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INVESTIGATION OF VORTEX COOLING FOR WEAPON APPLICATIONS

TECHNICAL REPORT

Ronald B. Nelson

June 1972

RESEARCH DIRECTORATE

WEAPONS LABORATORY AT ROCK ISLAND

RESEARCH, DEVELOPMENT AND ENGINEERING DIRECTORATE

U. S. ARMY WEAPONS COMMAND

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13. ABSTRACT

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An earlier In-House Laboratory Independent Research investigation of the feasibility of using vortex cooling for gun barrels was extended by the Research Directorate of the Weapons Laboratory at Rock Island. Earlier experimental data for the convection heat transfer coefficient of a vortex tube in cooling steel rods arranged coaxially with and internal to the vortex tube are verified for a full-scale device. The potential of this concept for transferring surface heat fluxes of the magnitude encountered in a typical weapon from a cylindrical surface is demonstrated.

CONTENTS

OBJECTIVE

The objective of this project was (1) to continue an earlier investigation of the feasibility of using vortex cooling for gun barrels by verification that heat transfer coefficients measured earlier for a small vortex tube could also be achieved in a full-scale device, and (2) to demonstrate adequate cooling of a simulated gun barrel during sustained fire operation.

INTRODUCTION

In an earlier report, heat transfer coefficients were obtained for a small commercial vortex tube in cooling heated rods arranged internally to and coaxially with the vortex tube.[1] The rods were heated electrically, and 0.125, 0.25, and 0.50 inch diameter rods were used in the convection coefficient measurements. Although the values for the convection coefficient obtained in the earlier effort were not as large as had been indicated elsewhere,[2] they were significantly larger than values usually encountered in forced air convection. Also, the earlier work indicated that vortex cooling might well be adequate for cooling gun barrels to preclude excessive barrel erosion at typical firing rates currently used.

In the earlier portion of this feasibility investigation, metal rods were heated by an electric current through a section of the rod which was also cooled by the vortex column of the vortex tube. While this technique afforded a convenient means of monitoring the heating energy supplied, the electrical resistance of the rods was quite low, with the result that inconveniently large currents were required to generate the higher heat flux levels of interest. The earlier investigation was, therefore, necessarily limited to heat flux levels significantly smaller than those representative of sustained fire operation in typical automatic weapons. Consequently, the work described here was undertaken to verify the earlier data for a full-scale vortex flow device and to demonstrate the capability for adequate cooling of a simulated gun barrel subjected to heat flux levels representative of sustained fire operation in automatic weapons.

THEORY AND TECHNIQUES

The initial portion of this effort was focused on the verification that the convection transfer coefficients obtained with a small vortex tube could also be realized in a full size device. The approach used to verify the convection coefficients was similar to that used in the earlier work, where electrically heated tubes were positioned axially and concentrically within a forced vortex cooling column.

A commercially available vortex tube was used as the vortex cooling source. Pertinent aspects of the theory of this type of device, also known as a Ranque-Hilsch tube or Hilsch tube, are discussed in the earlier report and are not repeated here. The device employed for this project was a Vortec Corporation Model 454 vortex tube.

The vortex tube was procured with both the 250 CFM and the 500 CFM vortex generators. The length of this device is 53 inches measured from the cold exhaust to the hot exhaust throttling valve.

A 2-inch-diameter inlet is used, and the inner diameter of the vortex column section is approximately 2.125 inches. A 1.25-inch gate valve is used to throttle the hot exhaust. The vortex tube with the thermocouple monitoring instrumentation used for the the investigation is illustrated in Figure 1.

The tests made to measure the heat transfer coefficients were all conducted in the zero cold mass fraction operating configuration. The cold exhaust port of the vortex tube was removed and a flat plate was mated to the flange section of the device. The plate served both as an end wall for the device and as a mounting point for the heater configurations that were used in the measurements.

Separate diaphragms were supplied with the Vortec Model 454 for the 250 CFM and for the 500 CFM vortex generators. The 500 CFM diaphragm was used exclusively in the investigation since the restriction in the 250 CFM generator was too small to accommodate the heater apparatus that had to be inserted through the restriction In fact, the restriction had to be opened on the 500 CFM diaphragm to approximately 1.3 inches in diameter to facilitate tests with the heaters used.

The 500 CFM generator was used in all measurements reported herein. This was done after an initial test with the 0.750 inch heater revealed that significantly better cooling was obtained when the large size generator was used. Air obtained from a large compressor was filtered to remove particulates and oil, and used to supply the vortex tube. Inlet pressure at the vortex tube ranged from 82 to 88 psig The air supply flow rate was not measured, but was probably less than 500 CFM since this rating applies at 100 psig inlet conditions.

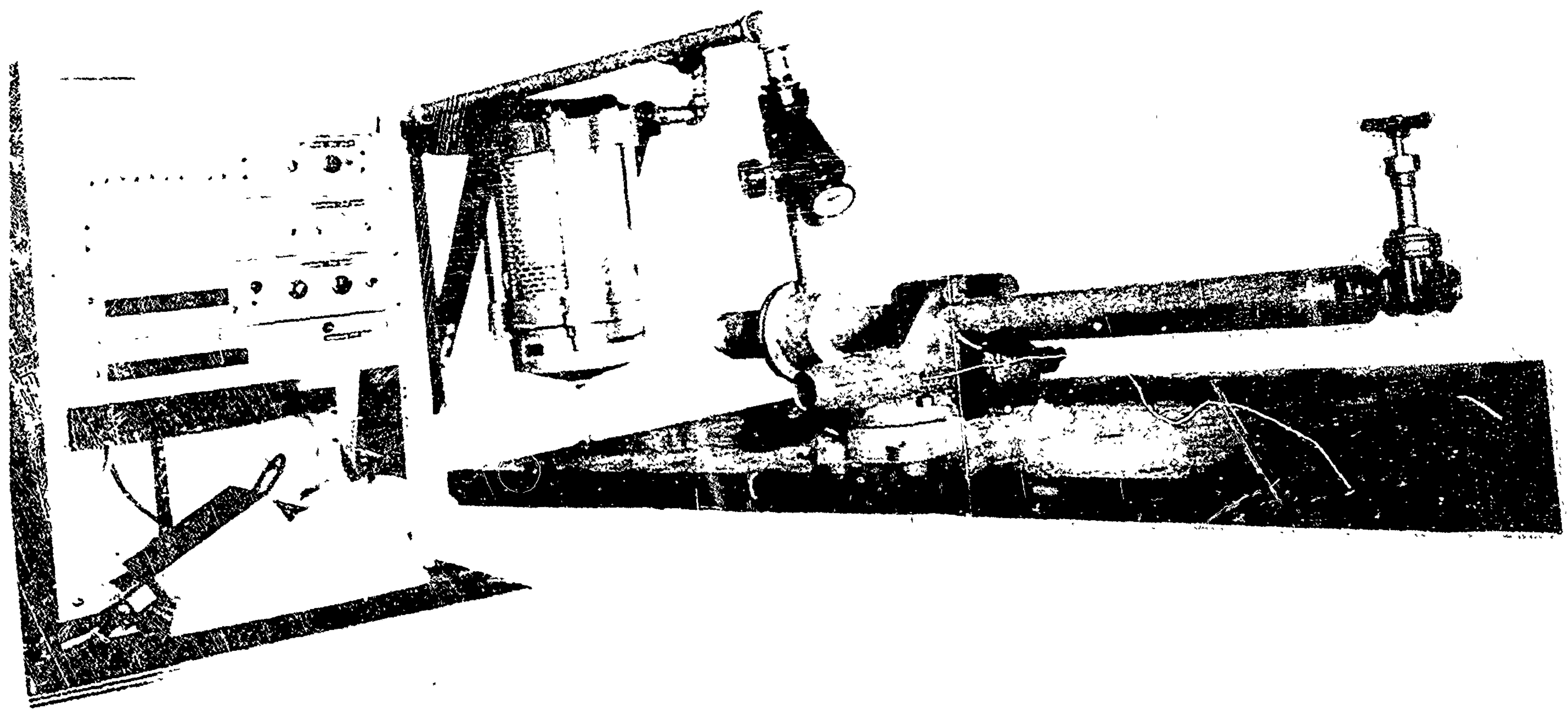

FIGURE 1 Vortex Tube with Thermocouple Monitoring Instrumentation

Because of the larger size of the Model 454 vortex tube relative to the Model 328 used in the earlier work, the length of the heated section of the test cylinder had to be limited to keep the heating power requirements within the limits of the facilities available. The electric heater used in the measurement of the heat transfer coefficients for the 0.75 inch and larger cylinders was rated at 2 kilowatts at 120 volts. This heater had a heated length of approximately 9.6 inches in an overall length of 10.5 inches with an outer diameter of 0.75 inch. For measurement of the heat transfer coefficient for the larger cylinder sizes, metal tubes of the desired diameter were fitted over the 0.75 inch diameter heater. This approach has the effect of reducing the surface heat flux emanating from the larger cylinder surfaces, but, this approach was used because heaters of the required configuration were unavailable when this work was accomplished. The 0.625 inch diameter heater used contained two 5.0 inch heating coils separated by about 0.25 inch in an overall length of 14.5 inches and had a 4.0 inch unheated section at the lead end of the heater

The brake (vane) assembly at the end of the vortex column was not modified and was left in place for all tests conducted. Slots were cut in one end of a metal cylinder approximately 0.84 inch in outer diameter to accommodate the vanes in the brake assembly The cylinder was then inserted axially into the brake assembly with the vanes sliding into the corresponding slots in the cylinder. The other end of the cylinder mated with the electric heaters used in the tests, and the cylinder-heater assembly was used in this manner to mount the electric heater along the axis of the vortex tube.

The amount of throttling provided by the throttling valve on the vortex tube was determined by a separate test With a 0.75-inch-diameter electric heater installed, the vortex tube was operated with the heater energized in the same configuration used in subsequent tests The amount of throttling was adjusted so that the maximum amount of cooling (as indicated by heater thermocouple temperatures) was obtained Since the amount of throttling required for optimum cooling with other heater configurations used was similarly determined to be essentially the same, this position of the throttling valve was used for all subsequent tests

Thermocouples were installed at selected points on the surfaces of the heated cylinders to measure the surface temperatures The thermocouples used had an outer sheath of Inconel 0.020 inch in outer diameter over iron and constantan wires 0.004 inch in diameter. To attach the thermocouples to the heated surfaces, the sheath was spot-welded to the surface and was reinforced with small strips of gauge stock 0.002-inch-thick. The reinforcement strips were necessary to prevent disattachment of the thermocouples from the heated surface because of the action of the vortex flow over the surface. The junction area was initially covered with the gauge material also, but this practice was discontinued when tests showed that significantly higher temperatures resulted from covered versus uncovered junctions under otherwise identical conditions. A typical heater configuration with thermocouples installed is shown in Figure 2.

The approach taken to estimate the heat transfer coefficients existing on the heated cylindrical surfaces was the same as that used in the earlier investigation.

The air was supplied to the vortex tube initially without the heater energized, and the equilibrium surface temperatures were recorded. Power was then supplied to the heater, and the new surface temperatures were recorded when thermal equilibrium appeared to be achieved. The surface temperatures under no-heat conditions were taken as the temperature of the cooling gas for the heated condition, and a resulting heat transfer coefficient was calculated for each point on the heated surface. Though this method of obtaining the local gas temperatures is obviously only approximate, its use will tend to provide conservative estimates of the heat transfer coefficient. Conduction heat transfer in the heaters in the axial direction was considered negligible in comparison with the heat transferred radially by convection and radiation. This assumption was found to be justified in the earlier work with metal tubes, and it should also be justifiable for the heaters used here, constructed of a thin metal sheath over metal oxide ceramic material.

The coefficients obtained by the procedure given above, are, therefore, for lumped radiation and convection heat transfer between the heated surface and the air or internal walls of the vortex tube. The temperature of the walls of the vortex tube were observed to be essentially at the temperature of the cooling air, which ranged between 73 and 80°F at the inlet. The calculated radiant heat flux transferred to the vortex tube interior walls as a function of heated surface temperatures for representative selected values of heated surface emissivity is shown in Figure 3. Assumptions implicit in the data of Figure 3 are that the inner heated surface "sees" only the vortex tube interior, that the interior surface is at 80°F, and that the emissivity of the interior walls is 0.2. For these conditions, in which

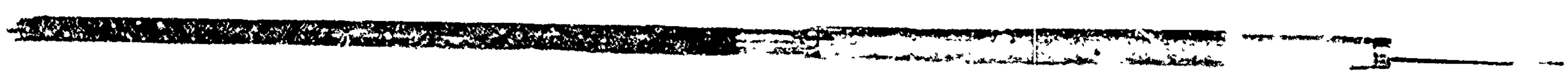

FIGURE 2 1.25 Inch Diameter Heated Cylinder Assembly

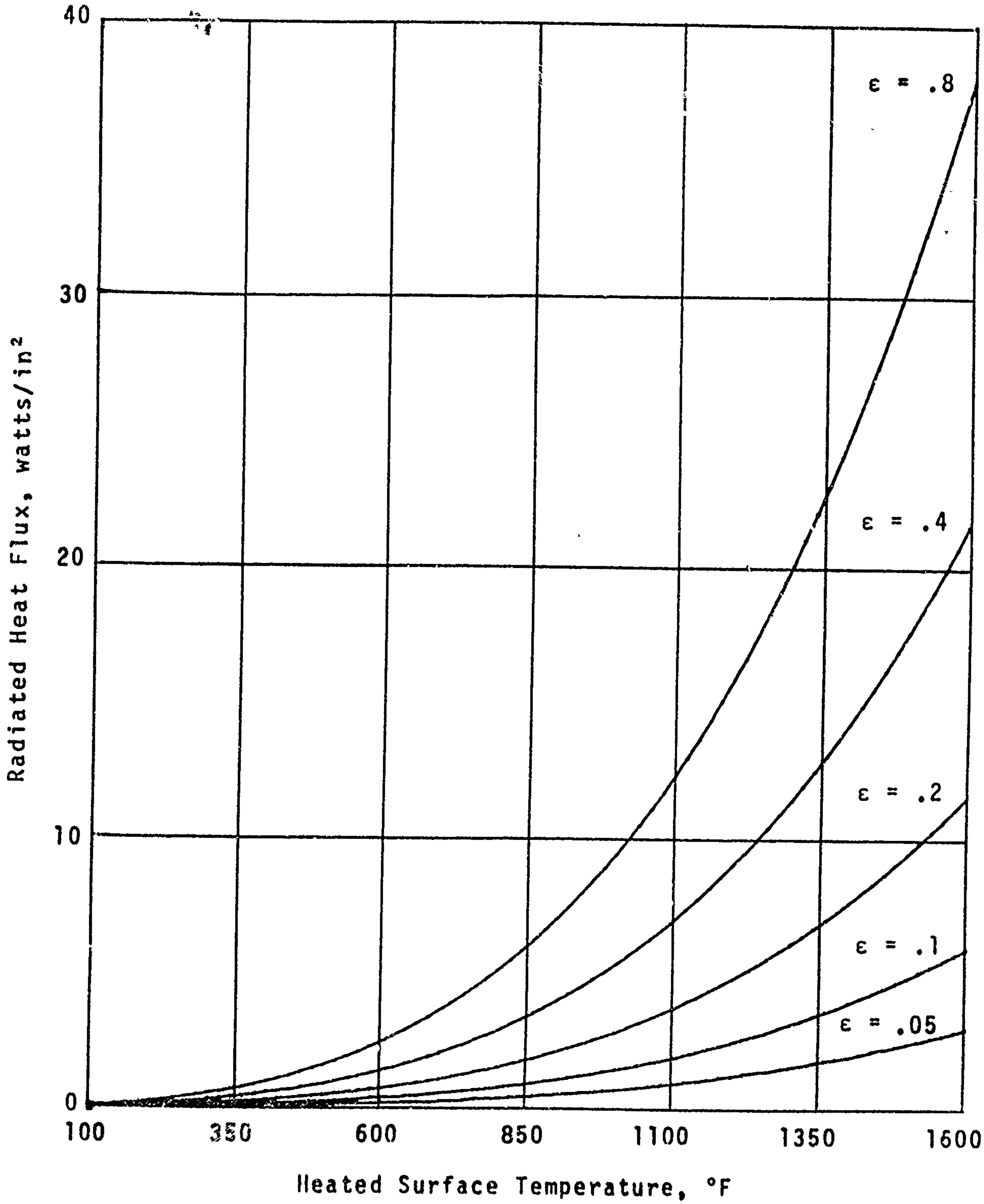

FIGURE 3 Radiated Heat Flux Versus Heater Surface Temperature

the highest surface temperature was less than 400°F, the radiated heat flux is at most about 2 BTU/hr-ft^2 which was typically a small fraction of the total heat flux levels used in the tests for calculation of heat transfer coefficients. On the basis of this observation and in consideration of the purposes of this work, the heat transfer from the heated surface was assumed to be entirely due to convection.

For determination of the total heat flux levels transferred, the electrical energy supplied and the heat generated in the heater were equated and the heat was assumed to be generated homogeneously along the heated length of the heater. In accordance with the assumptions discussed above, the radial heat flux at the heater surface was taken as the quotient of the supplied energy divided by the heated surface area

A secondary objective of this investigation was to demonstrate the capability of cooling a simulated gun barrel under sustained-fire operating conditions using vortex flow. Because of the limitations of the available equipment while this effort was conducted, the simulation had to be restricted to a heated cylindrical segment with heat flux comparable to that in an actual weapon.

An indication of the heat generation rates existing in automatic weapons was obtained by a review of data developed for the XM140. Hypothetical heat generation rates which would exist at thermal equilibrium at a point 31.5 inches from the breech in the XM140 barrel for various bore temperatures were calculated for a 400 round per minute firing rate. A plot of the approximate variation in heat flux at the external barrel surface with bore temperature under these conditions is shown in Figure 4. The expected increased heating rates in the barrel existing at lower bore temperatures are illustrated in the Figure.

The heat flux to be removed by a potential cooling concept at the exterior barrel surface for a given barrel geometry and firing rate during steady-state conditions is therefore primarily a function of the desired steady-state barrel operating temperatures. Under these conditions, the choice of barrel exterior surface operating temperature could conceivably be made on the basis of safety from catastrophic failure, or on the basis of elimination of excessive barrel wear, or on some other criterion. However, for weapon systems in which cooling is of interest, increased firing rates might also be reasonably expected so that the choice of heat load to be removed by a cooling concept is complicated further in this regard. For these reasons, the heat flux to be removed by a potential cooling

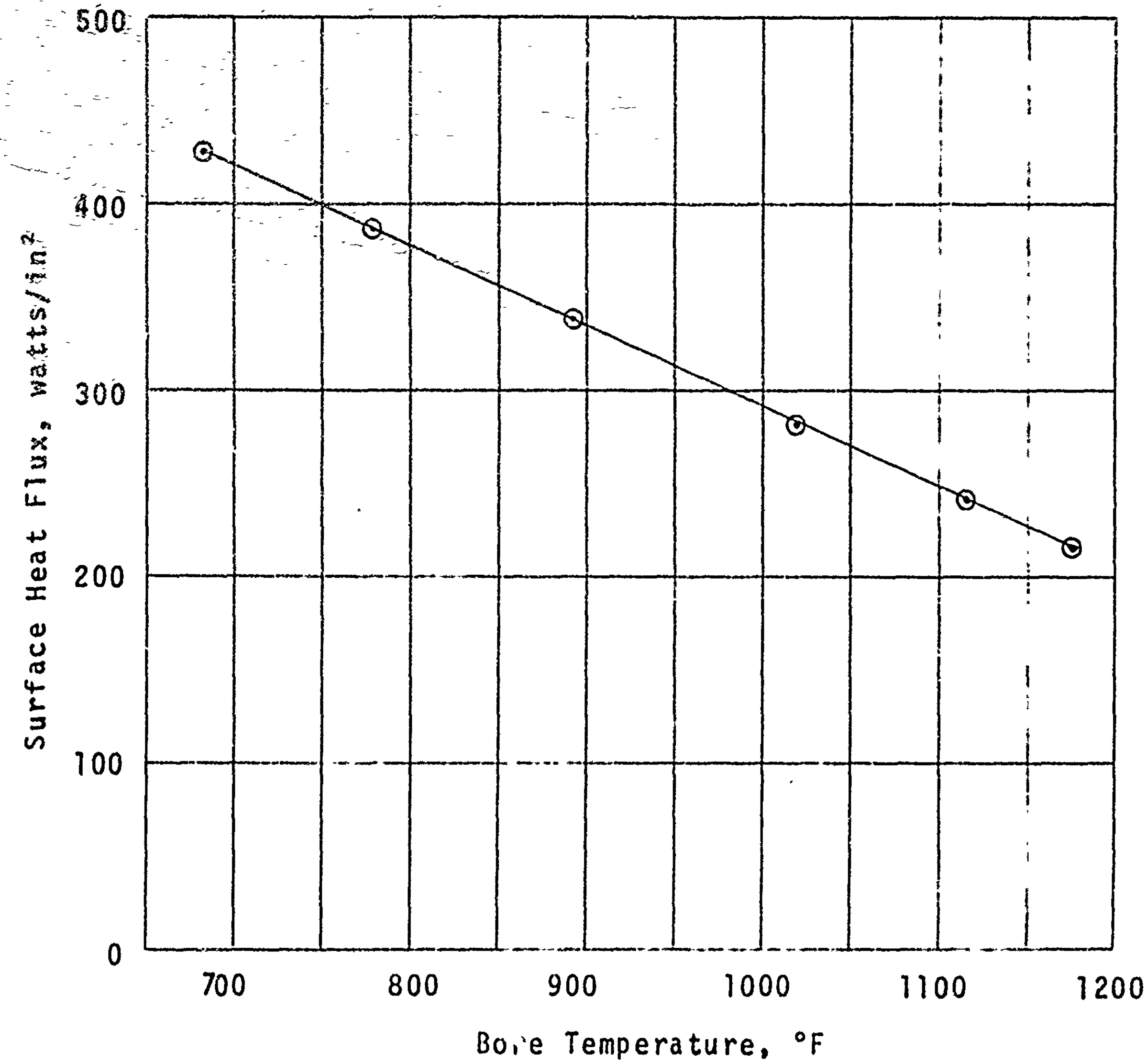

FIGURE 4 XM140 Barrel Surface Heat Flux Versus Bore Temperature

technique from future weapon systems cannot be generally determined and may be determined ultimately for a specific weapon design by the capabilities of the available cooling. The assumption can probably be made, however, that the heat flux to be removed from weapons in general will be at least of the magnitude of that emanating from the XM-140. Consequently, a heat flux of 200 to 300 watts/in^2 was set as a feasibility demonstration goal for the cooling capability of the vortex tube.

The only electrical heaters available to produce heat flux levels of this magnitude were 0.625 inch in outer diameter and 14.5 inches in length with a 10 inch heated section. These heaters had a rated capacity of 6 kilowatts at 480 volts, and provided a surface heat flux of about 295 watts/in^2 at the local power conditions.

RESULTS AND DISCUSSION

The data obtained for estimation of the heat transfer coefficient of the vortex tube in cooling the 0.625, 0.75, 1.0, and 1.25-inch outer diameter cylinders are shown respectively in Figures 5a, 6a, 7a, and 8a. In each figure, the lumped heat transfer coefficient estimated by the procedure described earlier is plotted for the thermocouple position shown in the lower accompanying figure.

Because of the approximations discussed earlier, the values for the coefficients shown should be regarded only as estimates.

The average magnitude of the coefficients is significantly larger for the 1.0 and 1.25 inch diameter cylinders than for the smaller cylinders. This effect was noticed in the earlier report also, where heated tubes 0.125, 0.250, and 0.50 inch in outer diameter were cooled in a vortex tube of approximately 0.7 inch in inner diameter. In that investigation, average values obtained for the heat transfer coefficient were about 45 BTU/hr-ft^2-°F for the smallest tube size, with values in excess of 100 BTU/hr-ft^2-°F being observed for both of the larger tube sizes. These values are in general agreement with the data of Figures 5a - 8a since the earlier heated tube sizes would scale to approximately 0.4, 0.8, and 1.6 inch diameters relative to the 2.125 inch inner diameter vortex tube used in this investigation.

A possible explanation for this trend is that, for the smaller cylinder diameters, a tendency toward a division of flow of the type described by Sibulkin for the more conventional

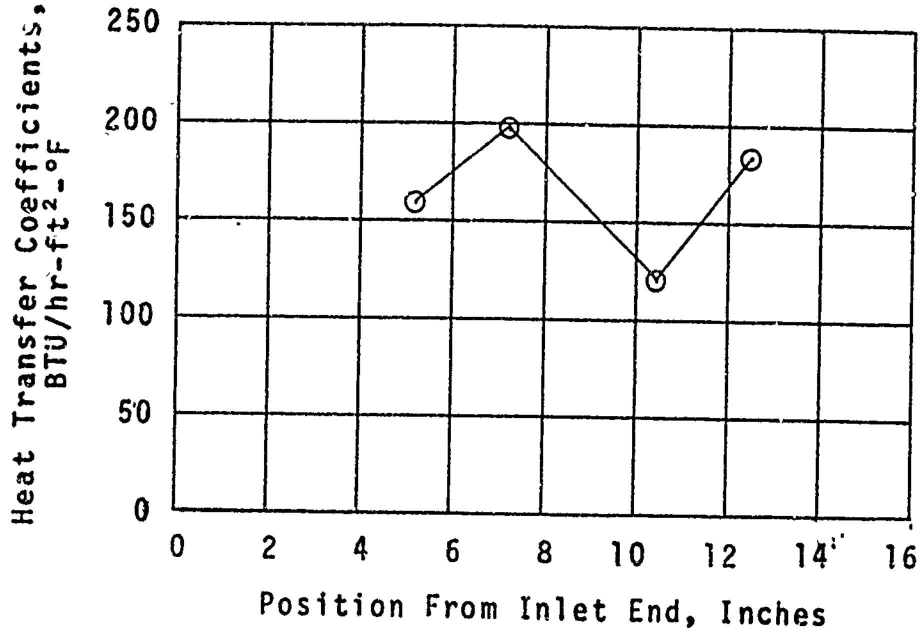

FIGURE 5a   Heat Transfer Coefficients for 0.625 Inch Cylinder

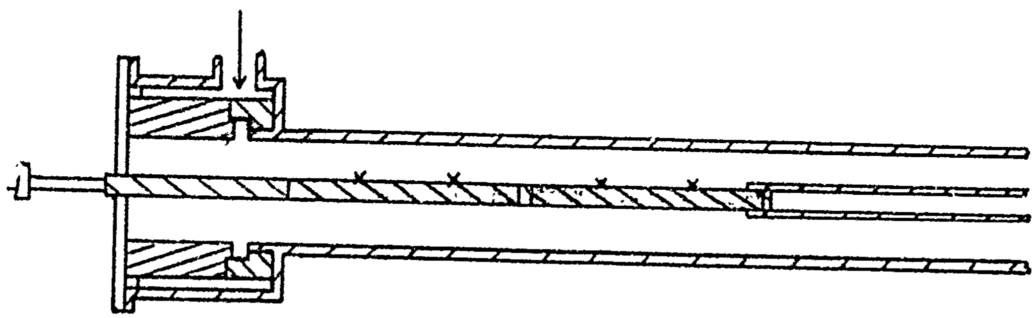

FIGURE 5b   Thermocouple Locations on 0.625 Inch Cylinder

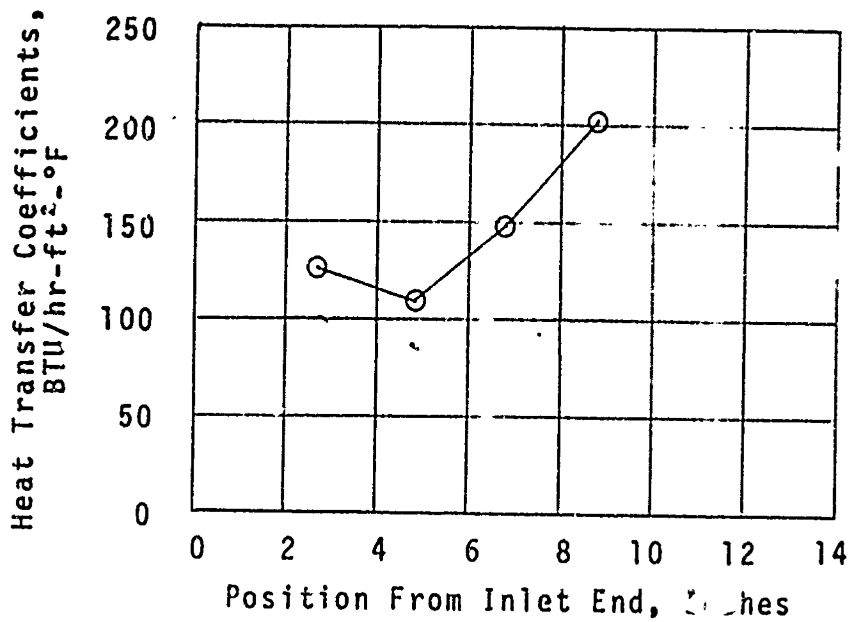

FIGURE 6a Heat Transfer Coefficients for 0.75 Inch Cylinder

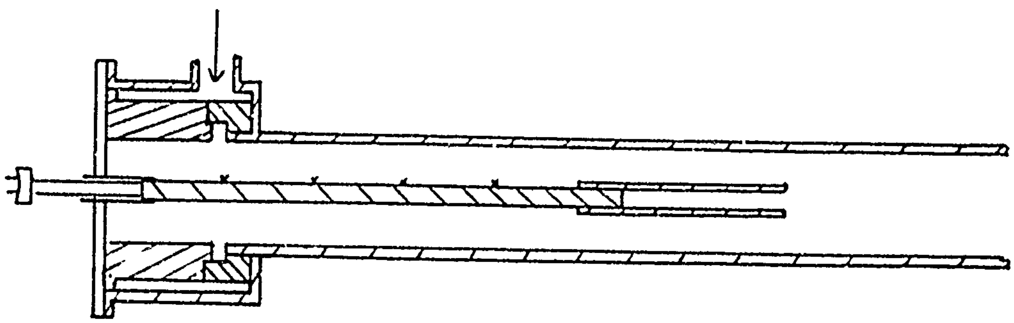

FIGURE 6b Thermocouple Locations on 0.75 Inch Cylinder

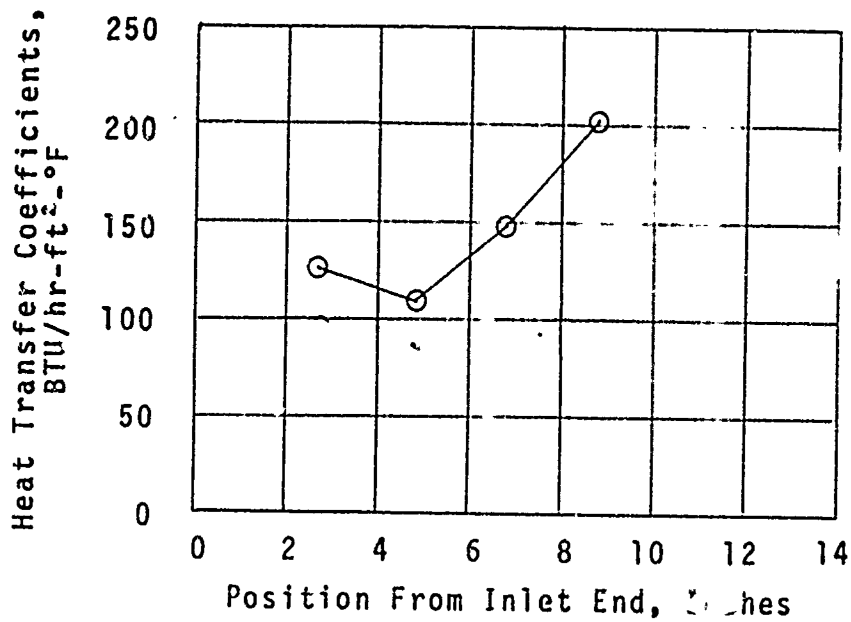

FIGURE 6a Heat Transfer Coefficients for 0.75 Inch Cylinder

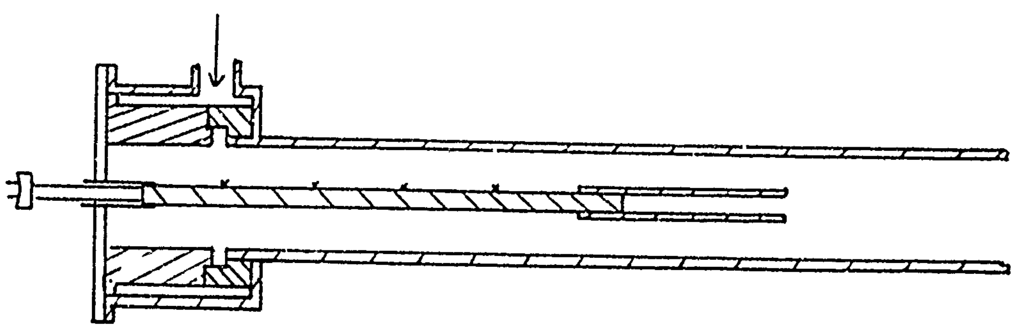

FIGURE 6b Thermocouple Locations on 0.75 Inch Cylinder

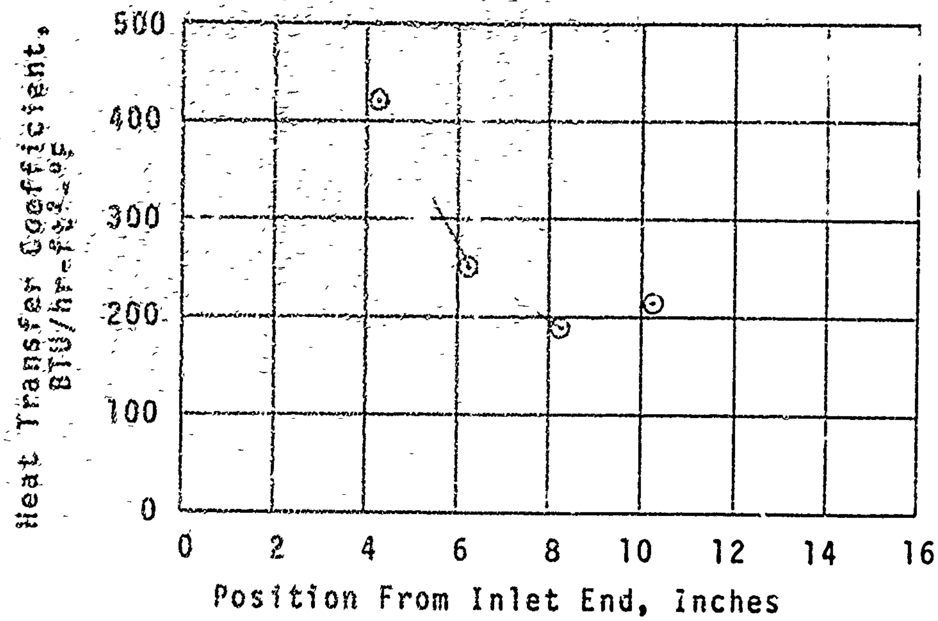

FIGURE 8a Heat Transfer Coefficients for 1.25 Inch Cylinder

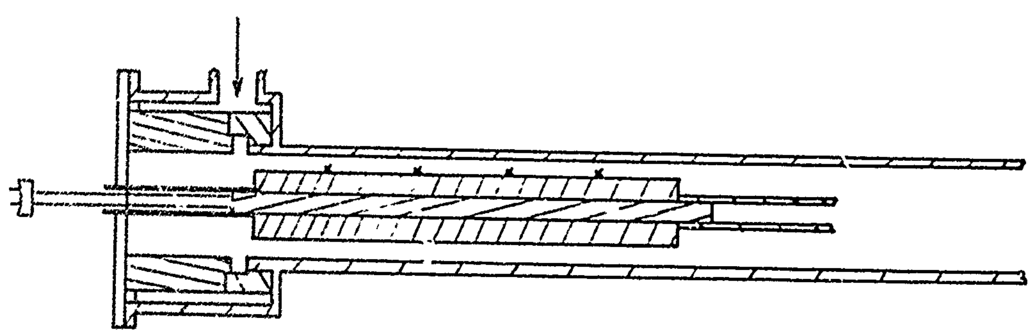

FIGURE 8b Thermocouple Locations on 1.25 Inch Cylinder

vortex tube operation exists.[3] This divided flow probably is not as likely to occur as the size of the annular region between heated cylinder and vortex tube wall decreases, as it does for the larger heated cylinders. Some basis for this explanation is provided by the fact that the gas temperatures measured in the absence of heating were significantly lower relative to inlet conditions for the smaller heated cylinder sizes.

Differences in the vortex flow patterns for the different heated cylinder sizes are also thought to be partly responsible for the lack of uniformity as to the positions of maximum and minimum relative heat transfer for the individual cylinders. End effects at the outer edges of the heated sections undoubtedly also contribute to this lack of uniformity, particularly for the larger cylinders.

The surface heat flux levels in the current measurements were respectively 17, 75, 55, and 45 watts/in^2 for the data in Figures 5-8. These flux levels resulted from the characteristics of the various heater configurations available, as no attempt was made to preselect the flux levels. The heat flux used in the measurements reported earlier ranged between 7 and 20 watts/in^2. Sensitivity of the apparent heat transfer coefficient to the heat flux level used in the measurements is not readily evident in the data over the range of heat flux values used in the measurements. A check was made on this possibility with the 0.75-inch-diameter cylinder at three heat flux levels using a variable transformer. The resulting data for the apparent heat transfer coefficient are shown in Figure 9, which further support the observation made above

The secondary objective of this project was to demonstrate the capability of adequate cooling on surfaces subjected to heat flux levels of the magnitude typical of high performance automatic weapons. In an attempt to accomplish this objective, the 0.625-inch diameter heaters used in the heat transfer coefficient tests were used in the same configuration shown in Figure 5b, but operated at 470 volts. Several tests were made because a considerable amount of experimental difficulty was experienced

In the initial test, a 0.625-inch hole was drilled through the axis of a 1.0-inch-diameter iron cylinder to form a sleeve to fit over the heater. The outer diameter of the heater was specified as 0.621± 002 by the supplier The drilled interior surface of the sleeve was not smooth, and the heater could be inserted into the sleeve with no interference This assembly was instrumented with thermocouples at positions directly over the heater coils on the outer sleeve surface and installed in

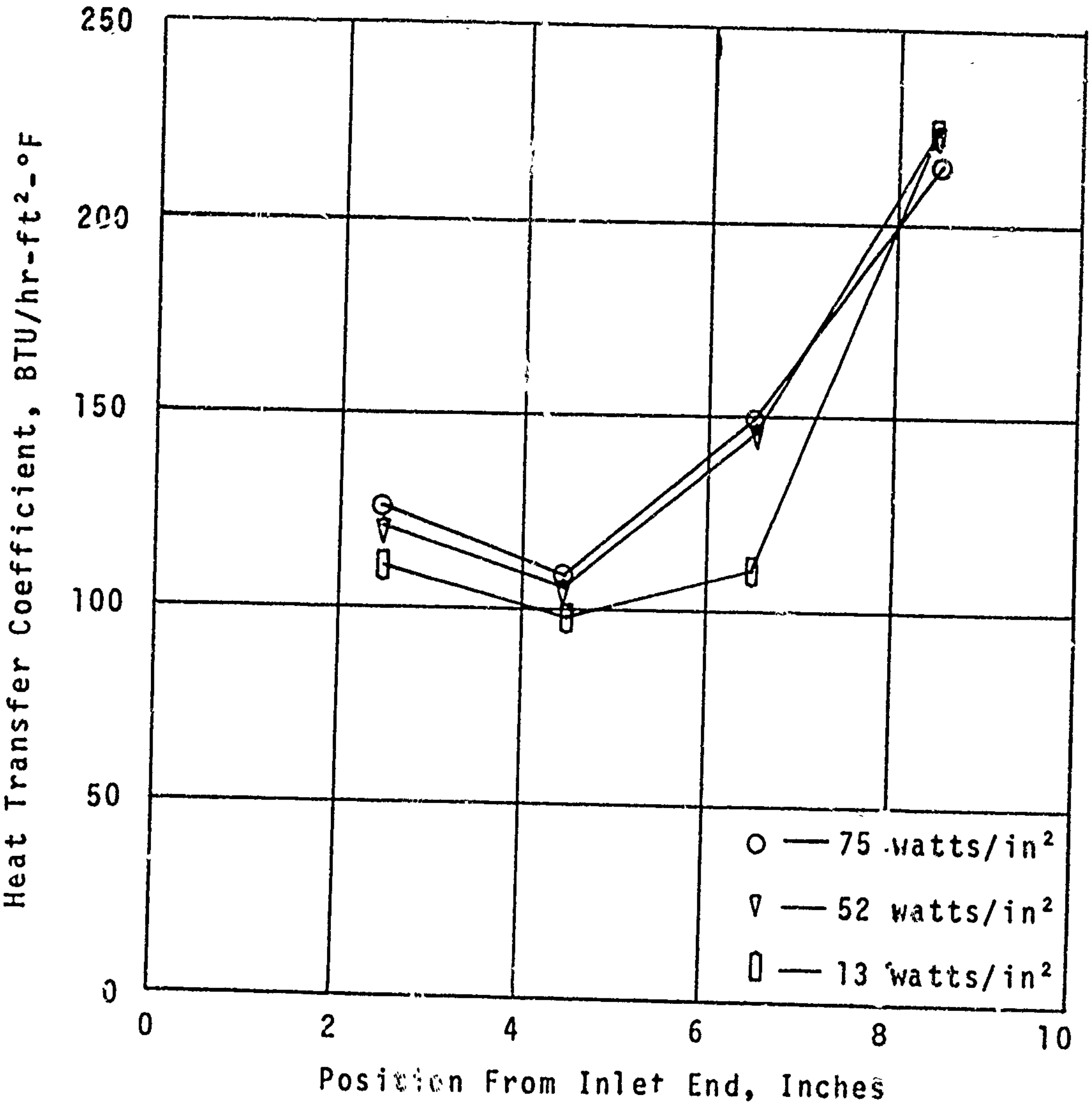

FIGURE 9 Heat Transfer Coefficient for 0.75 Inch Cylinder at Three Heat Flux Levels

the vortex tube in the same configuration used on the earlier tests with this heater. In the subsequent test, the heater was burned out before thermal equilibrium was reached. The maximum temperatures indicated on the outer surface of the sleeve were slightly less than 600°F. Since no means were readily available to improve the fit of a larger cylinder over the heater, this approach was abandoned.

In the next test, the 0.625-inch heater was installed in the vortex tube in the configuration shown in Figure 5b. Thermocouples were installed at points 1.5 inches in from the ends of each of the two 5.0 inch heating coils. During the course of this test, the heater became loose in the mounting assembly and all electrical leads were sheared as the heater rotated about its longitudinal axis under the action of the torque exerted by the vortex flow. A plot of the temperatures reached before the test was terminated is given in Figure 10

The heater was reinstalled, and the test was conducted again on two subsequent occasions in both cases, all thermocouples failed either intermittently or completely before thermal equilibrium had been reached However, on the basis of intermittent data from the latter tests and on extrapolation of the data in Figure 10, the equilibrium temperatures are estimated to have probably ranged between [illegible]100°F and 1400°F

At temperatures in the above range, radiation heat transfer is not obviously negligible The magnitude of the heat flux transferred by radiation under these conditions is estimated to lie between 12 and 25 watts/in^2 In this estimate, emissivities are assumed to be 0 2 for the aluminum vortex tube interior and 0.4 to 0 8 for the oxidized heater radiating surface In addition, approximations are made that the heater radiating surface "sees" only the interior of the vortex tube (at 100°F) and that the ratio of the heated surface area to the vortex tube interior surface area is of the order 0 [illegible]

Upon correction of the surface heat flux produced by the heater in the amounts of [illegible]0 watts/in for radiation transfer, the resulting apparent convection heat transfer coefficients would be in the range of 100 to 130 BTU/hr ft [illegible] F on the basis of the equilibrium surface temperature range estimated above This is roughly in agreement with the data of Figure 5a A significant increase in the cooling performance of the vortex tube would be expected for larger cylinders on the basis of the data of Figure 7a and 8a

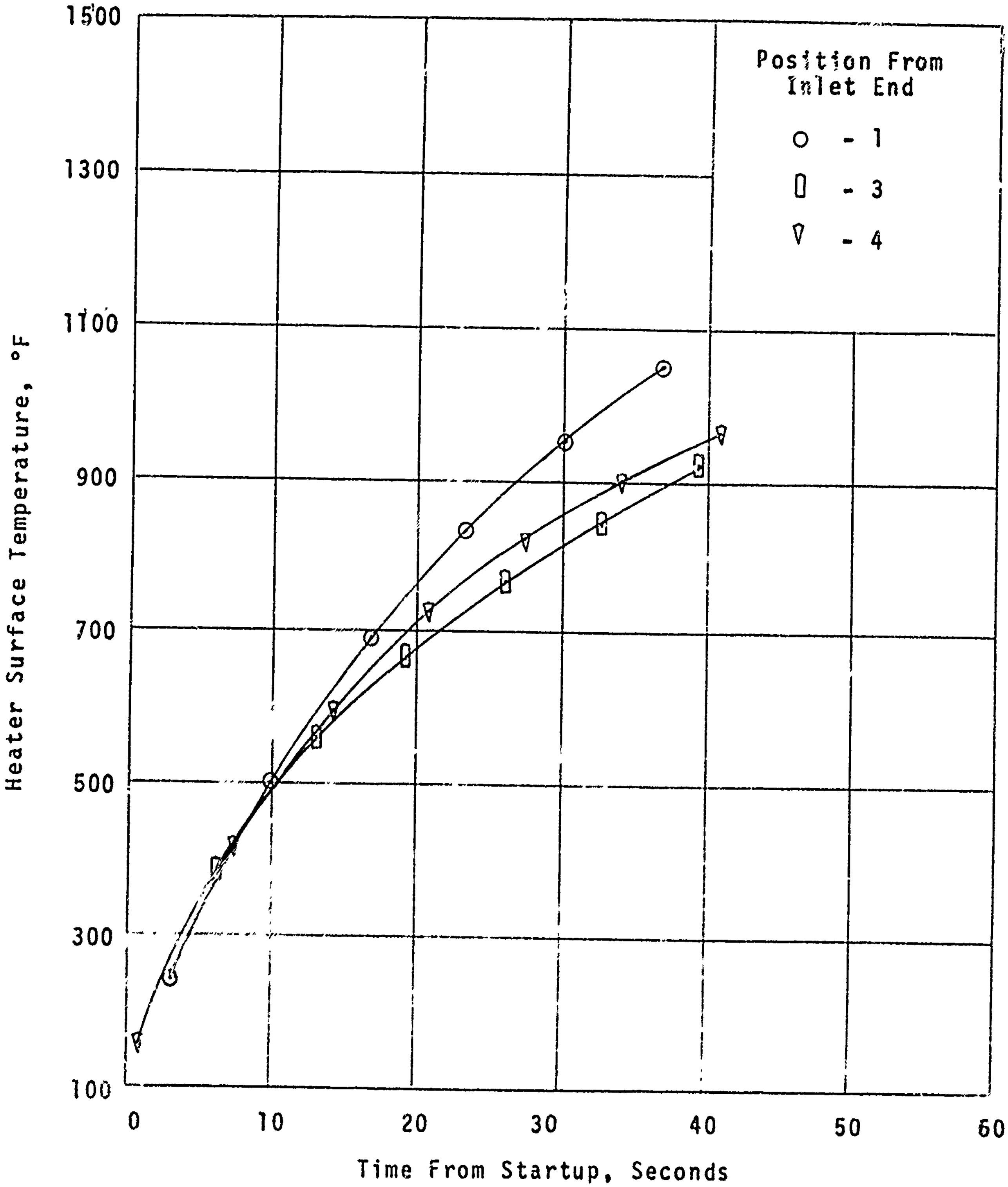

FIGURE 10 Thermocouple Temperature Versus Time

CONCLUSIONS AND RECOMMENDATIONS

The data presented in this report are in good general agreement with similar data for a smaller device reported earlier and support the earlier conclusion regarding the cooling capabilities of vortex flow. The concept appears to have potential applicability for cooling weapons such as the XM140.

Optimized configurations of vortex flow devices should be investigated relative to specific system design applications, particularly the effects of increased supply pressures. The choice of vortex air cooling for a particular system application should be based on the results of an analysis of the relative merits of this approach compared with other approaches with consideration given to system weight, cost, reliability, logistics, and cooling performance.

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