APPENDIX I

AN INVESTIGATION OF THE BEHAVIOR OF A PASSIVE HEAT TRANSFER CONTROL DEVICE

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TABLE OF CONTENTS

CONCLUSIONS

The average temperature at which a device of this type will control can be predicted with accuracy, and the device will control temperature within a reasonable range of power inputs. The thermal conductance behavior of the conical washer appears to be ideal for this application with the exception of the relatively high initial leakage through the circular contact points.

Additional investigation is necessary to determine the control's upper limits and its feasibility as a small package without framework, dependent on the difference in thermal expansion of two metals.

This investigation is concerned with the problem of maintaining a predetermined temperature in the near vicinity of a variable source of thermal energy. A typical situation where need for such a control exists is a solid state power circuit which generates a fairly large amount of heat, dependent on power requirements, and whose stability is temperature dependent.

The use of the thermal expansion properties of metals to actuate a direct control device was introduced in the Semi-Annual Report, NASA Grant NsG-711/44-07-004.[1] The concept at that time involved two rigidly placed thermal conductors with a small gap or gaps at their interface and a heat source and heat sink as shown in Figure 1. This idea was considered and modified for the following reasons.

1. Extremely high contact pressures would be required to obtain significant deformation of such a gap.
2. Operation without yielding in the material appeared unlikely.
3. The assumptions involved in prediction of the deformation of the gap blocked reasonable theoretical analysis of the problem.

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[1] Heat Transfer Across Surfaces in Contact: Practical Effects of Transient Temperature and Pressure Environments, April 1, 1965, to October 1, 1965, pp 2, 7

Various geometric shapes were then considered to act as intermediate control elements between the expanding metal adjacent to the heat source, and the heat sink. Consideration involved two primary criteria, variability of contact area and ease of fabrication. A conical washer was chosen as the intermediate element for this study because of its highly predictable behavior under load, extremely large changes in contact area possible and ease of manufacture.

The model used in this investigation is as described in Figure 2, consisting of a rigid framework and active elements mounted as shown. The active elements are:

1. A threaded adjustable head containing a heat source of Ni-Chrome wire operated by 60 cycle alternating current and capable of a maximum output of approximately 2,000 BTU/hr at 110 volts rms.
2. A 5 1/2 inch long, 3 inch diameter solid cylinder of 6061 T6 aluminum to provide vertical motion and force as a result of thermal expansion.
3. A 3 inch outside diameter, 1 inch inside diameter conical washer with 0.018 inches dish from inner diameter to outer diameter and a thickness of 0.100 inch.
4. A 3 1/2 inch diameter, 0.75 inch thick heat sink with an internal labyrinth to provide efficient heat transfer to the cooling water.

Heat input to the system is varied by controlling the heater power with a variable transformer. The voltage drop across the heater is monitored and used to calculate the power dissipated by the known resistance of the heater.

The temperature of the heat sink is kept essentially constant by using a large flow of tap water as the coolant. Heat sink temperature is monitored by periodic measurement of inlet temperature, outlet temperature and one sensing point on the sink itself to insure that the flow is sufficient to keep the sink at the same temperature throughout a control period.

The above described model control is used as the basis for predictions of control temperature as a function of the preload, or initial gap at the outer edge of the conical washer with all elements of the control at some known temperature. Heat "leakage" through the two rings of contact at the washer prior to full compression controls heat flow before the control point is reached. Contact conductance between the annular area of the washer and the hot cylinder and the heat sink governs temperature of the aluminum cylinder after full compression of the washer is accomplished.

Experimentation consists of two simple data gathering procedures. First, the heat sink is replaced by a thermal insulator of high compressive strength, a glass fibre reinforced resin block. Power input is recorded for a succession of steady-state temperatures to determine the system's losses to its surroundings as a function of column temperature.

Second, the heat sink is replaced below the washer and the washer compressed to a predetermined gap at its outer edge. Power input is increased in steps up to and beyond the control point and temperatures in the cylinder are recorded after steady state conditions are reached at each power setting.

The initial gap required to achieve control at any temperature is easily determined when the coefficient of thermal expansion of the main cylinder and the initial temperature of the system are known. The change in length, or gap, is formulated as:

$$L_2 - L_1 = \alpha L(T_2 - T_1)$$

α = Coefficient of thermal expansion

L = Length of main cylinder

T = Average temperature of main cylinder

This results in an average temperature within the cylinder equal to the control temperature at power inputs equal to or greater than those required to overcome losses to the surroundings plus the leakage through the initial circular contacts at the washer.

Heat flow at the initial circular contacts and through the annular contact areas of the washer after full deflection is not analyzed, since there is no data available on the thermal behavior of a metal interface with non-uniform contact pressure, or of a circular line contact.

Loss runs at temperatures between 75F and 200F as described above, result in a straight line when power input is plotted vs sample temperature, Figure 3, indicating no significant radiation losses at these temperatures. This loss data is used in reducing the data recorded in control runs. During the loss runs, equilibrium is assumed to be attained when there is no discernable temperature difference between the upper and lower thermocouples in the main cylinder and when there is no noticeable change in their value for a period of 15 minutes.

Results of two control runs, one designed to control at an average cylinder temperature of 150F, the other at 185F, show a positive temperature control, especially the higher temperature run. Power input, taking into account losses, vs average cylinder temperature is shown in Figure 4. Control is probably less pronounced in the lower temperature run due to the proximity of the data points to the straight line representing the thermal conductivity of the aluminum used for the active elements of the control. In the high temperature run, control appears to have been achieved well within 5F of the average cylinder temperature predicted.

Temperature distribution within the elements of the control for four data points of the 185F run (figure 5) indicates the temperature discontinuity across the washer as a function of temperature. A contact coefficient of thermal conduction, h, defined by the equation

$$q = hA\ T$$

q = Heat conducted per unit time

A = Contact area

T = Temperature discontinuity across the contact

is assumed for each face of the conical washer; in addition, the coefficients for the two faces are assumed equal. The discontinuities across the washer found above enable h to be shown as a function of the cylinder temperature (Figure 6). Before control temperature is reached, h is an indication of the leakage through the washer's two circular contacts and remains very nearly constant. Beyond the control point, the contact conductance increases very rapidly, doubling its value during this run.

A third control run determines the characteristics of the control during cyclic operation. Control temperature for the run is 200F. Power throughput vs average cylinder temperature is shown in Figure 7. Hysteresis is evident as surface asperities are reduced; however, after the first heat input reduction, cylinder temperatures remain within a few degrees of 190F as heat input varies.

RIGIDLY PLACED CONDUCTORS IN CONTACT

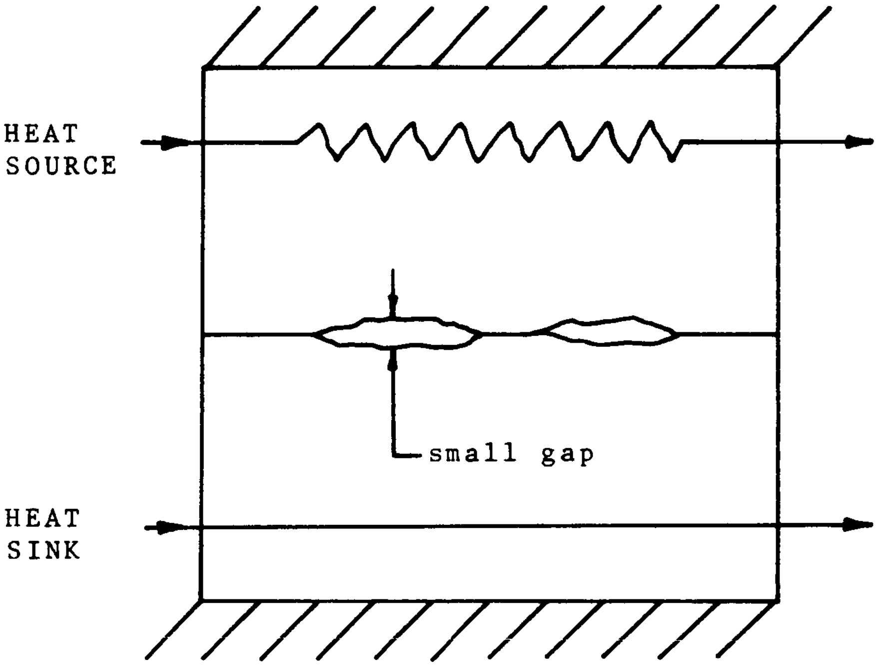
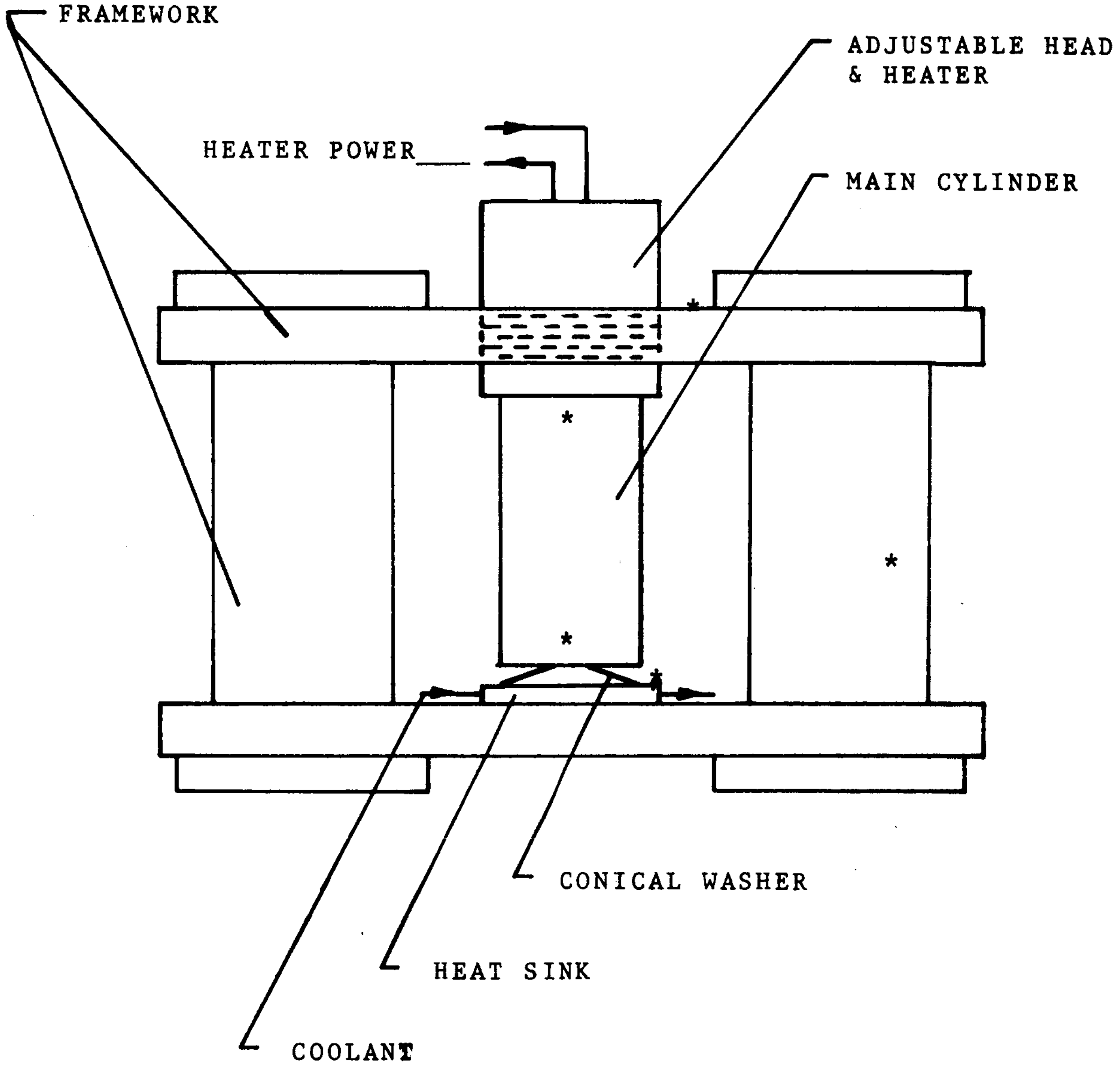


FIGURE 1 - PASSIVE CONTROL DEVICE



* Thermocouple Locations

FIGURE 2 - SCHEMATIC OF CONTROL MODEL

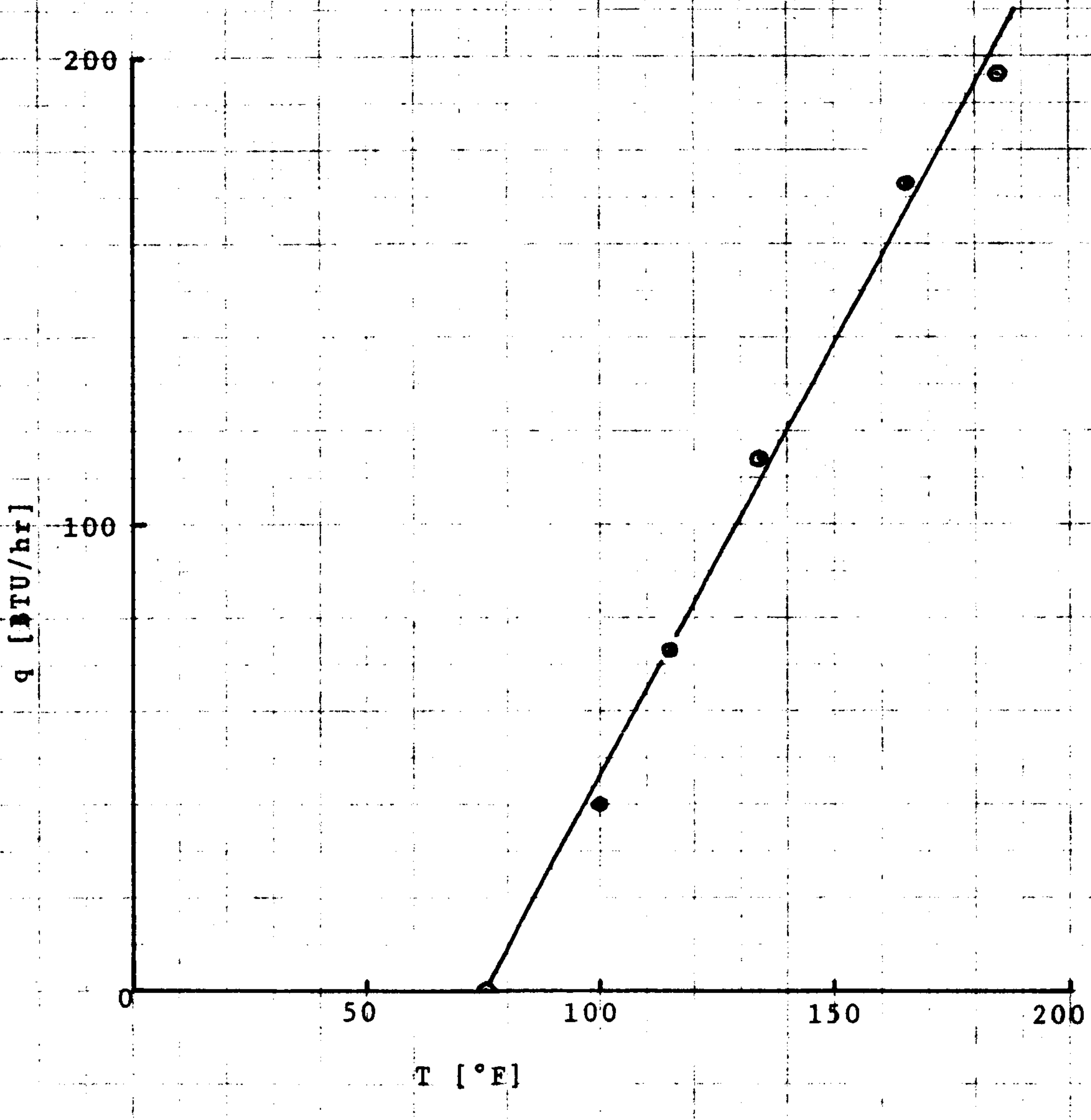


FIGURE 3 - HEAT INPUT vs CYLINDER TEMPERATURE (losses)

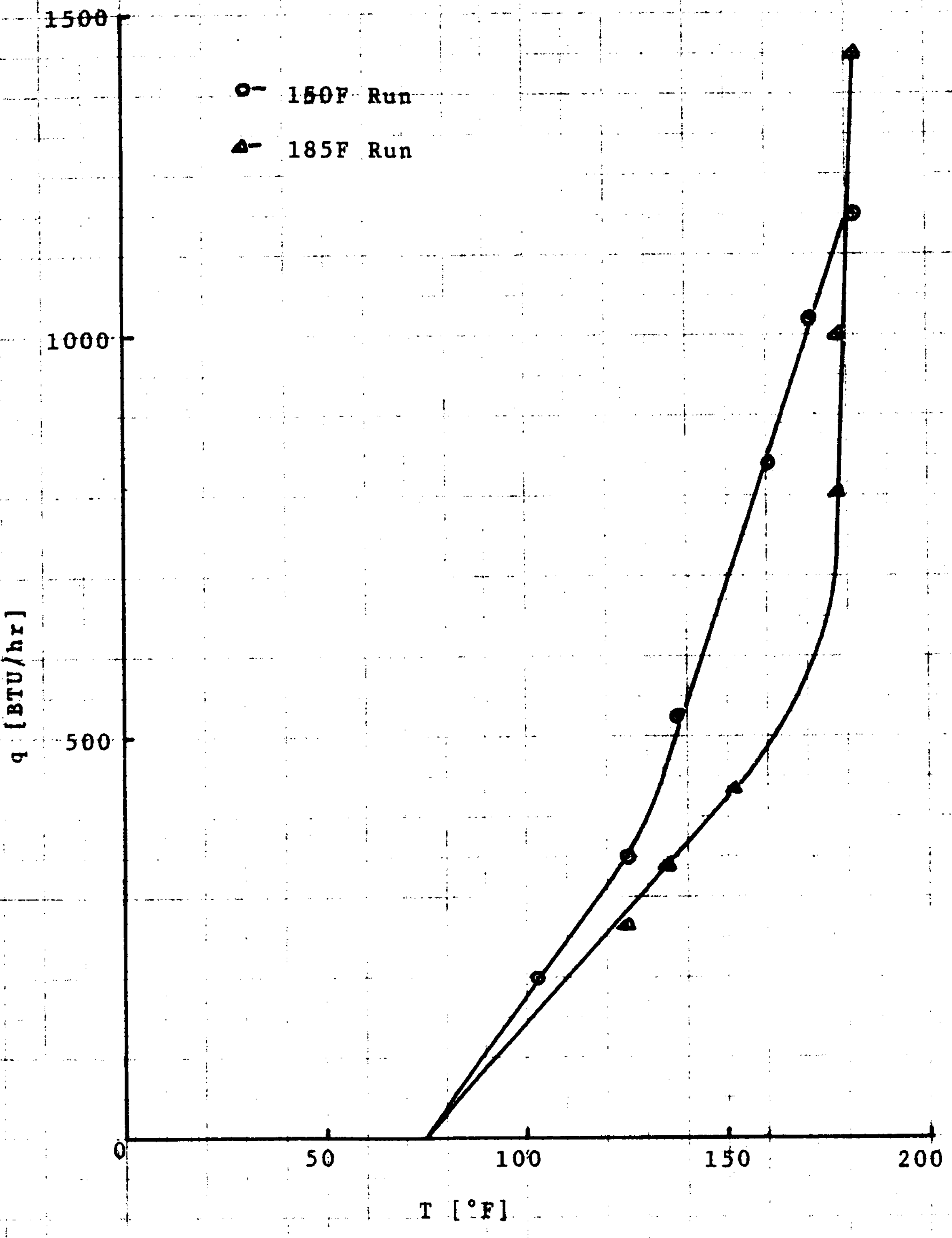


FIGURE 4 - HEAT THROUGHPUT vs AVERAGE CYLINDER TEMPERATURE

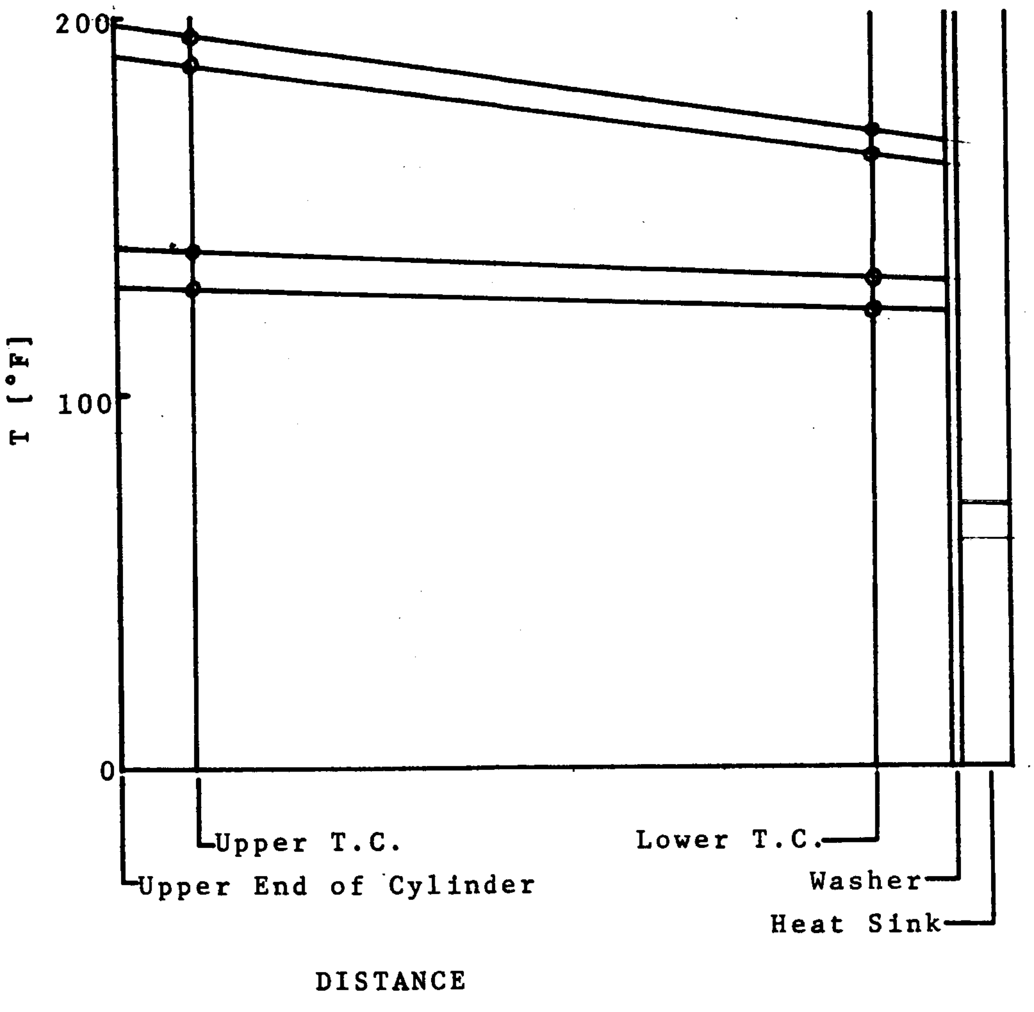


FIGURE 5 - TEMPERATURE DISTRIBUTION

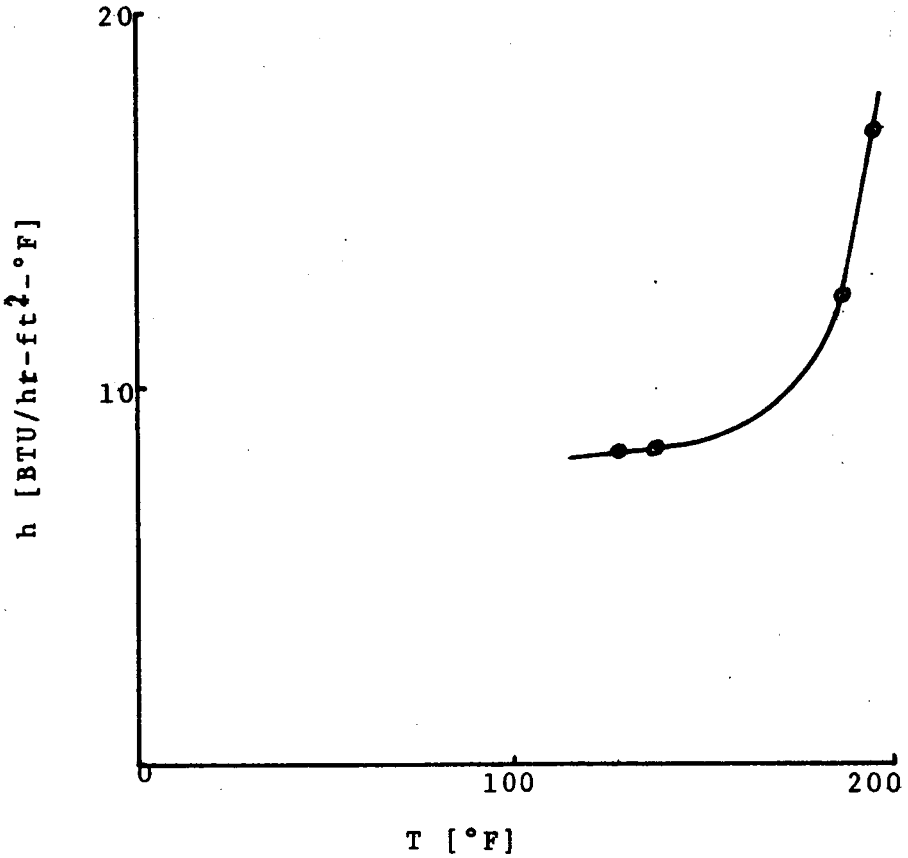


FIGURE 6 - COEFFICIENT OF CONDUCTANCE vs TEMPERATURE

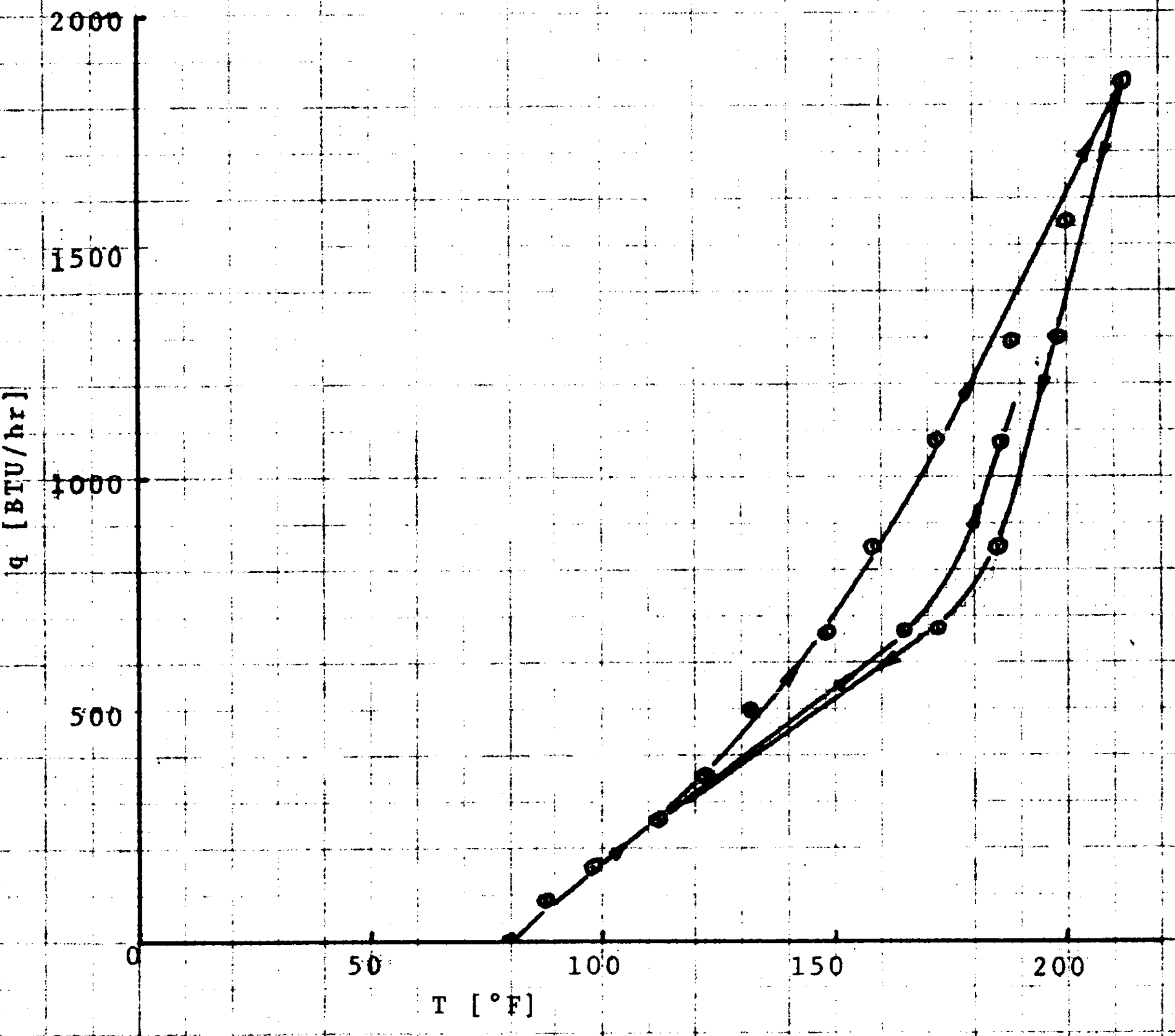


FIGURE 7 - HEAT THROUGHPUT vs AVERAGE CYLINDER TEMPERATURE