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Transient analogy to the steady state problem of heat transfer from a vibrating horizontal cylinder

Joseph M. Harth
Lehigh University

TRANSIENT ANALOGY TO THE STEADY STATE PROBLEM OF HEAT TRANSFER FROM A VIBRATING HORIZONTAL CYLINDER

by

Joseph M. Harth

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Benjamin E. Nevis
Professor in charge

Ferdinand P. Neer
Head of Department

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ABSTRACT

A transient method of finding the effect of vibration on heat transfer from a horizontal cylinder to air was developed using amplitudes from 0.001 to 0.75 inches, and frequencies from 10 to 500 cycles per second. The tests were run with Grashof-Prandtl products of approximately 19,000 and 29,000.

This transient method assumes that there are no temperature gradients in the test specimen, and that the specimen cools slowly enough so that the boundary layer at any temperature is the same as that boundary layer associated with the steady state specimen at the same temperature. Results of this transient method when compared to steady state results of other investigators, as well as work carried out in this report, were found to agree quite favorably.

Heat transfer as the result of vibration was found to increase from 3 to 5 times that resulting from free convection.

INTRODUCTION

The effect of vibration on heat transfer from a horizontal cylinder has been approached in the literature from the standpoint of achieving steady state. Essentially this method involves some means of continually supplying heat to a test specimen while keeping some significant temperature of the specimen constant. As the rate of heat transfer is increased the heat input is also increased.

The problems involved in such a method, although numerous, are not insolvable; and results have been obtained by various investigators.

R. C. Martinelli and L. M. Boelter(1)[1] did some of the original work on this problem using a 0.75 inch cylinder being vibrated sinusoidally in water with amplitudes from 0 to 0.10 of an inch, and frequencies from 0 to 40 cycles per second. Later F. K. Deaver, W. R. Penney and T. B. Jefferson(2) extended this work using a 0.007 inch platinum wire with amplitudes from 0.09 to 2.76 inches, and frequencies from 0 to 4.25 cycles per second.

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[1]Numbers in brackets designate references listed in the bibliography

As a result of the latter group's work they state that a good approximation of the Nusselt number can be obtained from:

$$NU=1.15(GR*PR)^{0.15}$$

for the free convection zone, which they define as a region in which free convection predominates over forced convection. A conservative dividing line between these two regions is defined by:

$$RE=0.44(GR*PR)^{0.5}$$

A Reynolds number for a given run less than the above being in the free convection zone; one higher being in the forced convection zone, which they define as a region in which the effects of free convection are negligible.

For free convection from horizontal cylinders McAdams(3) recommends:

$$NU=0.53(GR*PR)^{0.25}$$

for products of Grashof and Prandtl numbers from 10^3 to 10^9. The results of this equation represent the midpoint of a range of reported experimental results and other equation recommended by Rice(3) and Nusselt(3). This range of results varies 8 to 12 percent from the results obtained using the McAdams equation.

Work has also been done in this field by

J. R. Cary(4), W. Elenbass(5), H. Kramers(6), R. Lemlich(7), R. C. Martinelli(8), Y. T. Tsui(9), and others.

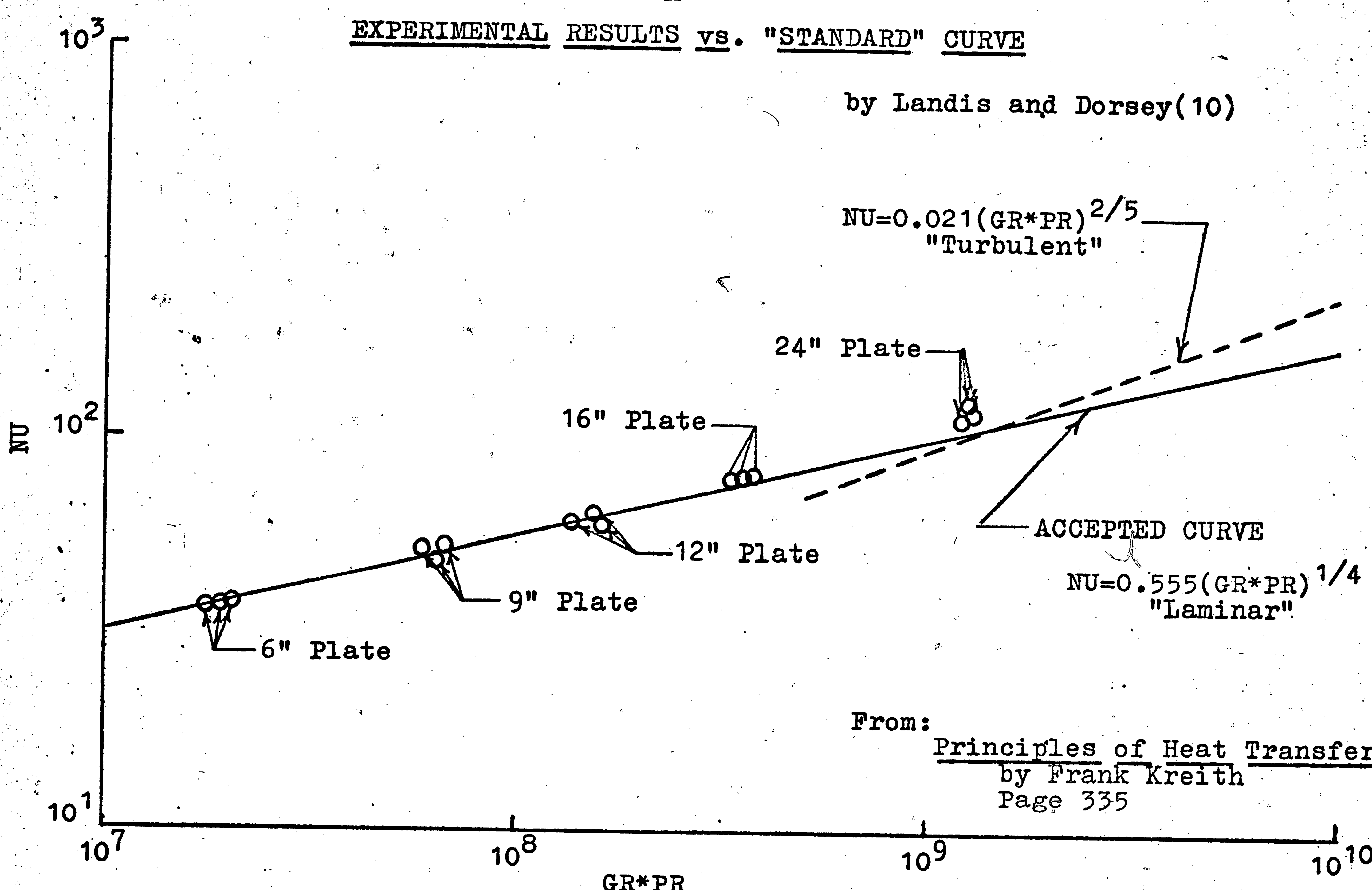
The advantages of using a transient method of obtaining the rate of heat transfer lie chiefly in its simplicity. In the steady state method three difficulties immediately present themselves. One, installation of the heater and symmetrical heating of the specimen. Two, measuring the heat input. Three, equipment breakdown due to vibration. The transient method eliminates these problems in that only a time-temperature history of the cooling specimen is needed after the initial heating is done in an oven.

This transient method assumes that there are no temperature gradients in the test specimen, and that the specimen cools slowly enough so that the boundary layer at any temperature is the same as that boundary layer associated with the steady state specimen at the same temperature. The first assumption allows easy calculation of the heat given up to the cooling medium by the specimen, whereas the second assumption assumes in substance that the two conditions are analogous.

Work has been done using this transient technique for free convection for various sized flat plates by W. J. Landis and W. G. Dorsey, Jr.(10); and as can be seen from their graph of "Experimental Results vs. 'Standard' Curve" on page 6 the results appear to be good. In order to prove, however, that such a transient analogy could be used for the solution of the steady state vibrational problem, experimental work was done using both a steady state method and a transient method.

FIGURE 1

EXPERIMENTAL RESULTS vs. "STANDARD" CURVE



APPARATUS

The equipment used in this investigation to vibrate the test cylinders was an MB Electronics vibration exciter model number C10E and an MB Electronics exciter control model number N575/N576. The exciter control panel was equipped with instruments that allowed the frequency and amplitude to be read directly. Amplitudes above 0.01 of an inch were also checked by the use of a V-scope optical indicator that was mounted directly on the brackets used to hold the test cylinders to the vibration exciter. These brackets were made out of 1 1/4 inch by 5/16 inch aluminum bar stock as shown on page 7.

In order to protect the test cylinders from the air disturbances caused by the movement of the vibration exciter's moving parts it was necessary to enclose the cylinders in an open top box during the testing. This box was approximately 2 feet long, by 2 feet wide, by 3 feet high.

The millivolt readings of the thermocouples were recorded by a Honeywell six point recording potentiometer.

FIGURE 2: TEST SET UP FOR STEADY STATE TESTS

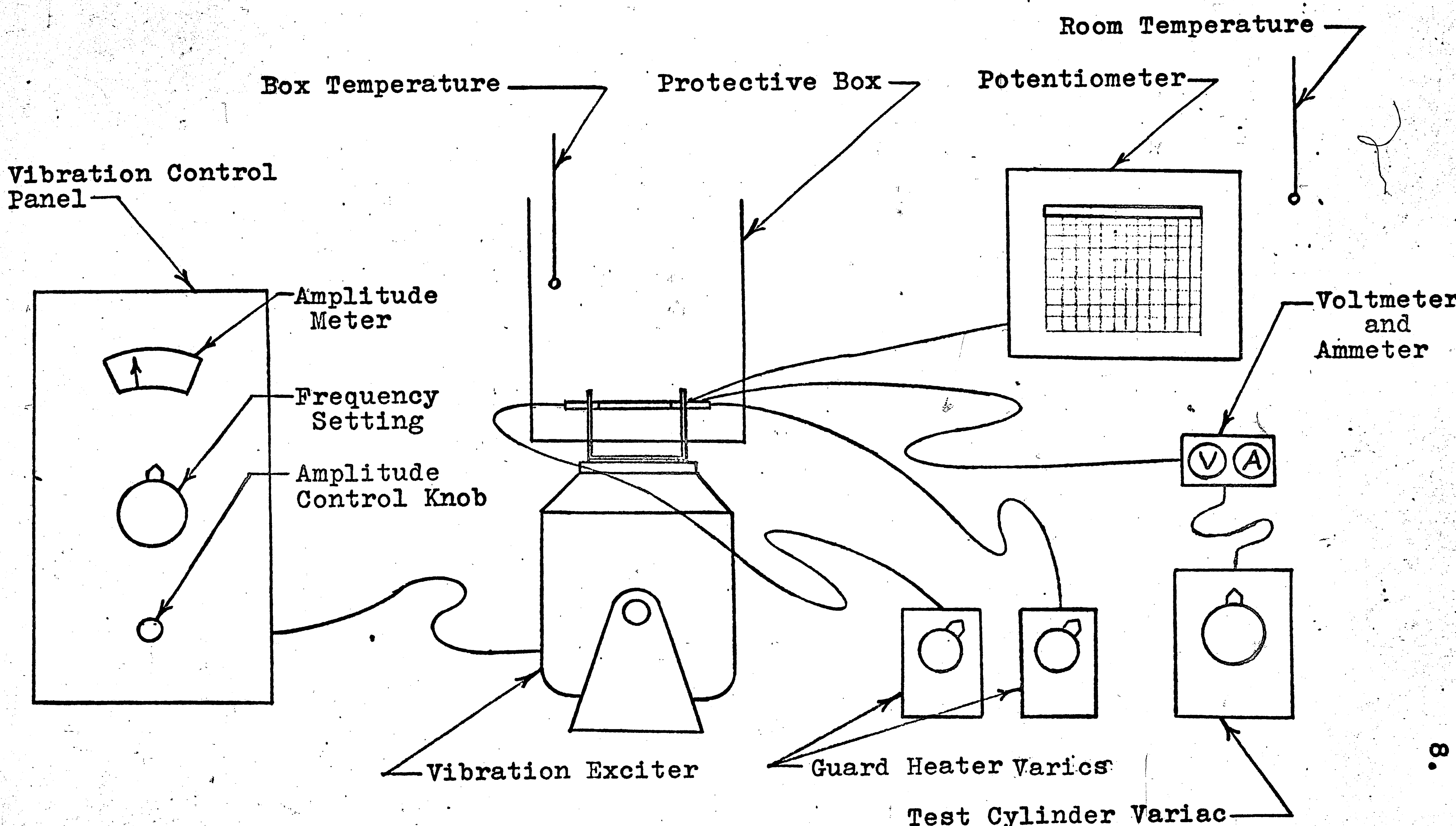
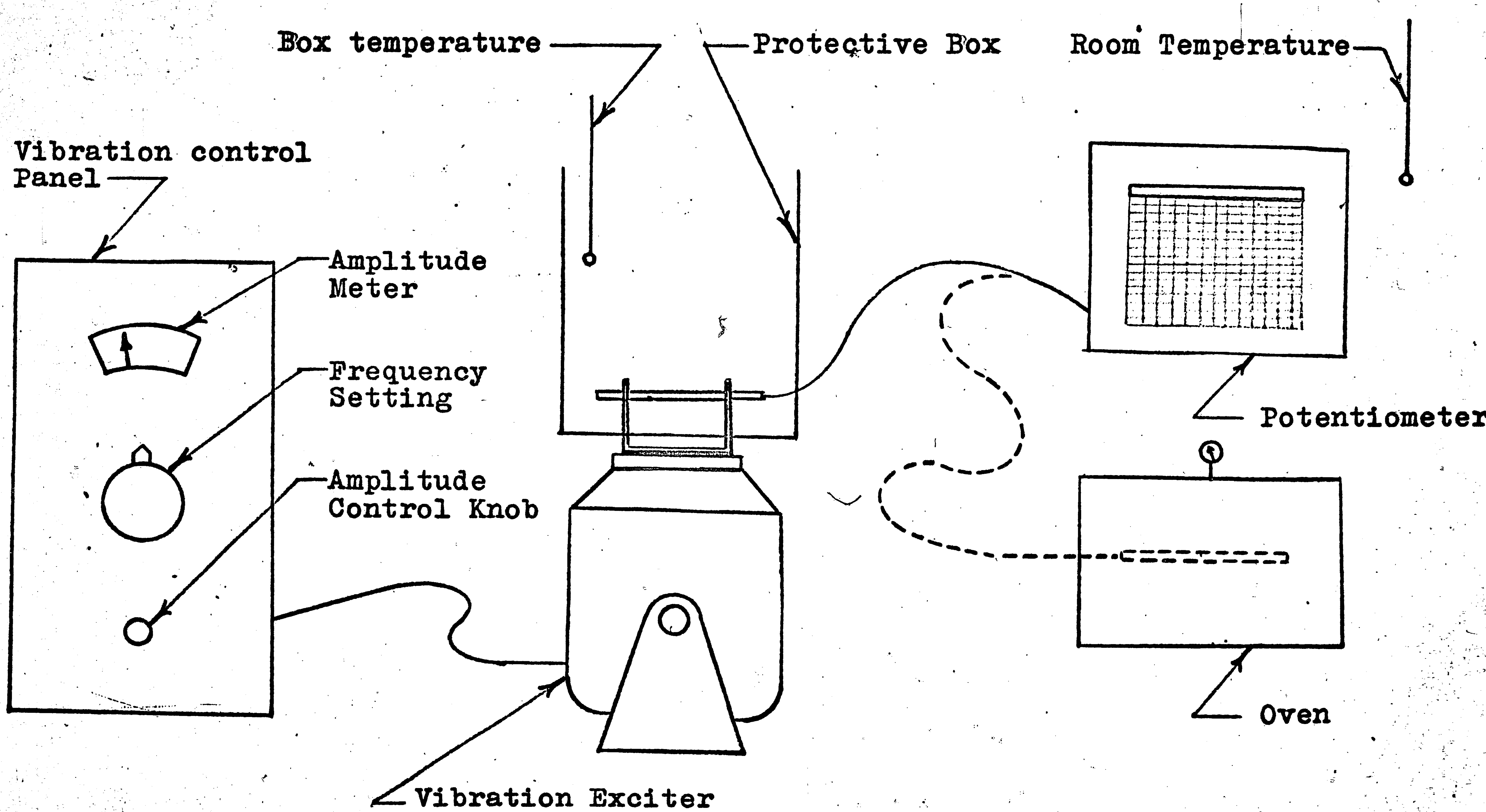


FIGURE 3: TEST SET UP FOR TRANSIENT TESTS



The steady state specimen consisted of an aluminum cylinder 0.75 inches in diameter by 6 inches long. A 3/8 inch hole was drilled the full length of the cylinder in order that a General Electric cartridge heater could be inserted running the full length of the cylinder. To each end of the cylinder guard heaters were attached to eliminate end effects. Each guard heater consisted of an aluminum cylinder 0.75 inches in diameter by 2 inches long, with an Unger soldering iron heating unit placed in one end of the cylinder to serve as the heating element.

The temperature of the test specimen was measured at four points by iron-constantan thermocouples that were placed in holes drilled in the cylinder wall running parallel to its longitudinal axis. The holes were placed such that the temperature could be measured at points 0.5 inches and 2 inches from each end of the test cylinder and at an angle of 180 degrees from one another. The temperature of the guard heaters were measured in the same manner as the test cylinder, at a point 0.5 inches from the end nearest the test cylinder for each heater, and on the same line as the thermocouple nearest it in the test specimen.

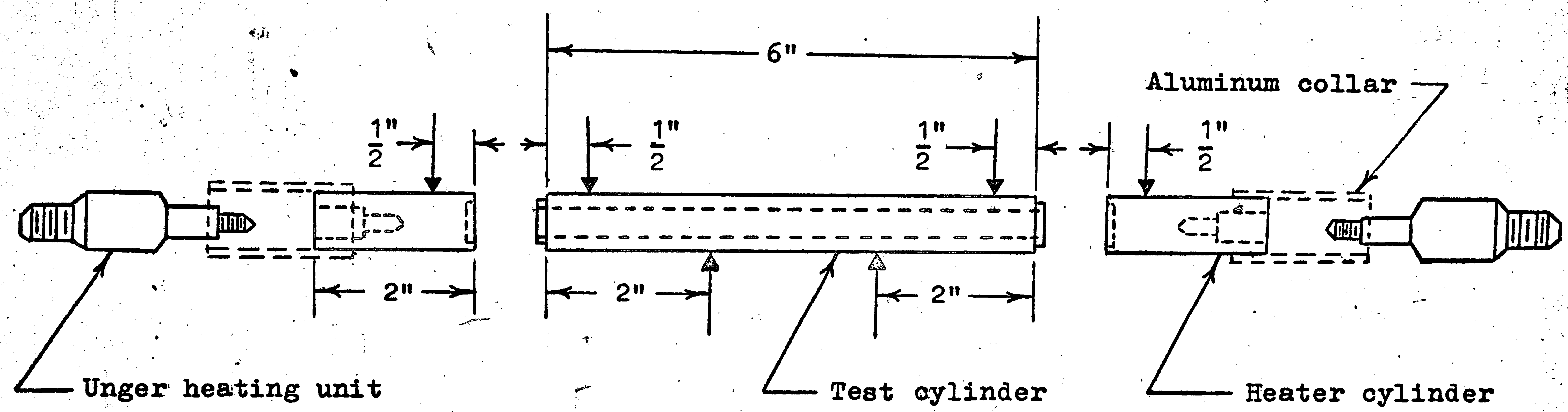
It became necessary during the testing to add a collar covering a portion of the aluminum cylinder of the heater and the porcelain insulation of the heating unit. The collar was made of approximately 22 gauge aluminum and was fastened to each part with a hose clamp. This was done in order to keep the porcelain from separating from the metal part of the heating unit during the higher frequency testing.

The transient test specimen was made of an aluminum cylinder 0.75 inches in diameter by 16 inches long with a 3/8 inch hole running its full length. To each end a one inch end cap made of the same material as the test specimen was attached. One of these end caps had a 3/8 inch hole drilled to a point approximately 1/8 of an inch from one of its ends. The other end cap was made in the same manner as the first except that a hole of a smaller diameter was continued where the 3/8 inch hole was stopped in order to allow the thermocouple leads to extend out of the bar. It was the purpose of these end caps to stop the circulation of air from cooling the inside of the cylinder. The effective length of the test cylinder with the end caps was 18 inches.

The temperature of the transient test specimen was measured at six points by iron-constantan thermocouples. Each thermocouple was installed in

FIGURE 4:

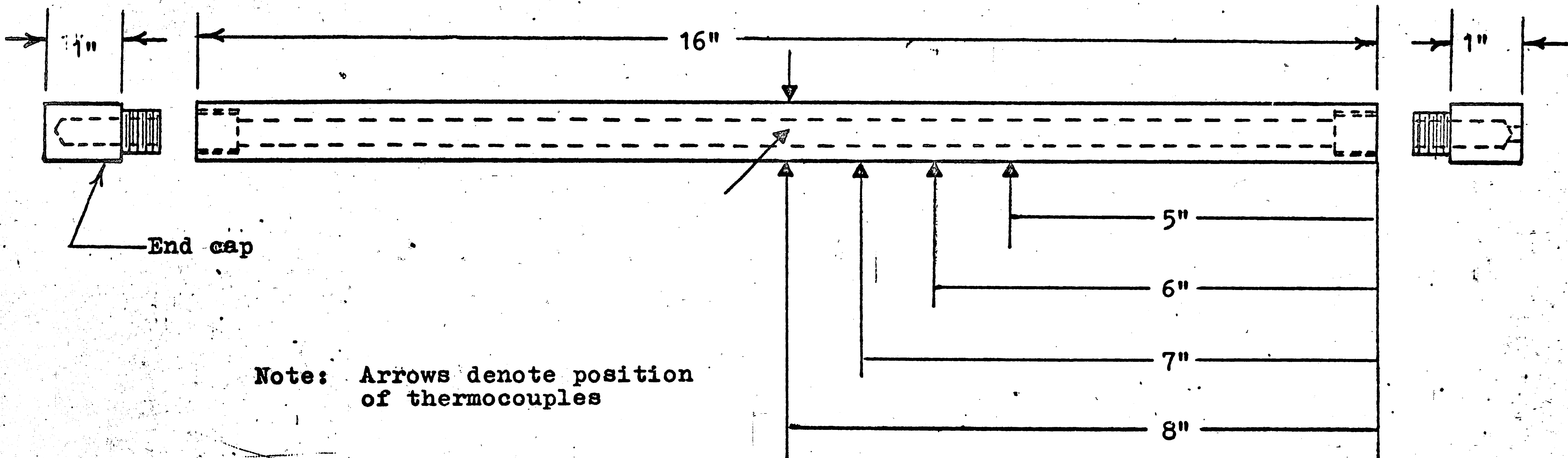
STEADY STATE TEST CYLINDER



Note: Arrows denote position of thermocouples

FIGURE 5:

TRANSIENT TEST CYLINDER



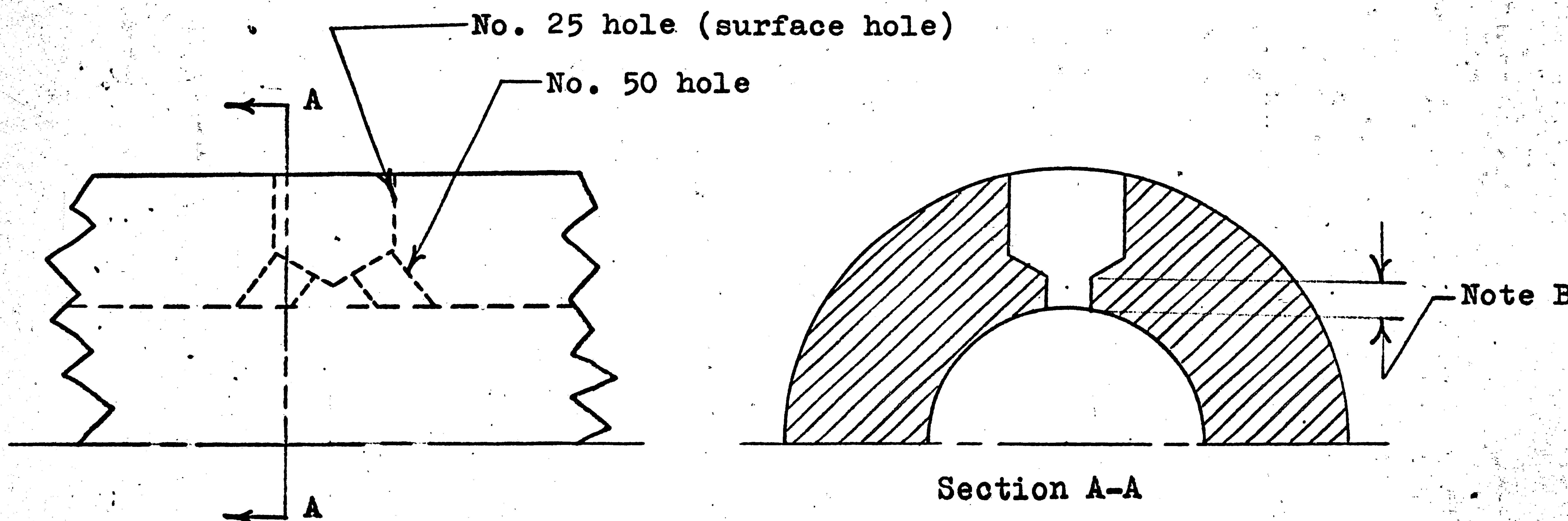
Note: Arrows denote position of thermocouples the cylinder by drilling a radial surface hole to a specified depth. At the bottom of this surface hole two smaller holes were then drilled through the remaining portion of the cylinder wall. Each of the wires necessary for the thermocouple were then fed through the smaller holes and pulled through the cylinder until the thermocouple sat in the bottom of the surface hole. Aluminum filings were then used to partially fill the surface hole, which was then closed off with an aluminum plug that was force fitted into place.

Three of the thermocouples were used to measure the temperature at the center of the cylinder at positions 90 degrees from one another with their surface holes drilled to a depth of 5/32 of an inch. The other three thermocouples were on the same line as the top most center thermocouple and one inch from one another. The depth of each of the surface holes starting with the one nearest the center position was: 1/8, approximately 11/64, and 5/32 of an inch. It became apparent, though, during the installation of the thermocouples that the depth at which the temperature was actually being measured could vary approximately 1/32 of an inch for any given hole.

This variation of depth, however, would have no effect on the thermocouple arrangement making it possible to find the temperature distribution as a function of radial and longitudial position, as well as seeing if the temperature varied with depth.

FIGURE 6:

TRANSIENT CYLINDER HOLE DETAIL



Note B: depth to vary as specified

EXPERIMENTAL PROCEDURE

The equipment was set up as shown on page 8 and the following procedure followed for the steady state tests:

1. The frequency control on the vibration exciter control panel was set at the desired frequency.
2. Power to the vibration exciter was turned on and the test cylinder brought to the desired amplitude by the use of the amplitude control knob on the vibration exciter control panel.
3. The main variac was set so that the potentiometer showed a millivolt reading of the two center most thermocouples in the test cylinder corresponding to the desired temperature.
4. The two guard heater variacs were set so that the two thermocouples nearest the guard heaters in the test cylinder showed a reading the same as the original readings of the two center most thermocouples in the test cylinder.
5. Steps 3 and 4 were repeated until the readings of the four thermocouples in the test cylinder were within $\pm$ 2 ^{o}F of the desired temperature.

6. The input volts and amperes to the test cylinder, as well as the temperature of the room air and the temperature of the air in the protective box were recorded.

7. Steps 1 through 6 were repeated for each frequency, amplitude and temperature combination required.

The equipment was set up as shown on page 9 and the following procedure followed for the transient tests:

1. The potentiometer was turned on to its slow paper recording speed and the test cylinder placed in the oven and allowed to heat up until the potentiometer showed a reading of about 8 millivolts.

2. While the test cylinder was heating up the frequency control was set at the desired frequency with the power to the vibration exciter off (power to the vibration exciter control was on and allowed to warm up).

3. Just prior to the end of the test cylinder heat up cycle the temperature of the room air and the temperature of the air in the protective box were recorded.

5. When the test cylinder reached the desired temperature it was transferred from the oven to the test bracket on the vibration exciter, and the potentiometer turned to its fast paper recording speed.
6. The test cylinder was allowed to cool until the potentiometer showed a reading of 1 millivolt.
7. Power to the vibration exciter was turned off, and the temperature of the room air and the temperature of the air in the protective box again recorded.
8. Steps 1 through 7 were repeated for each frequency and amplitude combination required.

CALCULATION PROCEDURE

For the steady state calculations the heat input to the test cylinder was determined from:

$$Q=3.413(AMPS)(VOLTS)$$

A correction factor for the radiation losses was then found using the Stefan-Boltzmann law for gray bodies in which an emissivity of 0.07 was used. This was determined based on published data for aluminum in Kreith(11).

$$E=\epsilon\sigma(T_c^4-T_b^4)$$

The heat loss as a result of convection was then found from:

$$QC=Q-E$$

The convective heat-transfer coefficient is:

$$H=QC/(A*(TC-TB))$$

The Nusselt number is then found from:

$$NU=D*H/K$$

In the transient part of the experiment the recording potentiometer produced data of millivolts vs. time. An equation of the following form was then fitted to this data for the interval from 5 to 1 millivolts:

$$KK=AA+BA(MC)+CA(MC)^2+DA(MC)^3+EA(MC)^4 +FA(MC)^5+GA(MC)^6+HA(MC)^7$$

The slope of the cooling curve was then found by taking the derivative of the above equation:

$$DKDMC=BA+2CA(MC)+3DA(MC)^2+4EA(MC)^3 +5FA(MC)^4+6GA(MC)^5+7HA(MC)^6$$

and then changing this to the derivative with respect to temperature:

$$DKDT=-0.0295(DKDMC)$$

This was then used in conjunction with the equation:

$$Q=mC_p(DTDK)$$

to find the instantaneous heat loss at any given time and temperature of the cylinder. This heat loss was then corrected for radiation and end losses:

$$QC=Q-E-EL$$

Calculations from this point on proceed as in the steady state case.

The properties of air for both the steady state and transient cases were evaluated at the mean film temperature:

$$TA=(TC-TB)/2$$

These properties were broken into two temperature regions, and assumed to be linear within each region.

For TA less than or equal to 100:

$$P=0.086-0.00015*TA$$

$$K=0.0133+0.000021*TA$$

$$U=(1.11+0.00175*TA)*10^{-5}$$

$$B=(2.14-0.0035*TA)*10^{-3}$$

For TA less than or equal to 200:

$$P=0.0815-0.000107*TA$$

$$K=0.0133+0.000021*TA$$

$$U=(1.125+0.00162*TA)*10^{-5}$$

$$B=(2.06-0.0027*TA)*10^{-3}$$

In order to correct for the potentiometer using room temperature as its working reference this temperature was changed to its corresponding value of millivolts, and this then added to the millivolt reading of the cylinder:

$$MR=0.029(TR)-0.96$$

$$M=MR+MC$$

The equation to change millivolts to degrees F for M less than 6.72 is:

$$TC=35+33.582(M)$$

for M greater than 6.72:

$$TC=41.9+32.582(M)$$

All calculations were done on the Lehigh University GE-225 Computer and written in Lewiz algebraic language. The coefficients of the polynomial used in the transient calculations were obtained by the use of "Least Squares Polynomial Curve Fit Package AAU."

TABLE 1:

STEADY STATE RESULTS

MC=2

F	X	TC	GR PR	RE	NU
0	0	149.9	19,596	0	4.53
10	0.02	143.9	19,386	11.1	4.77
10	0.1	145.8	20,516	55.7	5.57
10	0.2	145.8	20,516	111.5	5.84
10	0.5	147.8	21,285	278.4	7.99
10	0.75	147.8	20,927	417.0	13.59
20	0.02	151.7	18,946	21.8	4.91
20	0.1	149.7	17,870	109.3	5.67
20	0.2	145.8	18,408	221.1	6.66
20	0.5	143.9	17,643	553.7	13.05
20	0.75	145.8	18,064	828.3	20.67
100	0.001	144.9	20,308	5.5	4.64
100	0.002	147.8	20,927	11.1	4.61
100	0.01	144.9	19,243	55.6	5.36
100	0.02	145.8	19,804	111.2	5.20
100	0.1	145.8	19,452	555.3	13.72
500	0.001	143.9	17,643	27.6	4.88
500	0.002	145.8	18,064	55.2	5.33
500	0.003	149.7	18,885	82.3	5.34
500	0.004	149.7	18,885	109.8	5.56

TABLE 2:

MC=4

F	X	TC	GR PR	RE	NU
0	0	216.9	32,305	0	5.53
10	0.02	216.9	29,326	9.9	6.47
10	0.1	216.9	29,004	49.9	6.51
10	0.2	218.8	29,216	99.5	6.60
10	0.5	218.8	29,216	248.9	8.31
10	0.75	218.8	29,216	373.4	16.52
20	0.02	216.9	27,117	19.8	6.39
20	0.1	220.8	27,235	98.3	7.04
20	0.2	215.9	27,630	198.8	7.40
20	0.5	215.9	27,630	497.1	14.31
20	0.75	216.9	27,738	744.6	21.36
100	0.001	214.9	28,789	5.0	5.83
100	0.002	214.9	28,789	10.0	6.49
100	0.01	213.0	29,542	50.4	6.69
100	0.02	214.0	29,652	100.6	6.98
100	0.1	214.9	29,760	502.7	14.11
500	0.001	216.9	29,649	25.0	6.03
500	0.002	214.9	29,111	50.1	6.58
500	0.003	214.0	29,002	75.3	6.92
500	0.004	214.9	29,435	100.4	7.09

TABLE 3:

TRANSIENT RESULTS

MC=2

F	X	TC	GR PR	RE	NU
0	0	147.8	18,821	0	7.37
10	0.02	149.7	19,228	11.0	8.92
10	0.1	149.7	19,228	55.0	8.01
10	0.2	149.7	17,870	109.3	9.58
10	0.5	152.7	18,471	272.3	10.24
10	0.75	145.8	19,101	415.9	15.23
20	0.02	144.9	18,893	22.2	8.71
20	0.1	148.8	19,025	110.1	8.46
20	0.2	149.7	18,545	219.3	8.72
20	0.5	151.7	18,946	546.9	14.77
20	0.75	151.7	18,608	819.3	25.96
100	0.001	147.8	18,821	5.5	7.81
100	0.002	146.8	18,961	11.0	7.04
100	0.01	145.8	18,408	55.2	7.33
100	0.02	147.8	18,821	110.3	7.35
100	0.1	147.8	18,821	551.5	8.09
500	0.001	147.8	18,821	27.5	7.41
500	0.002	147.8	18,821	55.1	7.86
500	0.003	149.7	18,206	82.1	7.47
500	0.004	147.8	18,821	110.3	6.65

TABLE 4:

MC=4

F	X	TC	GR PR	RE	NU
0	0	214.9	30,088	0	7.97
10	0.02	216.9	29,649	10.0	12.49
10	0.1	216.9	30,301	50.2	11.20
10	0.2	214.9	29,435	100.4	12.73
10	0.5	219.8	28,685	247.9	13.16
10	0.75	212.0	30,423	380.2	16.16
20	0.02	211.1	30,312	20.3	11.70
20	0.1	214.0	29,980	100.8	12.36
20	0.2	216.9	29,974	200.5	11.92
20	0.5	218.8	29,859	499.3	16.80
20	0.75	217.9	30,079	751.0	26.02
100	0.001	214.9	30,750	5.04	10.97
100	0.002	213.0	29,871	10.0	8.94
100	0.01	211.1	28,667	50.4	7.68
100	0.02	214.9	30,088	100.6	8.69
100	0.1	214.9	29,435	502.0	11.82
500	0.001	214.9	29,760	25.1	9.41
500	0.002	215.9	29,542	50.1	10.45
500	0.003	214.9	29,435	75.3	9.49
500	0.004	215.9	29,542	100.2	8.36

FIGURE 8:

NUSSELT NUMBER vs. REYNOLDS NUMBER FOR A GRASHOF PRANDTL PRODUCT OF APPROXIMATELY 19,000

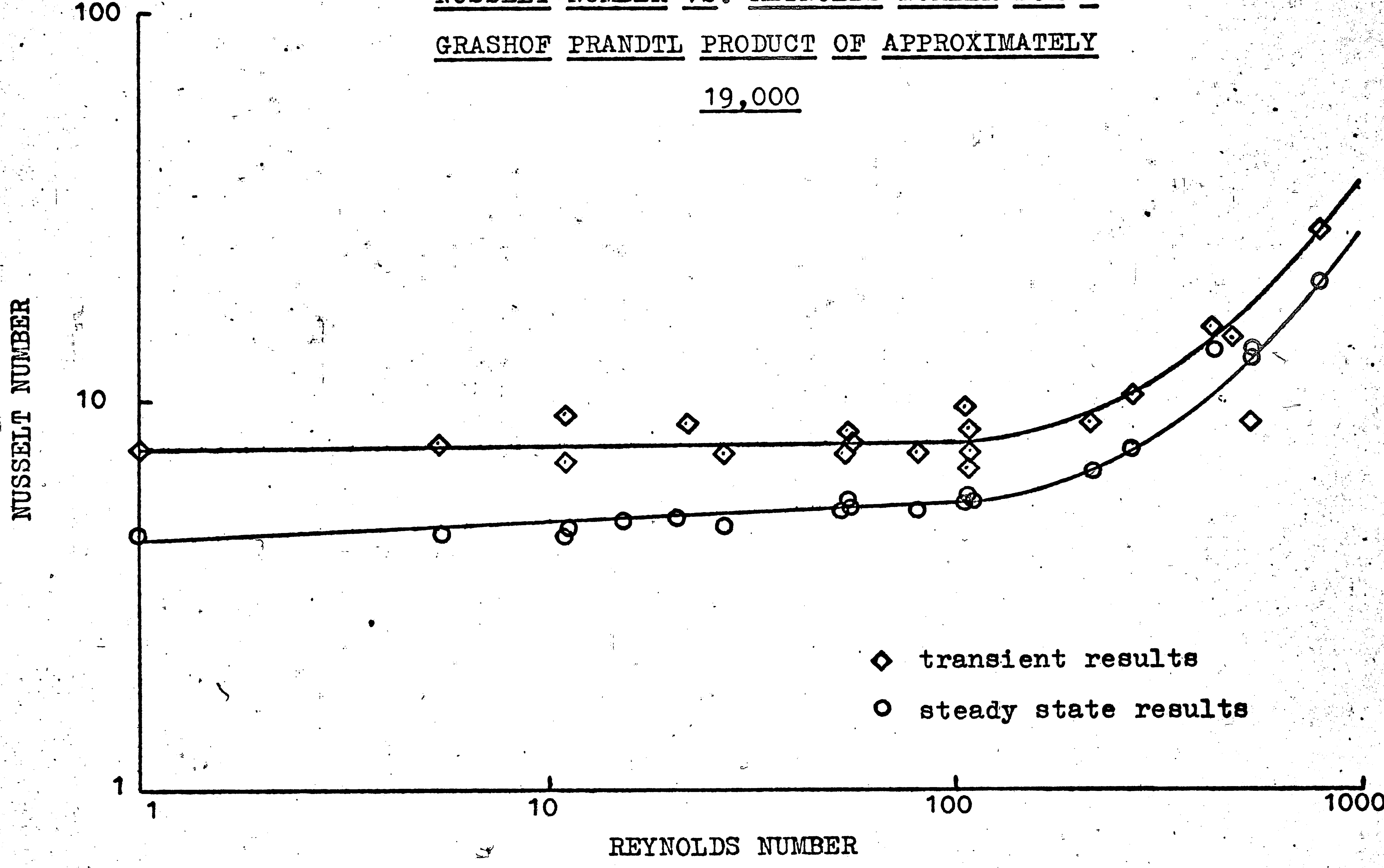


FIGURE 9:

NUSSELT NUMBER vs REYNOLDS NUMBER FOR A GRASHOF PRANDTL PRODUCT OF APPROXIMATELY 29,000

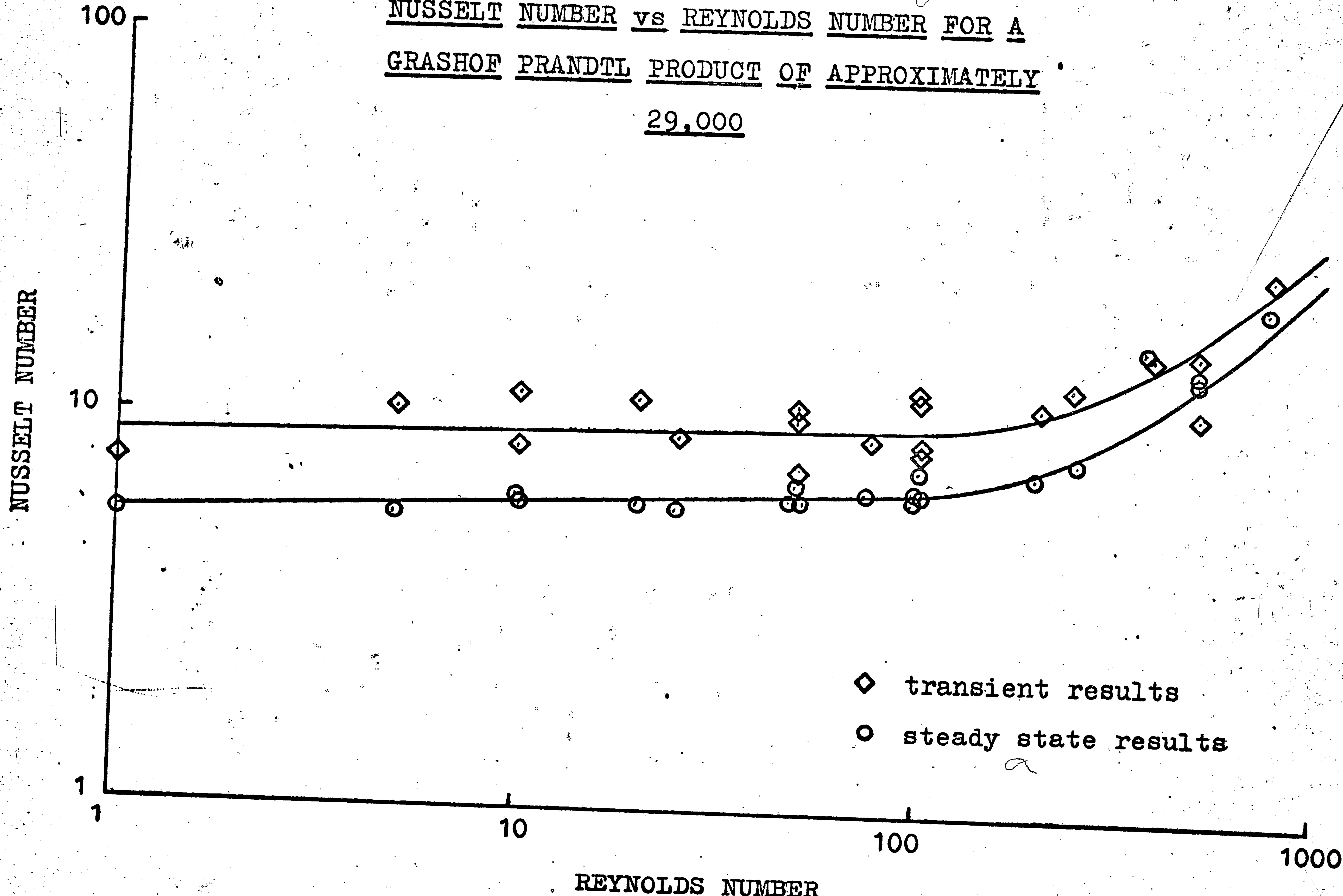


FIGURE 10:

COMPARISON OF STEADY STATE AND TRANSIENT RESULTS TO WORK DONE BY OTHERS FOR A GRASHOF PRANDTL PRODUCT OF APPROXIMATELY 19,000

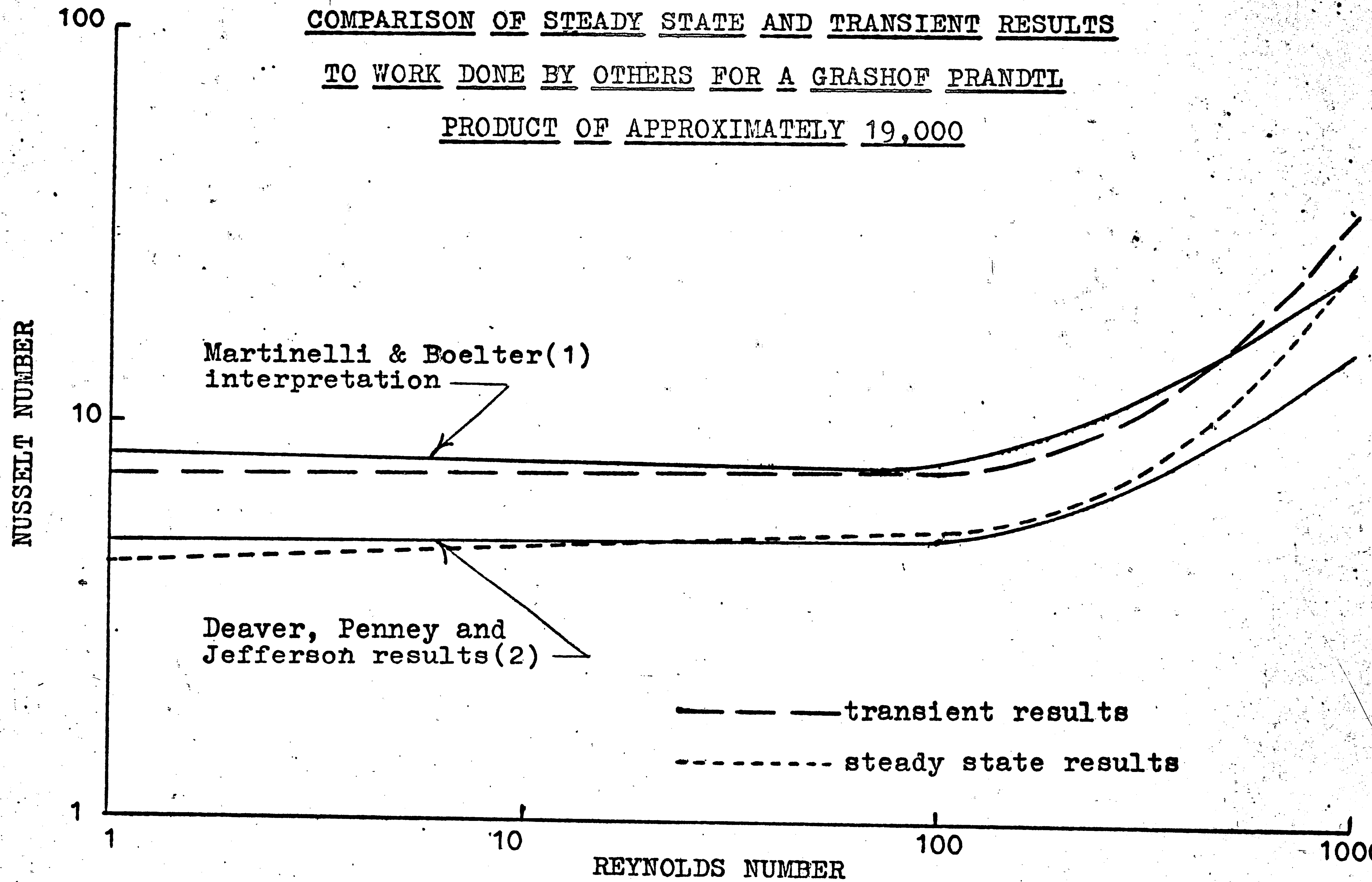
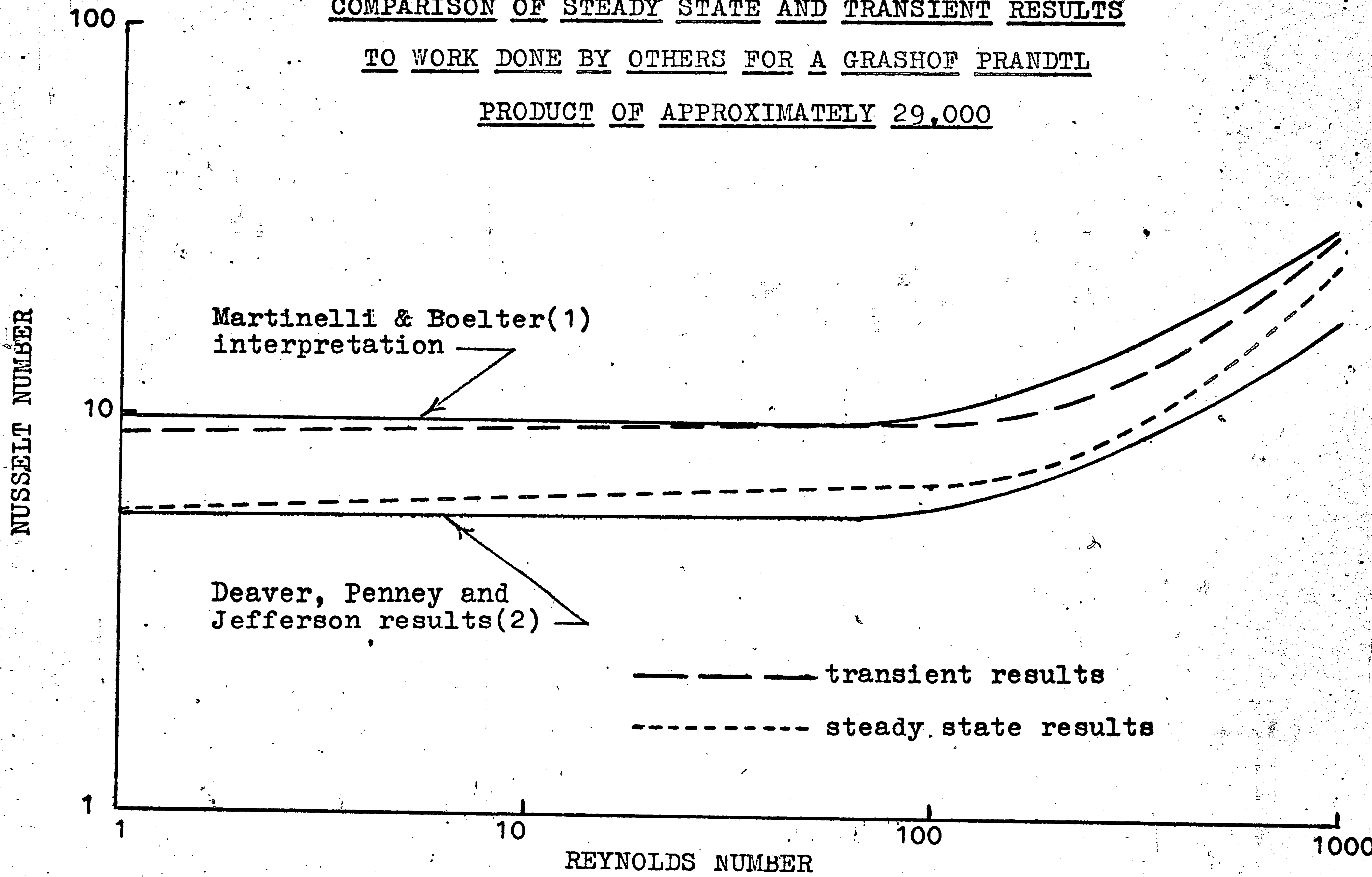


FIGURE 11:

COMPARISON OF STEADY STATE AND TRANSIENT RESULTS TO WORK DONE BY OTHERS FOR A GRASHOF PRANDTL PRODUCT OF APPROXIMATELY 29,000



ANALYSIS OF RESULTS

The results predicted by using the equations of Deaver, Penney and Jefferson(2) are shown by the solid lower lines on the graphs labeled "Comparison of Steady State and Transient Results to Work Done by Others." These equations, however, when used to predict the results obtained by Martinelli and Boelter(1) are from 60 to 80 percent lower than those actually found by these two investigators for the range of Reynolds numbers and Grashof-Prandtl products used in this study. The top solid line on these graphs represent an increase of approximately 60 percent of the results predicted by the former investigators. Thus, a range of results that is suggested by other investigators is shown on these "Comparison" graphs.

For the case of natural convection the most widely accepted results are those that are obtained from the equation recommended by McAdams. These results fall somewhat closer to the results predicted by Deaver, Penney and Jefferson then they do towards the Martinelli and Boelter interpretation; with the Deaver, et al., results being on the low side and the Martinelli and Boelter interpretation being on the high side. However, as was pointed out before, other investigators besides Martinelli and Boelter, and Deaver, et al., have reported results differeing from 8 to 12 percent from those obtained using the McAdams equation.

Both the transient and the steady state results differ from the McAdams results by about the same amount, an average of approximately 16 percent. And, as can be seen from the close paralleling of the two results, the deviation between the two methods remained fairly constant throughout the entire range of Reynolds numbers tested.

Summing up the results, it may be said that for the range of Reynolds numbers and Grashof-Prandtl products used in this study, the transient analogy may be used to solve the steady state problem of heat transfer from a vibrating horizontal cylinder.

APPENDIX A:

NOMENCLATURE

SYMBOL	QUANTITY	UNITS
A	Surface area of cylinder	ft^2
AMPS	Input amperes to steady state cylinder	amperes
B	Temperature coefficient of volume expansion	$1/^oF$
C_p	Specific heat at constant Volume	Btu/ibm ^oF
D	Diameter of cylinder	ft
DKDMC	First derivative of time with respect to millivolts	sec/millivolt
DKDT	First derivative of time with respect to temperature	$sec/^oF$
DTDK	Reciprocal of DKDT	$^oF/sec$
E	Radiation heat loss	Btu/hr
F	Frequency	cps
g	Gravitational constant	$\frac{lbm\ ft}{lbf\ sec^2}$ or $\frac{ft}{sec^2}$
H	Combined unit-surface convective conductance	Btu/hr ft^2 ^oF
K	Thermal conductivity	Btu/hr ft ^oF
KK	Time in cooling curve equation	sec
m	Mass of cylinder	lbm
M	Total millivolts(MC+MR)	millivolts
MC	Millivolt reading of cylinder	millivolts
MR	Millivolts corresponding to room temperature	millivolts
P	Density of air	lbm/ft^3

SYMBOL	QUANTITY	UNITS
Q	Total heat input or total heat loss of cylinder	Btu/hr
QC	Heat input or heat loss of cylinder excluding radiation	Btu/hr
T_b	Temperature of box	^oR
T_c	Temperature of cylinder	^oR
TA	Mean film temperature of air	^oF
TC	Temperature of air in box housing cylinder	^oF
TIME	Time in cooling curve tables corresponding to KK in cooling equations	sec
TR	Temperature of room air	^oF
U	Absolute viscosity	lbm/ft hr
V	Velocity	ft/sec
VOLTS	Input volts to steady state cylinder	volts
X	Double amplitude	inches
ϵ	Emissivity for radiation	none
σ	Stefan-Boltzmann constant	Btu/hr ft^2 R^4
XX/XX	First number refers to temperature at start of test, second number refers to temperature at end of test (e.g. 70/80)	^oF

APPENDIX B:

DIMENSIONLESS GROUPS

SYMBOL	GROUP
GR	Grashof number=$BgD^3(TC-TB)P^2/U^2$
NU	Nusselt number=D(H)/K
PR	Prandtl number=C_pU/K
	=0.72 (assumed constant)
RE	Reynolds number=V(P)(D)/U
	where the velocity (V) is defined from work done by Deaver, Penney and Jefferson(2) V=2(X)(F)

APPENDIX C:

SAMPLE CALCULATIONS

Steady state: Data: F=10 X=0.75

TR=80 TB=74

VOLTS=21.45 AMPS=0.345

MC=2

$$MR=0.029(TR)-0.96$$
$$=0.029(80)-0.96$$
$$=1.32 \text{ millivolts}$$

$$M=MR+MC$$
$$=1.32+2$$
$$=3.32 \text{ millivolts}$$

$$TC=35+33.582(M)$$
$$=35+33.582(3.32)$$
$$=146.4\ ^{\circ}F$$

$$TA=(TC+TB)/2$$
$$=(146.4+74)/2$$
$$=110.4\ ^{\circ}F$$

$$P=0.0815-0.000107(TA)$$
$$=0.0815-0.000107(110.4)$$
$$=0.0696 \text{ lbm/ft}^3$$

$K=0.0133+0.000021(TA)$

$=0.0133+0.000021(110.4)$

$=0.0156$ Btu/hr ft ^{o}F

$U=(1.125+0.00162*TA)*10^{-5}$

$=(1.125+0.00162*110.4)*10^{-5}$

$=1.304*10^{-5}$ lbm/ft sec

$B=(2.06-0.0027*TA)*10^{-3}$

$=(2.06-0.0027*110.4)*10^{-3}$

$=1.76*10^{-3}$ $1/^{o}F$

$Q=3.413(AMPS)(VOLTS)$

$=3.413(0.345)(21.45)$

$=25.25$ Btu/hr

$E=1.2*10^{-10}((TC+460)^4-(TB+460)^4)(A)$

$=1.2*10^{-10}((146.4+460)^4-(74+460)^4)(0.098)$

$=0.649$ Btu/hr

$QC=Q-E$

$=25.25-0.649$

$=24.60$ Btu/hr

H=QC/(A*(TC-TB)

=24.60/(0.098*(146.4-74)

=3.40 Btu/hr ft^2 ^{o}F

NU=D(H/K)

=0.0625(3.40/0.0156)

=13.59

GR=BgD^3(TC-TB)P^2/U^2

=1.76(10^{-3})(32.2)(0.0625^3)(146.4-74)*

(0.0696^2)/(1.304*10^{-5})^2

=2.90(10^4)

RE=0.01042(X)(F)(P)/U

=0.01042(0.75)(10)(0.0696)/(1.304*10^{-5})

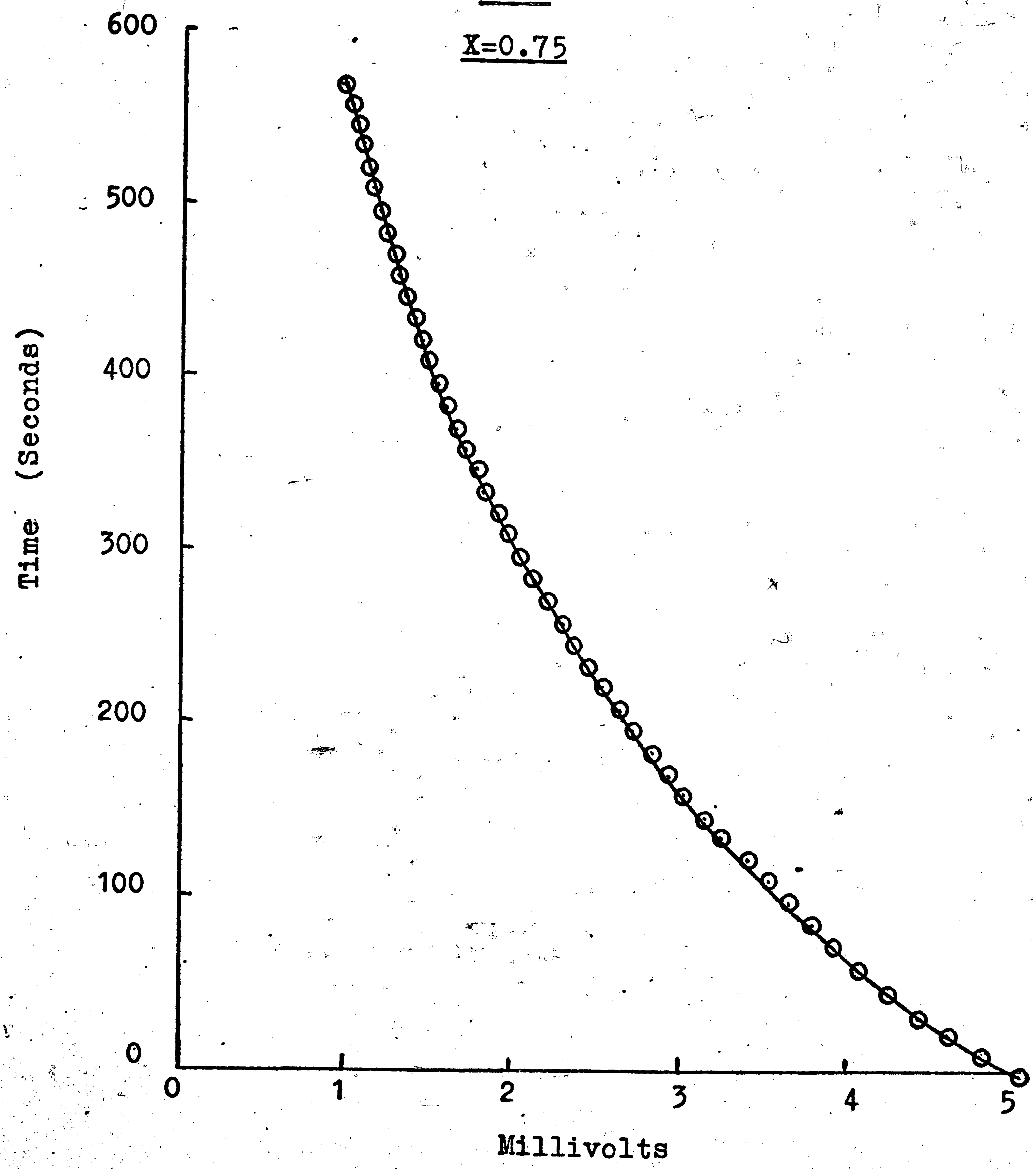
=417

FIGURE 12:

COOLING CURVE FOR

F=10

X=0.75



Transient state: Data: F=10 X=0.75

TR=78 TB=78

MC=2

The cooling curve equation is:

$$KK=8.60780\times10^{2}-3.93706\times10(MC)-6.01819\times10^{2}(MC)^{2}$$
$$+5.06745\times10^{2}(MC)^{3}-2.02200\times10^{2}(MC)^{4}$$
$$+4.38325\times10(MC)^{5}-4.96166(MC)^{6}$$
$$+2.29930\times10^{-1}(MC)^{7}$$

MR=0.029(TR)-0.96

=0.029(79)-0.96

=1.30 millivolts

M=MR+MC

=1.30+2

=3.30 millivolts

TC=35+33.582(M)

=35+33.582(3.30)

=145.8 ^{o}F

TA=(TC+TB)/2

=(145.8+78)/2

=111.9 ^{o}F

$$P=0.0815-0.000107(TA)$$
$$=0.0815-0.000107(111.9)$$
$$=0.0695 \text{ lbm/ft}^3$$

$$K=0.0133+0.000021(TA)$$
$$=0.0133+0.000021(111.9)$$
$$=0.0156 \text{ Btu/hr ft }^{o}F$$

$$B=(2.06-0.0027*TA)*10^{-3}$$
$$=(2.06-0.0027*111.9)*10^{-3}$$
$$=1.75*10^{-3} \quad 1/^{o}F$$

$$U=(1.125+0.00162*TA)*10^{-5}$$
$$=(1.125+0.00162*111.9)*10^{-5}$$
$$=1.30*10^{-5} \text{ lbm/ft sec}$$

$$DKDMC=BA+2CA(MC)+3DA(MC)^2+4EA(MC)^3$$
$$+5FA(MC)^4+6GA(MC)^5+7HA(MC)^6$$
$$=-3.93706x10+2(-6.01819x10^2)(2)$$
$$+3(5.06745x10^2)(2)^2+4(-2.02200$$
$$x10^2)(2)^3+5(4.38325x10)(2)^4$$
$$+6(-4.96166)(2)^5$$
$$+7(2.29930x10^{-1})(2)^6$$
$$=-178.9 \text{ sec/millivolt}$$

DKDT=-0.0295(DKDMC)

$=-0.0295(-178.9)$

$=5.27$ sec/^{o}F

DTDK=1/DKDT

$=1/5.27$

$=0.189$ ^{o}F/sec

$Q=mC_p(DTDK)$

$=314(0.189)$

$=59.48$ Btu/hr

$E=(1.2*10^{-10})((TC+460)^4-(TB+460)^4)(A)$

$=(1.2*10^{-10})((145.8+460)^4-$

$(78+460)^4)(0.196)$

$=1.19$ Btu/hr

QC=Q-E-EL

$=59.48-1.19-8.70$

$=49.59$ Btu/hr

H=QC/(A*(TC-TB))

$=49.59/(0.196*(145.8-78))$

$=3.73$ Btu/hr ft^2 ^{o}F

NU=D(H/K)

$=0.0625(3.73/0.0156)$

$=15.23$

$$GR=BgD^3(TC-TB)P^2/U^2$$
$$=1.75*10^{-3}(32.2)(0.0625^3)(145.8-78)*(0.0695^2)/(1.30*10^{-5})^2$$
$$=2.65(10^4)$$

$$RE=0.01042(X)(F)(P)/U$$
$$=0.01042(0.75)(10)(0.0695)/(1.30*10^{-5})$$
$$=415.9$$

APPENDIX D:

CORRECTION FOR END LOSSES

It was discovered during the calculations that the heat losses for the transient cylinder were excessively high. The reason for this was later found to be due to the test bracket acting as a cooling fin for the case of the transient cylinder. In order to correct for this an end loss factor was obtained by cooling the transient cylinder suspended by fine wires, and comparing the results of this test to the results obtained in the original test. This end loss was then used to correct each of the heat losses of the cylinder.

For the case of MC equal to 2, the end losses were found to be 8.70 Btu/hr; for MC equal to 4, the end losses were found to be 9.75 Btu/hr.

The equation of the corrective cooling curve is:

$$KK=2.94735x10^{3}-3.18057x10^{3}(MC)+2.37872x10^{3}(MC)^{2}$$
$$-1.16593x10^{3}x10^{3}(MC)^{3}+3.42873x10^{2}(MC)^{4}$$
$$-5.78472x10(MC)^{5}+5.09408(MC)^{6}$$
$$-1.77783x10^{-1}(MC)^{7}$$

APPENDIX E:

STEADY STATE EXPERIMENTAL DATA

MC=2

F	X	TR	TB	VOLTS	AMPS
0	0	77	76	12.4	0.195
10	0.02	76	76	12.5	0.200
10	0.1	78	74	13.9	0.220
10	0.2	78	74	14.2	0.225
10	0.5	80	73	16.8	0.267
10	0.75	80	74	21.4	0.345
20	0.02	84	82	13.0	0.205
20	0.1	82	84	13.5	0.213
20	0.2	78	80	14.5	0.230
20	0.5	76	81	19.6	0.310
20	0.75	78	81	24.9	0.395
100	0.001	77	74	12.7	0.200
100	0.002	80	74	12.9	0.204
100	0.01	77	77	13.3	0.210
100	0.02	78	76	13.3	0.210
100	0.1	78	77	20.5	0.340
500	0.001	76	81	12.5	0.190
500	0.002	78	81	13.0	0.205
500	0.003	82	81	13.5	0.210
500	0.004	82	81	13.7	0.215

MC=4

F	X	TR	TB	VOLTS	AMPS
0	0	82	72	20.2	0.310
10	0.02	82	81	21.1	0.335
10	0.1	82	82	21.1	0.335
10	0.2	84	82	21.4	0.340
10	0.5	84	82	23.8	0.380
10	0.75	84	82	33.1	0.530
20	0.02	82	88	20.5	0.325
20	0.1	86	89	21.7	0.345
20	0.2	81	86	22.0	0.350
20	0.5	81	86	30.5	0.475
20	0.75	82	86	36.0	0.600
100	0.001	80	82	19.9	0.315
100	0.002	80	82	20.5	0.338
100	0.01	78	79	21.2	0.338
100	0.02	79	79	21.8	0.345
100	0.1	80	79	31.0	0.48
500	0.001	82	80	20.5	0.325
500	0.002	80	81	21.1	0.335
500	0.003	79	81	21.5	0.342
500	0.004	80	80	22.0	0.347

APPENDIX F:

TRANSIENT CALCULATED DATA

Coefficients of the polynomial:

	Free convection	F=10 X=0.02	F=10 X=0.1
AA	2.65230×10^{3}	2.59257×10^{3}	2.62452×10^{3}
BA	-2.99686×10^{3}	-3.48666×10^{3}	-3.39569×10^{3}
CA	2.07724×10^{3}	2.77693×10^{3}	2.68188×10^{3}
DA	-8.77485×10^{2}	-1.39297×10^{3}	-1.37285×10^{3}
EA	2.11478×10^{2}	4.33137×10^{2}	4.40869×10^{2}
FA	-2.67780×10	-8.09128×10	-8.51546×10
GA	1.39396	8.31056	9.00283
HA	-2.31564×10^{-3}	-3.60570×10^{-1}	-3.99176×10^{-1}

	F=10 X=0.2	F=10 X=0.5	F=10 X=0.75
AA	2.59257×10^{3}	1.21302×10^{3}	8.60780×10^{2}
BA	-3.48666×10^{3}	1.48407×10^{2}	-3.93706×10
CA	2.77693×10^{3}	-1.39630×10^{3}	-6.01819×10^{2}
DA	-1.39297×10^{3}	1.20292×10^{3}	5.06745×10^{2}
EA	4.33137×10^{2}	-5.02677×10^{2}	-2.02200×10^{2}
FA	-8.09128×10	1.14445×10^{2}	4.38325×10
GA	8.31056	-1.36032×10	-4.96166
HA	-3.60570×10^{-1}	6.61344×10^{-1}	2.29930×10^{-1}

	F=20 X=0.02	F=20 X=0.1	F=20 X=0.2
AA	2.13835×10^{3}	1.79931×10^{3}	2.52807×10^{3}
BA	-2.06107×10^{3}	-1.02257×10^{3}	-3.13909×10^{3}
CA	1.14764×10^{3}	-1.66662×10^{2}	2.31765×10^{3}
DA	-4.18655×10^{2}	4.38245×10^{2}	-1.10093×10^{3}
EA	9.62873×10	-2.18850×10^{2}	3.28813×10^{2}
FA	-1.29763×10	5.37143×10	-5.93948×10
GA	8.75486×10^{-1}	-6.50291	5.90855
HA	-1.91157×10^{-2}	3.21367×10^{-1}	-2.48000×10^{-1}

	F=20 X=0.5	F=20 X=0.75	F=100 X=0.001
AA	1.10616×10^{3}	8.83797×10^{2}	2.39698×10^{3}
BA	-6.93548×10^{2}	-1.04692×10^{3}	-2.61405×10^{3}
CA	7.12576×10	8.28285×10^{2}	1.76519×10^{3}
DA	1.41397×10^{2}	-4.18937×10^{2}	-8.35082×10^{2}
EA	-9.10187×10	1.28335×10^{2}	2.6500×10^{2}
FA	2.52357×10	-2.30434×10	-5.28284×10
GA	-3.42062	2.22504	5.90551
HA	1.84042×10^{-1}	-8.89532×10^{-2}	-2.80179×10^{-1}

	F=100 X=0.002	F=100 X=0.01	F=100 X=0.02
AA	2.14295×10^{3}	2.31492×10^{3}	3.08861×10^{3}
BA	-1.36184×10^{3}	-1.44301×10^{3}	-4.20834×10^{3}
CA	1.20070×10^{2}	1.41092×10^{2}	3.45781×10^{3}
DA	2.92809×10^{2}	2.84676×10^{2}	-1.77374×10^{3}
EA	-1.77795×10^{2}	-1.74257×10^{2}	5.58175×10^{2}
FA	4.65513×10	4.54908×10	-1.04851×10^{2}
GA	-5.93177	-5.76072	1.07864×10
HA	2.99536×10^{-1}	2.88657×10^{-1}	-4.67316×10^{-1}

	F=100 X=0.1	F=500 X=0.001	F=500 X=0.002
AA	$2.96175x10^3$	$1.69349x10^3$	$2.60190x10^3$
BA	$-4.01653x10^3$	$-4.49733x10^2$	$-3.00494x10^3$
CA	$3.11615x10^3$	$-7.33369x10^2$	$2.05583x10^3$
DA	$-1.47209x10^3$	$7.19095x10^2$	$-9.07690x10^2$
EA	$4.17964x10^2$	$-2.98548x10^2$	$2.52729x10^2$
FA	-6.91851x10	6.59720x10	-4.28005x10
GA	6.10089	-7.57440	4.02163
HA	$-2.19074x10^{-1}$	$3.55712x10^{-1}$	$-1.60725x10^{-1}$

	F=500 X=0.003	F=500 X=0.004
AA	$1.60603x10^3$	$4.15993x10^3$
BA	$2.99644x10^2$	$-7.72510x10^3$
CA	$-2.04412x10^3$	$8.12457x10^3$
DA	$1.74473x10^3$	$-5.03510x10^3$
EA	$-7.26596x10^2$	$1.84849x10^3$
FA	$1.64835x10^2$	$-3.94684x10^2$
GA	-1.95035x10	4.52091x10
HA	$9.42839x10^{-1}$	-2.14505

APPENDIX G:

TRANSIENT EXPERIMENTAL DATA

Natural Convection TR: 80/80 TB: 76/76

TIME	MC	TIME	MC	TIME	MC	TIME	MC
0	5.06	266	3.16	530	2.10	796	1.38
12	4.94	278	3.10	542	2.07	808	1.37
24	4.82	290	3.04	554	2.03	820	1.36
36	4.72	302	2.98	566	2.00	832	1.35
50	4.62	314	2.92	578	1.96	844	1.32
62	4.53	326	2.88	590	1.93	856	1.30
74	4.43	338	2.82	602	1.89	868	1.28
86	4.34	350	2.77	614	1.85	880	1.24
98	4.23	362	2.71	626	1.82	892	1.23
110	4.15	374	2.67	638	1.80	904	1.21
122	4.06	386	2.62	652	1.74	916	1.19
134	3.98	398	2.59	664	1.70	928	1.17
146	3.90	410	2.52	676	1.68	940	1.15
158	3.81	422	2.48	688	1.66	952	1.12
170	3.72	434	2.42	700	1.62	964	1.10
182	3.63	446	2.38	712	1.60	976	1.09
194	3.58	458	2.34	724	1.58	988	1.08
206	3.50	470	2.32	736	1.54	1000	1.07
218	3.44	482	2.27	748	1.50	1012	1.04
230	3.36	494	2.22	760	1.48	1024	1.02
242	3.30	506	2.18	772	1.44	1036	1.00
254	3.22	518	2.14	784	1.41		

F=10 TR: 82/82

X=0.02 TB: 80/80

TIME	MC	TIME	MC	TIME	MC	TIME	MC
0	5.02	216	2.94	432	1.93	650	1.32
12	4.88	228	2.88	444	1.88	662	1.31
24	4.70	240	2.80	456	1.85	674	1.29
36	4.57	252	2.74	468	1.82	686	1.27
48	4.42	264	2.66	480	1.78	698	1.25
60	4.39	276	2.59	492	1.74	710	1.23
72	4.15	288	2.52	504	1.70	722	1.21
84	4.03	300	2.36	516	1.68	734	1.19
96	3.90	312	2.42	528	1.62	746	1.16
108	3.78	324	2.35	542	1.58	758	1.13
120	3.68	336	2.30	554	1.54	770	1.12
132	3.56	348	2.24	566	1.52	782	1.10
144	3.48	360	2.21	578	1.48	794	1.08
156	3.37	372	2.15	590	1.46	806	1.06
168	3.28	384	2.10	602	1.43	818	1.04
180	3.20	396	2.04	614	1.40	830	1.02
192	3.11	408	2.01	626	1.38	842	1.01
204	3.02	420	1.97	638	1.35	854	1.00

F=10 TR: 82/82

X=0.1 TB: 78/80

TIME	MC	TIME	MC	TIME	MC	TIME	MC
0	5.08	228	2.92	456	1.92	686	1.34
12	4.90	240	2.85	468	1.88	698	1.32
24	4.72	252	2.78	480	1.85	710	1.31
26	4.58	264	2.72	492	1.82	722	1.29
48	4.44	276	2.65	504	1.78	734	1.27
60	4.30	288	2.58	516	1.75	746	1.23
72	4.18	300	2.52	528	1.71	758	1.21
84	4.05	312	2.48	540	1.68	770	1.20
96	3.93	324	2.42	552	1.64	782	1.18
108	3.82	336	2.36	564	1.62	794	1.15
120	3.71	348	2.32	576	1.58	806	1.13
132	3.61	360	2.26	588	1.55	818	1.12
144	3.51	372	2.22	600	1.53	830	1.10
156	3.42	384	2.16	612	1.51	842	1.08
168	3.33	396	2.12	626	1.57	854	1.07
180	3.25	408	2.08	638	1.43	866	1.05
192	3.16	420	2.03	650	1.42	878	1.03
204	3.08	432	2.00	662	1.40	890	1.02
216	3.00	444	1.98	674	1.36	902	1.00

F=10 TR: 80/82

X=0.2 TB: 80/84

TIME	MC	TIME	MC	TIME	MC	TIME	MC
0	5.10	252	2.86	504	1.85	758	1.32
12	4.92	264	2.80	516	1.81	770	1.30
24	4.78	276	2.73	528	1.79	782	1.28
36	4.63	288	2.67	540	1.75	794	1.26
48	4.50	300	2.61	552	1.72	806	1.23
60	4.37	312	2.54	566	1.70	818	1.20
72	4.24	324	2.50	578	1.67	830	1.19
84	4.12	336	2.44	590	1.64	842	1.17
96	4.01	348	2.40	602	1.62	854	1.16
108	3.90	360	2.34	614	1.60	866	1.14
120	3.78	372	2.30	626	1.57	878	1.12
132	3.68	384	2.24	638	1.54	890	1.10
144	3.59	396	2.20	650	1.52	902	1.09
156	3.50	408	2.16	662	1.50	914	1.08
168	3.41	420	2.12	674	1.47	926	1.06
180	3.32	432	2.08	686	1.43	938	1.04
192	3.23	444	2.03	698	1.41	950	1.02
204	3.15	456	1.99	710	1.40	962	1.01
216	3.08	468	1.95	722	1.36	974	1.00
228	3.01	480	1.92	734	1.35		
240	2.93	492	1.88	746	1.33		

F=10 TR: 85/85

X=0.5 TB: 84/84

TIME	MC	TIME	MC	TIME	MC	TIME	MC
0	5.08	204	3.00	408	1.95	614	1.33
12	4.91	216	2.92	420	1.90	626	1.31
24	4.73	228	2.84	432	1.85	638	1.28
36	4.59	240	2.78	444	1.80	650	1.26
48	4.44	252	2.70	456	1.77	662	1.22
60	4.30	264	2.63	468	1.72	674	1.20
72	4.17	276	2.54	480	1.70	686	1.18
84	4.02	288	2.50	492	1.64	698	1.16
96	3.91	300	2.43	504	1.62	710	1.13
108	3.79	312	2.38	516	1.58	722	1.11
120	3.68	324	2.32	528	1.56	734	1.09
132	3.58	336	2.27	542	1.51	746	1.06
144	3.47	348	2.20	554	1.49	758	1.03
156	3.36	360	2.14	566	1.44	770	1.01
168	3.28	372	2.10	578	1.42	782	1.00
180	3.18	384	2.03	590	1.39		
192	3.10	396	2.00	602	1.36		

F=10 TR: 77/78

X=.75 TB: 76/78

TIME	MC	TIME	MC	TIME	MC
0	5.01	192	2.79	386	1.62
12	4.82	204	2.70	398	1.56
24	4.64	218	2.57	410	1.51
36	4.48	230	2.50	422	1.48
48	4.30	242	2.42	434	1.42
60	4.14	254	2.33	446	1.38
72	3.99	266	2.25	458	1.33
84	3.85	278	2.20	470	1.30
96	3.71	290	2.10	482	1.26
108	3.58	302	2.03	494	1.22
120	3.45	314	1.97	506	1.18
132	3.32	326	1.90	518	1.13
144	3.21	338	1.84	530	1.10
156	3.10	350	1.78	542	1.06
168	3.00	362	1.72	554	1.02
180	2.89	374	1.68	566	1.00

F=20 TR: 76/77

X=0.02 TB: 76/78

TIME	MC	TIME	MC	TIME	MC	TIME	MC
0	5.11	230	2.96	458	1.93	686	1.34
12	4.93	242	2.88	470	1.90	698	1.32
24	4.78	254	2.81	482	1.85	710	1.30
36	4.62	266	2.75	494	1.82	722	1.27
48	4.50	278	2.68	506	1.78	734	1.25
60	4.38	290	2.61	518	1.75	746	1.22
72	4.25	302	2.55	530	1.72	758	1.21
84	4.12	314	2.50	542	1.68	770	1.20
96	4.00	326	2.44	554	1.65	784	1.18
108	3.89	338	2.38	566	1.62	796	1.15
120	3.78	350	2.34	578	1.58	808	1.12
132	3.69	362	2.28	590	1.55	820	1.11
144	3.58	374	2.23	602	1.53	832	1.10
156	3.50	386	2.19	614	1.51	844	1.08
168	3.41	398	2.13	626	1.48	856	1.05
182	3.27	410	2.09	638	1.45	868	1.02
194	3.18	422	2.05	650	1.42	880	1.01
206	3.10	434	2.00	662	1.40	892	1.00
218	3.02	446	1.97	674	1.35		

F=20 TR: 79/81

X=0.1 TB: 78/80

TIME	MC	TIME	MC	TIME	MC	TIME	MC
0	5.01	230	2.85	458	1.85	686	1.31
14	4.78	242	2.78	470	1.83	698	1.30
26	4.62	254	2.71	484	1.80	710	1.27
38	4.48	266	2.65	494	1.75	722	1.25
50	4.35	278	2.58	506	1.72	734	1.23
62	4.21	290	2.52	518	1.69	746	1.21
74	4.10	302	2.48	530	1.66	758	1.19
86	3.98	314	2.41	542	1.62	770	1.17
98	3.85	326	2.37	554	1.60	782	1.14
110	3.74	338	2.30	566	1.58	794	1.12
122	3.62	350	2.26	578	1.55	806	1.10
134	3.52	362	2.21	590	1.52	818	1.09
146	3.43	374	2.15	602	1.50	830	1.07
158	3.34	386	2.11	614	1.46	842	1.05
170	3.26	398	2.07	626	1.43	854	1.03
182	3.17	410	2.02	638	1.40	866	1.02
194	3.08	422	1.99	650	1.39	878	1.00
206	3.00	434	1.93	662	1.36		
218	2.93	446	1.90	674	1.33		

F=20 TR: 79/82

X=0.2 TB: 82/82

TIME	MC	TIME	MC	TIME	MC	TIME	MC
0	5.03	230	2.88	458	1.87	686	1.31
12	4.87	242	2.82	470	1.83	698	1.30
24	4.71	254	2.73	482	1.80	710	1.27
36	4.57	266	2.67	494	1.77	724	1.23
48	4.42	278	2.61	506	1.73	736	1.22
60	4.30	290	2.53	518	1.70	748	1.20
72	4.18	302	2.48	530	1.66	760	1.18
84	4.04	314	2.42	542	1.63	772	1.17
96	3.93	326	2.37	554	1.60	784	1.13
108	3.82	338	2.32	566	1.57	796	1.12
122	3.66	350	2.27	578	1.54	808	1.10
134	3.57	362	2.22	590	1.51	820	1.09
146	3.47	374	2.17	602	1.49	834	1.07
158	3.38	386	2.12	614	1.47	844	1.05
170	3.29	398	2.08	626	1.43	856	1.03
182	3.20	410	2.04	638	1.40	868	1.02
194	3.11	422	2.00	650	1.37	880	1.00
206	3.02	434	1.94	662	1.34		
218	2.96	446	1.91	674	1.33		

F=20 TR: 84/84

X=0.5 TB: 80/82

TIME	MC	TIME	MC	TIME	MC
0	5.04	192	2.66	386	1.56
12	4.72	204	2.55	398	1.50
24	4.61	216	2.48	410	1.46
36	4.42	228	2.39	422	1.42
48	4.27	240	2.32	434	1.37
60	4.08	252	2.23	446	1.32
72	3.92	264	2.16	458	1.29
84	3.76	276	2.09	470	1.24
96	3.62	288	2.01	482	1.22
108	3.48	300	1.97	494	1.18
120	3.33	312	1.88	506	1.13
132	3.21	324	1.82	518	1.10
144	3.10	338	1.77	530	1.07
156	2.98	350	1.70	542	1.03
168	2.88	362	1.64	554	1.01
180	2.76	374	1.59	566	0.98

F=20 TR: 83/84

X=0.75 TB: 79/82

TIME	MC	TIME	MC
0	5.14	192	2.06
12	4.82	204	1.96
24	4.55	216	1.83
36	4.28	228	1.75
48	4.05	240	1.66
60	3.82	252	1.57
72	3.60	264	1.48
84	3.39	276	1.40
96	3.20	288	1.33
108	3.02	300	1.27
120	2.85	312	1.21
132	2.70	324	1.13
144	2.55	336	1.07
156	2.43	348	1.02
168	2.30	360	0.98
180	2.18		

F=100 TR: 80/80

X=0.001 TB: 76/78

TIME	MC	TIME	MC	TIME	MC	TIME	MC
0	4.94	242	2.84	482	1.88	724	1.32
12	4.80	254	2.78	494	1.84	736	1.30
24	4.65	266	2.71	506	1.80	748	1.27
38	4.46	278	2.64	518	1.78	760	1.25
50	4.32	290	2.59	530	1.73	772	1.23
62	4.20	302	2.53	542	1.72	784	1.21
74	4.09	314	2.48	554	1.68	796	1.20
86	3.97	326	2.43	566	1.66	808	1.18
98	3.86	338	2.38	578	1.62	820	1.17
110	3.74	350	2.32	590	1.60	832	1.13
122	3.63	362	2.28	602	1.56	844	1.12
134	3.54	374	2.23	614	1.52	856	1.10
146	3.46	386	2.19	626	1.50	868	1.09
158	3.39	398	2.14	640	1.48	880	1.08
170	3.30	410	2.10	652	1.46	892	1.06
182	3.22	422	2.06	664	1.43	904	1.03
194	3.13	434	2.02	676	1.42	916	1.02
206	3.05	446	1.98	688	1.40	928	1.00
218	2.98	458	1.95	700	1.37		
230	2.92	470	1.92	712	1.34		

P=100 TR: 78/79

X=0.002 TB: 78/79

TIME	MC	TIME	MC	TIME	MC	TIME	MC
0	5.06	276	3.04	554	1.98	830	1.33
12	4.93	288	3.00	566	1.93	842	1.32
24	4.80	300	2.93	578	1.90	854	1.30
36	4.70	312	2.82	590	1.88	866	1.28
48	4.59	324	2.81	602	1.83	878	1.26
60	4.49	336	2.77	614	1.81	890	1.25
72	4.38	348	2.72	626	1.78	902	1.22
84	4.28	360	2.66	638	1.75	914	1.21
96	4.19	372	2.60	650	1.72	926	1.20
108	4.10	384	2.56	662	1.69	938	1.18
120	4.00	396	2.51	674	1.67	950	1.16
132	3.92	408	2.47	686	1.63	962	1.13
144	3.82	420	2.42	698	1.61	974	1.11
156	3.74	432	2.38	710	1.58	986	1.10
168	3.67	444	2.34	722	1.55	998	1.08
180	3.59	456	2.29	734	1.53	1010	1.06
192	3.50	468	2.26	746	1.51	1022	1.04
204	3.45	480	2.21	758	1.49	1034	1.03
216	3.38	492	2.18	770	1.46	1046	1.02
228	3.31	506	2.13	782	1.45	1058	1.00
240	3.23	518	2.10	794	1.41		
252	3.18	530	2.03	806	1.40		
264	3.11	542	2.01	818	1.37		

F=100 TR: 76/78

X=0.01 TB: 81/80

TIME	MC	TIME	MC	TIME	MC	TIME	MC
0	4.99	302	3.04	602	2.01	904	1.37
12	4.88	314	3.00	614	1.98	916	1.35
24	4.77	326	2.93	626	1.95	928	1.33
36	4.66	338	2.90	638	1.92	940	1.31
48	4.58	350	2.84	650	1.90	952	1.30
60	4.47	362	2.81	662	1.85	964	1.28
72	4.39	374	2.74	674	1.83	976	1.26
84	4.29	386	2.72	686	1.81	988	1.23
96	4.21	398	2.67	698	1.78	1000	1.22
108	4.12	410	2.61	710	1.74	1012	1.20
120	4.03	422	2.57	722	1.72	1024	1.18
132	3.96	434	2.52	734	1.70	1036	1.16
144	3.88	446	2.48	746	1.66	1048	1.15
156	3.81	458	2.44	758	1.63	1060	1.13
168	3.72	470	2.40	770	1.62	1072	1.12
180	3.66	482	2.37	782	1.60	1084	1.11
192	3.60	494	2.32	794	1.57	1096	1.10
204	3.52	506	2.30	806	1.55	1108	1.08
216	3.46	518	2.26	818	1.52	1120	1.06
228	3.40	530	2.21	830	1.50	1132	1.04
242	3.33	542	2.18	844	1.48	1144	1.02
254	3.28	554	2.15	856	1.46	1156	1.00
266	3.22	566	2.12	868	1.43		
278	3.16	578	2.10	880	1.42		
290	3.10	590	2.03	892	1.39		

F=100 TR: 80/80

X=0.02 TB: 78/80

TIME	MC	TIME	MC	TIME	MC	TIME	MC
0	5.03	264	3.02	530	1.98	794	1.34
12	4.90	276	2.97	542	1.93	808	1.32
24	4.78	290	2.91	554	1.90	820	1.30
36	4.66	302	2.83	566	1.85	832	1.28
48	4.53	314	2.79	578	1.83	844	1.26
60	4.42	326	2.72	590	1.80	856	1.23
72	4.32	338	2.68	602	1.75	866	1.22
84	4.22	350	2.61	614	1.72	878	1.20
96	4.12	362	2.56	626	1.71	892	1.19
108	4.02	374	2.51	638	1.68	904	1.16
120	3.93	386	2.47	650	1.64	916	1.15
132	3.84	398	2.41	662	1.62	928	1.13
144	3.75	410	2.38	674	1.60	940	1.11
156	3.67	422	2.32	686	1.56	952	1.10
168	3.59	434	2.27	698	1.53	964	1.09
180	3.51	446	2.23	710	1.51	976	1.05
192	3.42	458	2.20	722	1.50	988	1.04
204	3.36	470	2.16	734	1.46	1000	1.03
216	3.29	482	2.12	746	1.45	1012	1.02
228	3.22	494	2.08	758	1.41	1024	1.01
240	3.14	506	2.04	770	1.39	1036	1.00
252	3.07	518	2.00	782	1.36		

F=100 **TB:** 80/80

X=0.1 **TB:** 80/80

TIME	MC	TIME	MC	TIME	MC	TIME	MC
0	5.10	240	2.90	482	1.90	722	1.32
12	4.92	252	2.82	494	1.87	734	1.31
24	4.76	264	2.77	506	1.83	746	1.29
36	4.51	276	2.70	518	1.80	758	1.28
48	4.48	288	2.63	530	1.77	770	1.25
60	4.32	300	2.59	542	1.73	782	1.23
72	4.21	312	2.55	554	1.70	794	1.20
84	4.09	324	2.50	566	1.67	806	1.19
96	3.98	336	2.43	578	1.63	818	1.17
108	3.87	348	2.40	590	1.61	830	1.14
120	3.74	360	2.33	602	1.58	842	1.13
132	3.63	372	2.30	614	1.55	854	1.12
144	3.55	384	2.24	626	1.52	866	1.10
156	3.46	396	2.20	638	1.50	878	1.09
168	3.36	408	2.15	650	1.47	890	1.07
180	3.28	420	2.12	662	1.44	902	1.04
192	3.18	432	2.08	674	1.41	914	1.03
204	3.12	444	2.03	686	1.39	926	1.02
216	3.03	456	1.98	698	1.38	938	1.01
228	2.97	468	1.94	710	1.34	950	1.00

P=500 TR: 80/80

X=0.001 TB: 79/80

TIME	MC	TIME	MC	TIME	MC	TIME	MC
0	5.1	254	3.00	528	1.94	792	1.32
12	4.94	276	2.94	540	1.90	804	1.31
24	4.82	288	2.88	552	1.87	816	1.29
36	4.69	300	2.82	564	1.82	828	1.27
48	4.57	312	2.76	576	1.80	840	1.25
60	4.46	324	2.70	588	1.78	852	1.23
72	4.34	336	2.63	600	1.74	864	1.21
84	4.24	348	2.58	612	1.71	876	1.19
96	4.14	360	2.53	624	1.68	890	1.13
108	4.03	372	2.50	636	1.64	902	1.12
120	3.94	384	2.44	648	1.62	914	1.11
132	3.87	396	2.40	660	1.60	926	1.10
144	3.77	408	2.35	672	1.57	938	1.08
156	3.67	420	2.31	684	1.54	950	1.06
168	3.58	432	2.27	696	1.52	962	1.04
180	3.51	444	2.22	708	1.50	974	1.02
192	3.42	456	2.17	720	1.48	986	1.01
204	3.35	468	2.13	732	1.46	998	1.00
216	3.27	480	2.09	744	1.42		
228	3.20	492	2.06	756	1.39		
240	3.13	504	2.02	768	1.37		
252	3.08	516	1.99	780	1.35		

F=500 TR: 81/80

X=0.002 TB: 80/80

TIME	MC	TIME	MC	TIME	MC	TIME	MC
0	4.97	252	2.90	506	1.87	758	1.30
12	4.82	264	2.82	518	1.83	770	1.28
24	4.70	276	2.77	530	1.81	782	1.28
36	4.56	288	2.70	542	1.78	794	1.25
48	4.43	300	2.64	554	1.74	806	1.22
60	4.31	312	2.59	566	1.70	818	1.21
72	4.20	324	2.53	578	1.68	830	1.18
84	4.10	336	2.48	590	1.64	842	1.17
96	3.98	348	2.43	602	1.62	854	1.14
108	3.87	360	2.38	614	1.59	866	1.12
120	3.77	372	2.34	626	1.57	878	1.10
132	3.67	384	2.29	638	1.54	890	1.09
144	3.59	396	2.24	650	1.51	902	1.07
156	3.50	408	2.20	662	1.49	914	1.06
168	3.41	420	2.15	674	1.46	926	1.04
180	3.33	432	2.11	686	1.43	938	1.03
192	3.25	444	2.07	698	1.40	950	1.01
204	3.17	456	2.02	710	1.38	962	1.00
216	3.10	470	1.99	722	1.36		
228	3.03	482	1.94	734	1.33		
240	2.97	494	1.91	746	1.31		

F=500 TR: 80/82

X=0.003 TB: 80/83

TIME	MC	TIME	MC	TIME	MC	TIME	MC
0	4.97	266	2.97	530	1.94	796	1.33
12	4.78	278	2.91	542	1.90	808	1.32
26	4.70	290	2.84	554	1.87	820	1.31
38	4.58	302	2.80	566	1.83	832	1.29
50	4.48	314	2.73	578	1.81	844	1.27
62	4.37	326	2.68	590	1.77	856	1.24
74	4.26	338	2.63	602	1.73	868	1.23
86	4.14	350	2.58	614	1.72	880	1.21
98	4.06	362	2.52	628	1.69	892	1.20
110	3.97	374	2.48	640	1.65	904	1.17
122	3.87	386	2.43	652	1.62	916	1.16
134	3.78	398	2.39	664	1.60	928	1.14
146	3.69	410	2.34	676	1.58	940	1.12
158	3.60	422	2.30	688	1.55	952	1.11
170	3.52	434	2.24	700	1.52	964	1.08
182	3.44	446	2.22	712	1.50	976	1.07
194	3.38	458	2.17	724	1.48	988	1.05
206	3.31	470	2.11	736	1.46	1000	1.03
218	3.23	482	2.08	748	1.43	1012	1.02
230	3.17	494	2.03	760	1.40	1024	1.00
242	3.10	506	2.00	772	1.38		
254	3.03	518	1.99	784	1.36		

F=500 TR: 81/80

X=0.004 TB: 80/80

TIME	MC	TIME	MC	TIME	MC	TIME	MC
0	4.98	266	2.88	530	1.89	794	1.32
12	4.83	278	2.81	542	1.87	806	1.30
24	4.70	290	2.76	554	1.83	820	1.28
36	4.68	302	2.69	566	1.80	832	1.26
48	4.45	314	2.63	578	1.78	842	1.25
60	4.33	326	2.58	590	1.75	856	1.22
72	4.22	338	2.52	602	1.72	868	1.20
84	4.11	350	2.48	614	1.68	880	1.19
96	4.00	362	2.42	626	1.66	892	1.17
108	3.91	374	2.38	638	1.63	904	1.14
120	3.82	386	2.33	650	1.61	916	1.12
132	3.72	398	2.30	662	1.58	928	1.11
144	3.63	410	2.26	674	1.56	940	1.09
156	3.54	422	2.21	686	1.53	952	1.07
168	3.47	434	2.17	698	1.50	964	1.06
180	3.48	446	2.13	710	1.48	976	1.05
192	3.41	458	2.10	722	1.44	988	1.04
204	3.23	470	2.07	734	1.42	1000	1.03
216	3.16	482	2.02	746	1.40	1012	1.02
228	3.09	494	1.99	758	1.38	1024	1.00
240	3.01	506	1.96	770	1.36		
254	2.97	518	1.92	782	1.33		

Correction Curve TR: 76/76

TB: 76/76

TIME	MC	TIME	MC	TIME	MC	TIME	MC
0	5.01	324	3.20	650	2.17	974	1.45
12	4.90	336	3.16	662	2.12	986	1.43
24	4.80	348	3.10	674	2.08	998	1.40
36	4.72	360	3.07	686	2.06	1010	1.38
48	4.64	372	3.00	698	2.02	1022	1.36
60	4.57	384	2.98	710	2.00	1034	1.34
72	4.50	396	2.91	722	1.98	1046	1.32
84	4.43	408	2.87	734	1.94	1058	1.30
96	4.34	420	2.83	746	1.92	1070	1.28
108	4.28	432	2.80	758	1.90	1082	1.26
120	4.21	444	2.76	770	1.88	1094	1.24
132	4.15	456	2.72	782	1.84	1106	1.22
144	4.08	468	2.68	794	1.82	1118	1.21
156	4.00	480	2.62	806	1.80	1130	1.20
168	3.93	492	2.60	818	1.76	1142	1.18
180	3.89	504	2.55	830	1.72	1154	1.16
192	3.82	516	2.52	842	1.71	1166	1.14
204	3.75	528	2.47	854	1.69	1178	1.12
216	3.68	540	2.48	866	1.65	1190	1.10
228	3.62	552	2.41	878	1.63	1202	1.09
240	3.58	564	2.40	890	1.61	1214	1.08
252	3.51	576	2.37	902	1.60	1226	1.06
264	3.47	588	2.33	914	1.55	1238	1.04
276	3.41	602	2.26	926	1.52	1250	1.02
288	3.37	614	2.24	938	1.51	1262	1.00
300	3.30	626	2.22	950	1.48		
312	3.25	638	2.18	962	1.46		

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BIOGRAPHY

Joseph Michael Harth was born on September 25, 1943 in Orange, New Jersey. He attended elementary schools in Newark, New Jersey, and graduated from Summit High School in Summit, New Jersey, in June of 1961. Four years later he graduated from Newark College of Engineering with a Bachelor of Science in Mechanical Engineering.

That June he went to work for Ross Engineering Company where he worked until entering Lehigh University in September of 1966. He has been a Graduate Assistant at Lehigh and working for his Master's Degree since that time.