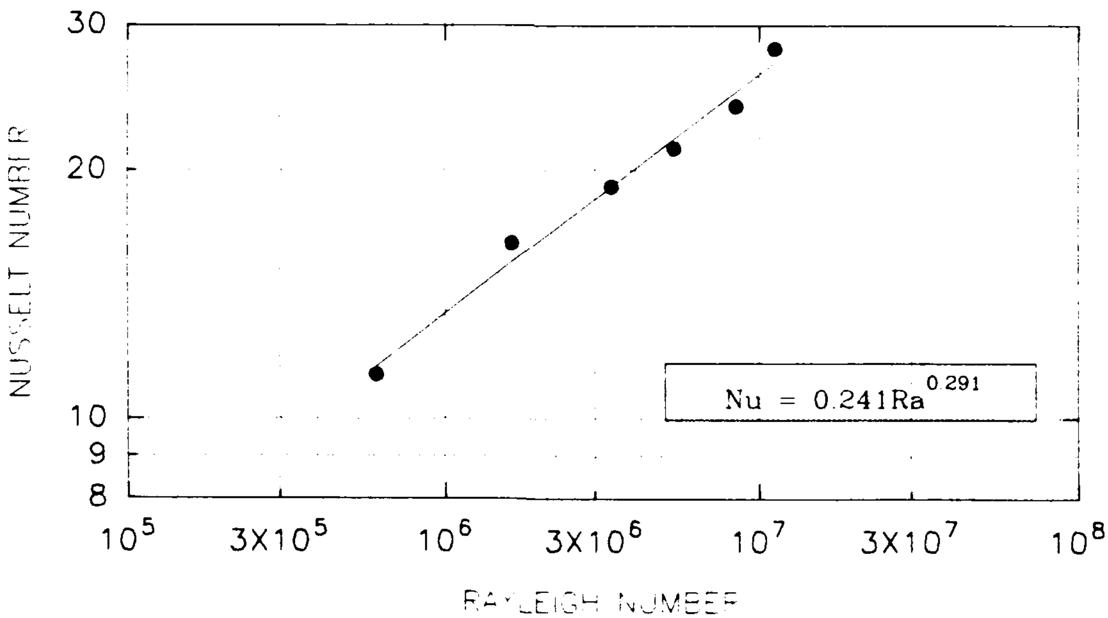

Figure 35. Nu vs. Ra for FC-71, Bottom Row Averaged, Vertical Orientation, and 28 mm Spacing

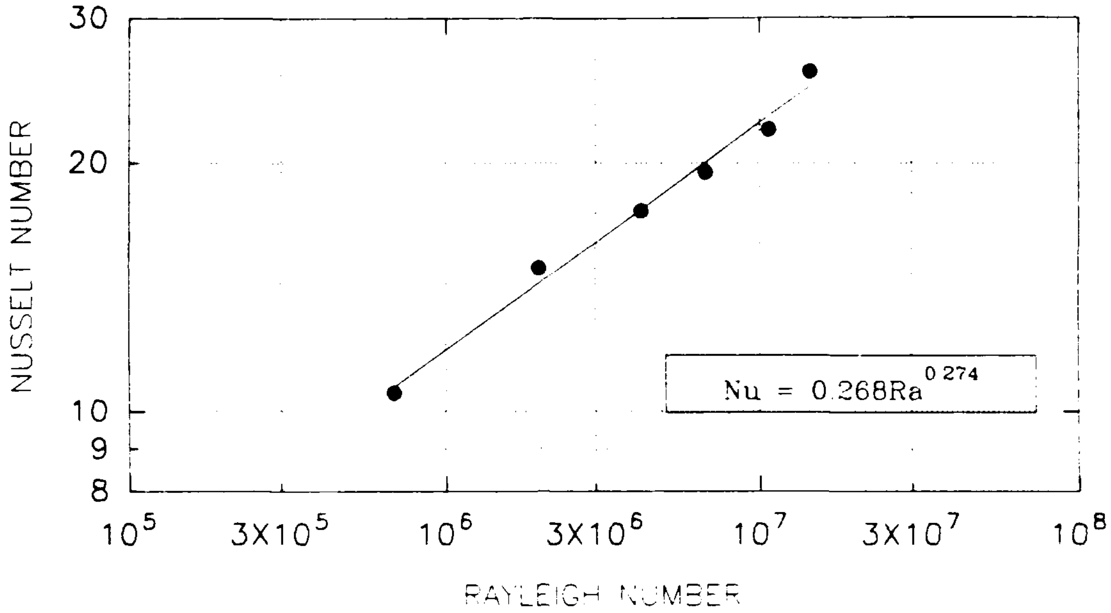

Figure 36. Nu vs. Ra for FC-71, Middle Row Averaged, Vertical Orientation, and 28 mm Spacing

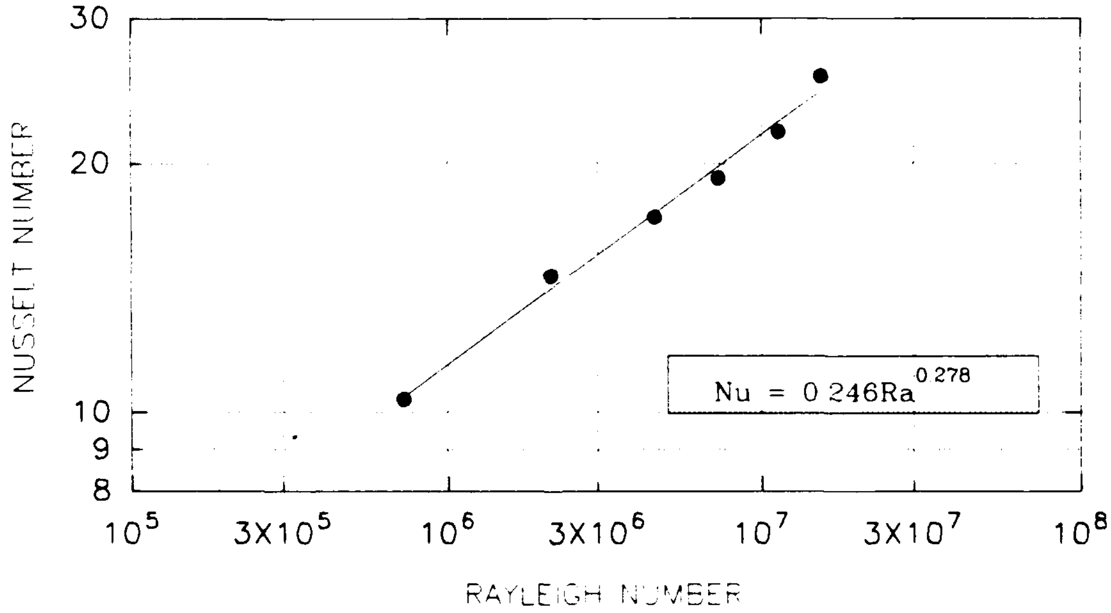

Figure 37. Nu vs. Ra for FC-71, Top Row Averaged, Vertical Orientation, and 28 mm Spacing

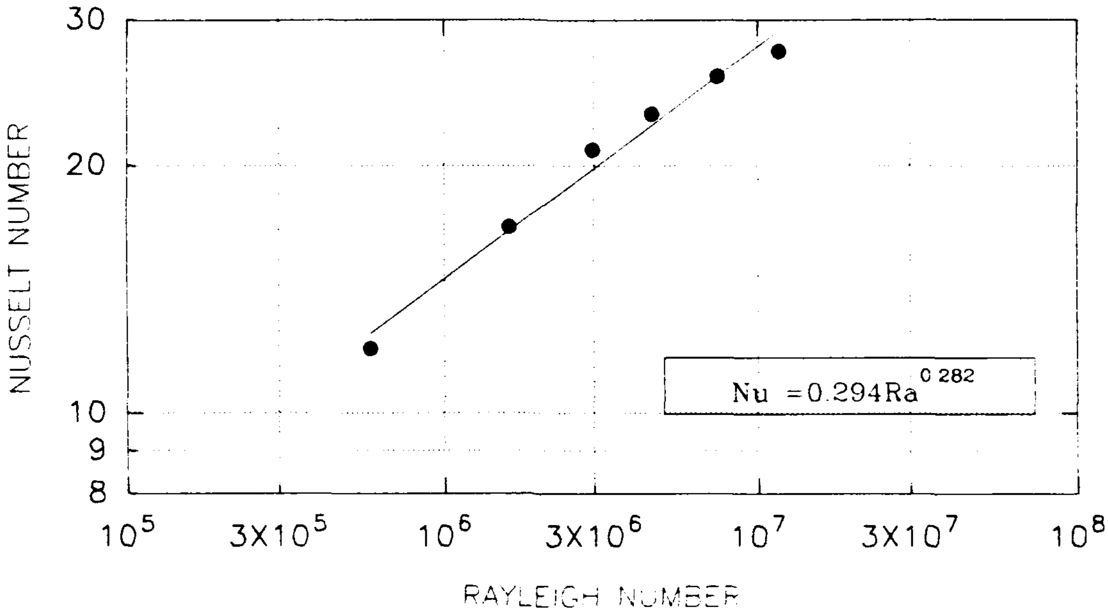

Figure 38. Nu vs. Ra for FC-71, Bottom Row Averaged, Vertical Orientation, and 40 mm Spacing

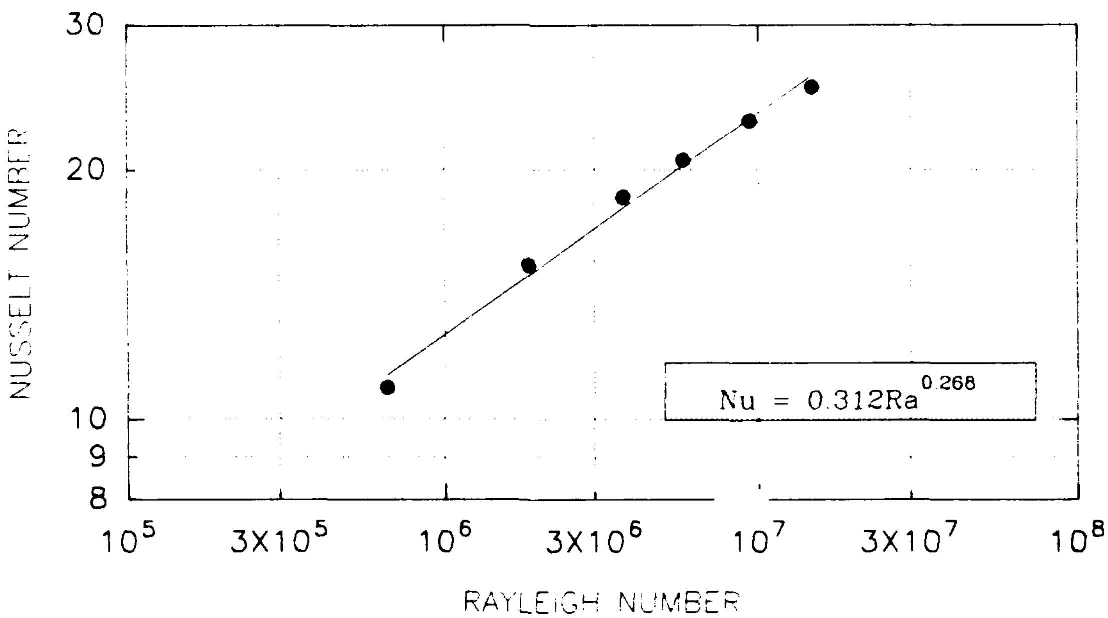

Figure 39. Nu vs. Ra for FC-71, Middle Row Averaged, Vertical Orientation, and 40 mm Spacing

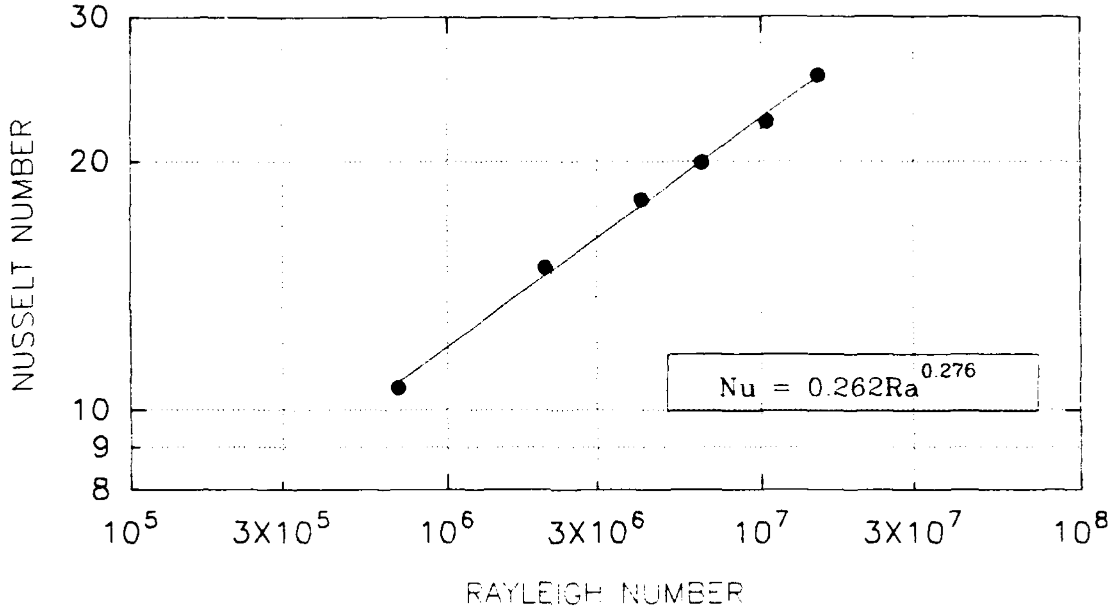

Figure 40. Nu vs. Ra for FC-71, Top Row Averaged, Vertical Orientation, and 40 mm Spacing

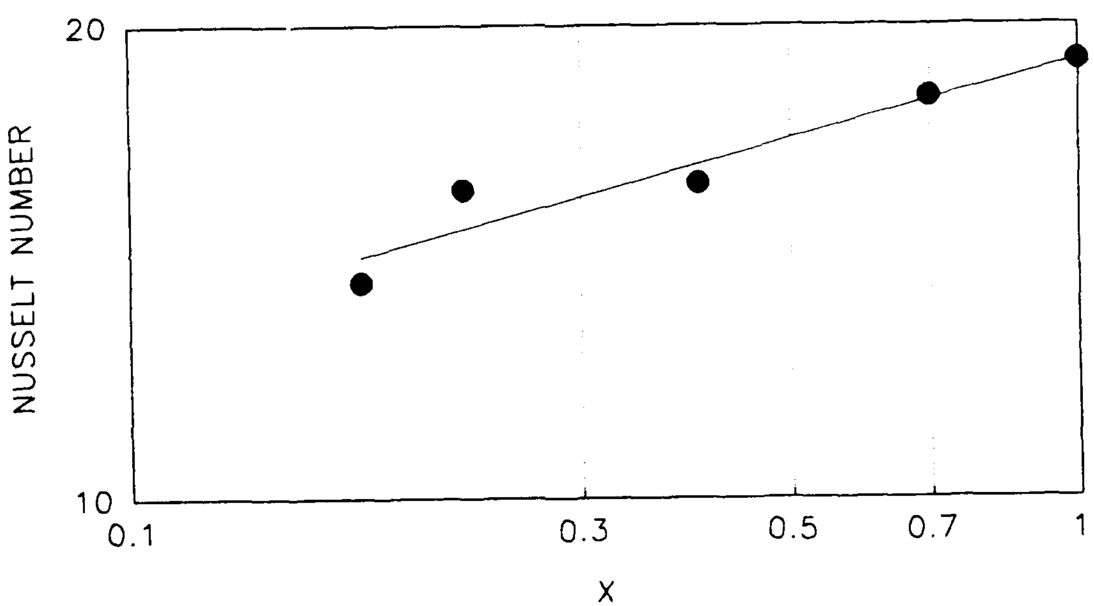

Figure 41. Nu vs. X for FC-71, Array Averaged, Vertical Orientation, and all Enclosure Widths

It is valid over the ranges:

$$9 \times 10^5 < Ra < 2 \times 10^7$$

$$0.175 < X < 1.0$$

However, this correlation was found to be accurate only to within 11% of the array averaged curve fit equations. In order to achieve improved accuracy, representative values of Ra were chosen for the general correlation and each spacing's correlation. The Nu number results were then compared, and a trial and error approach was used to come up with a better value for c_1. When the value for c_1 was changed from 0.383 to 0.435, the accuracy improved to 4%. Therefore, a better correlation for FC-71 is:

$$Nu = 0.435 Ra^{0.249} X^{0.165}$$

It is valid over the same ranges as listed above.

VI. NSWC CIRCUIT BOARD RESULTS

A. GENERAL

The next logical step in the dielectric liquid natural convection studies was to replace simulated electronic components with the actual electronic devices. A three by three array of 8.9 mm square thermal evaluation devices were tested on a Plexiglas circuit board assembly of the same dimensions as the previous experiment. All three dielectric liquids were tested. Additionally, the same enclosure, spacers, and data acquisition equipment were used again. Due to manufacturing tolerances, the enclosure widths this time were 8, 10, 16, 28, and 40 mm. Power levels were chosen to match those of the previous studies, but they were limited to the 125 °C maximum temperature of the temperature sensing elements (TSEs) inside each chip. Therefore, TSE temperatures were purposely limited to about 100 °C to meet this criterion in conjunction with the TSE's calibration range. For FC-43 and FC-75, power levels of 0.34, 0.57, 0.8, 1.3, and 1.48 W/chip were chosen. For the typically hotter FC-71, the power levels were 0.34, 0.57, 0.8, and 1 0 W/chip. Note that the 0.115 W power level was completely eliminated due to lessons learned from the previous experiments.

A total of 70 data runs were recorded and analyzed for the three dielectric liquids. The analysis of the dimensional results is similar to Matthews' and Aytar's work, but the non-dimensional analysis is somewhat different. After the FC-75 and FC-43 data runs were complete, it was realized that plots of Nu versus Grashof number, Gr, were linear, independent of Pr or power level. Therefore, CALC2 was altered to compute Gr in parallel with Ra. Average Pr was also calculated. The data, stored on floppy disk with the ACQ2 program, was then re-run with the modified CALC2 program. The extensive non-dimensional data thus obtained was used to produce a correlation for Nu. The correlation is of the following form:

$$Nu = aGr^{b1}X^{b2}$$

where Nu is based on the chip dimension in the direction of gravity. X is again the non-dimensional enclosure width, and a, b1, and b2 are constants.

B. DIMENSIONAL RESULTS

1. FC-71

As before, $T_{avg} - T_{sink}$ was plotted against Q_{net} for all spacings. As it can be seen in Figure 42, the data is linear for all spacings. The maximum chip temperature of 75.4 °C occurred in chip #6 at a power level of 1.0 W and a spacing of 8 mm. For comparison purposes, the chip temperature data was also row averaged like the previous experiments. However, recall that temperature data for the top and bottom rows of TSEs was based on a single chip each.

For all spacings and power levels, the order of average row temperatures were always top > middle > bottom. As in the previous study, this pattern indicated the dominance of the buoyant forces over the viscous forces in the fluid. The maximum temperature difference between the top and middle rows was 1.4 °C. For the middle and bottom rows, it was 5.4 °C. These differences were noted at a power level of 1.0 W and a spacing of 8 mm.

The thermocouples installed on the alumina substrate surface and the back of the Plexiglas circuit board assembly also indicated a temperature gradient. The upper two substrate temperatures were within 0.5 °C of each other; the same could be said for the lower two temperature readings. The upper pair of readings were always higher than the two substrate readings below. Similarly, when the nine backside temperatures were grouped by row, the magnitude order was always top > middle > bottom.

2. FC-43

Results for FC-43 were very similar to FC-71. Figure 43 shows the $T_{avg} - T_{sink}$ versus Q_{net} plots for all spacings. It is noted that the slope of the FC-43 data is smaller that its FC-71 counterpart. This

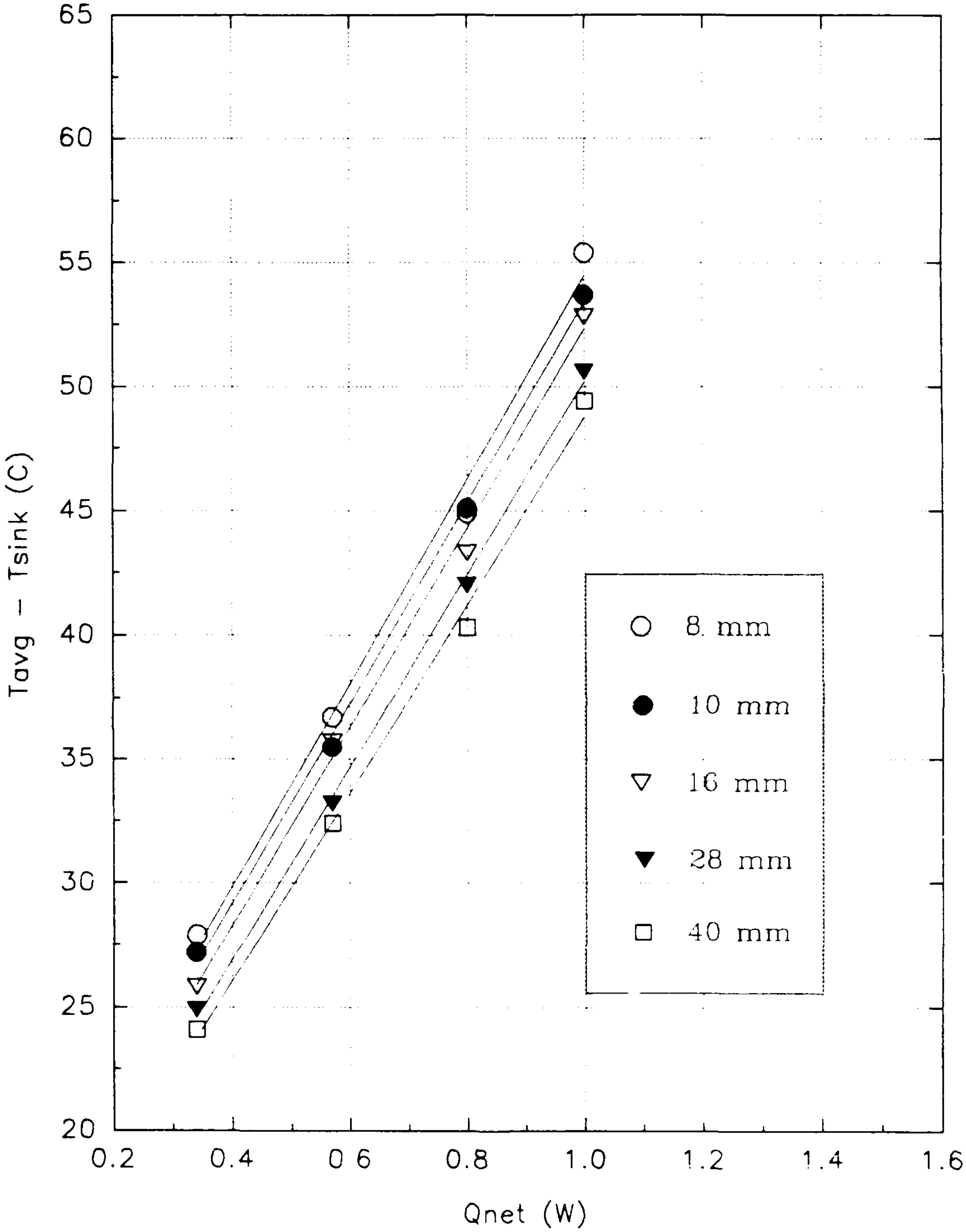

Figure 42. Array Average Temperature vs. Net Power for FC-71, NSWC Circuit Board

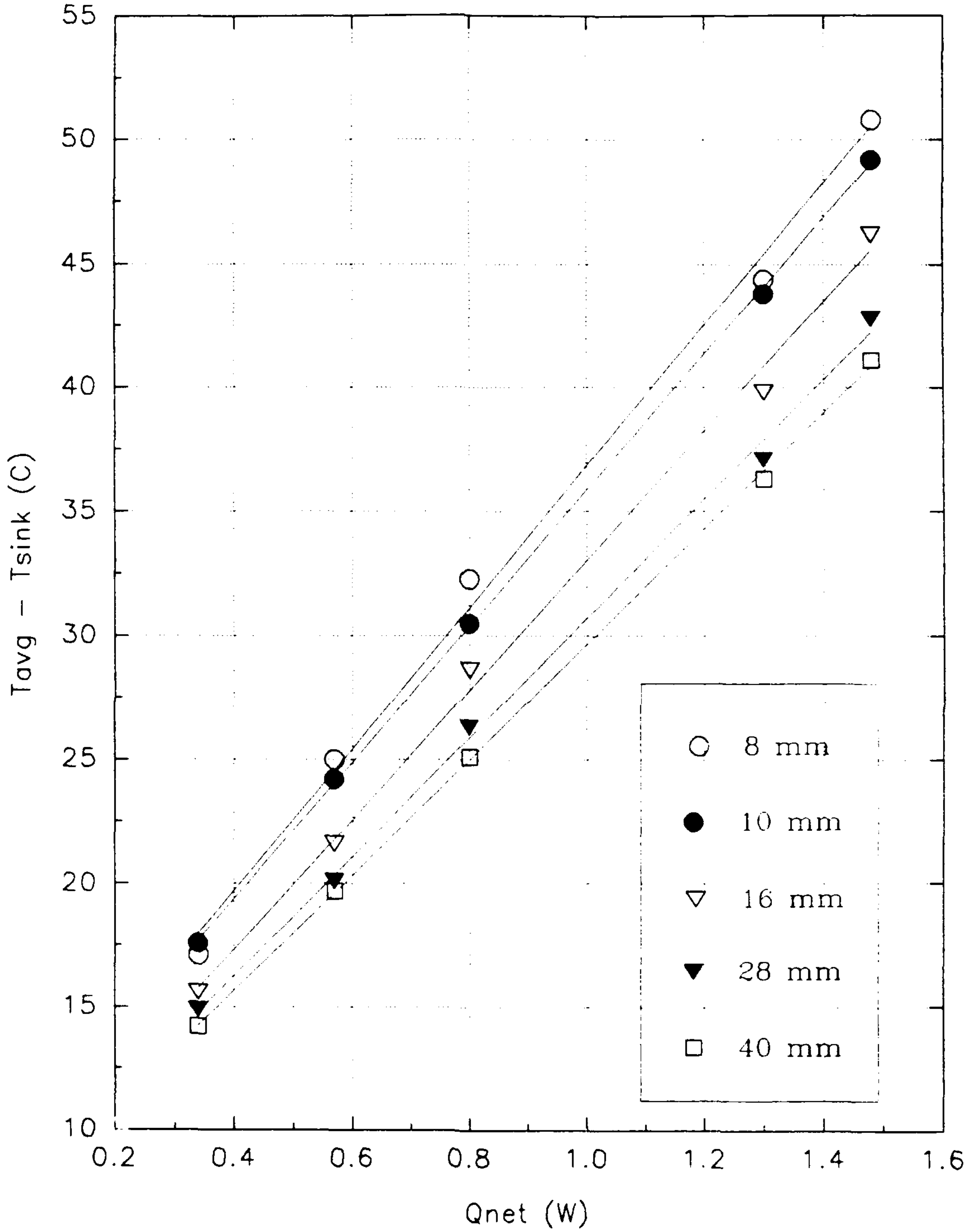

Figure 43. Array Average Temperature vs. Net Power for FC-43, NSWC Circuit Board

indicates that FC-43 is a more efficient heat transfer medium for the chips at a given power level.

The average row temperature order remained the same as the previous fluid. The maximum chip temperature of 101.9 °C was noted on chip #6 at a spacing of 8 mm and a power level of 1.48 W. Maximum temperature differences were 2.1 °C between the top and middle rows and 4.9 °C between the middle and bottom rows. As before, these differences occurred at the highest power level, 1.48 W, and minimum spacing, 8 mm. Finally, the remaining substrate and circuit board assembly temperatures exhibited the same trends as described for the FC-71.

3. FC-75

The third fluid, FC-75, exhibited almost identical results to FC-43. In Figure 44, the T_{avg} - T_{sink} versus Q_{net} plots are again linear, and the slope of the FC-75 data is the smallest of the three liquids studied. The maximum chip temperatures achieved was only 92.3 °C. As expected, it occurred on chip #6 under maximum power and minimum spacing conditions.

As previously noted, the average row temperature data was again always top > middle > bottom. However, the maximum differences between rows was small. Only 0.4 °C separated the top and middle rows, and 3.3 °C was the difference between the middle and bottom rows. These row averaged temperature differences were noted at a spacing of 8 mm and a power level of 1.48 W. The established pattern of top > middle > bottom was again observed for row wise substrate surface and circuit board assembly temperatures.

4. FC-71, FC-43, and FC-75 as a Group

For comparison purposes, Figure 45 through Figure 49 are plots of T_{avg} - T_{sink} versus Q_{net} for all three fluids. This means of presenting the data highlights the following conclusions:

- *For a given power level, the dielectric fluid FC-75 convects heat away from the chips more efficiently than either FC-43 or FC-71.*

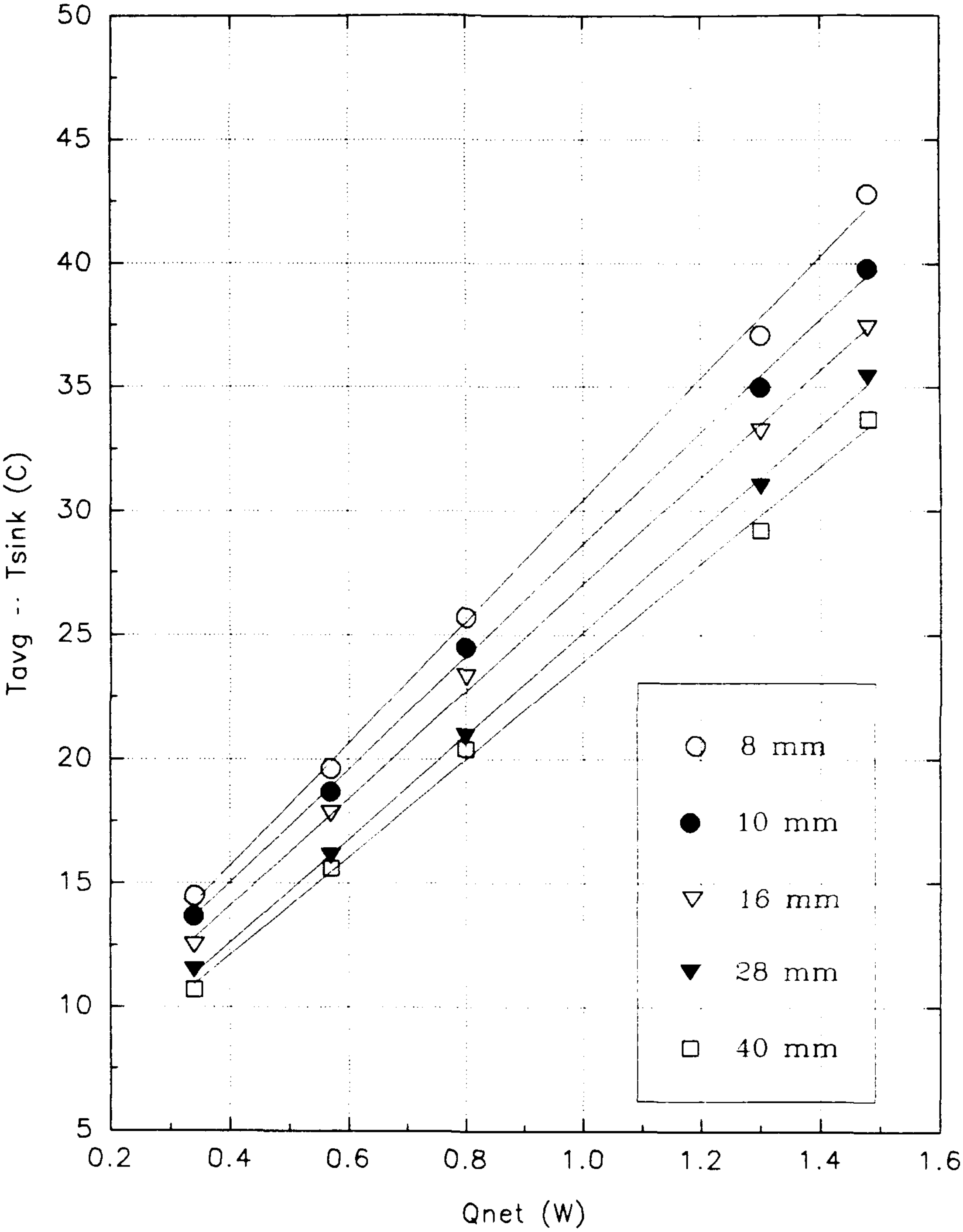

Figure 44. Array Average Temperature vs. Net Power for FC-75, NSWC Circuit Board

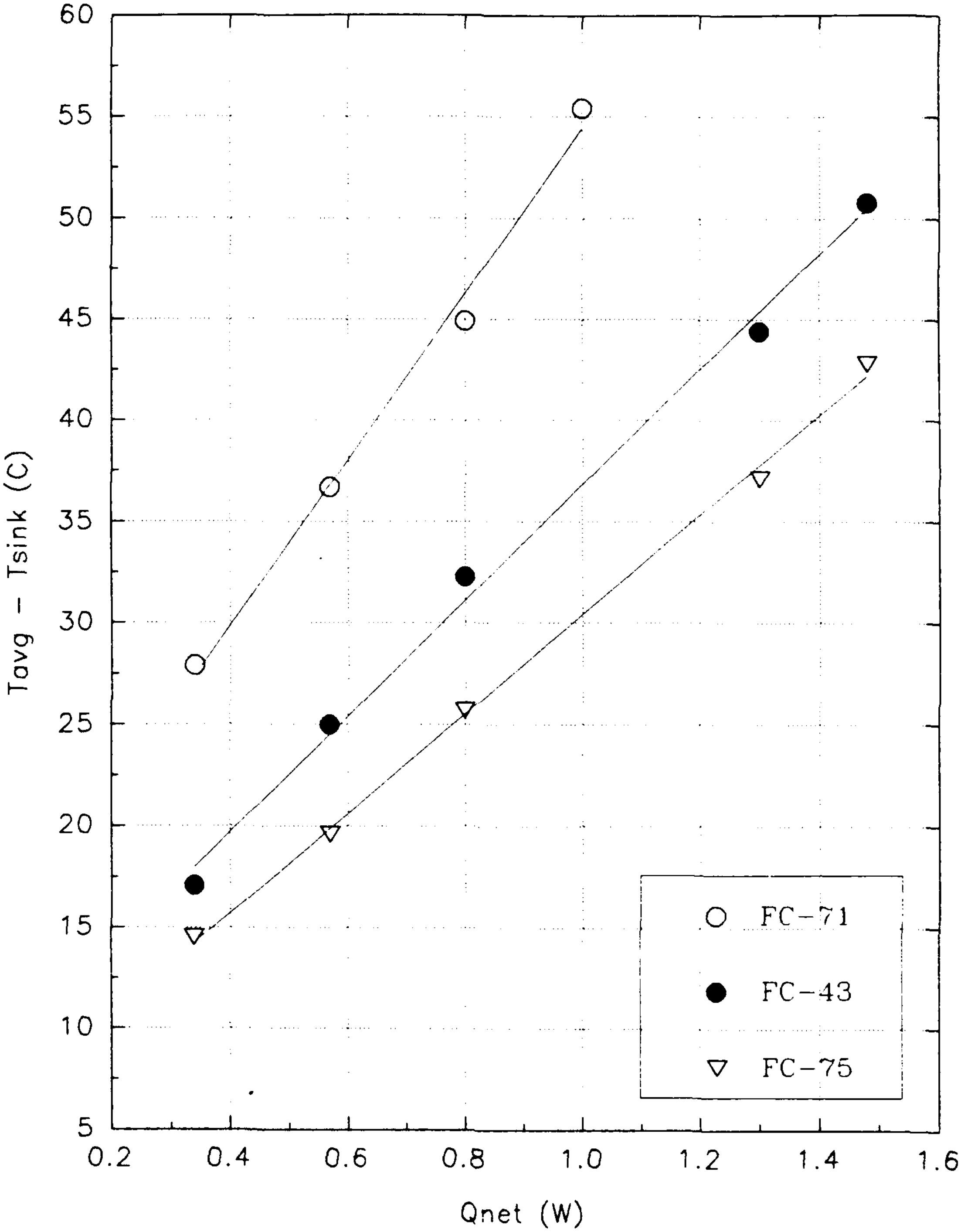

Figure 45. Array Average Temperature vs. Net Power for FC-71, 43, and 75, 8 mm Spacing, NSWC Circuit Board

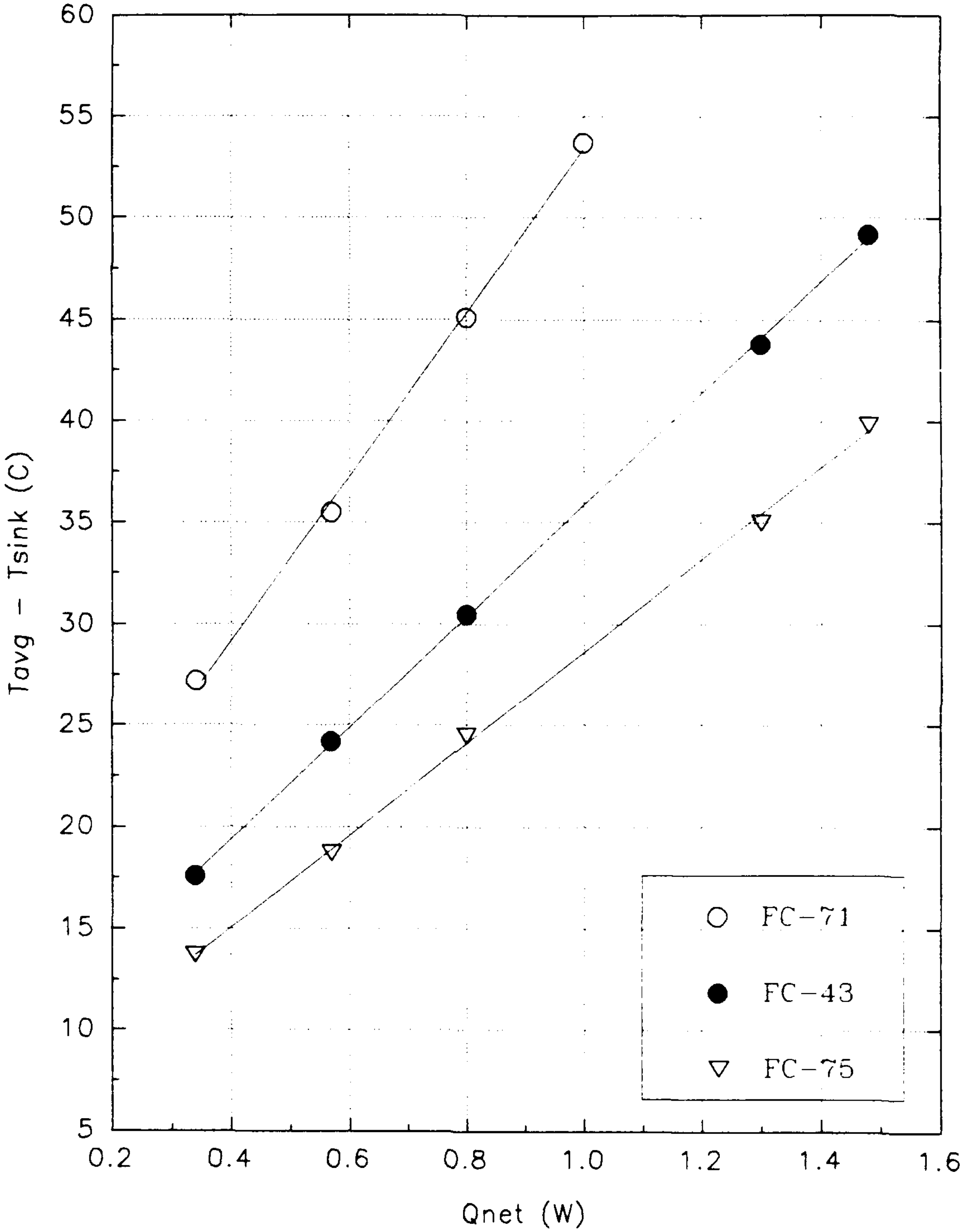

Figure 46. Array Average Temperature vs. Net Power for FC-71, 43, and 75, 10 mm Spacing, NSWC Circuit Board

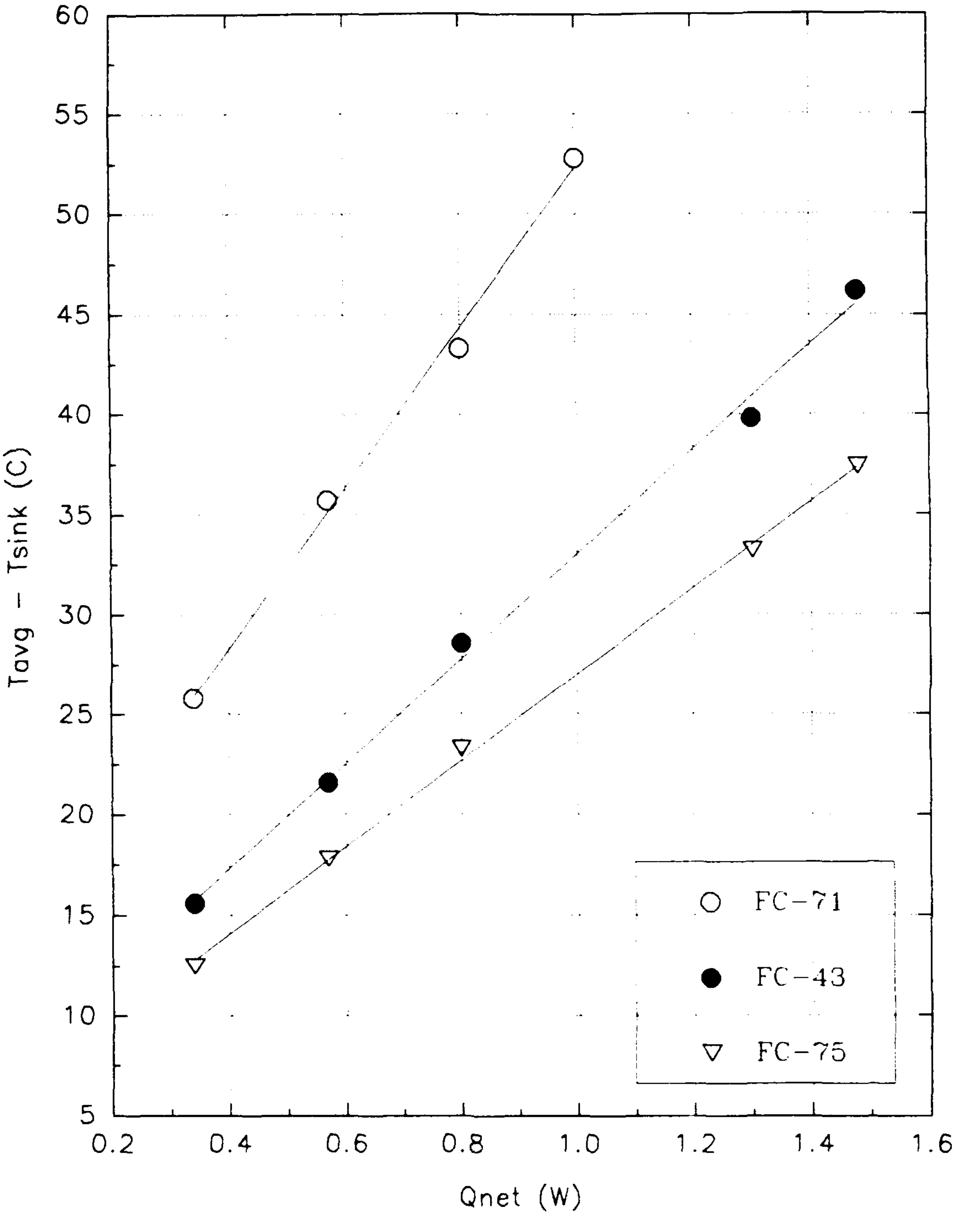

Figure 47. Array Average Temperature vs. Net Power for FC-71, 43, and 75, 16 mm Spacing, NSWC Circuit Board

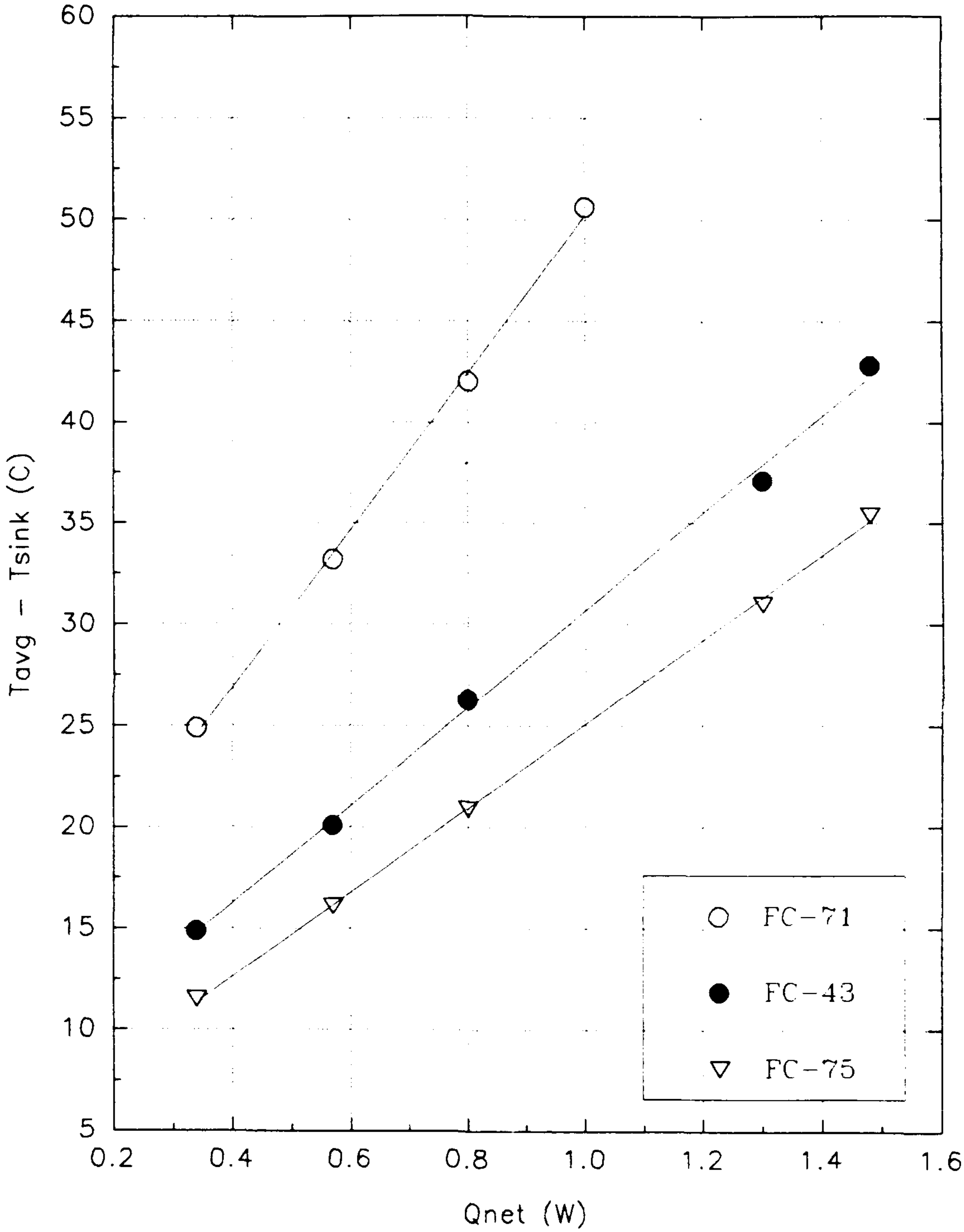

Figure 48. Array Average Temperature vs. Net Power for FC-71, 43, and 75, 28 mm Spacing, NSWC Circuit Board

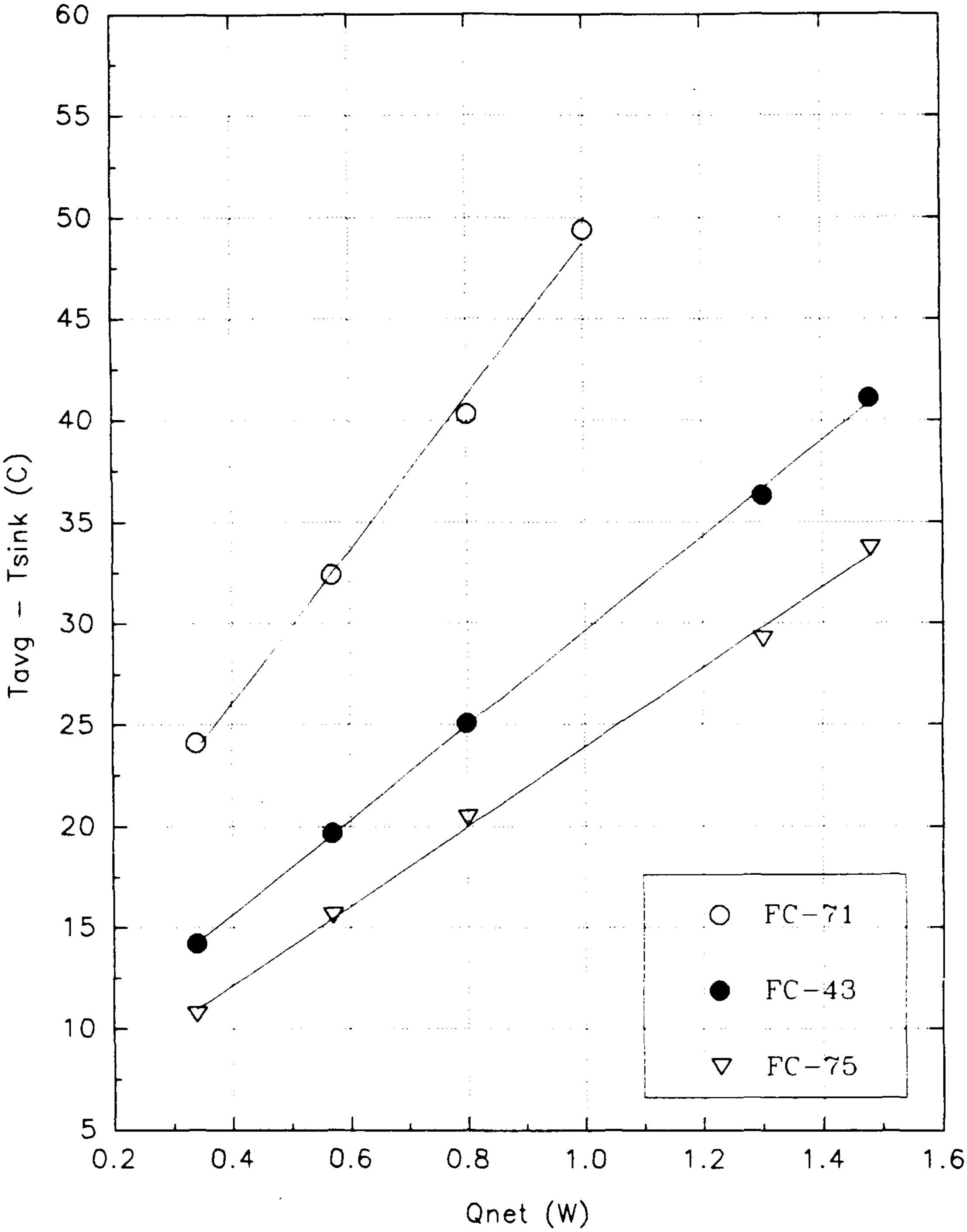

Figure 49. Array Average Temperature vs. Net Power for FC-71, 43, and 75, 40 mm Spacing, NSWC Circuit Board

- Operation with FC-71 leads to the highest chip temperatures. This would be a major disadvantage in the selection of the best dielectric liquid for immersion cooling.

C. NON-DIMENSIONAL RESULTS

1. General

The analysis of the non-dimensional data for the three dielectric liquids was grouped together. This was done because each liquid behaved similarly for a given power level or spacing. The maximum Nu and Gr were always noted at the highest power level for a given liquid, which was 1.0 W for the FC-71 and 1.48 W for the FC-43 or FC-75. Similarly, the minimum Nu and Gr always occurred at the minimum power level of 0.34 W for all liquids. Additionally, the maximum uncertainty in Nu and Gr was observed at this minimum power level and a minimum spacing of 8 mm.

Specifically, the following extremes were noted as described above:

- Maximum Nu at a spacing of 40 mm: 16.37 for FC-71, 31.04 for FC-43, and 41.44 for FC-75.
- Maximum Gr at a spacing of 8 mm: 3450 for FC-71, 2.478×10^5 for FC-43, and 1.224×10^6 for FC-75.
- Minimum Nu at a spacing of 8 mm: 9.81 for FC-71, 17.19 for FC-43, and 21.32 for FC-75.
- Minimum Gr at a spacing of 40 mm: 59 for FC-71, 1.030×10^4 for FC-43, and 1.112×10^5 for FC-75.
- Maximum uncertainties in Nu and Gr, respectively: 3.4% and 2.0% for FC-71, 4.2% and 3.3% for FC-43, and 4.7% and 3.8% for FC-75.

2. Effect of Grashof Number

As previously stated, the final goal of the non-dimensional analysis was to produce an empirical correlation for Nu. Figure 50 through Figure 54 are plots of Nu versus Gr for each individual spacing. When all three dielectric liquids are plotted together as shown, a linear relationship is realized.

This relationship was assumed to be of the form:

$$Nu = c_1 Gr^{b1}$$

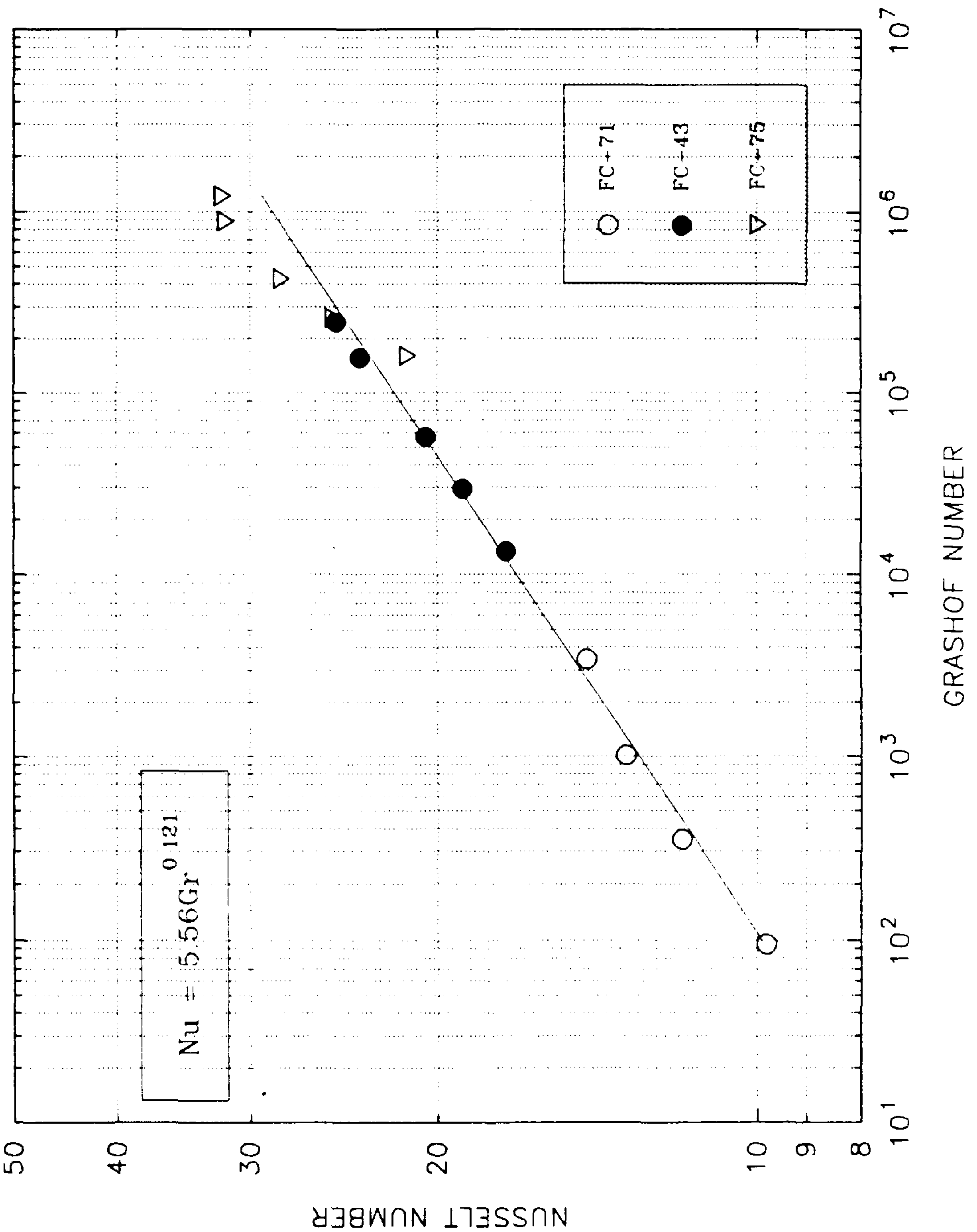

Figure 50. Nu vs. Gr for FC-71, 43, and 75, Array Averaged, NSWC Circuit Board, and 8 mm Enclosure Width

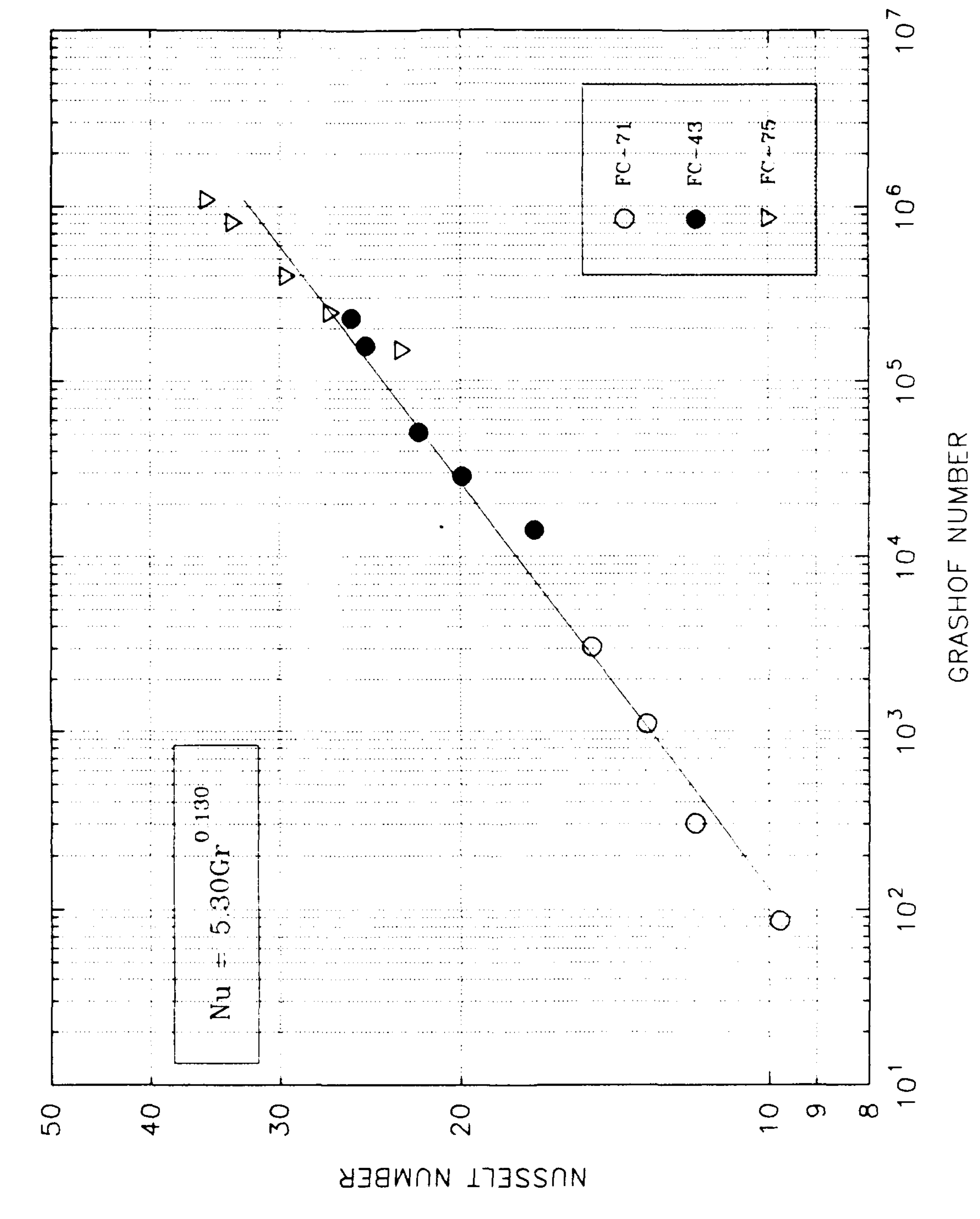

Figure 51. Nu vs. Gr for FC-71, 43, and 75, Array Averaged, NSWC Circuit Board, and 10 mm Enclosure Width

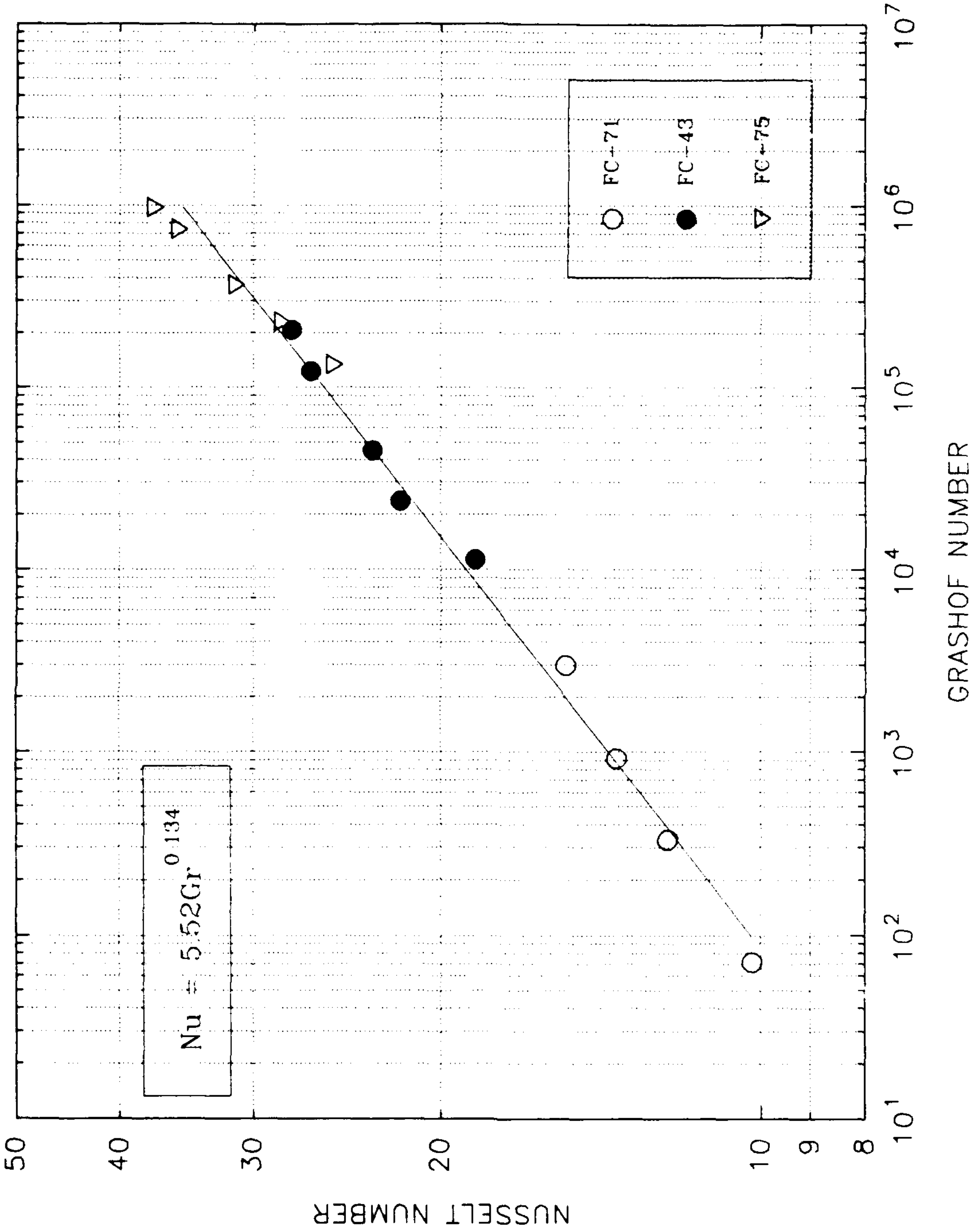

Figure 52. Nu vs. Gr for FC-71, 43, and 75, Array Averaged, NSWC Circuit Board, and 16 mm Enclosure Width

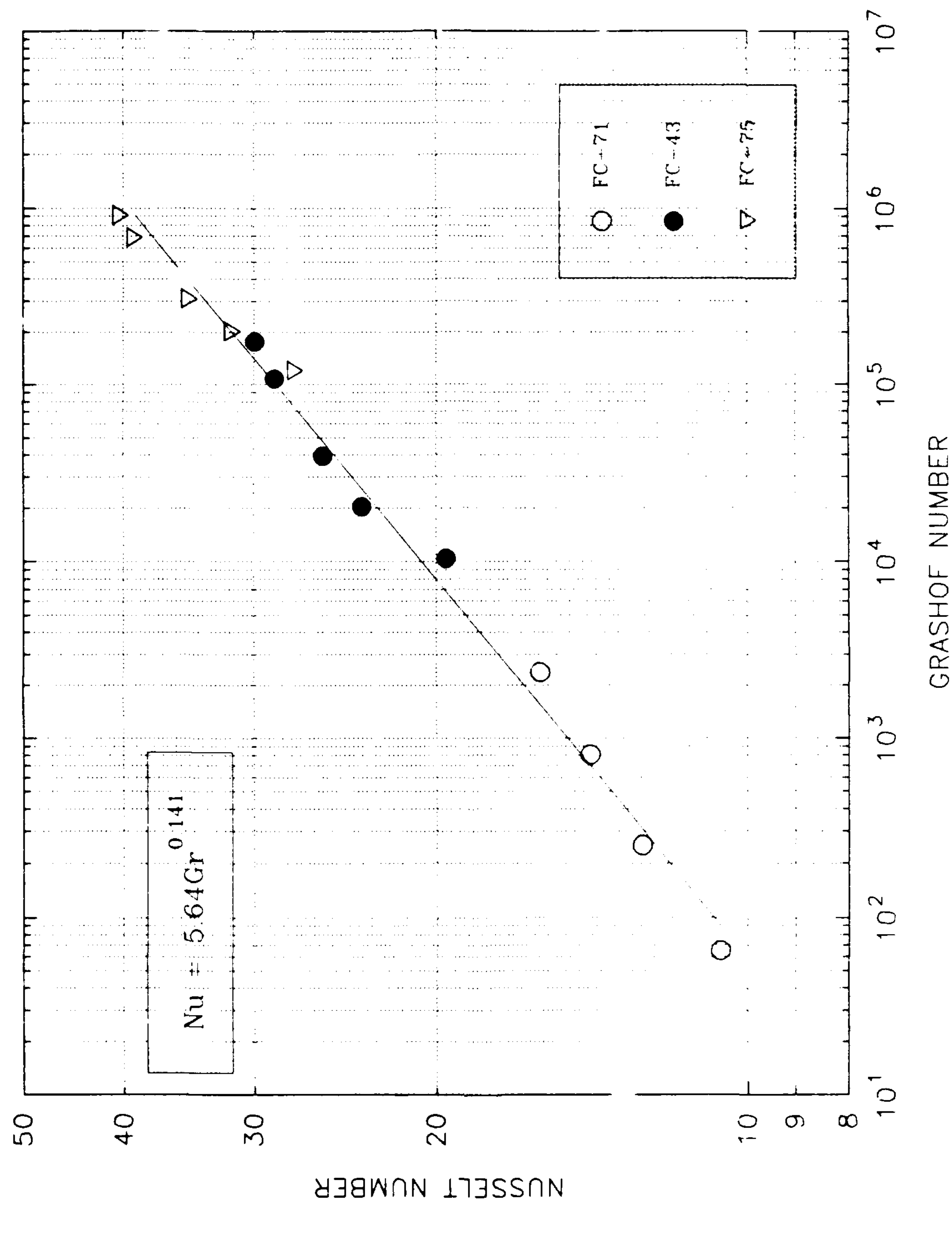

Figure 53. Nu vs. Gr for FC-71, 43, and 75, Array Averaged, NSWC Circuit Board, and 28 mm Enclosure Width

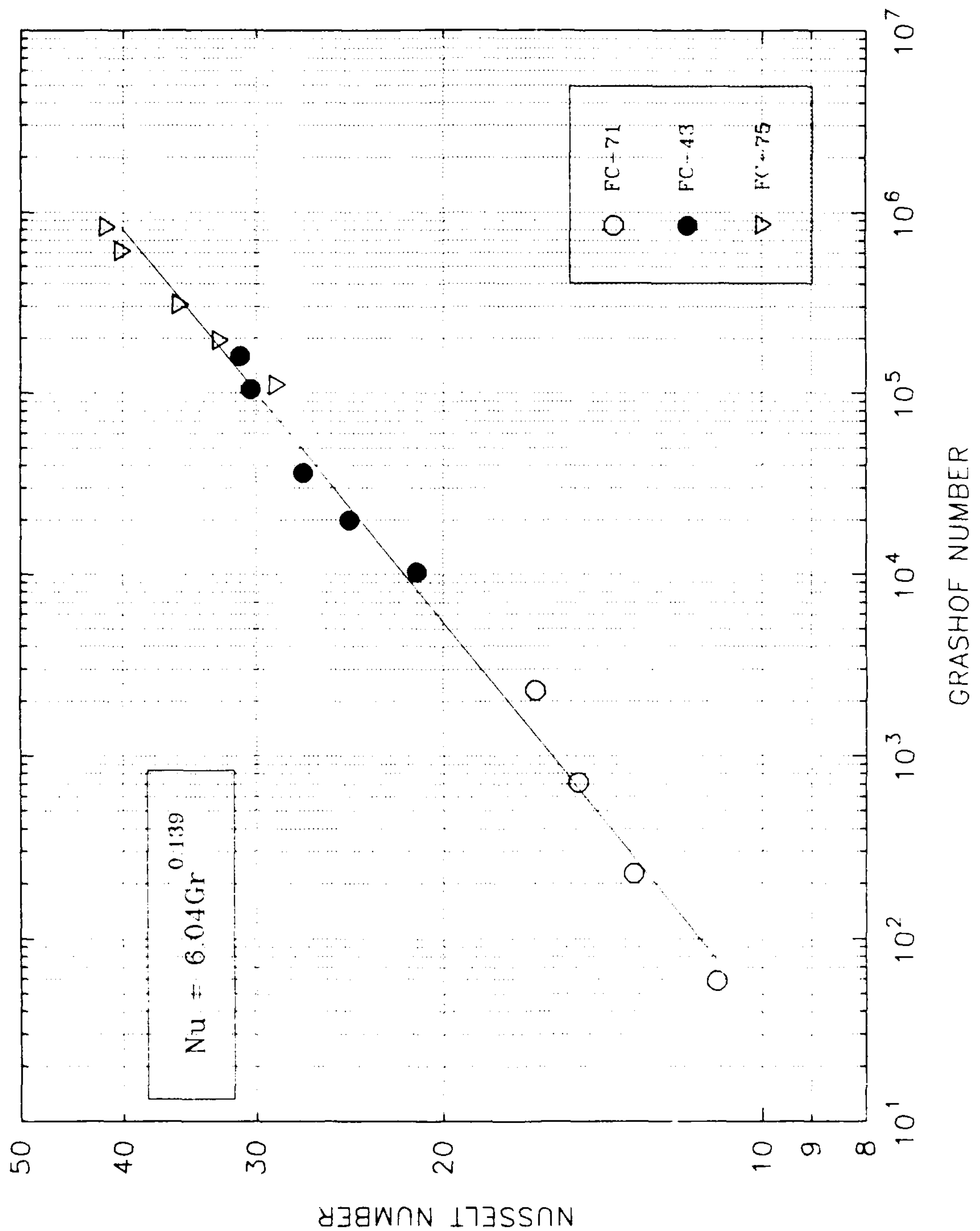

Figure 54. Nu vs. Gr for FC-71, 43, and 75, Array Averaged, NSWC Circuit Board, and 40 mm Enclosure Width

where c_1 and b1 are constants. Again, TABLECURVE was used to find the constants in the above equation. The constant c_1 varied from 5.30 to 6.04, and the average was equal to 5.61. The constant b1 was found to vary from 0.121 to 0.141, with the average being equal to 0.133.

3. Effect of Enclosure Width

Enclosure width effects were accounted for by the following equation:

$$Nu = c_2X^{b2}$$

where b2 is a constant and c_2 is the Gr dependence. X is again the non-dimensional enclosure width. Similar to the previous study, the constant c_2 can be represented by:

$$c_2 = c_3Gr^{b3}$$

The constant b2 was derived from a plot of Nu versus X for the five spacings, which is shown in Figure 55. The values for Nu were derived

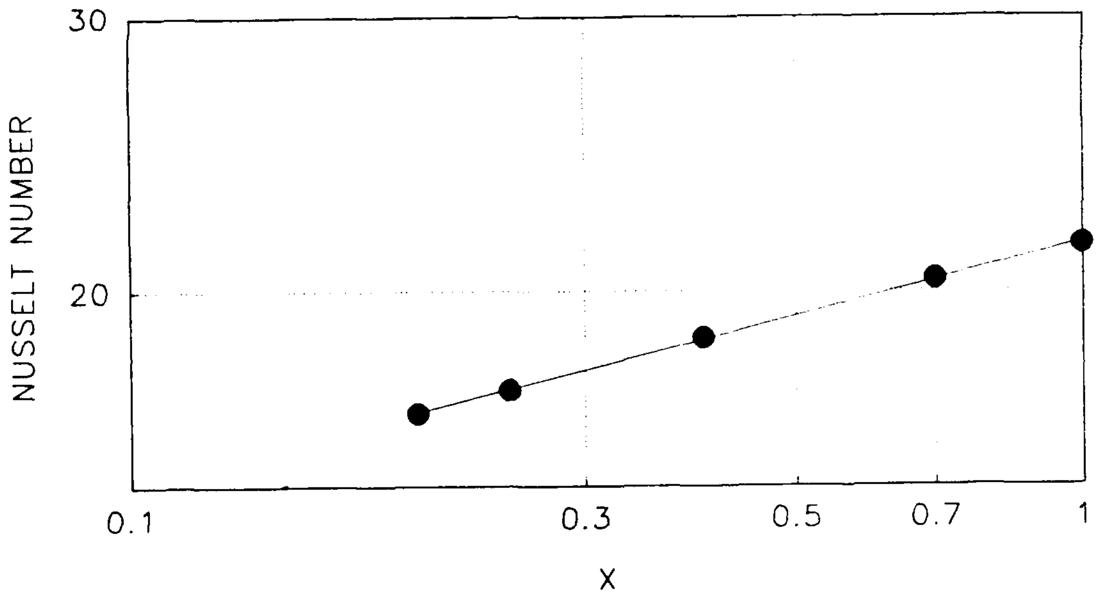

Figure 55. Nu vs. X for FC-71, 43, and 75, Array Averaged, NSWC Circuit Board, and all Enclosure Widths

from the curve fit equations for each spacing's data using an average Gr of 9×10^3. The resulting value for the exponent b2 was 0.154.

Combining the above results gives the following general correlation for the three dielectric liquids:

$$Nu = 5.61Gr^{0.133}X^{0.154}$$

It is valid over the ranges:

$$1 \times 10^2 < Gr < 8 \times 10^6$$

$$0.20 < X < 1.0$$

Five representative Grashof numbers per spacing were selected to determine values for Nu from the respective curve fit equations. These results were then compared to the Nusselt number produced from the correlation. The average difference in Nu for the 25 data points was 12.3%. Similar to the previous study, a trial and error approach was used to improve the accuracy of the general correlation. When the value for c_1 was changed from 5.61 to 6.40, the agreement improved to less that 2%. Therefore, a refined correlation for the three dielectric liquids is:

$$Nu = 6.40Gr^{0.133}X^{0.154}$$

It is valid over the ranges:

$$1 \times 10^2 < Gr < 8 \times 10^6$$

$$0.20 < X < 1.0$$

VII. CONCLUSIONS

Two studies of the natural convection heat transfer of heated protrusions immersed in dielectric liquids were conducted. The first study used a three by three array of computer chip sized aluminum blocks immersed in FC-71. The other study used a three by three array of 8.9 mm square thermal evaluation devices. Three fluids, FC-71, FC-43, and FC-75 were evaluated. Both studies used an insulated Plexiglas enclosure with a top mounted heat exchanger. Spacers were used to vary the enclosure width, and the maximum spacing was 40 mm. Conclusions from the two studies are as follows:

1. For the first study, an empirical correlation for Nusselt number was developed. It took into account variations in Rayleigh number and non-dimensional enclosure width, X. The correlation was based on array averaged data. It is listed below:

$$Nu = 0.435 Ra^{0.249} X^{0.165}$$

$$9 \times 10^{5} < Ra < 2 \times 10^{7}$$

$$0.175 < X < 1.0$$

The maximum uncertainty in the Nusselt number was 7.4%, and the correlation was accurate to within 4% of the array averaged data.

2. When the FC-71 data was combined with Matthews' FC-43 and FC-75 data, several generalizations could be made. For array averaged plots of $T_{avg} - T_{sink}$ versus Q_{net}, the order of temperatures for the three fluids was FC-71 > FC-43 > FC-75. Additionally, the temperatures increased as power level increased or enclosure width was decreased. For log-log plots of Nu versus Ra, each liquid exhibited a linear relationship. The FC-71 data had the highest Nu and Ra numbers for each spacing.

3. For the electronic chip study, a general correlation was developed for Nusselt number from the combined data of the three dielectric fluids. This correlation took into account variations in Grashof number and non-dimensional enclosure width, X. As before, it was based on array averaged data. The correlation is as follows:

$$Nu = 6.40 Gr^{0.133} X^{0.154}$$

$$1 \times 10^{2} < Gr < 8 \times 10^{6}$$

$$0.20 < X < 1.0$$

The maximum uncertainty in the Nusselt number was 4.7%, and the correlation was accurate to within 2% of the array averaged data.

4. Plots of $T_{avg} - T_{sink}$ versus Q_{net} for the three liquids again showed that the order of temperatures was FC-71 > FC-43 > FC-75 for each spacing. For all three liquids, the order of the averaged temperature data was always top > middle > bottom. This same order was also exhibited by the row averaged Plexiglas substrate back and alumina substrate surface temperatures.

5. Overall, the best liquid for natural convection heat transfer was FC-75. The best liquid is defined as the one which produced the lowest component temperatures for a given power level or spacing. Lower chip temperatures equate to longer chip lives.

VIII. RECOMMENDATIONS

The following recommendations are made for further research:

1. Manufacture additional NSWC circuit boards that have every chip wired individually. Use these boards to assemble a large array equivalent in size to a typical mainframe computer circuit board.

2. Test the above array in a suitably sized enclosure filled with FC-75. Produce an empirical correlation for the Nusselt number.

3. In parallel with the experimental work, produce computer models which can also be used to predict heat transfer characteristics. Compare these results with the experimental results and modify the programs as necessary.

APPENDIX A. COMPUTER PROGRAM ACQUIRE

```
10     ! FILE ACQUIRE
20     !
30     ! EDITED BY BY LCDR R. THOMPSON
40     ! 1/12/92.  FROM ORIGINALS OF PAMUK,
50     ! BENEDICT, TORRES, AYTAR AND MATTHEWS.
60     !
70     ! READ FILE "READ_ME"
80     !
90     COM /Co/ D(7)
100    DIM Emf(76),Power(9),T(76),Rp(8)
110    !
120    !CORRELATION FACTORS TO CONVERT EMF TO DEGREES CELSIUS. SOURCE:
130    !HP APPLICATION NOTE 290, P. 6, NBS POLYNOMIAL COEFFICIENTS FOR
140    !TYPE T (COPPER-CONSTANTAN) THERMOCOUPLES.
150    DATA 0.10086091,25727.9,-767345.8,78025596,
160    DATA -9247486589,6.98E11,-2.66E13,3.94E14
170    !RESISTANCES SERIES TO HEATERS
180    DATA 2.0,2.0,2.0,2.0,2.0,2.0,2.0,2.0,2.0
190    !
200    READ D(*)
210    READ Rp(*)
220    PRINTER IS 701
230    BEEP
240    !
250    INPUT "ENTER THE INPUT MODE: 0=SYS, 1=FILE",Im
260    !
270    IF Im=1 THEN
280    BEEP
290    INPUT "ENTER THE NAME OF THE FILE TO BE READ",Oldfile$
300    !
310    PRINT USING "15X,""THESE RESULTS ARE STORED IN FILE :  "",10A";Oldfile$
320    ELSE
330    BEEP
340    INPUT "ENTER THE NAME OF THE NEW FILE",Newfile$
350    PRINT USING "10X,""THESE RESULTS ARE STORED IN FILE:  "",10A";Newfile$
360    END IF
370    PRINT
380    !
390    INPUT "FLOW VIZ? Y/N",Ans$
400    !
410    INPUT "ENTER THE BATH TEMP",B$
420    PRINT USING "15X,""BATH TEMP WAS:  "",10A";B$
430    !
440    IF Ans$="Y" THEN PRINT USING "15X,""THIS RUN WAS RECORDED WITH FLOW VIZ"",
10A"
450    !
460    INPUT "ENTER THE WALL SPACING",Wall$
470    PRINT USING "15X,""SPACING WAS:  "",10A";Wall$
480    !
490    INPUT "ENTER THE TYPE OF LIQUID USED",Liquid$
```

```
500  PRINT USING "15X,""THE FLUORINERT USED WAS:  "",10A";Liquid$
510  IF Im=1 THEN ASSIGN @File TO Oldfile$
520  !
530  IF Im=0 THEN
540  CREATE BDAT Newfile$,5
550  ASSIGN @File TO Newfile$
560  END IF
570  !
580  ! READ DATA
590  !
600  IF Im=0 THEN
610  OUTPUT 709;"AF AF00 AL79"
620  OUTPUT 722;"F1 R1 T1 Z0 FL0"
630  !
640  FOR I=0 TO 76
650  OUTPUT 709;"AS"
660  WAIT 1
670  ENTER 722;Emf(I)
680  IF Emf(I)<0. THEN
690  Emf(I)=-Emf(I)
700  END IF
710  BEEP
720  NEXT I
730  !
740  ! CORRECTION FOR OFFSET IN HP 3497A DAS ICE
750  ! POINT REFERENCE
760  FOR I=0 TO 19
770   Emf(I)=Emf(I)-6.5E-6
780  NEXT I
790  FOR I=20 TO 39
800   Emf(I)=Emf(I)-1.05E-5
810  NEXT I
820  FOR I=40 TO 59
830   Emf(I)=Emf(I)-5.0E-6
840  NEXT I
850  FOR I=60 TO 76
860   Emf(I)=Emf(I)-2.55E-5
870  NEXT I
880  !
890  OUTPUT @File;Emf(*)
900  !
910  ELSE
920  ENTER @File;Emf(*)
930  END IF
940  !
950  OUTPUT 709;"TD"
960  !
970  FOR I=0 TO 60
980  Sum=0.
990  FOR J=0 TO 7
1000 Sum=Sum+D(J)*Emf(I)^J
1010 NEXT J
1020 T(I)=Sum
1030 NEXT I
1040 !
1050 FOR I=71 TO 76
1060 Sum=0
```

```
1070  FOR J=0 TO 7
1080  Sum=Sum+D(J)*Emf(I)^J
1090  NEXT J
1100  T(I)=Sum
1110  NEXT I
1120  !
1130  PRINT USING "15X,""VOLTMETER READING WAS:  "",D.DDDD";Emf(61)
1140  PRINT USING "15X,""AMBIENT TEMP WAS:  "",DD.D";T(76)
1150  PRINT
1160  ! POWER CALCULATIONS
1170  !
1180  J=1
1190  Volt=Emf(61)
1200  !
1210  FOR I=62 TO 70
1220  Power(J)=Emf(I)*(Volt-Emf(I))/Rp(I-62)
1230  J=J+1
1240  NEXT I
1250  !
1260  BEEP
1270  BEEP
1280  !
1290  PRINT USING "10X,""ALL TEMPERATURES ARE IN DEGREES CELSIUS"""
1300  !
1310  PRINT
1320  !
1330  PRINT USING "12X,""CENTER       TOP          RIGHT       LEFT       BOTTOM
 BACK"""
1340  PRINT
1350  PRINT USING "1X,""CHIP NO1: "",6(DDD.DD,5X)";T(0),T(1),T(2),T(3),T(4),T(5)
1360  PRINT USING "5X,""POWER (WATTS):  "",D.DDD";Power(1)
1370  PRINT
1380  PRINT USING "1X,""CHIP NO2: "",6(DDD.DD,5X)";T(6),T(7),T(8),T(9),T(10),T(1
1)
1390  PRINT USING "5X,""POWER (WATTS):  "",D.DDD";Power(2)
1400  PRINT
1410  PRINT USING "1X,""CHIP NO3: "",6(DDD.DD,5X)";T(12),T(13),T(14),T(15),T(16)
,T(17)
1420  PRINT USING "5X,""POWER (WATTS):  "",D.DDD";Power(3)
1430  PRINT
1440  PRINT USING "1X,""CHIP NO4: "",6(DDD.DD,5X)";T(18),T(19),T(20),T(21),T(22)
,T(23)
1450  PRINT USING "5X,""POWER (WATTS):  "",D.DDD";Power(4)
1460  PRINT
1470  PRINT USING "1X,""CHIP NO5: "",6(DDD.DD,5X)";T(24),T(25),T(26),T(27),T(28)
,T(29)
1480  PRINT USING "5X,""POWER (WATTS):  "",D.DDD";Power(5)
1490  PRINT
1500  PRINT USING "1X,""CHIP NO6: "",6(DDD.DD,5X)";T(30),T(31),T(32),T(33),T(34)
,T(35)
1510  PRINT USING "5X,""POWER (WATTS):  "",D.DDD";Power(6)
1520  PRINT
1530  PRINT USING "1X,""CHIP NO7: "",6(DDD.DD,5X)";T(36),T(37),T(38),T(39),T(40)
,T(41)
1540  PRINT USING "5X,""POWER (WATTS):  "",D.DDD";Power(7)
1550  PRINT
```

```
1560  PRINT USING "1X,""CHIP NO8: "",6(DDD.DD,5X)";T(42),T(43),T(44),T(45),T(46)
,T(47)
1570  PRINT USING "5X,""POWER (WATTS):   "",D.DDD";Power(8)
1580  PRINT
1590  PRINT USING "1X,""CHIP NO9: "",6(DDD.DD,5X)";T(48),T(49),T(50),T(51),T(52)
,T(53)
1600  PRINT USING "5X,""POWER (WATTS):   "",D.DDD";Power(9)
1610  !
1620  PRINT
1630  PRINT
1640  !
1650  PRINT USING "5X,""HEAT EXCHANGERS TEMPERATURES:       RIGHT      CENTER      LE
FT"""
1660  PRINT USING "10X,""BOTTOM IS INSULATED"""
1670  PRINT USING "10X,""TOP:"",24X,3(DD.DD,5X)";T(54),T(55),T(56)
1680  PRINT
1690  PRINT
1700  !
1710  PRINT USING "5X,""BACK PLANE TEMPERATURES ARE :"""
1720  PRINT
1730  PRINT USING "10X,""T(57):"",2X,DD.DD";T(57)
1740  PRINT USING "10X,""T(58):"",2X,DD.DD";T(58)
1750  PRINT USING "10X,""T(59):"",2X,DD.DD";T(59)
1760  PRINT USING "10X,""T(60):"",2X,DD.DD";T(60)
1770  PRINT USING "10X,""T(71):"",2X,DD.DD";T(71)
1780  PRINT USING "10X,""T(72):"",2X,DD.DD";T(72)
1790  PRINT USING "10X,""T(73):"",2X,DD.DD";T(73)
1800  PRINT USING "10X,""T(74):"",2X,DD.DD";T(74)
1810  PRINT USING "10X,""T(75):"",2X,DD.DD";T(75)
1820  BEEP
1830  PRINTER IS 1
1840  !
1850  ASSIGN @File TO *
1860  END
```

APPENDIX B. COMPUTER PROGRAM CALCDIEL

```
10    !**********************
20    ! PROGRAM  CalcDiel    *
30    !**********************
40    !
50    ! MODIFIED BY LCDR R. THOMPSON 1/13 AND 4/15/92.
60    ! FROM ORIGINALS OF PAMUK, BENEDICT, TORRES,
70    ! AYTAR AND MATTHEWS.
80    !
90    !****************************************
100   ! THIS PROGRAM ANALYZES THE DATA READ FROM *
110   ! A DATA FILE DESIGNATED BY THE OPERATOR.IT*
120   ! REDUCES THE DATA TO CALCULATIONS OF NET  *
130   ! POWER, RAYLEIGH AND NUSSELT NUMBERS.  THE*
140   ! UNCERTAINTY ANALYSIS IS ALSO INCLUDED.   *
150   !****************************************
160   !
170   ! VARIABLES USED ARE:
180   ! EMF   : VOLTAGE FROM THE THERMOCOUPLES.
190   ! POWER : POWER DISSIPATED BY THE HEATERS
200   ! T(I)  : TEMPERATURE CONVERTED FROM THERMO-
210   !         COUPLE VOLTAGE
220   ! Tavg  : IS THE AVERAGE TEMPERATURE OF THE
230   !         CHIP. IT IS OBTAINED MULTIPLYING
240   !         THE TEMPERATURE FOUND IN EACH FACE
250   !         BY THE AREA AND DIVIDING BY THE TO-
260   !         TAL AREA
270   ! Ts    : CHIP BACK SURFACE TEMPERATURE
280   ! Tfilm : FILM TEMPERATURE OF THE DIELECTRIC
290   ! Qnet  : ELECTRIC POWER MINUS CONDUCTION LOSSES
300   ! Tsink : AVERAGE OF THE 3 THERMOCOUPLES IN
310   !         THE UPPER HEAT EXCHANGER
320   ! Nu1   : LENGTH BASED NUSSELT NUMBER
330   ! Nu2   : AREA-PERIMETER BASED NUSSELT NUMBER
340   ! D...  : UNCERTAINTY OF A VARIABLE (EXCEPT
350   !         Dliq and Delt)
360   ! OTHER VARIABLES ARE SELF-EXPLANATORY
370   !******************************************
380   !
390   COM /Co/ D(7)
400   !
410   DIM Emf(76),Power(9),T(76),Tavg(9),Ts(9)
420   DIM Tfilm(9),Qnet(9),H(9),K(9),Rho(9),Cp(9)
430   DIM N(9),Nu1(9),Ra1(9),Delt(9),Alfa(9),Pr(9)
440   DIM Gr1(9),Beta(9),Dpower(9),Ra2(9)
450   DIM Gr2(9),Raf1(9),Raf2(9),Nu2(9)
460   DIM Rowra1(3),Rownu1(3)
470   !
480   ! CORRELATION FACTORS TO CONVERT Emf TO DEGREES CELSIUS. SOURCE:
490   ! HP APPLICATION NOTE 290, P. 8, NBS POLYNOMIAL COEFFICIENTS FOR
500   ! TYPE T (COPPER-CONSTANTAN) THERMOCOUPLES.
510   DATA 0.10086091,25727.9,-767345.8,78025596,
```

```
520   DATA -9247486589,6.98E11,-2.66E13,3.94E14
530   !
540   READ D(*)
550   ! PRECISION RESISTOR VALUE IN OHMS
560   Rp=2.0
570   !
580   PRINTER IS 701
590   BEEP
600   BEEP
610   !
620   INPUT "ENTER THE NAME OF THE FILE CONTAINING DATA",Oldfile$
630   !
640   PRINT USING "10X,""THE RAW Emf DATA ARE FROM THE FILE:     "",10A";Oldfile$
650   !
660   INPUT "ENTER THE POWER SETTING ",Power$
670   PRINT USING "9X,"" THE POWER SETTING PER CHIP WAS:    "",10A";Power$
680   !
690   INPUT "ENTER THE TYPE OF LIQUID USED",Liquid$
700   PRINT USING "10X,""THE FLUORINERT USED WAS:  "",10A";Liquid$
710   INPUT "ENTER THE TYPE OF DIELECTRIC:0=FC-75,1=FC-43,2=FC-71",Dliq
720   !
730   INPUT "ENTER THE WALL SPACING",Wall$
740   PRINT USING "10X,""THE DISTANCE TO THE FRONT WALL WAS:  "",10A";Wall$
750   !
760   INPUT "ENTER THE GEOMETRY TYPE: 0=HORIZONTAL,1=VERTICAL",Geo
770   INPUT "ENTER THE CHIP ORIENTATION",Chip$
780   PRINT USING "10X,""THE CHIP ORIENTATION WAS:  "",10A";Chip$
790   !
800   BEEP
810   BEEP
820   ASSIGN @File TO Oldfile$
830   ENTER @File;Emf(*)
840   !
850   !**********************************
860   ! CONVERT Emf TO DEGREES CELSIUS  *
870   !**********************************
880   !
890   FOR I=0 TO 60
900   Sum=0
910   FOR J=0 TO 7
920   Sum=Sum+D(J)*Emf(I)^J
930   NEXT J
940   T(I)=Sum
950   NEXT I
960   FOR I=71 TO 76
970   Sum=0
980   FOR J=0 TO 7
990   Sum=Sum+D(J)*Emf(I)^J
1000  NEXT J
1010  T(I)=Sum
1020  NEXT I
1030  !
1040  !************************
1050  ! CONVERT Emf TO POWER   *
1060  !************************
1070  !
1080  J=1
```

```
1090 Volt=Emf(61)
1100 FOR I=62 TO 70
1110 Power(J)=Emf(I)*(Volt-Emf(I))/Rp
1120 J=J+1
1130 NEXT I
1140 !
1150 IF Geo=0 THEN
1160 L1=8.E-3
1170 Alef=4.8E-5
1180 Arig=4.8E-5
1190 Atop=1.44E-4
1200 Abot=1.44E-4
1210 Le=L1*1000
1220 PRINT USING "10X,""HORIZONTAL LENGTH SCALE IS (MM):   ,DD.D";Le
1230 ELSE
1240 L1=2.4E-2
1250 Alef=1.44E-4
1260 Arig=1.44E-4
1270 Atop=4.8E-5
1280 Abot=4.8E-5
1290 Le=L1*1000
1300 PRINT USING "10X,""VERTICAL LENGTH SCALE IS (MM):   "",DD.D";Le
1310 END IF
1320 Acen=1.92E-4
1330 Atot=5.76E-4
1340 !
1350 !*****************************************************
1360 !CALCULATE THE AVERAGE TEMPERATURES OF THE BLOCK FACES
1370 !
1380 Tavg(1)=(T(0)*Acen+T(1)*Atop+T(2)*Arig+T(3)*Alef+T(4)*Abot)/Atot
1390 Tavg(2)=(T(6)*Acen+T(7)*Atop+T(8)*Arig+T(9)*Alef+T(10)*Abot)/Atot
1400 Tavg(3)=(T(12)*Acen+T(13)*Atop+T(15)*Arig+T(16)*Abot+Alef*T(14))/Atot
1410 Tavg(4)=(T(18)*Acen+T(19)*Atop+T(20)*Arig+T(21)*Alef+T(22)*Abot)/Atot
1420 Tavg(5)=(T(24)*Acen+T(25)*Atop+T(26)*Arig+T(27)*Alef+T(28)*Abot)/Atot
1430 Tavg(6)=(T(30)*Acen+T(31)*Atop+T(32)*Arig+T(33)*Alef+T(34)*Abot)/(Atot)
1440 Tavg(7)=(T(36)*Acen+T(37)*Atop+T(38)*Arig+T(39)*Alef+T(40)*Abot)/Atot
1450 Tavg(8)=(T(42)*Acen+T(43)*Atop+T(44)*Arig+T(45)*Alef+T(46)*Abot)/(Atot)
1460 Tavg(9)=(T(48)*Acen+T(49)*Atop+T(50)*Arig+T(51)*Alef+T(52)*Abot)/Atot
1470 ! ACCURACY OF THERMOCOUPLES IS 0.5 DEGREES C.
1480 Dt=.5
1490 Dtavg=.5
1500 Dtsink=.5
1510 !
1520 ! RESISTANCE AND UNCERTAINTY OF PLEXIGLASS FOUND WITH
1530 ! A CONDUCTIVITY OF 0.195 W/m.K & A LENGTH OF 12.0 MM
1540 Rc=320.51
1550 Drc=10.05
1560 !
1570 !********************************
1580 ! CHIP BACK SURFACE TEMPERATURES *
1590 !********************************
1600 Ts(1)=T(5)
1610 Ts(2)=T(11)
1620 Ts(3)=T(17)
1630 Ts(4)=T(23)
1640 Ts(5)=T(29)
1650 Ts(6)=T(35)
```

```
1660  Ts(7)=T(41)
1670  Ts(8)=T(47)
1680  Ts(9)=T(53)
1690  Tssum=0
1700  FOR J=1 TO 9
1710  Tssum=Tssum+Ts(J)
1720  NEXT J
1730  !
1740  Tsavg=Tssum/9
1750  !
1760  !*******************************
 770  ! CONDUCTION LOSS CALCULATION  *
1780  !*******************************
1790  Qloss1=(T(5)-T(57))/Rc
1800  Qloss2=(T(11)-T(58))/Rc
1810  Qloss3=(T(17)-T(59))/Rc
1820  Qloss4=(T(23)-T(60))/Rc
1830  Qloss5=(T(29)-T(71))/Rc
1840  Qloss6=(T(35)-T(72))/Rc
1850  Qloss7=(T(41)-T(73))/Rc
1860  Qloss8=(T(47)-T(74))/Rc
1870  Qloss9=(T(53)-T(75))/Rc
1880  Qloss=(Qloss1+Qloss2+Qloss3+Qloss4+Qloss5+Qloss6+Qloss7+Qloss8+Qloss9)/9.
1890  Dqloss=(Qloss)*((Dt/T(57)^2)+(Drc/Rc)^2)^.5
1900  !
1910  !**************************************
1920  ! AVERAGE SINK TEMPERATURE CALCULATION *
1930  !**************************************
1940  !
1950  Tsink=(T(54)+T(55)+T(56))/3.
1960  !
1970  PRINT USING "10X,""AVERAGE SINK TEMPERATURE (C):  "",DDD.DD";Tsink
1980  !
1990  PRINT
2000  !
2010  ! TWO CHARACTERISTIC LENGTHS WILL BE USED TO CALCULATE NUSSELT NUMBERS:
2020  ! L1 IS BASED ON THE VERTICAL OR HORIZONTAL DIMENSION OF THE CHIP
2030  ! L2 IS BASED ON THE SUMMATION OF THE AREAS DIVIDED BY THE PERIMETER
2040  !
2050  L2=(2.*(6.*24./60.)+2.*(6.*6./28.)+6.*24./64.)*.001
2060  !
2070 PRINT USING "9X,""CHIP   Qnet(W)  Tavg-Ts      Nu1       Nu2      %UNC IN N
U"",10A"
2080 PRINT
2090  !
2100  !***********************************************
2110  ! CALCULATION OF NET POWER, Nu, Ra AND UNCERTAINTIES *
2120  !***********************************************
2130  !
2140  FOR J=1 TO 9
2150  !
2160  ! Dpower IS BASED ON ACCURACY OF THE VOLTMETER AND THE PRECISION RESISTORS
.
2170  ! Dv FOR THE VOLTAGE DROPS ACROSS THE CHIP HEATERS OR PRECISION RESISTORS
2180  ! IS 5E-6 V.  Drp=0.05 OHMS.
2190  Dv=5.E-6
2200  Drp=.05
```

```
2210  Dpower(J)=Power(J)*((Dv/Emf(J+61))^2+(Dv/(Volt-Emf(J+61)))^2+(Drp/Rp)^2)^.
5
2220  !
2230  ! CALCULATION OF Qnet
2240  Qnet(J)=Power(J)-Qloss
2250  Dqnet=(Dpower(J)^2+Dqloss^2)^.5
2260  !
2270  ! CALCULATION OF Tfilm
2280  Tfilm(J)=(Tavg(J)+Tsink)/2
2290  !
2300  ! CALCULATION OF A DELTA TEMPERATURE
2310  Delt(J)=Tavg(J)-Tsink
2320  Ddelt=(Dtavg^2+Dtsink^2)^.5
2330  !
2340  ! CALCULATION OF CONVECTION COEFFICIENT
2350  H(J)=Qnet(J)/(Atot*Delt(J))
2360  Dh=H(J)*((Dqnet/Qnet(J))^2+(Ddelt/Delt(J))^2)^.5
2370  !
2380  ! PHYSICAL PROPERTIES ARE TAKEN FROM THE 1985 3M PRODUCT MANUAL
2390  ! FOR FLUORINERT ELECTRONIC LIQUIDS
2400  !
2410  IF Dliq=0 THEN
2420  !
2430  ! CALCULATION OF FC-75 THERMAL CONDUCTIVITY
2440  K(J)=(.65-7.89474E-4*Tfilm(J))/10
2450  !
2460  ! CALCULATION OF FC-75 DENSITY
2470  Rho(J)=(1.825-.00246*Tfilm(J))*1000
2480  !
2490  ! CALCULATION OF FC-75 SPECIFIC HEAT
2500  Cp(J)=(.241111+3.7037E-4*Tfilm(J))*4187
2510  ! THE 4187 CONVERTS FROM CALORIES TO JOULES
2520  !
2530  ! CALCULATION OF FC-75 KINEMATIC VISCOSITY
2540  N(J)=1.4074-2.964E-2*Tfilm(J)+3.8018E-4*Tfilm(J)^2-2.7308E-6*Tfilm(J)^3+8.
1679E-9*Tfilm(J)^4
2550  ! CONVERT FROM CENTISTOKES TO m^2/s
2560  N(J)=N(J)*1.E-6
2570  !
2580  ! CALCULATION OF THE COEFFICIENT OF THERMAL
2590  ! EXPANSION [BETA]
2600  Beta(J)=.00246/(1.825-.00246*Tfilm(J))
2610  !
2620  END IF
2630  !
2640  IF Dliq=1 THEN
2650  !
2660  ! CALCULATION OF FC-43 THERMAL CONDUCTIVITY
2670  K(J)=(.0666-9.864E-6*Tfilm(J))
2680  !
2690  ! CALCULATION OF FC-43 DENSITY
2700  Rho(J)=(1.913-.00218*Tfilm(J))*1000
2710  !
2720  ! CALCULATION OF FC-43 SPECIFIC HEAT
2730  Cp(J)=(.241111+3.7037E-4*Tfilm(J))*4187
2740  !
2750  ! CALCULATION OF FC-43 KINEMATIC VISCOSITY
```

```
2760  N(J)=8.875-.47007*Tfilm(J)+1.387E-2*Tfilm(J)^2-2.1469E-4*Tfilm(J)^3+1.3139
E-6*Tfilm(J)^4
2770  !
2780  N(J)=N(J)*1.E-6
2790  !
2800  ! CALCULATION OF COEFFICIENT OF THERMAL
2810  ! EXPANSION [BETA]
2820  Beta(J)=.00218/(1.913-.00218*Tfilm(J))
2830  !
2840  END IF
2850  !
2860  IF Dliq=2 THEN
2870  !
2880  ! CALCULATION OF FC-71 THERMAL CONDUCTIVITY
2890  K(J)=.71/10
2900  !
2910  ! CALCULATION OF FC-71 DENSITY
2920  Rho(J)=(2.002-.00224*Tfilm(J))*1000
2930  !
2940  ! CALCULATION OF FC-71 SPECIFIC HEAT
2950  Cp(J)=(.241111+3.7037E-4*Tfilm(J))*4187
2960  !
2970  ! CALCULATION OF FC-71 KINEMATIC VISCOSITY
2980  N(J)=EXP(6.8976-.1388*Tfilm(J)+1.331E-3*Tfilm(J)^2-7.041E-6*Tfilm(J)^3+1.5
23E-8*Tfilm(J)^4)
2990  !
3000  N(J)=N(J)*1.E-6
3010  !
3020  ! CALCULATION OF THE COEFFICIENT OF THERMAL
3030  ! EXPANSION [BETA]
3040  Beta(J)=.00224/(2.002-.00224*Tfilm(J))
3050  !
3060  END IF
3070  !
3080  ! CALCULATION OF THERMAL DIFFUSIVITY [ALPHA]
3090  Alfa(J)=K(J)/(Rho(J)*Cp(J))
3100  !
3110  ! CALCULATION OF PRANDTL NUMBER
3120  Pr(J)=N(J)/Alfa(J)
3130  !
3140  ! CALCULATION OF NUSSELT NUMBERS
3150  Nu1(J)=H(J)*L1/K(J)
3160  Nu2(J)=H(J)*L2/K(J)
3170  Dnu1=Nu1(J)*(Dh/H(J))
3180  Pernu1=(Dnu1/Nu1(J))*100
3190  !
3200  ! CALCULATION OF GRASHOF NUMBERS
3210  Gr1(J)=9.81*Beta(J)*(L1^3)*Delt(J)/N(J)^2
3220  Gr2(J)=9.81*Beta(J)*(L2^3)*Delt(J)/N(J)^2
3230  Dgr1=Gr1(J)*(Ddelt/Delt(J))
3240  !
3250  ! CALCULATION OF RAYLEIGH NUMBERS
3260  Ra1(J)=Gr1(J)*Pr(J)*1.E-6
3270  Ra2(J)=Gr2(J)*Pr(J)*1.E-6
3280  Dra1=Ra1(J)*(Dgr1/Gr1(J))
3290  Perra1=(Dra1/Ra1(J))*100
3300  !
```

```
3310  ! CALCULATION OF FLUX BASED RAYLEIGH NUMBERS
3320  Raf1(J)=((9.81*Beta(J)*L1^4*Qnet(J))/(K(J)*N(J)*Alfa(J)*Atot))*1.E-6
3330  !
3340  Raf2(J)=((9.81*Beta(J)*L2^4*Qnet(J))/(K(J)*N(J)*Alfa(J)*Atot))*1.E-6
3350  !
3360  ! DATA AND UNCERTAINTY OUTPUT
3370  !
3380  PRINT USING "10X,D,1X,4(4X,DDD.DD,),6X,DDD.DD";J,Qnet(J),Delt(J),Nu1(J),Nu
2(J),Pernu1
3390  PRINT
3400  !
3410  PRINT USING "12X,""TEMP BASED RAYLEIGH NUMBER * E-6 IS: "",DDDDDD.DDD";Ra1
(J)
3420  PRINT USING "12X,""FLUX BASED RAYLEIGH NUMBER * E-6 IS: "",DDDDDD.DDD";Raf
1(J)
3430  PRINT USING "12X,""AVERAGE TEMPERATURE:"",DDD.DD";Tavg(J)
3440  PRINT
3450  PRINT USING "6X,""UNC IN THE NUSSELT NUMBER (Nu1) IS:                  "",
DD.DD";Dnu1
3460  PRINT USING "6X,""TEMP BASED RAYLEIGH NUMBER * E-6 IS:                 "",DDD
D.DDD";Ra1(J)
3470  PRINT USING "6X,""UNC IN THE TEMP BASED RAYLEIGH NUMBER * E-6 IS:      "",
DD.DD";Dra1
3480  PRINT USING "6X,""%UNC IN THE TEMPERATURE BASED RAYLEIGH NUMBER IS:   "",D
DD.DD";Perra1
3490  PRINT
3500  NEXT J
3510  !
3520  Ra1sum=0.
3530  Raf2sum=0.
3540  Nu1sum=0.
3550  Nu2sum=0.
3560  Qnetsum=0.
3570  Deltsum=0.
3580  FOR J=1 TO 9
3590    Ra1sum=Ra1(J)+Ra1sum
3600    Raf2sum=Raf2(J)+Raf2sum
3610    Nu1sum=Nu1(J)+Nu1sum
3620    Nu2sum=Nu2(J)+Nu2sum
3630    Qnetsum=Qnet(J)+Qnetsum
3640    Deltsum=Delt(J)+Deltsum
3650  NEXT J
3660  Ra1(Avg)=Ra1sum/9.
3670  Raf2(Avg)=Raf2sum/9.
3680  Nu1(Avg)=Nu1sum/9.
3690  Nu2(Avg)=Nu2sum/9.
3700  Qnet(Avg)=Qnetsum/9.
3710  Delt(Avg)=Deltsum/9.
3720  !
3730  FOR J=1 TO 3
3740   Rowra1(J)=0
3750   Rownu1(J)=0
3760  NEXT J
3770  FOR J=1 TO 3
3780   Rowra1(J)=(Ra1(J)+Ra1(J+3)+Ra1(J+6))/3.0
3790   Rownu1(J)=(Nu1(J)+Nu1(J+3)+Nu1(J+6))/3.0
3800  NEXT J
```

```
3810 '
3820 PRINT
3830 PRINT
3840 PRINT
3850 PRINT USING "12X,""ARRAY AVG Ra1*E-6 IS:"",DDDDD.DDD";Ra1(Avg)
3860 PRINT USING "12X,""ARRAY AVG Nu1 IS:"",DDD.DD";Nu1(Avg)
3870 PRINT
3880 PRINT USING "12X,""ROW 1 AVG Ra1*E-6 IS:"",DDDDD.DDD";Rowra1(1)
3890 PRINT USING "12X,""ROW 1 AVG Nu1 IS:"",DDD.DD";Rownu1(1)
3900 PRINT
3910 PRINT USING "12X,""ROW 2 AVG Ra1*E-6 IS:"",DDDDD.DDD";Rowra1(2)
3920 PRINT USING "12X,""ROW 2 AVG Nu1 IS:"",DDD.DD";Rownu1(2)
3930 PRINT
3940 PRINT USING "12X,""ROW 3 AVG Ra1*E-6 IS:"",DDDDD.DDD";Rowra1(3)
3950 PRINT USING "12X,""ROW 3 AVG Nu1 IS:"",DDD.DD";Rownu1(3)
3960 PRINT
3970 PRINT USING "12X,""ARRAY AVG Qnet IS:  "",D.DD";Qnet(Avg)
3980 PRINT USING "12X,""ARRAY AVG (TAVG-TSINK) IS:  "",DD.DD";Delt(Avg)
3990 ASSIGN @File TO *
4000 END
```

APPENDIX C. COMPUTER PROGRAM ACQ2

```
10   ! FILE ACQ2
20   !
30   ! WRITTEN BY LCDR R. THOMPSON MAR 90.
40   !
50   ! THIS PROGRAM AQUIRES THE VOLTAGE DATA
60   ! FROM THE HP3456A DVM VIA THE HP3497A DAS
70   ! FOR THE 3 BY 3 ARRAY NWSC CIRCUIT BOARD.
80   ! IT IS WRITTEN IN BASIC 2.0.
90   ! DVM - DIGITAL VOLTMETER
100  ! DAS - DATA ACQUISITION SYSTEM
110  !
120  DIM Emf(64),Power(1:9),T(64)
130  !
140  !PRECISION RESISTOR VALUE IN OHMS
150  Rp=2.0
160  !
170  ! ASSIGN OUTPUT TO HP THINK JET PRINTER
180  PRINTER IS 701
190  BEEP
200  INPUT "ENTER THE INPUT MODE: 0=SYS, 1=FILE",Im
210  !
220  IF Im=1 THEN
230  BEEP
240  INPUT "ENTER THE NAME OF THE FILE TO BE READ",Oldfile$
250  !
260  PRINT USING "15X,""THESE RESULTS ARE STORED IN FILE :  "",10A";Oldfile$
270  ELSE
280  BEEP
290  INPUT "ENTER THE NAME OF THE NEW FILE",Newfile$
300  PRINT USING "10X,""THESE RESULTS ARE STORED IN FILE:  "",10A";Newfile$
310  END IF
320  PRINT
330  PRINT USING "15X,""DATA TAKEN BY THOMPSON"""
340  !
350  INPUT "ENTER THE BATH TEMP",B$
360  PRINT USING "15X,""BATH TEMP WAS:  "",10A";B$
370  !
380  INPUT "ENTER THE WALL SPACING",Wall$
390  PRINT USING "15X,""SPACING WAS:  "",10A";Wall$
400  !
410  INPUT "ENTER THE TYPE OF LIQUID USED",Liquid$
420  PRINT USING "15X,""THE FLUORINERT USED WAS:  "",10A";Liquid$
430  IF Im=1 THEN ASSIGN @File TO Oldfile$
440  !
450  IF Im=0 THEN
460  CREATE BDAT Newfile$,5
470  ASSIGN @File TO Newfile$
480  END IF
490  !
500  ! READ DATA INTO HP9826 COMPUTER. 709 IS THE DAS, 722 IS THE DVM.
```

```
510   !
520   IF Im=0 THEN
530   ! AR RESETS DAS. AF IS FIRST CHANNEL, AL IS LAST CHANNEL.
540   OUTPUT 709;"AR AF00 AL13"
550   ! F1 SETS FUNCTION TO DC VOLTS. R1 SETS RANGE TO AUTO.
560   ! T1 SETS TRIGGER TO INTERNAL. Z0 SETS AUTO ZERO TO OFF.
570   ! FL0 SETS FILTER TO OFF.
580   OUTPUT 722;"F1 R1 T1 Z0 FL0"
590   !
600   FOR I=0 TO 13
610   ! AS CAUSES THE DAS TO ANALOG STEP THROUGH THE CHANNELS.
620    OUTPUT 709;"AS"
630    WAIT 1
640   ! ENTER SENDS VOLTAGES FROM DVM TO DAS.
650    ENTER 722;Emf(I)
660    BEEP
670   NEXT I
680   OUTPUT 709;"AF AF41 AL64"
690   FOR I=41 TO 64
700    OUTPUT 709;"AS"
710    WAIT 1
720    ENTER 722;Emf(I)
730    BEEP
740   NEXT I
750   OUTPUT @File;Emf(*)
760   !
770   ELSE
780   ENTER @File;Emf(*)
790   END IF
800   !
810   ! AR RESETS DAS
820   OUTPUT 709;"AR"
830   !
840   ! CONVERT THERMOCOUPLE VOLTAGES TO TEMPERATURE IN DEGREES CELSIUS.
850   ! THERMOCOUPLES CALIBRATED AGAINST PLATINUM RESISTANCE THERMOMETER
860   ! MARCH 2-3, 1992. TEMP. RANGE 10-100 DEG. C.
870   ! CALIBRATION CURVE FIT BY TABLECURVE SOFTWARE.
880   ! NOTE: CAL. CURVE VOLTAGES ARE MILLIVOLTS, Emf(I)S ARE IN MICROVOLTS.
890   A=.24977483
900   B=24.896086
910   C=-.079219169
920   FOR I=11 TO 13
930    T(I)=A+B*Emf(I)*1.E+3+C*(1.E+3*Emf(I))^3
940   NEXT I
950   FOR I=41 TO 59
960    T(I)=A+B*Emf(I)*1.E+3+C*(1.E+3*Emf(I))^3
970   NEXT I
980   !
990   ! CHIP TSE'S (THE TRANSISTORS) ALSO CALIBRATED SAME TIME AS ABOVE.
1000  ! TEMP. (DEG. C) VS. BASE-EMITTER (Vbe) VOLTAGE CALIBRATION CURVES
1010  ! PRODUCED USING TABLECURVE SOFTWARE.
1020  T(60)=577.58074-575.54353*Emf(60)
1030  T(61)=575.66829-574.05057*Emf(61)
1031  T(62)=577.64556-575.50862*Emf(62)
1032  T(63)=576.98331-574.69738*Emf(63)
1033  T(64)=578.28560-575.99793*Emf(64)
1050  !
```

```
1060  PRINT USING "15X,""VOLTAGE SUPPLY WAS:  "",DD.DD";Emf(10)
1070  PRINT USING "15X,""AMBIENT TEMP WAS:  "",DD.D";T(50)
1080  PRINT
1090  ! POWER CALCULATIONS
1100  !
1110  FOR I=1 TO 3
1120   Power(I)=Emf(0)*Emf(5)/(3*Rp)
1130  NEXT I
1140  J=4
1150  FOR I=1 TO 3
1160   Power(J)=Emf(I)*Emf(I+5)/Rp
1170   J=J+1
1180  NEXT I
1190  FOR I=7 TO 9
1200   Power(I)=Emf(4)*Emf(5)/(3*Rp)
1210  NEXT I
1220  !
1230  BEEP
1240  !
1250  PRINT USING "10X,""ALL TEMPERATURES ARE IN DEGREES CELSIUS"""
1260  !
1270  PRINT
1280  !
1290  PRINT USING "12X,""CHIP              CHIP LID        POWER(W)"""
1300  PRINT
1310  PRINT
1320  PRINT USING "1X,""CHIP NO1:  N/A                 N/A              "",D.DDD";Powe
r(1)
1330  PRINT USING "12X,""                                  (AVG)"""
1340  PRINT
1350  PRINT USING "1X,""CHIP NO2: "",2(DDD.DD,10X),D.DDD";T(60),T(45),Power(2)
1360  PRINT USING "12X,""                                  (AVG)"""
1370  PRINT
1380  PRINT USING "1X,""CHIP NO3:  N/A                 N/A              "",D.DDD";Powe
r(3)
1390  PRINT USING "12X,""                                  (AVG)"""
1400  PRINT
1410  PRINT USING "1X,""CHIP NO4: "",2(DDD.DD,10X),D.DDD";T(61),T(46),Power(4)
1420  PRINT
1430  PRINT
1440  PRINT USING "1X,""CHIP NO5: "",2(DDD.DD,10X),D.DDD";T(62),T(47),Power(5)
1450  PRINT
1460  PRINT
1470  PRINT USING "1X,""CHIP NO6: "",2(DDD.DD,10X),D.DDD";T(63),T(48),Power(6)
1480  PRINT
1490  PRINT
1500  PRINT USING "1X,""CHIP NO7:  N/A                 N/A              "",D.DDD";Powe
r(7)
1510  PRINT USING "12X,""                                  (AVG)"""
1520  PRINT
1530  PRINT USING "1X,""CHIP NO8: "",2(DDD.DD,10X),D.DDD";T(64),T(49),Power(8)
1540  PRINT USING "12X,""                                  (AVG)"""
1550  PRINT
1560  PRINT USING "1X,""CHIP NO9:  N/A                 N/A              "",D.DDD";Powe
r(9)
1570  PRINT USING "12X,""                                  (AVG)"""
1580  PRINT
```

```
1590  PRINT USING "12X,""CIRCUIT BOARD SUBSTRATE SURFACE TEMPERATURES"""
1600  PRINT
1610  PRINT USING "1X,""A: "",DDD.DD";T(41)
1620  PRINT USING "1X,""B: "",DDD.DD";T(42)
1630  PRINT USING "1X,""C: "",DDD.DD";T(43)
1640  PRINT USING "1X,""D: "",DDD.DD";T(44)
1650  PRINT
1660  PRINT USING "5X,""HEAT EXCHANGER TEMPERATURES:      RIGHT      CENTER      LE
FT"""
1670  PRINT USING "10X,""BOTTOM IS INSULATED"""
1680  PRINT USING "10X,""TOP:"",24X,3(DD.DD,5X)";T(11),T(12),T(13)
1690  PRINT
1700  !
1710  PRINT USING "5X,""CIRCUIT BOARD ASSEMBLY BACK TEMPERATURES ARE:"""
1720  PRINT
1730  PRINT USING "10X,""CHIP NO1:"",2X,DD.DD";T(51)
1740  PRINT USING "10X,""CHIP NO2:"",2X,DD.DD";T(52)
1750  PRINT USING "10X,""CHIP NO3:"",2X,DD.DD";T(53)
1760  PRINT USING "10X,""CHIP NO4:"",2X,DD.DD";T(54)
1770  PRINT USING "10X,""CHIP NO5:"",2X,DD.DD";T(55)
1780  PRINT USING "10X,""CHIP NO6:"",2X,DD.DD";T(56)
1790  PRINT USING "10X,""CHIP NO7:"",2X,DD.DD";T(57)
1800  PRINT USING "10X,""CHIP NO8:"",2X,DD.DD";T(58)
1810  PRINT USING "10X,""CHIP NO9:"",2X,DD.DD";T(59)
1820  BEEP
1830  ! REASSIGN PRINTER TO THE CRT
1840  PRINTER IS 1
1850  ASSIGN @File TO *
1860  END
```

APPENDIX D. COMPUTER PROGRAM CALC2

```
10   ! FILE CALC2
20   !
30   ! WRITTEN BY LCDR R. THOMPSON MAR 92.
40   ! MODIFIED EARLY APR 92. BASED ON THE PROGRAM
50   ! CALCDIEL WRITTEN AND MODIFIED BY PAMUK,
60   ! BENEDICT, TORRES, AYTAR, MATTHEWS AND THOMPSON.
70   !
80   ! THIS PROGRAM ANALYZES THE DATA READ FROM
90   ! A DESIGNATED "ACQ2" DATA FILE. ACQ2 DATA FILES
100  ! ARE FOR THE 3 BY 3 ARRAY NWSC CIRCUIT BOARD.
110  ! IT REDUCES THE DATA TO CALCULATIONS OF NET POWER, RAYLEIGH
120  ! AND NUSSELT NUMBER. THE UNCERTAINTY ANALYSIS IS ALSO INCLUDED.
130  ! IT IS WRITTEN IN BASIC 2.0.
140  !
150  ! VARIABLES USED ARE:
160  ! EMF   : DATA FILE VOLTAGES.
170  ! POWER : POWER DISSIPATED BY THE CHIP RESISTORS (W)
180  ! T(I)  : TEMPERATURES CONVERTED FROM THERMO-
190  !         COUPLE VOLTAGES (DEG. C)
200  ! Ts    : CIRCUIT BOARD ASSEMBLY BACK TEMPERATURE (DEG. C)
210  ! Tfilm : DIELECTRIC FILM TEMPERATURE (DEG. C)
220  ! Tavg  : AVG. TEMP. OF THE 5 CHIP TSE's (DEG. C)
230  ! Qnet  : ELECTRIC POWER MINUS CONDUCTION LOSSES (W)
240  ! Tsink : AVERAGE OF THE 3 THERMOCOUPLES IN
250  !         THE UPPER HEAT EXCHANGER (DEG. C)
260  ! Nu    : LENGTH BASED NUSSELT NUMBER
270  ! Rc    : THERMAL RESISTANCE FOR CONDUCTION (DEG. C/W)
280  ! D...  : UNCERTAINTY OF A VARIABLE (EXCEPT
290  !         Dliq AND Delt)
300  ! OTHER VARIABLES NOT SELF-EXPLANATORY ARE DEFINED IN THE PROGRAM
310  !
320  DIM Emf(64),Power(1:9),T(64),Ts(1:9),Tside(1:9),Tlid(1:9)
330  DIM Qnet(1:9),Delt(1:9),H(1:9),Nu(1:9),Ra(1:9)
340  DIM Gr(1:9),Qloss(1:9),Dh(1:9),Dpower(1:9)
350  DIM Rowgr(1:3),Rowra(1:3),Rownu(1:3)
360  !
370  ! PRECISION RESISTOR VALUE IN OHMS
380  Rp=2.0
390  ! ASSIGN OUTPUT TO HP THINKJET PRINTER
400  PRINTER IS 701
410  BEEP
420  !
430  PRINT USING "10X,""DATA TAKEN BY THOMPSON"""
440  INPUT "ENTER THE NAME OF THE FILE CONTAINING DATA",Oldfile$
450  !
460  PRINT USING "10X,""THE RAW Emf DATA ARE FROM THE FILE:    "",10A";Oldfile$
470  !
480  INPUT "ENTER THE APPROX. POWER SETTING ",Power$
490  PRINT USING "9X,"" THE APPROX. POWER SETTING PER CHIP WAS:   "",10A";Power
$
500  !
```

```
510   INPUT "ENTER THE TYPE OF LIQUID USED",Liquid$
520   PRINT USING "10X,""THE FLUORINERT USED WAS:  "",10A";Liquid$
530   INPUT "ENTER THE TYPE OF DIELECTRIC:0=FC-75,1=FC-43,2=FC-71",Dliq
540   !
550   INPUT "ENTER THE WALL SPACING",Wall$
560   PRINT USING "10X,""THE DISTANCE TO THE FRONT WALL WAS:  "",10A";Wall$
570   !
580   BEEP
590   ASSIGN @File TO Oldfile$
600   ENTER @File;Emf(*)
610   !
620   ! CONVERT THERMOCOUPLE VOLTAGES TO TEMPERATURE IN DEGREES CELSIUS.
630   ! THERMOCOUPLES CALIBRATED AGAINST PLATINUM RESISTANCE THERMOMETER
640   ! MARCH 2-3, 1992. TEMP. RANGE 10-100 DEG. C.
650   ! CALIBRATION CURVE FIT BY TABLECURVE SOFTWARE.
660   ! NOTE: CAL. CURVE VOLTAGES ARE MILLIVOLTS, Emf(I)S ARE IN MICROVOLTS.
670   A=.24977483
680   B=24.896088
690   C=-.079219189
700   FOR I=11 TO 13
710    T(I)=A+B*Emf(I)*1.E+3+C*(1.E+3*Emf(I))^3
720   NEXT I
730   FOR I=41 TO 59
740    T(I)=A+B*Emf(I)*1.E+3+C*(1.E+3*Emf(I))^3
750   NEXT I
760   !
770   ! CHIP TSE's (THE TRANSISTORS) ALSO CALIBRATED SAME TIME AS ABOVE.
780   ! TEMP. (DEG. C) VS. BASE-EMITTER (Vbe) VOLTAGE CALIBRATION CURVES
790   ! PRODUCED USING TABLECURVE SOFTWARE.
800   T(60)=577.58074-575.54353*Emf(60)
810   T(61)=575.66889-574.05057*Emf(61)
820   T(62)=577.64556-575.50862*Emf(62)
830   T(63)=576.98331-574.69738*Emf(63)
840   T(64)=578.28560-575.99793*Emf(64)
850   Tavg=(T(60)+T(61)+T(62)+T(63)+T(64))/5
860   !
870   ! POWER CALCULATIONS
880   FOR I=1 TO 3
890    Power(I)=Emf(0)*Emf(5)/(3*Rp)
900   NEXT I
910   J=4
920   FOR I=1 TO 3
930    Power(J)=Emf(I)*Emf(I+5)/Rp
940    J=J+1
950   NEXT I
960   FOR I=7 TO 9
970    Power(I)=Emf(4)*Emf(9)/(3*Rp)
980   NEXT I
990   !
1000  ! BELOW LENGTHS AND AREAS BASED ON CHIP MODELED AS A SQUARE WAFER.
1010  ! ALL DIMENSIONS IN m OR SQUARE m.
1020  L1=8.89E-3
1030  Alef=1.65E-5
1040  Arig=Alef
1050  Atop=Alef
1060  Abot=Alef
1070  Alid=7.90E-5
```

```
1080  Le=L1*1000
1090  PRINT USING "10X,""LENGTH SCALE IS (mm): "",D.DD";Le
1100  ! Atot IS TOTAL AREA FOR CONVECTION
1110  Atot=Alef+Arig+Atop+Abot+Alid
1120  !
1130  ! CHIP SIDE TEMPERATURES. ASSUMES IT IS THE AVERAGE OF THE TSE TEMP.
1140  ! AND THE LID TEMP., WITH CHIP TEMPS. 1,4,7 ASSUMED TO BE EQUAL AND
1150  ! CHIP TEMPS. 3,6,9 ASSUMED TO BE EQUAL.
1160  !
1170  Tside(1)=(T(46)+T(61))/2
1180  Tside(2)=(T(45)+T(60))/2
1190  Tside(3)=(T(48)+T(63))/2
1200  Tside(4)=(T(46)+T(61))/2
1210  Tside(5)=(T(47)+T(62))/2
1220  Tside(6)=(T(48)+T(63))/2
1230  Tside(7)=(T(46)+T(61))/2
1240  Tside(8)=(T(49)+T(64))/2
1250  Tside(9)=(T(48)+T(63))/2
1260  !
1270  ! CHIP LID TEMPERATURES. SAME ASSUMPTION AS CHIP SIDES.
1280  Tlid(1)=T(46)
1290  Tlid(2)=T(45)
1300  Tlid(3)=T(48)
1310  Tlid(4)=T(46)
1320  Tlid(5)=T(47)
1330  Tlid(6)=T(48)
1340  Tlid(7)=T(46)
1350  Tlid(8)=T(49)
1360  Tlid(9)=T(48)
1370  !
1380  ! CIRCUIT BOARD ASSEMBLY BACK TEMPERATURES
1390  Tssum=0
1400  FOR I=1 TO 9
1410   Ts(I)=T(I+50)
1420   Tssum=Tssum+Ts(I)
1430  NEXT I
1440  !
1450  Tsavg=Tssum/9
1460  !
1470  ! CONDUCTION LOSS CALCULATION
1480  ! ONE DIMENSIONAL CONDUCTION ASSUMED THROUGH THE FOLLOWING:
1490  ! 4.06E-4 m (0.016") OF SILICON (CHIP)
1500  ! 7.62E-4 m (0.030") OF ALUMINA (CIRCUIT BOARD)
1510  ! 1.27E-4 m (0.005") OF SILICONE RUBBER
1520  ! 1.18E-2 m (0.465") OF ACRYLIC (PLEXIGLAS)
1530  ! VALUES FOR THERMAL CONDUCTIVITY K IN W/m-DEG. C. SOURCE:
1540  ! SILICON, ALUMINA: NWSC, MR. TONY BUECHLER
1550  ! ALL OTHERS: MATERIALS ENGINEERING 1978 MATERIALS SELECTOR, VOL. 86,
1560  ! NO. 6, REINHOLD PUBLISHING, 1977, PAGES 202, 143.
1570  !
1580  ! SILICON: 168*EXP(-0.00458*T). T IS SILICON TEMP. IN DEG. C.
1590  ! ALUMINA: 16.7  SILICON RUBBER: 0.225  ACRYLIC: 0.208
1600  ! HEAT FLUX q FOUND BY STANDARD EQUATION
1610  ! q = AREA*DELTA T/(SUM OF LENGTHS/K'S)
1620  !
1630  ! IT IS ASSUMED FOR CALCULATIONS THAT THE FOLLOWING TEMPS. ARE THE SAME:
1640  ! CHIP1 = CHIP4 = CHIP7
```

```
1650  ! CHIP3 = CHIP6 = CHIP9
1660  !
1670  ! E IS AREA (SQUARE m), F & S ARE L/K VALUES
1680  E=7.90E-5
1690  F=2.42E-6
1700  G=.00458
1710  S=5.73E-2
1720  !
1730  Qloss(1)=E*(T(61)-T(51))/(F*EXP(G*T(61))+S)
1740  Qloss(2)=E*(T(60)-T(52))/(F*EXP(G*T(60))+S)
1750  Qloss(3)=E*(T(63)-T(53))/(F*EXP(G*T(63))+S)
1760  Qloss(4)=E*(T(61)-T(54))/(F*EXP(G*T(61))+S)
1770  Qloss(5)=E*(T(62)-T(55))/(F*EXP(G*T(62))+S)
1780  Qloss(6)=E*(T(63)-T(56))/(F*EXP(G*T(63))+S)
1790  Qloss(7)=E*(T(61)-T(57))/(F*EXP(G*T(61))+S)
1800  Qloss(8)=E*(T(64)-T(58))/(F*EXP(G*T(64))+S)
1810  Qloss(9)=E*(T(63)-T(59))/(F*EXP(G*T(63))+S)
1820  !
1830  Qlosssum=0
1840  FOR I=1 TO 9
1850  Qlosssum=Qlosssum+Qloss(I)
1860  NEXT I
1870  Qlossavg=Qlosssum/9
1880  !
1890  ! Rc WILL BE CALCULATED ASSUMING SILICON TEMP. IS 60 DEG. C, WHICH IS
1900  ! ABOUT MID-RANGE FOR THE EXPERIMENTS
1910  ! Rc = (1/AREA)*SUM OF LENGTHS/K'S
1920  ! ALSO ASSUME Drc IS 5% OF Rc
1930  Rc=725
1940  Drc=36.3
1950  ! Dtlid, Dtside, Dtchip, Dts, AND Dtsink BASED ON THERMOCOUPLE CALIBRATION
1960  Dtchip=.3
1970  Dts=.3
1980  Dtlid=.3
1990  Dtside=.3
2000  Dtsink=.3
2010  ! SINCE CONDUCTION TEMP. DIFFERENCE = Tchip - Ts, Dt IS THE RMS OF Dtchip
AND Dts
2020  Dt=(Dtchip^2+Dts^2)^.5
2030  Dqloss=(Qlossavg)*((Dt/(Tavg-Tsavg))^2+(Drc/Rc)^2)^.5
2040  !
2050  ! AVERAGE SINK TEMPERATURE CALCULATION
2060  Tsink=(T(11)+T(12)+T(13))/3
2070  !
2080  PRINT USING "10X,""AVERAGE SINK TEMPERATURE (C):  "",DD.DD";Tsink
2090  PRINT
2100  !
2110  ! THE CHARACTERISTIC LENGTH TO BE USED TO CALCULATE THE NUSSELT NUMBER
2120  ! IS L1, WHICH WAS PREVIOUSLY DEFINED
2130  !
2140 PRINT USING "9X,""CHIP   Qnet(W)   Delta T     Nu       %UNC IN NU"",10A"
2150 PRINT
2160  !
2170  ! CALCULATION OF NET POWER, Nu, Ra AND UNCERTAINTIES
2180  FOR J=1 TO 9
2190  ! Dpower IS BASED ON ACCURACY OF THE DVM AND THE PRECISION RESISTORS.
2200  ! Dv FOR VOLTAGE DROPS ACROSS THE CHIP RESISTOR OR THE PRECISION RESISTOR
```

```
2210  ! IS 5E-6 V. Drp = 0.05 OHMS.
2220  Dv=5.E-6
2230  Drp=.05
2240  FOR I=1 TO 3
2250   Dpower(I)=Power(I)*((3*Dv/Emf(0))^2+(Dv/Emf(5))^2+(Drp/Rp)^2)^.5
2260  NEXT I
2270  L=4
2280  FOR I=1 TO 3
2290   Dpower(L)=Power(L)*((Dv/Emf(L))^2+(Dv/Emf(I+5))^2+(Drp/Rp)^2)^.5
2300   L=L+1
2310  NEXT I
2320  FOR I=7 TO 9
2330   Dpower(I)=Power(I)*((3*Dv/Emf(4))^2+(Dv/Emf(9))^2+(Drp/Rp)^2)^.5
2340  NEXT I
2350  !
2360  ! CALCULATION OF Qnet
2370  Qnet(J)=Power(J)-Qloss(J)
2380  Dqnet=(Dpower(J)^2+Dqloss^2)^.5
2390  !
2400  ! CALCULATION OF Tfilm
2410  Tfilm=(Tavg+Tsink)/2
2420  ! Dtavg BASED ON TSE CALIBRATION
2430  Dtavg=.275
2440  !
2450  ! CALCULATION OF Delta T BASED ON LID AREA COMPRISING ABOUT 55% OF TOTAL
2460  ! CONVECTION AREA, AND THE CHIP SIDES 45% OF THE AREA
2470  Delt(J)=(.55*Tlid(J)+.45*Tside(J))-Tsink
2480  Ddelt=(Dtlid^2+Dtside^2+Dtsink^2)^.5
2490  !
2500  ! CALCULATION OF CONVECTION COEFFICIENT
2510  H(J)=Qnet(J)/(Atot*Delt(J))
2520  Dh(J)=H(J)*((Dqnet/Qnet(J))^2+(Ddelt/Delt(J))^2)^.5
2530  NEXT J
2540  !
2550  ! PHYSICAL PROPERTIES ARE TAKEN FROM THE 1985 3M PRODUCT MANUAL
2560  ! FOR FLUORINERT ELECTRONIC LIQUIDS
2570  !
2580  IF Dliq=0 THEN
2590  !
2600  ! CALCULATION OF FC-75 THERMAL CONDUCTIVITY
2610  K=(.65-7.89474E-4*Tfilm)/10
2620  !
2630  ! CALCULATION OF FC-75 DENSITY
2640  Rho=(1.825-.00246*Tfilm)*1000
2650  !
2660  ! CALCULATION OF FC-75 SPECIFIC HEAT
2670  Cp=(.241111+3.7037E-4*Tfilm)*4187
2680  ! THE 4187 CONVERTS FROM CALORIES TO JOULES
2690  !
2700  ! CALCULATION OF FC-75 KINEMATIC VISCOSITY
2710  N=1.4074-2.964E-2*Tfilm+3.8018E-4*Tfilm^2-2.7308E-6*Tfilm^3+8.1679E-9*Tfil
m^4
2720  ! CONVERT FROM CENTISTOKES TO m^2/s
2730  N=N*1.E-6
2740  !
2750  ! CALCULATION OF THE COEFFICIENT OF THERMAL
2760  ! EXPANSION [BETA]
```

```
3330  Nu(J)=H(J)*L1/K
3340  Dnu=Nu(J)*(Dh(J)/H(J))
3350  Pernu=(Dnu/Nu(J))*100
3360  !
3370  ! CALCULATION OF GRASHOF NUMBER
3380  Gr(J)=9.81*Beta*(L1^3)*Delt(J)/N^2
3390  Dgr=Gr(J)*(Ddelt/Delt(J))
3400  Pergr=(Dgr/Gr(J))*100
3410  !
3420  ! CALCULATION OF RAYLEIGH NUMBER
3430  Ra(J)=Gr(J)*Pr*1.E-6
3440  Dra=Ra(J)*(Dgr/Gr(J))
3450  Perra=(Dra/Ra(J))*100
3460  !
3470  ! DATA AND UNCERTAINTY OUTPUT
3480  IF J=6 THEN
3490  PRINT
3500  PRINT
3510  PRINT
3520  PRINT
3530  PRINT
3540  PRINT
3550  PRINT USING "10X,""PAGE 2 OF FILE:  "",10A";Oldfile$
3560  PRINT
3570  PRINT USING "10X,D,1X,3(5X,DD.DD,),5X,DDD.DDD";J,Qnet(J),Delt(J),Nu(J),Per
nu
3580  ELSE
3590  PRINT
3600  PRINT USING "10X,D,1X,3(5X,DD.DD,),5X,DDD.DDD";J,Qnet(J),Delt(J),Nu(J),Per
nu
3610  END IF
3620  PRINT
3630  PRINT USING "12X,""TEMP BASED RAYLEIGH NUMBER * E-6 IS: "",DDDDDD.DDD";Ra(
J)
3640  PRINT USING "12X,""GRASHOF NUMBER IS:                    "",DDDDDDD.DDD";Gr(
J)
3650  PRINT
3660  PRINT USING "6X,""UNC IN THE NUSSELT NUMBER IS:                        "",D
D.DDD";Dnu
3670  PRINT USING "6X,""UNC IN THE TEMP. BASED RAYLEIGH NUMBER * E-6 IS:    "",D
D.DDD";Dra
3680  PRINT USING "6X,""UNC IN THE GRASHOF NUMBER IS:                     "",DDD
DDD.D";Dgr
3690  ! ALGEBRAICALLY, Perra = Pergr
3700  PRINT USING "6X,""%UNC IN THE RAYLEIGH OR GRASHOF NUMBER IS:         "",D
D.DDD";Perra
3710  NEXT J
3720  !
3730  Rasum=0
3740  Nusum=0
3750  Qnetsum=0
3760  Deltsum=0
3770  Grsum=0
3780  FOR J=1 TO 9
3790   Rasum=Ra(J)+Rasum
3800   Nusum=Nu(J)+Nusum
3810   Qnetsum=Qnet(J)+Qnetsum
```

```
3820  Deltsum=Delt(J)+Deltsum
3830  Grsum=Gr(J)+Grsum
3840 NEXT J
3850 Raavg=Rasum/9
3860 Nuavg=Nusum/9
3870 Qnetavg=Qnetsum/9
3880 Deltavg=Deltsum/9
3890 Gravg=Grsum/9
3900 !
3910 FOR J=1 TO 3
3920  Rowra(J)=0
3930  Rownu(J)=0
3940  Rowgr(J)=0
3950 NEXT J
3960 FOR J=1 TO 3
3970  Rowra(J)=(Ra(J)+Ra(J+3)+Ra(J+6))/3
3980  Rownu(J)=(Nu(J)+Nu(J+3)+Nu(J+6))/3
3990  Rowgr(J)=(Gr(J)+Gr(J+3)+Gr(J+6))/3
4000 NEXT J
4010 !
4020 PRINT
4030 PRINT USING "19X,""TOP ROW AVG Ra*E-6 IS:   "",DDDDD.DDD";Rowra(3)
4040 PRINT USING "19X,""TOP ROW AVG Nu IS:          "",DDD.DD";Rownu(3)
4050 PRINT USING "19X,""TOP ROW AVG Gr IS:     "",DDDDDDD.DDD";Rowgr(3)
4060 PRINT
4070 PRINT USING "19X,""MID ROW AVG Ra*E-6 IS:   "",DDDDD.DDD";Rowra(2)
4080 PRINT USING "19X,""MID ROW AVG Nu IS:          "",DDD.DD";Rownu(2)
4090 PRINT USING "19X,""MID ROW AVG Gr IS:     "",DDDDDDD.DDD";Rowgr(2)
4100 PRINT
4110 PRINT USING "19X,""BOT ROW AVG Ra*E-6 IS:   "",DDDDD.DDD";Rowra(1)
4120 PRINT USING "19X,""BOT ROW AVG Nu IS:          "",DDD.DD";Rownu(1)
4130 PRINT USING "19X,""BOT ROW AVG Gr IS:     "",DDDDDDD.DDD";Rowgr(1)
4140 PRINT
4150 PRINT USING "19X,""ARRAY AVG Qnet IS:            "",D.DD";Qnetavg
4160 PRINT USING "19X,""ARRAY AVG Delta T IS:        "",DD.DD";Deltavg
4170 PRINT USING "19X,""ARRAY AVG Ra*E-6 IS:     "",DDDDD.DDD";Raavg
4180 PRINT USING "19X,""ARRAY AVG Nu IS:            "",DDD.DD";Nuavg
4190 PRINT USING "19X,""ARRAY AVG Gr IS:       "",DDDDDDD.DDD";Gravg
4200 PRINT USING "19X,""ARRAY AVG Pr IS:            "",DDDD.D";Pr
4210 ASSIGN @File TO *
4220 END
```

APPENDIX E. UNCERTAINTY ANALYSIS

The software programs CALCDIEL and CALC2 also calculated a standard zeroth order uncertainty analysis as described in Beckwith and Marangoni (1990). The uncertainties were calculated for the Nusselt number and Rayleigh number for each component on the circuit board. A complete description of the CALCDIEL uncertainty analysis can be found in Matthews' thesis. The analysis performed by CALC2 for the NSWC circuit board is described below in expression form, with numerical results omitted for generality. The small uncertainty associated with the thermophysical properties was neglected. Other assumptions are included, where appropriate.

1. Conduction heat loss through the circuit board assembly

$$Q_{loss} = \frac{\Delta T_c}{R_c}$$

$$\delta Q_{loss} = Q_{loss}\sqrt{\left(\frac{\delta \Delta T_c}{\Delta T_c}\right)^2 + \left(\frac{\delta R_c}{R_c}\right)^2}$$

$$\Delta T_c = T_{chip} - T_s$$

$$\delta \Delta T_c = \sqrt{\delta T_{chip}^2 + \delta T_s^2}$$

$$\delta \Delta T_{chip} = \delta T_s = \pm 0.3\ ^\circ C$$

R_c was calculated for $T_{chip} = 60\ ^\circ C$. δR_c was then assumed to be 5% of R_c.

$$\delta R_c = \pm 36.3\ ^\circ C/W$$

2. Power supplied to the chip resistors

$$\delta Power = Power\sqrt{\left(\frac{\delta V_{htr}}{V_{htr}}\right)^2 + \left(\frac{\delta V_{rp}}{V_{rp}}\right)^2 + \left(\frac{\delta R_p}{R_p}\right)^2}$$

$$\delta V_{htr} = \delta V_{rp} = \pm 0.000005 \text{ V}$$

$$\delta R_p = \pm 0.05 \ \Omega$$

3. Net power dissipated

$$Q_{net} = Power - Q_{loss}$$

$$\delta Q_{net} = \sqrt{\delta Power^2 + \delta Q_{loss}^2}$$

4. Temperatures for calculation of average heat transfer coefficient

$$\delta T_{avg} = \pm 0.275 \ ^\circ C$$

$$\delta T_{sink} = \pm 0.3 \ ^\circ C$$

$$\Delta T = (0.55 T_{lid} + 0.45 T_{side}) - T_{sink}$$

55% of the exposed chip surface area is the lid, and the chip sides make up the remainder. T_{side} is based on the average between the lid temperature and the indicated chip temperature.

$$\delta \Delta T = \sqrt{\delta T_{lid}^2 + \delta T_{side}^2 + \delta T_{sink}^2}$$

$$\delta T_{lid} = \delta T_{side} = \delta T_{sink} = \pm 0.3 \ ^\circ C$$

5. Average heat transfer coefficient

$$h = \frac{Q_{net}}{A_{tot} \Delta T}$$

$$\delta h = h \sqrt{\left(\frac{\delta Q_{net}}{Q_{net}}\right)^2 + \left(\frac{\delta \Delta T}{\Delta T}\right)^2}$$

The small uncertainty in A_{tot} is neglected.

6. Nusselt number

$$Nu = \frac{hL}{k}$$

$$\delta Nu = Nu \sqrt{\left(\frac{\delta h}{h}\right)^2 + \left(\frac{\delta L}{L}\right)^2 + \left(\frac{\delta k}{k}\right)^2}$$

The small uncertainty in L is neglected, and δk is assumed to be negligible. Therefore

$$\delta Nu = Nu\frac{\delta h}{h}$$

7. Rayleigh number

$$Ra = GrPr$$

$$Gr = \frac{g\beta L^3 \Delta T}{\nu^2} \qquad Pr = \frac{\nu}{\alpha}$$

Neglecting property and length uncertainties,

$$\delta Gr = Gr\frac{\delta \Delta T}{\Delta T}$$

$$\delta Ra = Ra\frac{\delta Gr}{Gr}$$

APPENDIX F. TSE CALIBRATION

The entire NSWC circuit board assembly was placed inside a 400 W Central Scientific Company oven for calibration. The oven had a cylindrically shaped internal volume of 0.11 m^3. A platinum resistance thermometer was inserted through a small hole in the top of the oven. A Rosemont Engineering Company galvanometer and commutating bridge, accurate to ±0.0001 ohm, was used to measure the thermometer's resistance. Temperature was then read from pre-printed NBS calibration data, accurate to ±0.01 °C. Due to the expected nature of the dielectric liquid temperature fluctuations during the experimental runs, the calibration data was rounded to the nearest 0.1 °C.

This temperature was considered to be the reference temperature for the calibration curve. The V_{BE} voltages were read with a HP-3456A digital voltmeter, accurate to ±0.000005 V. Data points were taken at four different oven settings, ranging from 19.5 to 95.8 °C. Additional data points were taken as necessary to ensure steady state conditions had been reached. The data points used for the TSE calibration are included in the table below:

channel	60	61	62	63	64	
TSE #	2	4	5	6	8	Temp. (°C)
V_{BE} (V)	0.96907	0.96827	0.96925	0.96954	0.96955	19.5
V_{BE} (V)	0.92845	0.92752	0.92861	0.92875	0.92892	43.6
V_{BE} (V)	0.88470	0.88367	0.88486	0.88479	0.88521	68.6
V_{BE} (V)	0.83666	0.83551	0.83683	0.83697	0.83724	95.8

LIST OF REFERENCES

Bar-Cohen, A., "Thermal Management of Electronic Components with Dielectric Liquids," *Proceedings of the ASME/JSME Thermal Engineering Joint Conference*, Reno, Nevada, Vol. 2, pp. xv-xxxix, 1991.

Bergles, A. E., "Liquid Cooling for Electronic Equipment," *Cooling Techniques for Computers*, W. Aung, ed., Hemisphere, New York, p. 155, 1991.

Park, K. A., and Bergles, A. E., "Natural Convection Heat Transfer Characteristics of Simulated Microelectronic Chips," ASME *Journal of Heat Transfer*, Vol. 109, pp. 90-96, February 1987.

Kelleher, M. D., Knock, R. H., and Yang, K. T., "Laminar Natural Convection in a Rectangular Enclosure Due to a Heated Protrusion on One Vertical Wall-Part I: Experimental Investigation," *Proceedings of the ASME/JSME Thermal Engineering Joint Conference*, Honolulu, Hawaii, Vol. 2, pp. 169-177, 1987.

Joshi, Y., Kelleher, M. D., and Benedict, T. J., "Natural Convection Immersion Cooling of an Array of Simulated Electronic Components in an Enclosure Filled with Dielectric Fluid," *Electronic and Microelectronic Equipment*, A. E. Bergles, ed., Hemisphere, New York, pp. 445-468, 1990.

Joshi Y., Kelleher, M. D., Powell, M., and Torres, E. I., "Natural Convection Heat Transfer From and Array of Rectangular Protrusions in an Enclosure Filled with Dielectric Liquid," *Heat Transfer Enhancement in Electronics Cooling*, S H. Bhavnani and M. Greiner, eds., ASME HTD-Vol. 183, pp. 9-18, 1991.

Keyhani, M., Chen, L., and Pitts, D. R., "The Aspect Ratio Effect on Natural Convection in an Enclosure With Protruding Heat Sources," Transactions of the ASME, *Journal of Heat Transfer*, Vol. 113, pp. 883-891, November 1991.

Aytar, E., "Natural Convection Immersion Cooling of an Array of Heated Protrusions in an Enclosure Filled with Dielectric Liquid: Effects of Enclosure Width and Fluid Prandtl Number," Master's Thesis, Naval Postgraduate School, Monterey, California, March 1991.

Matthews, S. T., "Natural Convection Immersion Cooling of an Array of Vertically Oriented Heated Protrusions in an Enclosure Filled With Dielectric Liquid: Effects of Enclosure Width, Prandtl Number and Component Orientation," Master's Thesis, Naval Postgraduate School, Monterey, California, December 1991.

TABLECURVE software produced by Jandel Scientific, Corte Madera, California, version 2.1, July 1990.

SIGMAPLOT software produced by Jandel Scientific, Corte Madera, California, version 4.0, December 1989.

Beckwith, T. G., and Marangoni, R. D., *Mechanical Measurements*, 4th ed., Addison-Wesley, Reading, Massachusetts, pp. 37-48, 1990.

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