SEMI-ANNUAL

REPORT

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HEAT TRANSFER ACROSS SURFACES IN CONTACT: PRACTICAL EFFECTS OF TRANSIENT TEMPERATURE AND PRESSURE ENVIRONMENTS

Submitted By

H. A. Blum

C. J. Moore, Jr.

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TABLE OF CONTENTS

INTRODUCTION

1. During this period the following aspects of the study of heat transfer across surfaces in contact under transient conditions were emphasized:

   1.1 EXPERIMENTAL -

   As we pointed out, it was necessary to design, assemble, and test a new means for providing axial force control for the cylinders in contact. This has been completed and a couple of tests have shown that the system is operating successfully. The description of force system and these first experiments are described later in this report.

   1.2 THEORETICAL STUDIES -

   A numerical solution for two dimensional heat transfer across surfaces in contact under transient conditions has been completed and several cases have been run. In this study we are concerned with questions such as: How will a single cylinder in contact with a plate react to changes in contact resistance and thermal environment, and how closely can cylinders be placed on a plate without thermal interference? This type of information could be useful in designing the layout for heat generating equipment in space systems. The description of our model and some of the results will be described later in the report.

1.3 A POSSIBLE CONTROL APPLICATION -

There has been a wide interest in the development of passive control devices. In the previous report it was mentioned that if two conductors having slightly dished out sections in one or more places, were placed in rigid contact, as the temperature increased the two materials would be forced together which would increase the heat flux and thereby tend to decrease the temperature. If the materials were not stressed beyond the elastic limit, when the temperature levels decreased the area of contact would decrease likewise the heat flux. It was our intention to make some theoretical studies in order to evaluate the feasibility of such an idea. During this period we have devised a simple system to test out this idea experimentally. The system and the results will be described later.

1.4 METAL THERMAL CONDUCTIVITY -

In order to obtain more accurate values for contact conductance coefficients it is desirable to measure the thermal conductivity of the metals which we use in our systems. For this purpose we are constructing an apparatus almost identical to the one described by Watson and Robinson (1)

(1) T. W. Watson and H. E. Robinson, "Thermal Conductivity of Some Commercial Iron-Nickel Alloys," Journal of Heat Transfer, Nov. 1961, pp 403-408

2. ONE DIMENSIONAL TRANSIENT EXPERIMENTS

2.1 FORCE CONTROL SYSTEM -

The force control system is basically a closed-loop electro-hydraulic servomechanism. Figure 2.1 is a schematic of the main components of the system. A double ended hydraulic cylinder applies the force to the test samples. The cylinder is supplied with a constant pressure, constant flow stream of hydraulic oil by a hydraulic pump and flow regulator. A proportional type servovalve controls the pressure differential across the piston of the hydraulic cylinder and thus controls the force applied to the test samples. The servovalve adjusts the differential pressure according to the magnitude and polarity of the electrical signal on the servovalve coils.

As shown in Figure 2.2, the applied force is transmitted through the force cell. The force cell is a strain gage device. It is used as one leg of a wheatstone bridge so that the unbalanced voltage is proportional to the applied force. This voltage is used as a feedback signal. By means of a potentiometer an input signal is supplied to a summing junction at a polarity opposite to the feedback signal. The difference between these two voltages is the "error" signal, i.e. it is proportional to the difference between the input and the feedback force. This error signal is amplified and used to drive the servovalve. Thus, when

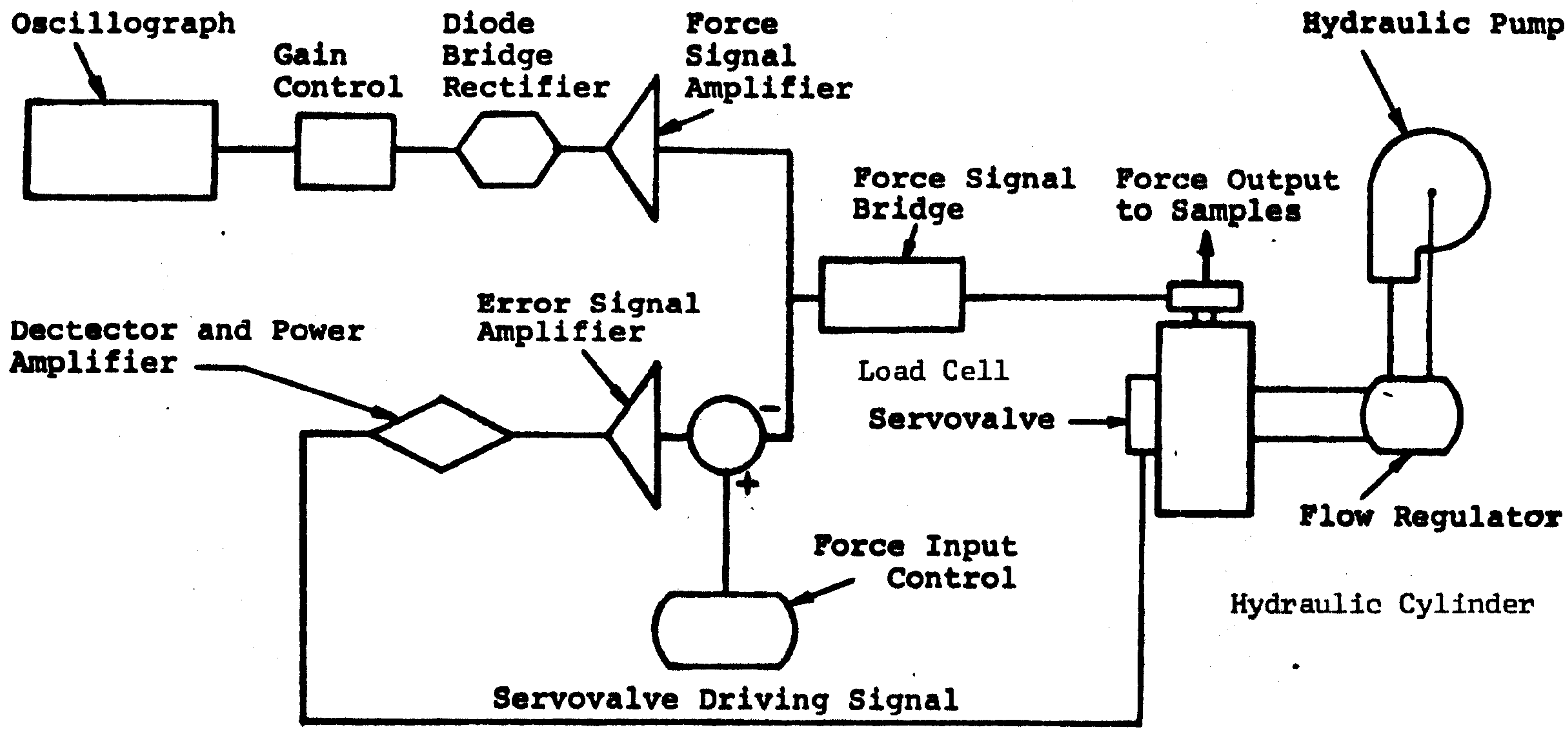


Figure 2.1 - Force Control System Schematic

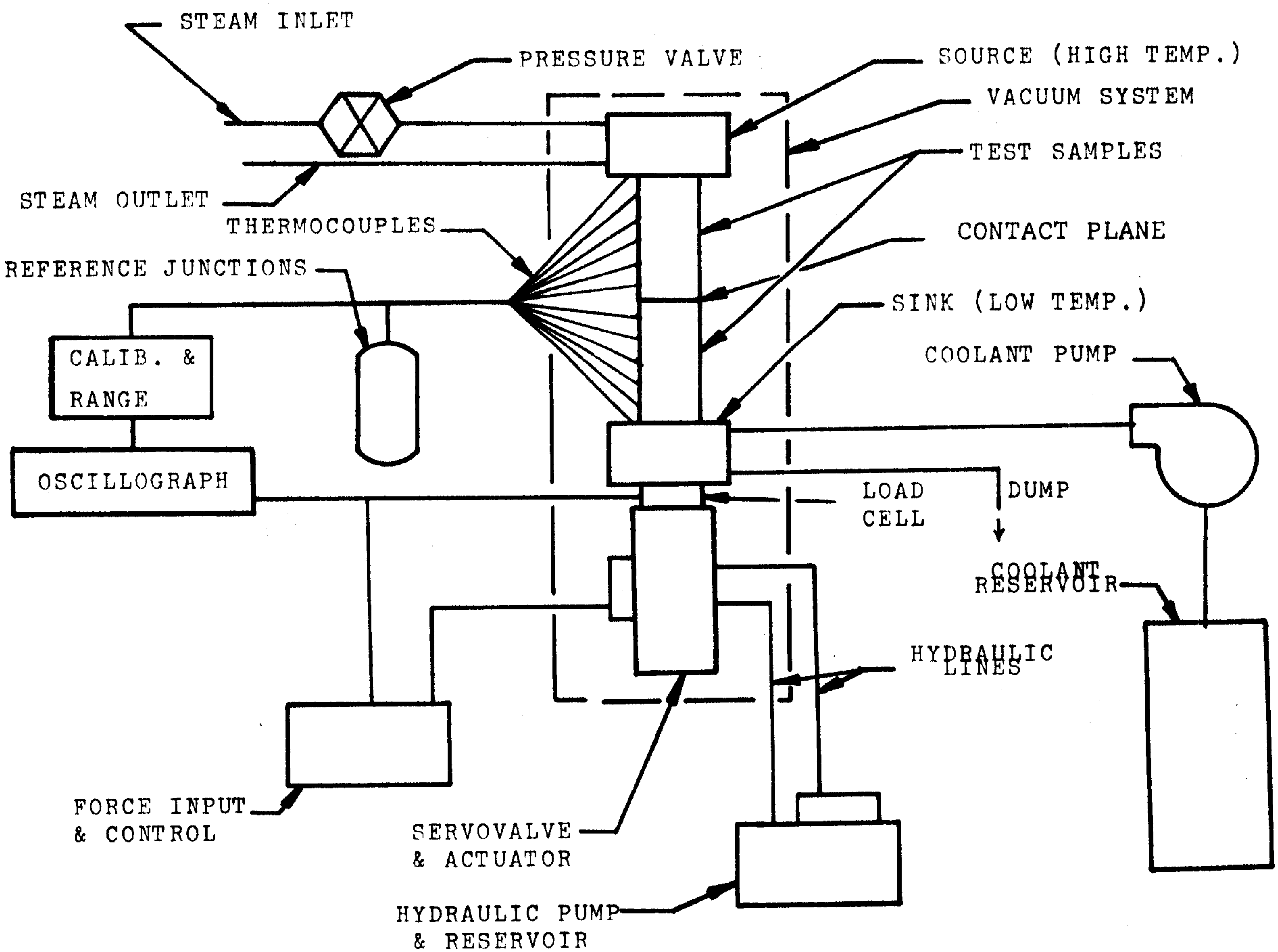

STEAM INLET
PRESSURE VALVE
SOURCE (HIGH TEMP.)
VACUUM SYSTEM
TEST SAMPLES
STEAM OUTLET
THERMOCOUPLES
CONTACT PLANE
REFERENCE JUNCTIONS
SINK (LOW TEMP.)
CALIB. & RANGE
COOLANT PUMP
OSCILLOGRAPH
LOAD CELL
DUMP
COOLANT RESERVOIR
HYDRAULIC LINES
FORCE INPUT & CONTROL
SERVOVALVE & ACTUATOR
HYDRAULIC PUMP & RESERVOIR

FIGURE 2.2

the feedback equals the input the servovalve holds the desired force on the system. The input control consists of two potentiometers connected by a two position switch, which allows a step change in the input to be accomplished. Tests have shown that the system response time is of the order of milliseconds, thus, for practical purposes, the load changes are instantaneous.

In addition to providing a feedback signal for the controller the force cell signal is also amplified and rectified for use in recording the force on the samples during the experiments. The force trace on the oscillograph is calibrated by comparing the trace deflection to the output of another load cell which has been calibrated on a testing machine.

2.2 EXPERIMENTAL RESULTS

We have prepared 8 test samples so far, 4 aluminum (2024S-T356) and 4 stainless steel (Type 303-MA). Of each of these materials 2 are 2.54 cm long and 2 are 5.08 cm long, one each with a "medium" and "rough" finish on the contact surface. Armco Iron samples of the same nature are currently being prepared. Thus far we have made five sets of test runs on samples. All are with sample 2 on the hot side and sample 1 on the cold side. Sample 2 is a 2.54 cm long aluminum sample with a surface roughness of 0.71 micrometer (rms) and sample 1 is a 5.08 cm long aluminum sample with a surface roughness of 0.35 micrometer (rms). Some of the results of these five runs are presented in Figures 2.3 through 2.5. All of these runs were made in the same manner which is as follows:

Phase 1.) The samples are pressed together between the source and sink blocks as shown in Figure 2.2. Cooling water is circulated through both the source and the sink blocks to bring the samples to a uniform temperature. Next, the samples are lowered so that the upper (hot side) sample no longer makes contact with the source block. The system is then evacuated to a pressure of 1-5 microns Hg. Then the source block is heated up to the desired value (nominally 150°C). Finally, the samples are raised and pressed together at a constant contact pressure. This closely approximates a step rise in the upper boundary temperature.

Phase 2.) After phase 1 has reached its steady state the contact pressure is raised suddenly to a new constant value by flipping a switch on the force controller. The system is held at this pressure until steady state has been reached.

Phase 3.) The procedure of phase 2 is reversed, returning the contact pressure to its original (lower) value and holding it constant until steady state is reached.

Phase 4.) Holding the contact pressure constant, air is allowed to enter the vacuum chamber as fast as possible and a new steady state is reached. The test data show that this is effectively a very rapid change. That is, the temperature traces on the oscillograph record respond almost as rapidly as in the phase 1 portion of the tests.

2.2.1 CONTACT CONDUCTANCE

For the data reported here Table 2.1 shows the contact pressures employed and the calculated steady state conductance. Note that several additional runs were made in air in runs 4 and 5. These were made to obtain some check values for steady state.

TABLE 2.1. STEADY STATE CONDUCTANCE VALUES

In Vacuum (1-5 μHg)				In Air (atm. press.)			
Run	Phase	Conductance (Watts/M^2°C)	Contact Pressure (Kilo Newtons/M^2)	Run	Phase	Conductance (Watt/M^2°C)	Contact Pressure (Kilo Newtons/M^2)
1	1	795	88	1	4	5110	88
1	2	3520	442	2	4	5080	79
1	3	855	88	3	4	6300	195
2	1	780	79	4	4	9735	628
2	2	2500	450	4	-	14346	1589
2	3	1070	79	4	-	9540	625
3	1	1135	192	5	4	5806	127
3	2	3750	801	5	-	15402	1287
3	3	1135	192	5	-	5915	121
4	1	2750	631				
4	2	6540	1597				
4	3	2970	631				
5	1	790	127				
5	2	6329	1287				
5	3	724	124				

Figures 2.3 and 2.4 show the transient contact conductance results. Comparison of phase 1 and phase 3 steady state values (for the same run) indicate that the conductance is fairly repeatable at these low contact pressures. These plots also show that the conductance is relatively constant after about 15-20 seconds for phases 1, 2, 3, but the phase 4 changes settle out a little slower. We are uncertain at the present time whether the sharp variation in the conductance during the early times is real or whether it is a result of the calculation method. We are investigating this question at the present time.

As a means of judging the over-all accuracy of our conductance values we have compared the steady state results in a vacuum with some values reported by Fried (AIAA Paper No. 65-661, September 1965). The results are shown in Figure 2.5. Two sets of Fried's data are shown, one set for a surface roughness of 0.2 micrometer (CLA), and one set for a 1.1 micrometer (CLA) roughness, both are 2024S-T4 aluminum. The results used are for those in which Fried assembled the joints in vacuum. Although our joints were touching before the air was evacuated it is believed that these results are more representative due to the nature of our contact surfaces. That is, the contact surfaces are parallel ridges placed perpendicularly to each other and should thus outgas quite easily. As can be seen in Figure 2.5 our results fall in between Fried's data. Since our surface roughness (0.35 and 0.71 micrometer RMS) was also in between his values we feel this is a good indication of the accuracy of our results.

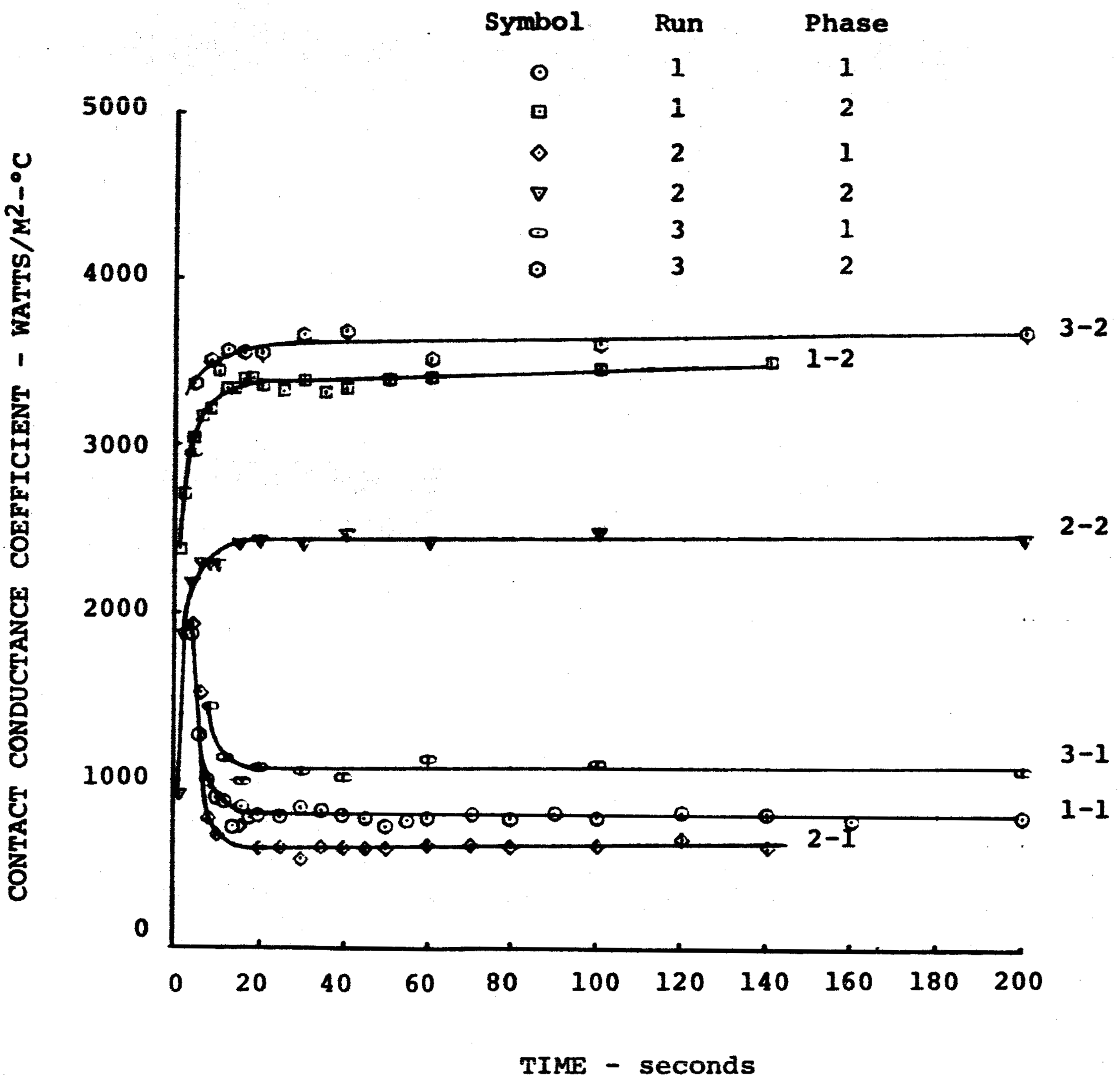


Figure 2.3 - Phase 1 and Phase 2 Transient Contact Conductance

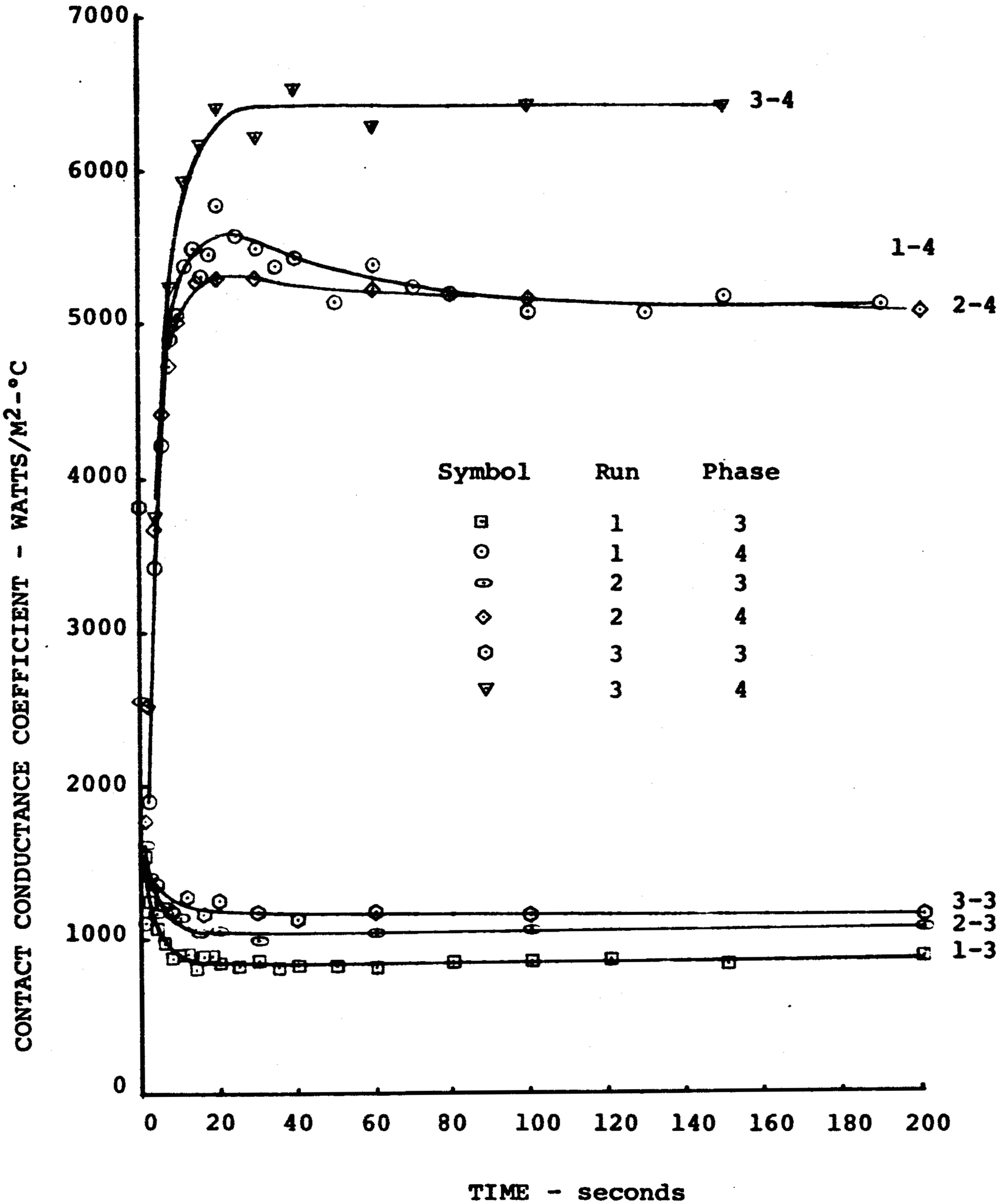


Figure 2.4 - Phase 3 and Phase 4 Transient Cc:tact Conductance

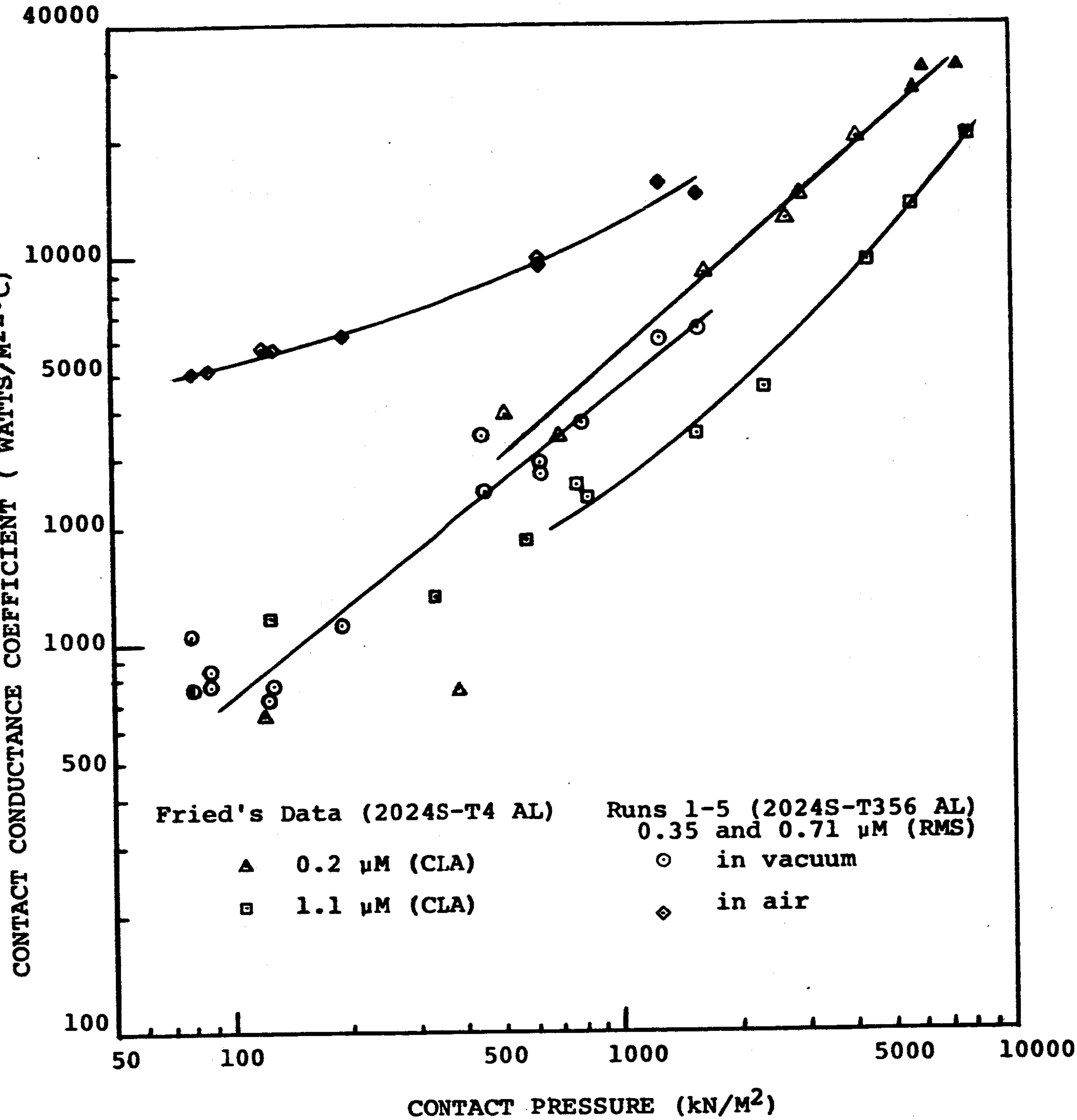


Figure 2.5 - Comparison of Steady State Contact Conductance Results

2.2.2 CONTACT TEMPERATURE DROP

Figure 2.6 shows how the contact temperature drop varied with time during the phase 1 part of runs 1 and 3. The amount of overshoot in ΔT_C, i.e., the percentages greater than the steady state value, is apparently sensitive to h for these low values of h. This result was expected from our earlier theoretical work. The dashed curve in Figure 2.6 is the theoretical prediction for a system consisting of the same materials (thermal properties), lengths, and contact conductance as those of run No. 3. A comparison shows that the amount (i.e. per cent of steady state value) of the peak overshoot in ΔT_C is lower than the theoretical, and that the time of occurrence of this peak is later than the theoretical. It is also noted that the steady state value of ΔT_C is lower than predicted (measured 41.1°C compared to the theoretical 55.0°C). The data show that there were contact resistances at the source and sink ends of the samples. Calculations show that this amounted to conductances of about 6250 and 5680 Watts/m^2-°C on the hot and cold ends, respectively. Using these values to account for the additional overall resistance the theoretical ΔT_C becomes 40.8°C. This compares very well to a measured value of 41.1°C. Thus it is our preliminary conclusion that the contact resistance on the ends of the samples is the primary cause of the difference between theory and experiment. This is backed up by the

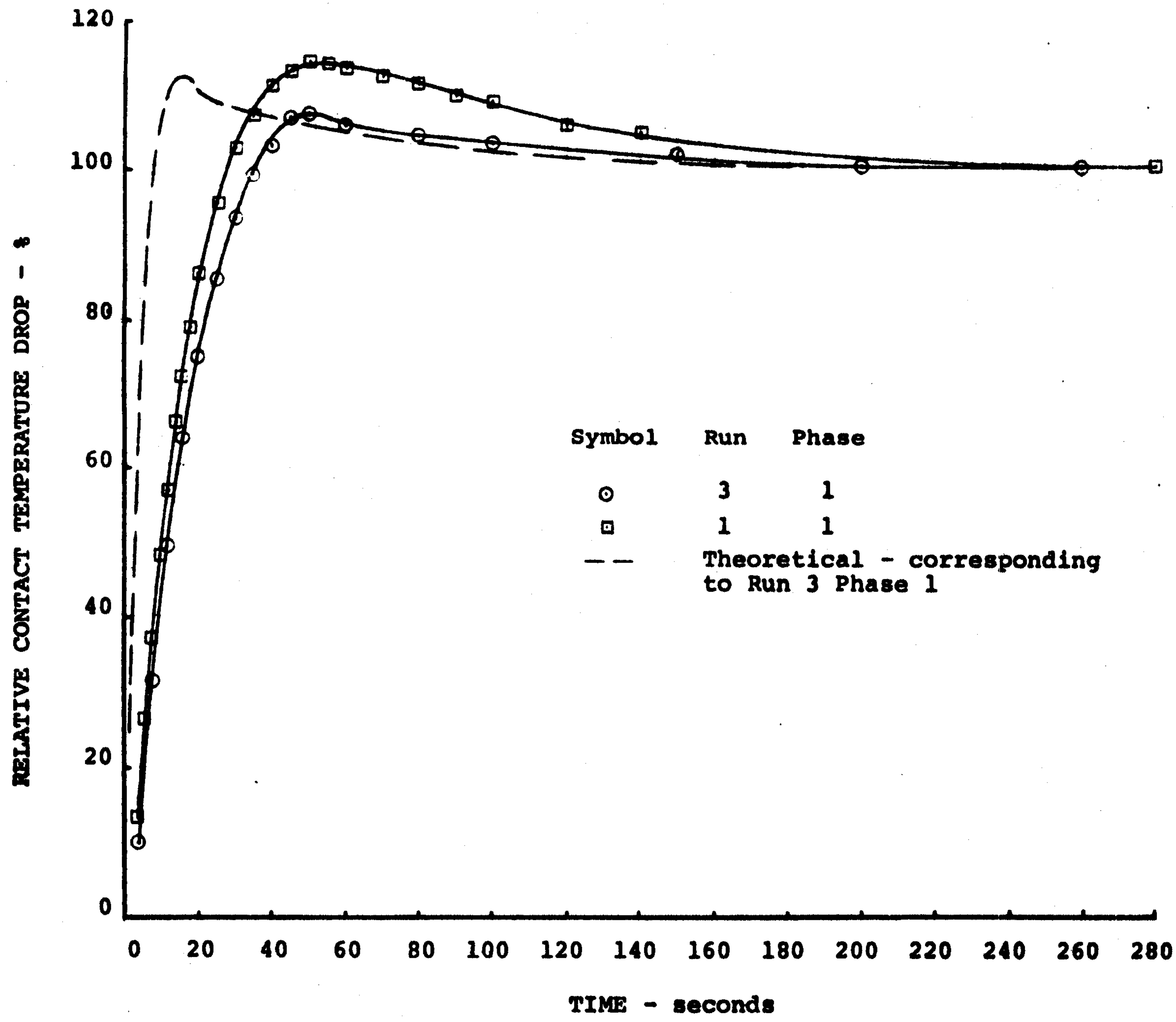


Figure 2.6 - Comparison of Theoretical and Experimental Contact Temperature Drop

theory in that it has shown that higher resistances (either in the materials or in contacts) has the same effect on the amount and occurrence time of the overshoot peak.

2.2.3 TIME TO REACH STEADY STATE

For the time to reach steady state correlations we have gone to 63.2% instead of the 99.0% of steady state. This fraction is the standard in most transient work in various fields. It gives the time to approach to within one "time constant" of steady state, i.e. to within e^{-1}, thus the fraction is $1-\frac{1}{e}$ = 63.2%. This change was made because it reduces the sensitivity to experimental error. Using this criterion the test results are compared with the theoretical prediction in Figure 2.7. The predicted values assume no end resistance is present. From the curves it appears that the experimental time is approximately twice the theoretical time.

In order to evaluate the conclusion mentioned above the theoretical transient program is being modified to include the end resistances and these results will be compared with the experimental results.

2.2.4 FUTURE EXPERIMENTS

The results obtained to date are encouraging and it appears that the apparatus and procedures are satisfactory. Further experiments are in progress and still others are planned. These include combinations of lengths and materials consisting of 2.54 and 5.08 cm samples of 2024S-T356

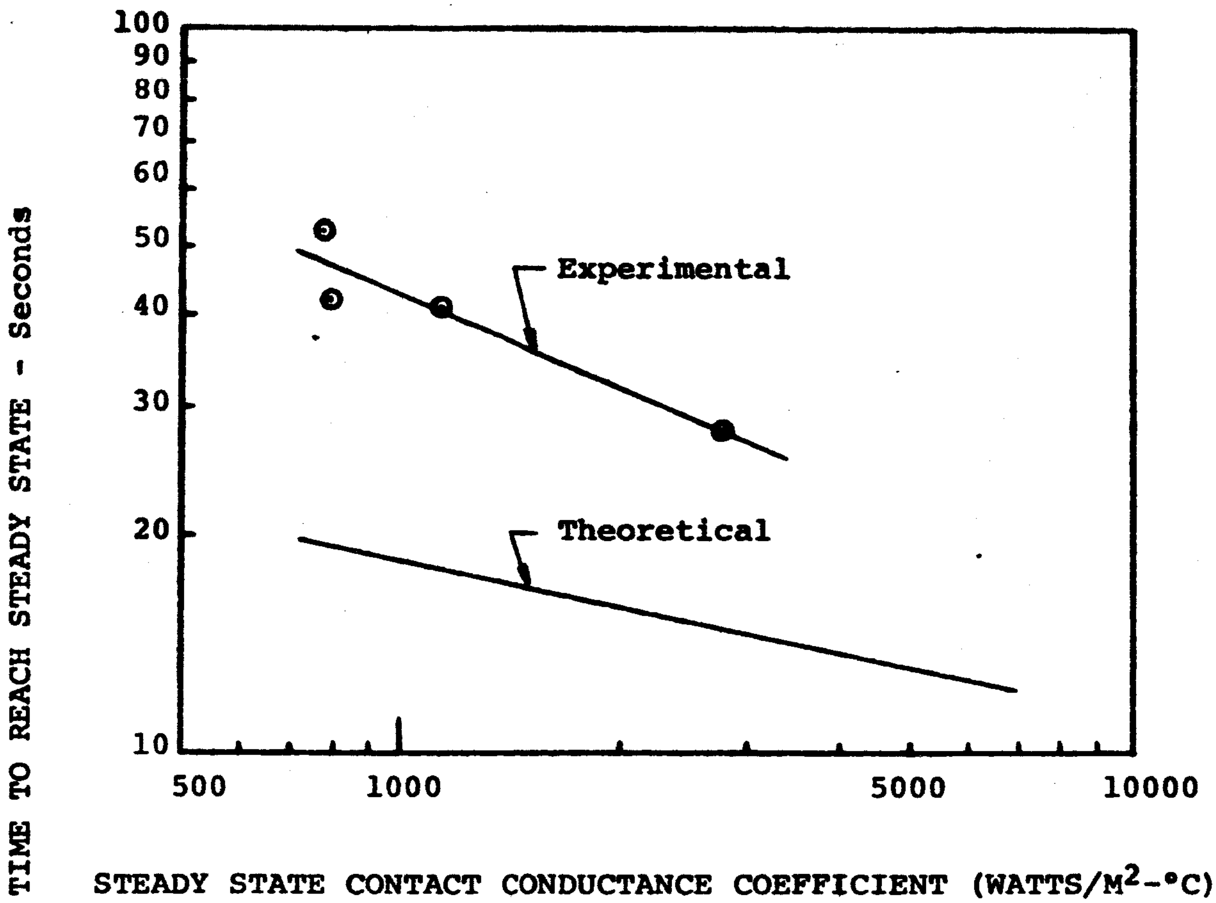


Figure 2.7 - Time to Reach Steady State Comparison for Runs 1-4

aluminum, type 303-MA stainless steel and Armco Iron. With these combinations it is felt that the theoretical predictions can be tested in a conclusive manner, and the experimental results, regardless of how the comparison turns out, will be indicative since these three materials are representative of the range of thermal properties of metals.

3. TWO DIMENSIONAL HEAT TRANSFER ACROSS SURFACES IN CONTACT: A THEORETICAL STUDY

3.1 BACKGROUND -

In the case where several pieces of equipment are attached to a common sink it would be desirable to determine the thermal interference of one piece of equipment with another. For planning purposes, if we knew the extent of the thermal interference, it would be possible to decide how many items could be placed against a common surface.

3.2 THE MODEL -

In view of our interest in the transient response of systems in which either the environment or the contact conductance changes our model includes surfaces in contact where the contact conductance coefficients can be varied. This model can be used for the case where the contact conductance is infinite, that is, where there is no contact for heat transfer purposes. The model considered so far consists of a rectangular block placed in contact with a plate (Figure 3.1). We assume adiabatic surfaces from the side of the block and from the top of the plate. Initially both the block and the plate are at the sink temperature. Suddenly the top of the block is brought to the source temperature and the numerical solution of the finite difference equation provides temperature versus distance and time for the whole system. In view of the computer time required, it was decided to

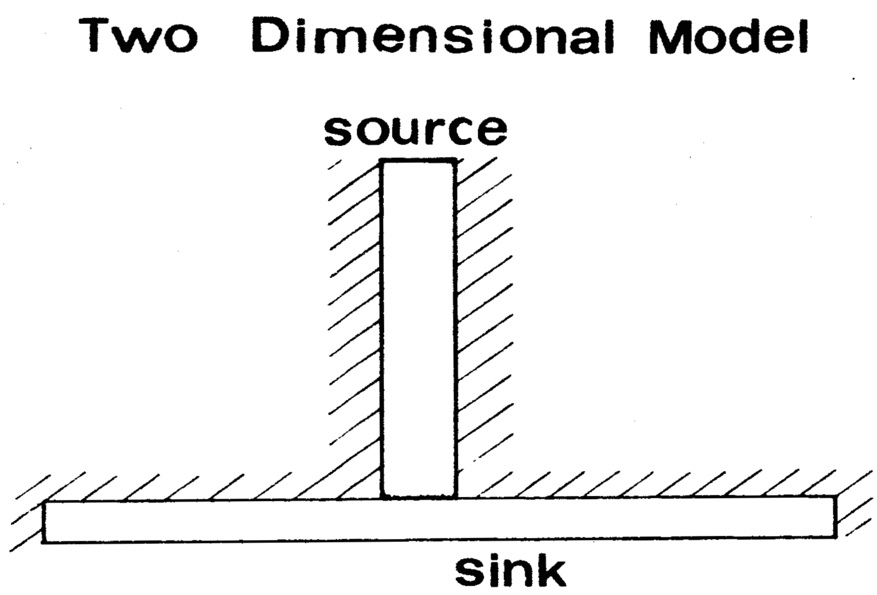


Figure 3.1-MODEL FOR TWO-DIMENSIONAL STUDIES

consider this phase of the theoretical experiment complete when the ratio of the heat leaving the plate to the heat entering from the source at the top of the block equals 0.67. For some cases a step function change in the contact conductance was assumed after the completion of phase one and the same type of information was obtained.

In all cases the plate was assumed to be aluminum, 25.4 centimeters wide and 1.77 centimeters deep. The blocks consisted of aluminum, armco iron, or stainless steel. The width for the block was kept constant in all cases studied so far at 2.54 centimeters but the length varied from 1.77 centimeters to 17.7 centimeters. The contact conductance coefficients ranged from 142 watts/M^2-HR-^oC (25 Btu/hr/ft^{2o}F) to 56,700 watts/M^2-HR-^oC (10,000 Btu/hr^{2o}F). In every case where a new contact conductance was introduced as a step function (phase two) the original contact conductance was 5670 watts/HR M^2 ^oC (1000 Btu/hr/ft^{2o}F).

3.3 <u>SOME RESULTS</u> -

In Table 3.1 are described some of the results for the cases studied to date. Columns 1 and 2 indicate the system for the upper block and lower plate. Columns 3-6 list the two critical dimensions for the upper block and for the lower plate. Columns 7-9 deal with the pertinent information for phase one of the theoretical experiment.

TABLE 3.1

Two Dimensional Heat Transfer Across Surfaces in Contact for Described Model
(Figure 3.1)

SYSTEM		GEOMETRY CM (inches)				PHASE 1			PHASE 2				
Upper Block	Lower Plate	Upper Block W	S	Lower Plate W	S	h contact WATTS/M^2°C (BTU/HR-FT^2-°F)	Time for Q_{out}/Q_{in}= 0.67 Sec.	Thermal Influence Distance (TID) CM (inches)	New h contact WATTS/M^2°C (BTU/HR-FT^2-°F)	Time for Q_o/Q_i 0.67	Temperature Depression (Max)	Time for Max. Temp. Depression (Seconds)	Thermal Influence Distance (TID) CM (inches)
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Al	Al	2.54 (1.0)	5.08 (2.0)	25.4 (10.0)	1.77 (0.5)	5670 (1000)	16.4	1.77 (0.5)	425 (75)	30.0	.076	3.0	0.254 (0.1)
Armco Iron(AI)	Al						55.2	0.76 (0.3)		107.7	.032	3.0	0.0
Stainless Steel(SS)	Al						167	0.0		191	.008	2.0	0.0
Al	Al	2.54 (1.0)	1.77 (0.5)	25.4 (10.0)	1.77 (0.5)		2.0	2.03 (0.8)		0.02			
Armco Iron	Al						5.6	1.78 (0.7)		9.3	.086	2.0	.76 (0.3)
SS	Al						12.5	1.77 (0.5)		24	.031	2.0	0.51 (0.2)
Al	Al	2.54 (1.0)	17.7 (5.0	25.4 (10.0)	1.77 (0.5)		71	1.77 (0.5)		143	.041	3.0	0.51 (0.2)
Armco Iron	Al						285	0.51 (0.2)		None			
Al	Al	2.54 (1.0)	5.08 (2.0)	25.4 (10.0)	1.77 (0.5)	56700 (10000)	10.3	2.03 (o.8)					
						2885 (500)	21.0	1.52 (0.6)					
						142 (25)	54.3	0.0					
Armco Iron	Al					56700 (10000)	42.6	1.77 (0.5)					
						2885 (500)	67.6	1.01 (0.4)					
						142 (25)	216	0.0					
SS	Al					56700 (10000)	154	0.25 (0.1)					
						2885 (500)	181	0.25 (0.1)					
						142 (25)	506	0.0					

Column 7 lists the contact conductance coefficient. The time for the ratio of the heat out from the lower plate to the heat into the upper block equal 0.67 is listed in Column 8. The thermal influence distance (TID) which is the distance from the edge of the upper block along the plate where the temperature is equal to or greater than 0.0001 ($T_{source} - T_{sink}$). In Columns 10-14 are listed information concerning phase two (where this was run on the computer). Column 10 has the new contact conductance coefficient. Column 11 has the time corresponding to Column 7. Column 12 has the maximum temperature depression at the top center of the plate when h is suddenly decreased at the end of phase one. The number listed in this column is the fraction of the temperature difference between the source and the sink. In Column 13 is listed the time it takes from the start of phase two for this maximum temperature depression to occur. The TID is listed in Column 14. This temperature depression occurs because the lowered contact conductance coefficient adds a thermal resistance to the system in such a way that the plate loses more heat than it receives from the block. The block heats up because of the extra resistance. When the temperature across the contact is high enough the flux increases thereby the temperature on the plate side of the contact begins to increase again, until the new steady state condition is reached. It was interesting to observe in the cases studied that the time for the maximum temperature depression to occur varied between two and three seconds for all the cases. This includes a variation in the block material and the height of the block material. The original and the new contact conductance coefficients were the same in all cases as well as the material and geometry for the lower plate.

One can see qualitatively from this table that as the contact conductance coefficient increases the thermal influence distance (TID) also increases. This, of course, would be expected as the total system resistance decreases. The transient response times for phase one also behaves as one might expect qualitatively, namely; that the approach to equilibrium takes less time as the contact conductance coefficient increases for a given material and that the thermal properties also affect the transient response time being less affected by the contact as the thermal resistance of the materials in contact increase.

No general correlations were attempted with the data obtained to date because there are some changes that we would like to add to this program which would make it of more general value. Specifically, convection and radiation from the sides plus internal power generation would make the program far more general. If in addition to this, we were to include variable properties the program would be quite valuable at least for the study of individual problems.

In addition to these modifications which will not be made simultaneously we will develop a separate program for the steady state case which should provide a valuable check for the transient program.

4. A PASSIVE THERMAL CONTROL DEVICE

The possibility of applying information about systems with contacts, for controls involve two aspects: First, the knowledge of how systems behave under transient conditions when either the environment or the contact conductance coefficients change would enable the designer of a system to plan the control system with more assurance concerning the response time of such systems. Second, it was believed that experiments under transient conditions with systems where contacts were present might result in the development of a passive control device. In the previous report we indicated that some theoretical studies might be made concerning feasibility of the latter.

Figure 4.1 is a sketch presented in the last report. Two rigidly placed conductors with some small gaps would be placed in contact and the heat flux would be observed for various temperature levels. Hopefully this would tell us the variation in heat flux for a change in the temperature of the hotter piece of a control device. The higher dq/dt, the more effective the control device is functioning, assuming that the objective of the control device is to keep the temperature of the hot piece relatively constant.

4.1 THE APPARATUS AND PROCEDURE -

The model that seemed most amenable to theoretical consideration was one in which the two pieces (a source whose temperature should be controlled and a sink to remove the heat) should have an intermediate control element where the variability of the contact area, ease of fabrication,

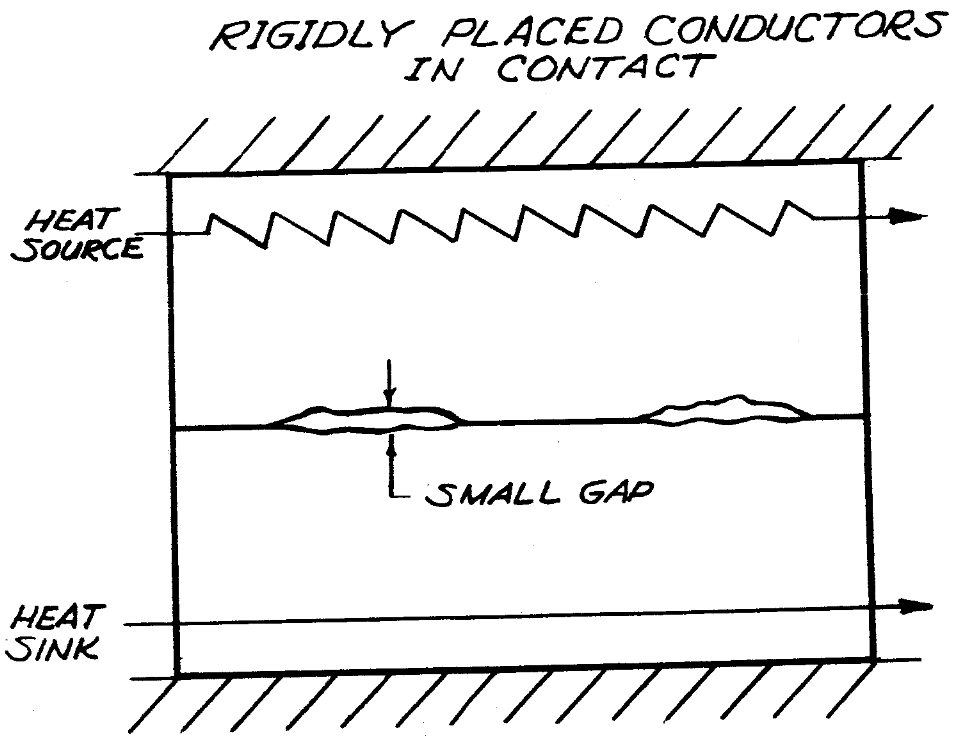


Figure 4.1-PASSIVE CONTROL DEVICE

and predictable behavior could be established. A conical washer seems to be best for this purpose.

Figure 4.2 is a schematic of the system for testing this device. Retaining plates and columns are used to provide a rigid system through which the thermal conductor, conical washer, and sink can operate.

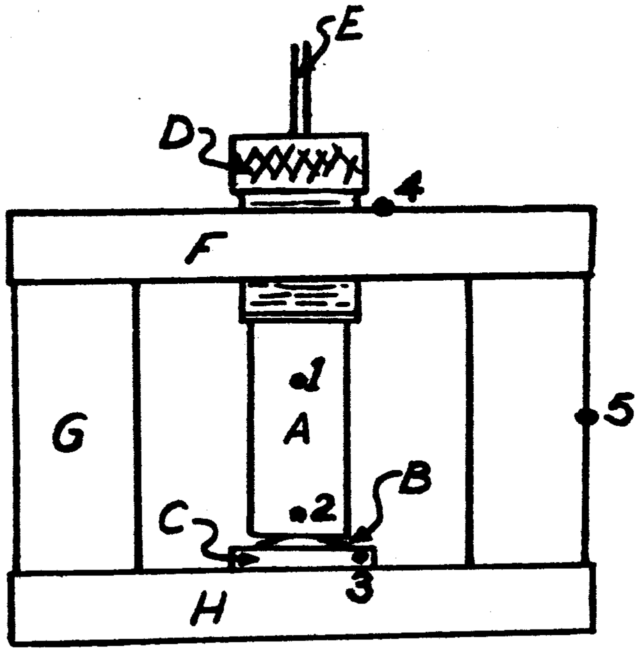
For testing the system the heater was turned on to a fixed level and the steady state temperatures were observed. The power was then increased until a new steady state condition was reached where the temperatures would then be recorded.

The controlled device action works such that as the power increases the temperature of the upper piece would increase thereby causing (by thermal expansion) the conical washer to eventually come in contact with the lower piece thereby providing a greater contact area so that for a given temperature a greater flux could pass through from the source to the sink. The conical washer was designed in such a manner that its elastic limit would never be exceeded thereby reproducibility would be expected.

At first the heat sink was replaced by a thermal insulator of high compressor strength. The power input was recorded for a succession of steady state temperatures to determine the system losses to the surroundings.
Figure 4.3 shows the power losses as a function of upper cylinder temperature.

With this information available the heat sink was then

APPARATUS



A - THERMAL CONDUCTOR 3"φ × 5½" 6061-T6 AL
B - CONICAL WASHER 3" O.D. × 1" I.D. × .090
C - HEAT SINK
D - VERNIER HEAD/HEATER
E - POWER INPUT - 60 CYCLE A.C.
F - UPPER RETAINING PLATE
G - COLUMNS (4)
H - LOWER RETAINING PLATE

1-5 - THERMOCOUPLE LOCATIONS

Figure 4.2 - EXPERIMENTAL CONTROL DEVICE

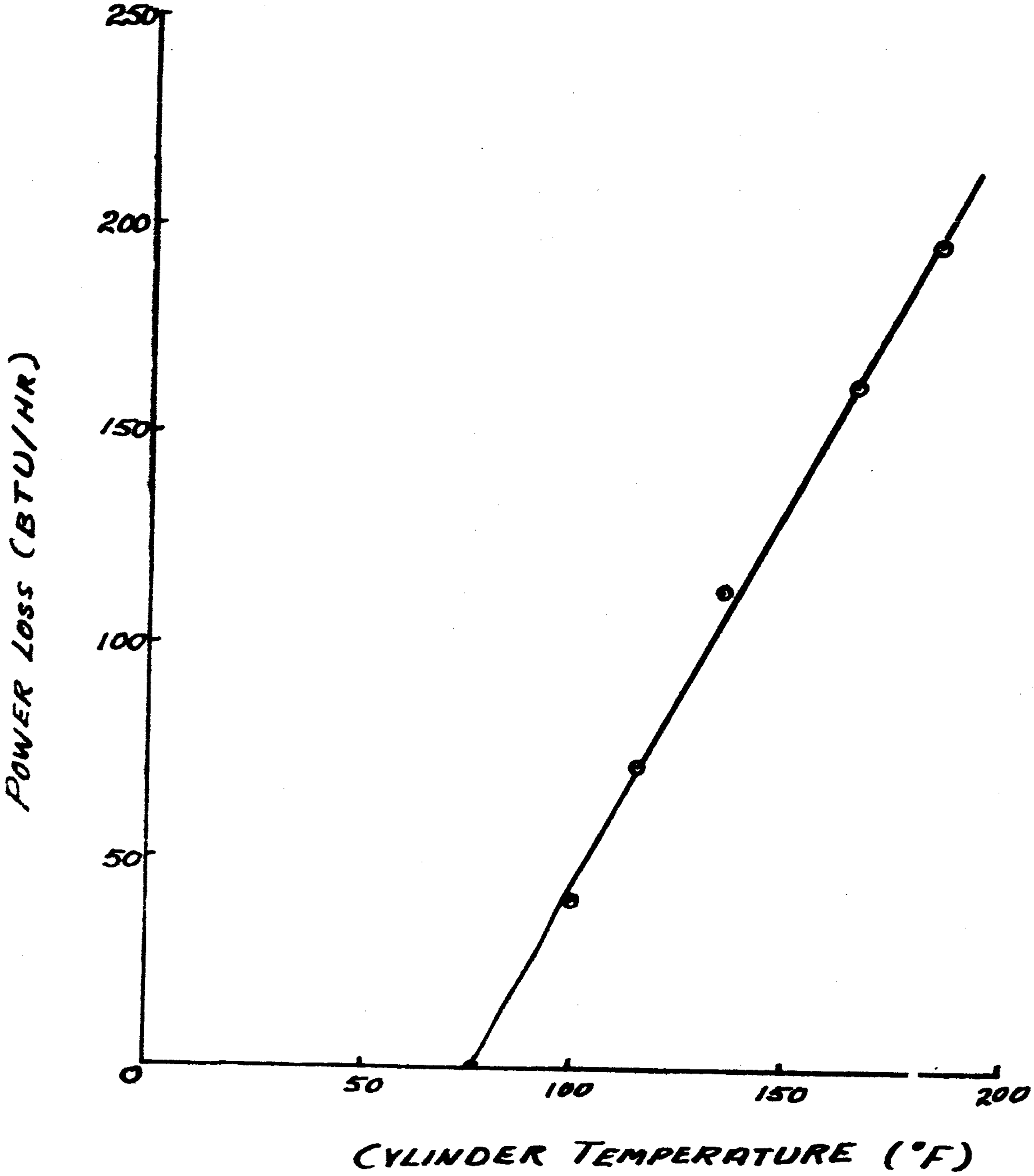


Figure 4.3 - POWER LOSS TO SURROUNDINGS

installed and the washer was compressed to a predetermined gap at its outer edge and the power input was increased in steps up to and beyond the point at which control begins. The temperatures in the cylinder were recorded after steady state was reached at each power setting. The initial gap depended on the allowable change in temperature before the surface was to close (make contact). This was estimated by knowing the length, coefficient of expansion, and the difference between the original temperature and the control temperature.

$$\Delta L = \beta L \Delta T \tag{4-1}$$

4.2 RESULTS -

The results of the two experiments done to date are illustrated in Figure 4.4 which is a plot of the power input (subtracting the losses) versus the temperature of the cylinder at the upper thermocouple and another curve for the lower thermocouple. This was done for two temperature levels. The control device seems to be working better at the higher temperature. The control action can best be seen by looking at the curves for the 200°F control. For example, if one looks at the results of plotting the power input against the upper thermocouple at 200°F one can see that somewhere about 180°F, dq/dt increases markedly which is an indication that the gap has closed and that there is more surface available for transferring heat. The upper limit of the control device was not reached in this experi-

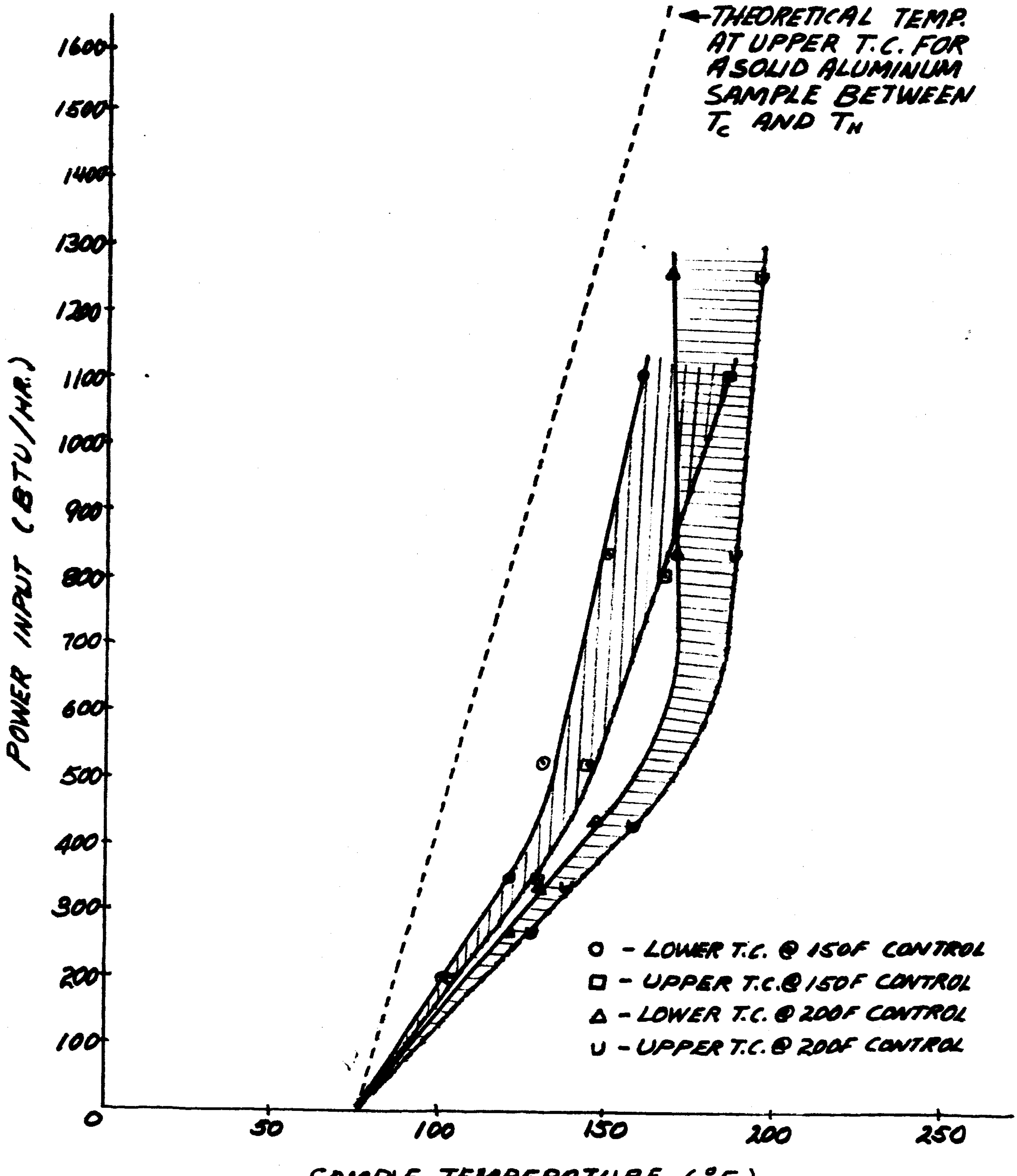


Figure 4.4 - TEMPERATURE CONTROL

ment primarily because the capacity of the heater was reached and the experiment had to be stopped to prevent burnout. At the point where the control device was working (referring to the same upper thermocouple curve) the heat transfer rate ranged from about 600 to 1200 Btu/hr with a change of about 5°F. The effective contact conductance coefficient as a function of cylinder temperature as recorded by the upper thermocouple is shown in Figure 4.5

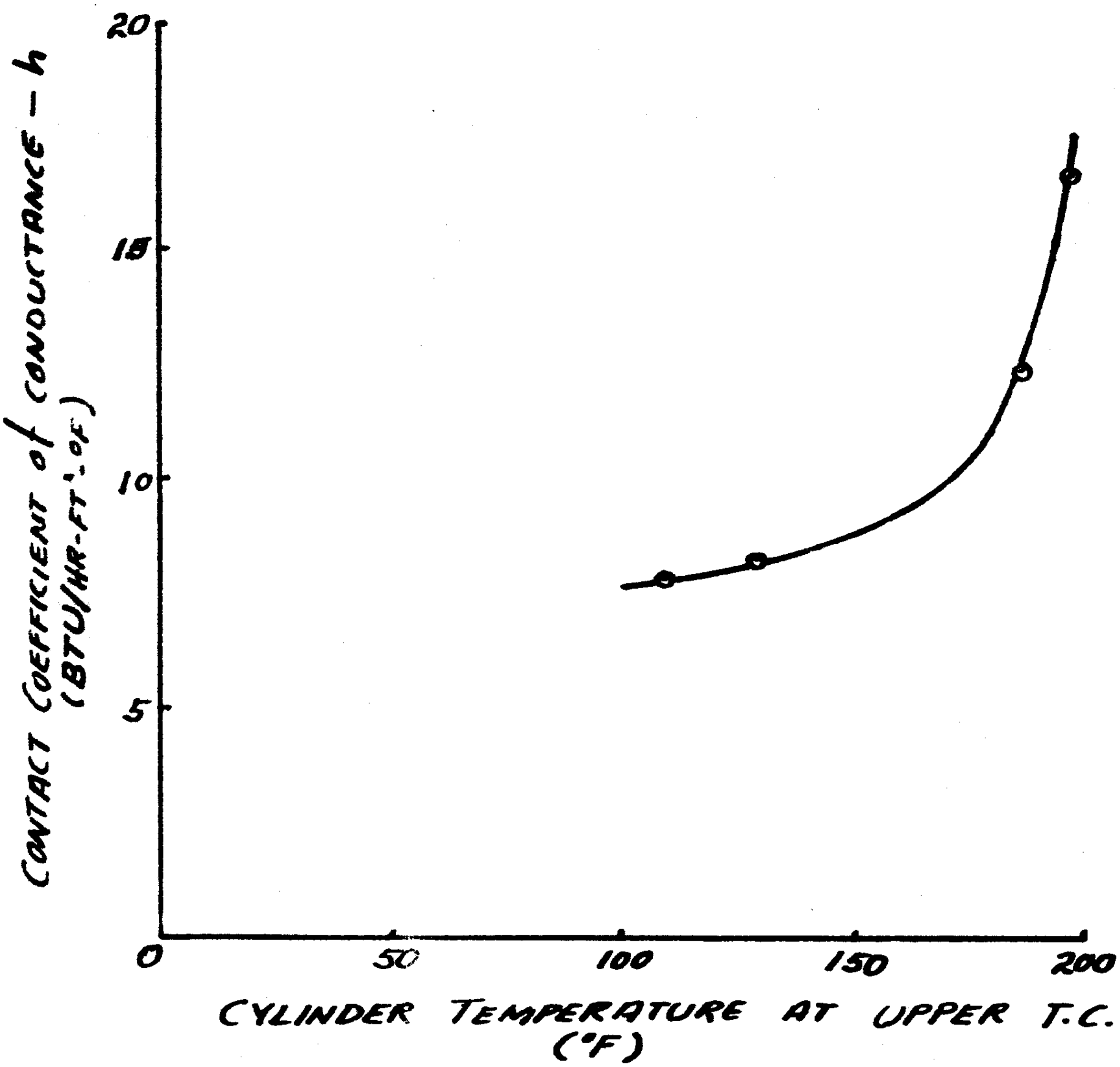


Figure 4.5 - VARIATION OF CONTACT CONDUCTANCE WITH CYLINDER TEMPERATURE

5. PERSONNEL

Harold A. Blum, Principal Investigator, Professor of Mechanical Engineering.

Clifford J. Moore, Jr., Graduate Student, expected to complete studies for Ph.D. by September, 1966.

Lenox Carruth, Graduate Student, Ph.D. studies in progress.

David Williams, Graduate Student, expected to complete studies toward master's degree in September, 1966.

Frank A. Fitz, Undergraduate Student, working on special problem (in connection with control) as senior project.

John Hutchison, Undergraduate Student, senior project (Contact Conductance Standards).

Thomas Ashley, Undergraduate Student, technician for project.

Robert Ashley, Undergraduate Student, technician for project.

Willa Bates, part-time secretary.

Starting in Fall, 1966 Messrs. J. V. Kenny and John Haessly will be part-time research assistants. They will be working toward their master's degrees. Mr. Virgil Robinson, a Ph.D. student, will start his dissertation work in the area of contact conductance.

In the last several months we have had the invaluable help of Professor Kenneth Heizer who designed the electronics for the force system and helped supervise the testing of it.