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RESEARCH MEMORANDUM

PRELIMINARY INVESTIGATION OF COOLING-AIR EJECTOR PERFORMANCE AT PRESSURE RATIOS FROM 1 TO 10

By C. W. Ellis, D. P. Hollister, and A. F. Sargent, Jr.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

PRELIMINARY INVESTIGATION OF COOLING-AIR EJECTOR PERFORMANCE AT PRESSURE RATIOS FROM 1 TO 10

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SUMMARY

A preliminary investigation was made of the performance of several cooling-air ejectors at primary jet pressure ratios from 1 to 10 and temperatures from 80° to 500° F. In order to determine the effectiveness of these ejectors, the cooling-air passage was blocked and the pressure drop in the ejector, which occurred when the primary pressure ratio and temperature were varied, was used as an indication of pumping ability. The thrust was also measured to determine the cost of this pumping in terms of jet thrust. The investigation was limited to conical shroud type ejectors with ratios of shroud to nozzle exit diameter from 1.10 to 1.58 for several ratios of the spacing between the exits to the primary jet nozzle exit diameter.

The results indicate that ejector thrust is a primary consideration in the proper selection of a cooling-air ejector inasmuch as a loss in jet thrust is incurred. This loss is a function of the minimum pressure obtained in the blocked cooling-air passage and increases as the cooling-air-passage pressure drops.

An increase in primary jet air temperature from 80° to 400° F had a detrimental effect on the pumping ability of ejectors having short spacings between the jet nozzle exit and the ejector shroud exit.

INTRODUCTION

The recent application of tail-pipe burning to turbojet engines and the expected use of ram-jet engines have greatly increased power plant operating temperatures and flight speeds of aircraft, which impose greater requirements on the cooling system over a wider range of operating conditions than without afterburning. Cooling requirements of turbojet engines without tail-pipe burning have been satisfied by the use of an exhaust-gas-driven ejector as a cooling air pump. Design and performance information over these wider ranges of operating conditions is, however, meager. Cooling-air-ejector design charts and temperature correction factors are available in references 1 and 2 for ratios of primary jet total pressure to ambient pressure from 1 to 2.8. Theoretical and experimental ejector performance for higher primary pressure ratios exists in reference 3, but for configurations for which the ratio of secondary weight flow to primary weight flow far exceeds that necessary for conventional exhaust-gas ejectors. Furthermore, the theoretical treatment cannot be extended to the short mixing-section ejector that is adequate for cooling purposes, because the assumption that complete mixing occurs between the primary jet and the fluid being pumped is not applicable.

An ejector analysis, based on certain assumptions shown to be applicable through experimental investigation, that provides some information on cylindrical ejector performance is available in reference 4. This reference considers ejector performance in the range of both pressure ratios and weight flows suitable for cooling purposes, but does not supply sufficient information to allow complete selection of cooling-air-ejector configurations.

An investigation is being conducted at the NACA Lewis laboratory which will provide sufficient air-flow-thrust information to allow rational selection of ejectors. The present preliminary investigation consisted of obtaining the pumping pressure rise, and the thrust of the ejector when the cooling-air passage was blocked and the primary pressure ratio, primary gas temperature, ratio of the spacing (between the exits of the shroud and the nozzle) to nozzle exit diameter and ratio of diameters of shroud exit to nozzle exit were varied. Several spacing ratios were investigated for each of several diameter ratios from 1.10 to 1.58. These resulting ejector configurations were investigated at primary pressure ratios from 1 to 10 and primary gas temperatures of 80°, 300°, and 500° F.

SYMBOLS

The following symbols are used in this report:

A	area
D	diameter
F	thrust
M	Mach number
m	mass flow
P	total pressure
p	static pressure

P_0/p_0	ram pressure ratio
S	space between nozzle and shroud exit
S/D_p	spacing ratio
T	total temperature
V	velocity
η	ram pressure recovery ratio
$\eta\ P_0/p_0$	cooling system inlet pressure ratio
γ	ratio of specific heats

Subscripts:

a	standard ambient pressure
e	ejector
j	jet nozzle
p	primary system
s	secondary system
sh	shroud
0	atmospheric pressure
1	primary nozzle exit
2	shroud exit

APPARATUS AND PROCEDURE

The apparatus used in this investigation is shown schematically in figure 1. The ejector consisted of a shrouded primary nozzle enclosed in a 16-inch-diameter duct connected to the laboratory exhaust system. The ejector was pivoted to a frame and connected by means of flexible bellows to the laboratory air supply to allow free movement for thrust measurement. Both the primary nozzle and the shroud were conical sections having 15° half-cone angles. The inlet diameter of the primary nozzle was 5 inches and the exit diameter was 4 inches. The inside diameter of the shroud inlet was maintained at 10 inches while the exit diameter was varied to obtain diameter ratios of 1.10, 1.21, 1.39, and 1.58. The spacing ratio was varied for each diameter ratio by inserting straight flanged spacers in the approach pipe ahead of the shroud.

The performance of each configuration was investigated over a range of primary pressure ratio from 1 to 10, which were obtained by varying both the primary total pressure and the exhaust pressure. The primary total pressure could be varied from zero gage to about 60 percent of the maximum of the supply system (40 lbs/sq in., gage). The exhaust pressure could be varied from ambient to about 8 inches of mercury absolute. The primary air could be supplied either with atmospheric dew point at 80° F or with -20° dew point at 80° F. The temperature of the air was varied from 80° to 500° F by burning fuel in a turbojet-engine combustor, which was inserted in the air supply duct. The secondary-air passage was blocked to prevent the induction of air through it by the primary jet and the resulting pressure variation in the shroud was investigated for each configuration. It was discovered at the conclusion of the investigation that a leak existed from the primary to the secondary allowing a secondary weight flow ratio of zero to 1 percent. This small amount of secondary flow was not sufficient to affect the trends of the curves presented, but did cause the secondary pressure and thrust ratios to be slightly high.

The total pressure and temperature of the primary air were measured by a total-pressure tube and an iron-constantan thermocouple located 16 inches upstream of the primary nozzle exit. The secondary total pressure, which in this case was identical to the static inasmuch as the secondary weight flow was zero, was measured by a total-head tube at approximately the same station at which the primary measurements were taken.

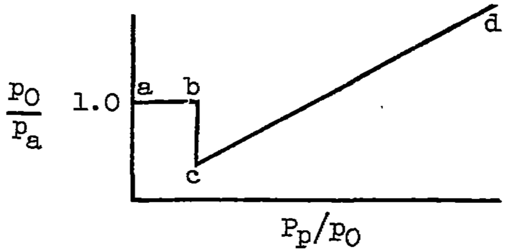
The exhaust pressure was measured from static taps located at the lip of the shroud in the plane of exit. This pressure was considered to be that into which the ejector discharged and to be representative of the pressure acting along the conical shroud. The difference in static pressure at the lip of the shroud and at the duct wall in the plane of the ejector exit varied to a maximum of 4 inches of water.

The resultant force composed of the ejector thrust and the force on the ejector produced by the difference between atmospheric and exhaust pressure, was measured by a strain gage located on the center line of the jet and anchored to the supporting frame. The actual ejector thrust was obtained by adding the pressure force as determined by calibration for various exhaust pressures to the force as read from the strain gage.

RESULTS AND DISCUSSION

The performance of a cooling-air ejector for aircraft can be evaluated by its ability to pump air and its effect upon jet thrust. These performance parameters are affected by both design and operational variables. Primary pressure ratio, the principle operational variable, is an indication of the combined potential and kinetic energy available in the driving jet to entrain or pump cooling air.

The effect of primary pressure ratio on ejector performance for an ejector with the secondary flow passage blocked is shown by the typical performance curves of figure 2. As the primary pressure ratio was increased, the secondary pressure ratio decreased to a minimum value and then increased linearly with increasing primary pressure ratio. This variation is similar to that observed for the wall pressures of a convergent-divergent nozzle. For example, the wall pressure at the exit of a supersonic nozzle is ambient until the internal normal shock moves to the exit whereupon the exit pressure abruptly takes on the value of the pressure upstream of the shock. This is shown in the accompanying sketch as the region from a to c.



Once the normal shock stands at the exit of the nozzle, the relation between the primary and exit pressure is fixed and remains so regardless of how high the primary pressure ratio becomes. Thus, as shown in the sketch (region c to d) the exit pressure ratio varies linearly with primary pressure ratio. From figure 2(a), it can be surmised that a shock system forms at the shroud exit in the primary pressure ratio range from C to E causing the secondary pressure to assume some low value as required by the pressure rise through the shock. Beyond E the curve is linear as with the supersonic nozzle. In the region from A to C the main part of the jet, which is subsonic at primary pressure ratios less than that at B and supersonic at ratios higher than that at B, does not greatly influence pressures within the shroud. The reduction in secondary pressure is due to the pressure rise required for the mixing region of the jet to emerge from the shroud at ambient pressure. Beyond C, the primary pressure ratio is such that the supersonic portion of the primary jet has expanded to fill the shroud exit and set up the shock system mentioned.

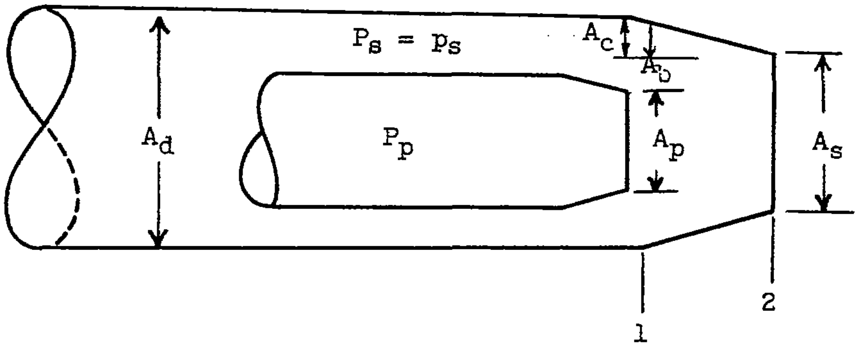
The variation of thrust ratio of figure 2(b) is similar to that which occurs with a supersonic nozzle operating at off-design conditions such as described in reference 5. Also the thrust ratio characteristics follow closely those of the secondary pressure ratio of figure 2(a). For example, the minimum secondary pressure ratio and thrust ratio occur at the same primary pressure ratio. This apparent dependence of thrust ratio upon secondary pressure ratio is explained in the following discussion.

2283

Thrust of an ejector can be written as

$$F_e = m_2V_2 + A_s(p_2 - p_0)$$

by referring to the accompanying sketch.



Writing the momentum equation between stations 1 and 2 gives

$$P_s(A_c + A_b) + p_1A_p + m_1V_1 - \int^{A_d-A_s} p_{sh} \, dA = p_2A_s + m_2V_2$$

By subtracting A_sp_0 from each side, simplifing, and noting that $A_b = A_s - A_p$, each side of the momentum equation becomes equal to ejector thrust F_e resulting in the expression

$$F_e = p_1A_p\left(1 + \gamma M_1{}^2\right) + P_s(A_s - A_p) - p_0A_s + P_sA_c - \int^{A_d-A_s} p_{sh} \, dA$$

This equation can be further simplified by utilizing the equation for primary nozzle thrust which is

$$F_j = p_1A_p\left(1 + \gamma M_1{}^2\right) - p_0A_p$$

Ejector thrust now becomes

$$F_e = F_j + (P_s - p_0)\,(A_s - A_p) + A_c P_s - \int^{A_d - A_s} p_{sh}\,dA \qquad (1)$$

The term $P_s A_c - \int^{A_d - A_s} p_{sh}\,dA$ can be neglected (as long as flow remains subsonic), inasmuch as the areas involved are equal and p_{sh}, being affected only by the subsonic flow, does not vary appreciably from P_s.

Therefore, the thrust of an ejector becomes

$$F_e \cong F_j + (P_s - p_0)\,(A_s - A_p) = F_j + p_0 A_p\left(\frac{P_s}{p_0} - 1\right)\left(\frac{A_s}{A_p} - 1\right) \qquad (2)$$

and the dependence upon secondary pressure ratio is shown. As the secondary pressure ratio decreases below unity the thrust loss increases and the thrust ratio reaches a minimum at the primary pressure ratio at which the jet fills the shroud. Further increases in the primary pressure ratio cause the secondary pressure ratio to increase and the thrust again increases. Examination of equation (2) indicates that the thrust loss should be zero when the secondary pressure ratio is unity. However, the shroud pressures are affected by the shock system and the term $P_s A_c - \int^{A_d - A_s} p_{sh}\,dA$ which was previously omitted must be included in the thrust equation to allow for the increasing shroud wall pressure. Therefore, the thrust ratio increases to a maximum value less than unity.

Effect of Humidity on Ejector Performance

In addition to the effect of primary pressure ratio, the effect of the operational variables humidity and air temperature were investigated briefly. Most ejector investigations are made with models supplied with compressed atmospheric air. The humidity of this air may be relatively high, as indicated by vapor trails leaving the ejector. In order to determine whether or not condensation within the ejector had been affecting performance, several configurations were investigated with both moist air (50° F dew point) supplied at 80° F and dry air (-20° F dew point) supplied at 80°, 300°, and 400° F. A comparison of ejector performance using the moist and dry air at these temperatures is shown in figure 3 for one ejector configuration. Use of dry air at 80° F eliminated condensation thus preventing the premature formation of the shock system due to condensation and allowed the secondary pressure ratio to decrease further until the internal compression shock system formed.

Because of the relative high expansion ratios of the primary air within the ejector, condensation was still theoretically possible with the dry air at 80° F. Air temperatures were therefore increased by burning part of the air with a hydrocarbon fuel. The 300° and 400° F temperatures used were selected on the basis of the data of reference 6 to insure condensation free flow. The effects of condensation had apparently been eliminated by use of the dry air at 80° F inasmuch as the use of heated air did not produce any additional change in pumping characteristics of this configuration. Additional effects of temperature will be discussed later.

The effects of condensation on thrust (fig. 3(b)) are not as well defined as the effects on pumping characteristics. This lack of definition results from the small thrust difference between the moist and dry air case. However, a trend towards a greater thrust loss is indicated when condensation is absent. The greater thrust loss is due to the attainment of a lower minimum secondary pressure ratio and the accompanying overexpansion of the primary jet stream.

Effect of Primary Air Temperature on Ejector Performance

Heating the dry air to insure that all condensation effects were eliminated resulted in reductions in thrust ratio as shown in figure 3(b) as well as other variations in performance of the ejectors having small spacing ratios (fig. 4(a) to 4(d)). The small-spacing-ratio ejectors gave higher secondary pressure ratios (less pumping) as the air temperature was increased. The effect of temperature on the pumping characteristics decreased as the ejector spacing ratio increased.

Possibly these effects resulted from changes in configuration caused by the difference in linear thermal expansion between the nozzle and the shroud. Investigation showed, however, that although the trends were in the right direction, the changes in diameter and spacing ratio were too small to account for the difference.

An explanation of the effect of temperature on ejector performance is suggested by evidence in reference 7 indicating that the primary jet spreads less rapidly (the efflux angle based on equal Mach numbers at the jet boundary is smaller), when the temperature is increased.

As the jet spreads less rapidly with increasing temperature, the maximum pumping effectiveness will occur at increasing primary pressure ratios. These variations were found to exist as shown in figure 4. As the spacing ratio was increased, allowing sufficient length for satisfactory attachment of the jet to the shroud wall, the ejector pumping performance was less sensitive to both primary temperatures and spacing ratio. The effect of temperature on thrust was relatively small.

Effect of Spacing Ratio on Ejector Performance

As shown in figures 5 to 8, when the primary jet temperature and diameter ratio were held constant, an increase in spacing ratio resulted in a decrease in the minimum secondary pressure ratio for any one spacing ratio, to a minimum value for the diameter ratio. Further increases in spacing ratio increased the minimum secondary pressure ratio. Also, the minimum secondary pressure ratio occurred at progressively lower primary pressure ratios as the spacing ratio was increased.

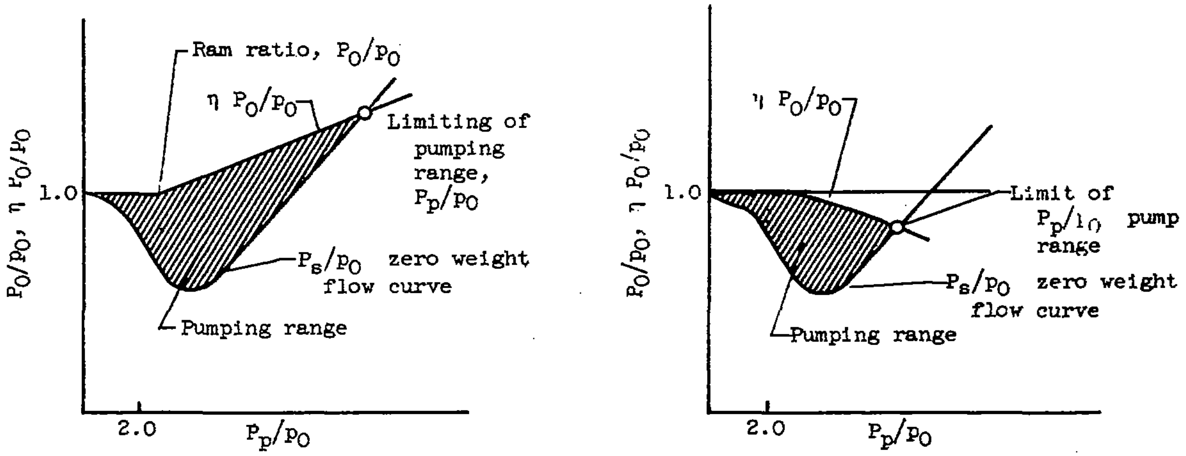
The thrust loss which accompanied the use of an ejector generally tended to increase with decreasing secondary pressure ratio for each diameter ratio. This trend is consistent with the thrust trends already discussed and results from the internal losses associated with overexpansion of the fluid stream. Generally for any operating condition an increase in spacing ratio increased the thrust loss of the ejector.

Effect of Diameter Ratio on Performance

An examination of figures 5 to 8 shows that the general effect of increasing diameter ratio was to shift the pumping range of an ejector to higher pressure ratios and to increase the range of primary pressures over which the ejector would pump. The lowest value of minimum secondary pressure ratio also decreased and occurred at higher spacing ratios as the diameter ratio became larger. The thrust ratio again followed the secondary pressure ratio trends, indicating a close association of pumping cost with the magnitude of the pumping. These data also indicate the magnitude of losses that would occur if throttling upstream of the ejector was used to control cooling-air flow. As the cooling-air flow approached zero, the thrust loss in the ejector would approach the values shown in figures 5 to 8 with thrust losses as great as 35 percent occurring.

Significance of Data

The pumping region of an ejector can be determined for various pressure conditions and aircraft flight speeds from the data presented herein as shown in the following sketches:



(a) Ram-type inlet, $P_0/p_0 \geqq \eta\ P_0/p_0 \geqq 1$.

(b) Zero-ram inlet, $1 \geqq \eta\ P_0/p_0 \geqq 0$.

The variation of secondary pressure ratio with primary pressure ratio under conditions of zero secondary weight flow, shown in the sketches as the curve of zero-weight-flow ratio, is one boundary of the pumping region. The other boundary is the variation of the cooling-system inlet pressure ratio with primary pressure ratio inasmuch as this inlet ratio cannot be exceeded by the secondary pressure ratio when the ejector is pumping. The latter boundary for the case of a ram-type inlet is shown in sketch (a) where $P_0/p_0 \geqq \eta_i\ P_0/p_0 \geqq 1$. The case of an inlet in which no ram exists is shown in sketch (b) where $1 \geqq \eta_i\ P_0/p_0 \geqq 0$. The primary pressure ratio at which the bounding pressure ratios become equal determines the limit of the primary-pressure-ratio range over which pumping can take place inasmuch as at this point the secondary weight flow is zero. This limit as shown in the sketches occurs at the intersection of the zero-weight-flow curve and the inlet-pressure-ratio curves. Primary pressure ratios higher than this limiting value would induce reverse flow through the cooling system inasmuch as the secondary pressure ratio then exceeds the inlet pressure ratio.

CONCLUDING REMARKS

The examination of these data showing pumping characteristics and associated thrust losses indicates that ejector thrust should be a primary consideration in the selection of a cooling-air ejector. Ejectors which provided high pumping pressure ratios introduced high thrust losses. Furthermore, any attempt to control cooling-air flow by throttling upstream of the ejector could lead, in some ejector configurations, to thrust losses approaching 35 percent of convergent nozzle thrust. The investigation indicates that ejectors should be designed with spacing ratios shorter than that which would produce the maximum pumping pressure ratio for any one diameter ratio. This type of configuration can give sufficient cooling flow with minimum thrust loss.

An increase in primary jet air supply temperature from 80° to 400° F had a detrimental effect on the pumping ability of the ejectors having short spacings between the exits of the primary jet nozzle and ejector shroud. The effect of temperature on thrust ratio was, however, small.

Increasing the humidity of the air supplied to the ejector showed detrimental effects on the pumping characteristics when condensation took place during the expansion of the air through the ejector. The use of -20° dew point air at 80° F was sufficient to eliminate humidity effects in the ejectors investigated.

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National Advisory Committee for Aeronautics
Cleveland, Ohio

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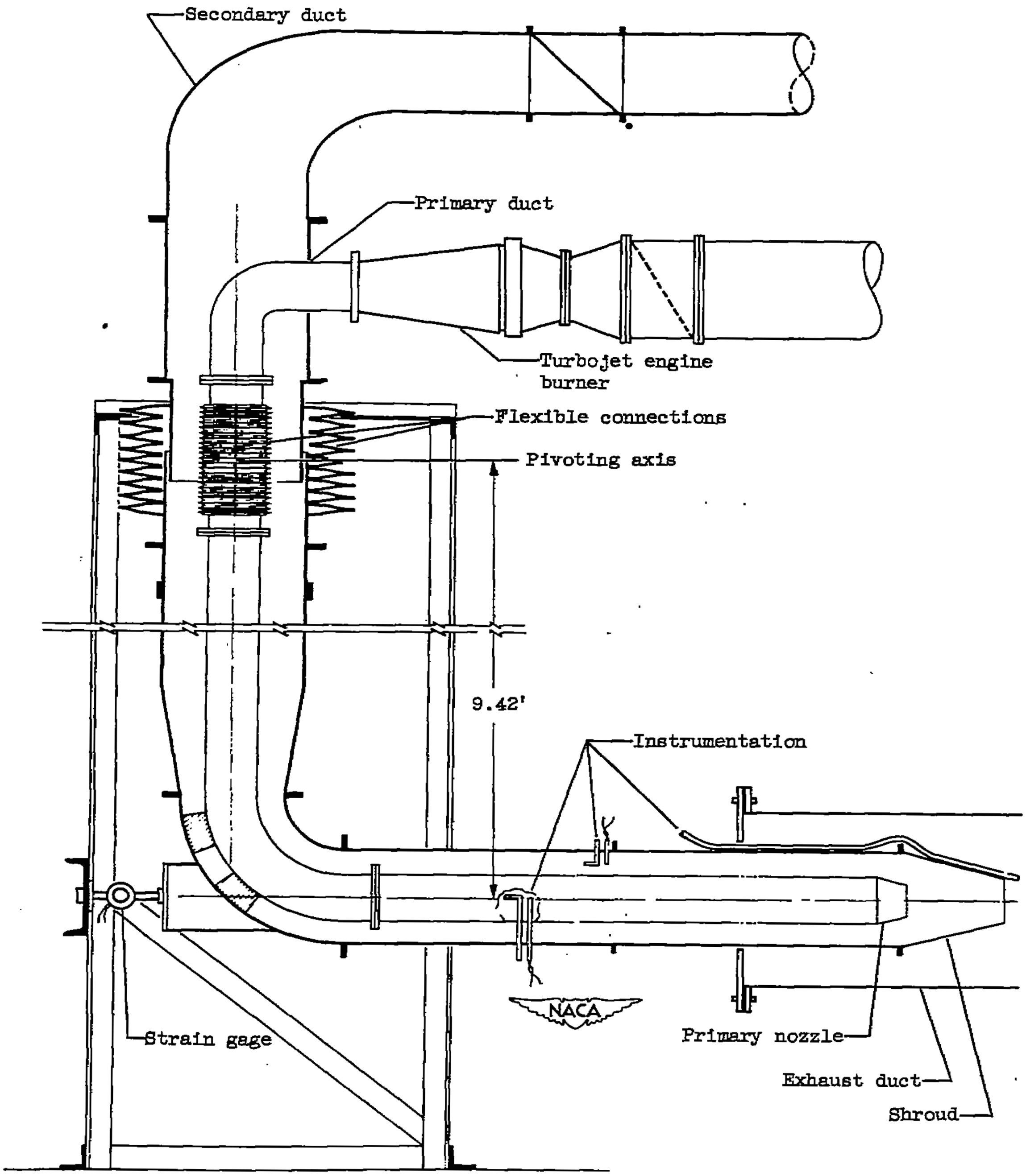

Figure 1. - Schematic diagram of model setup for ejector investigation.

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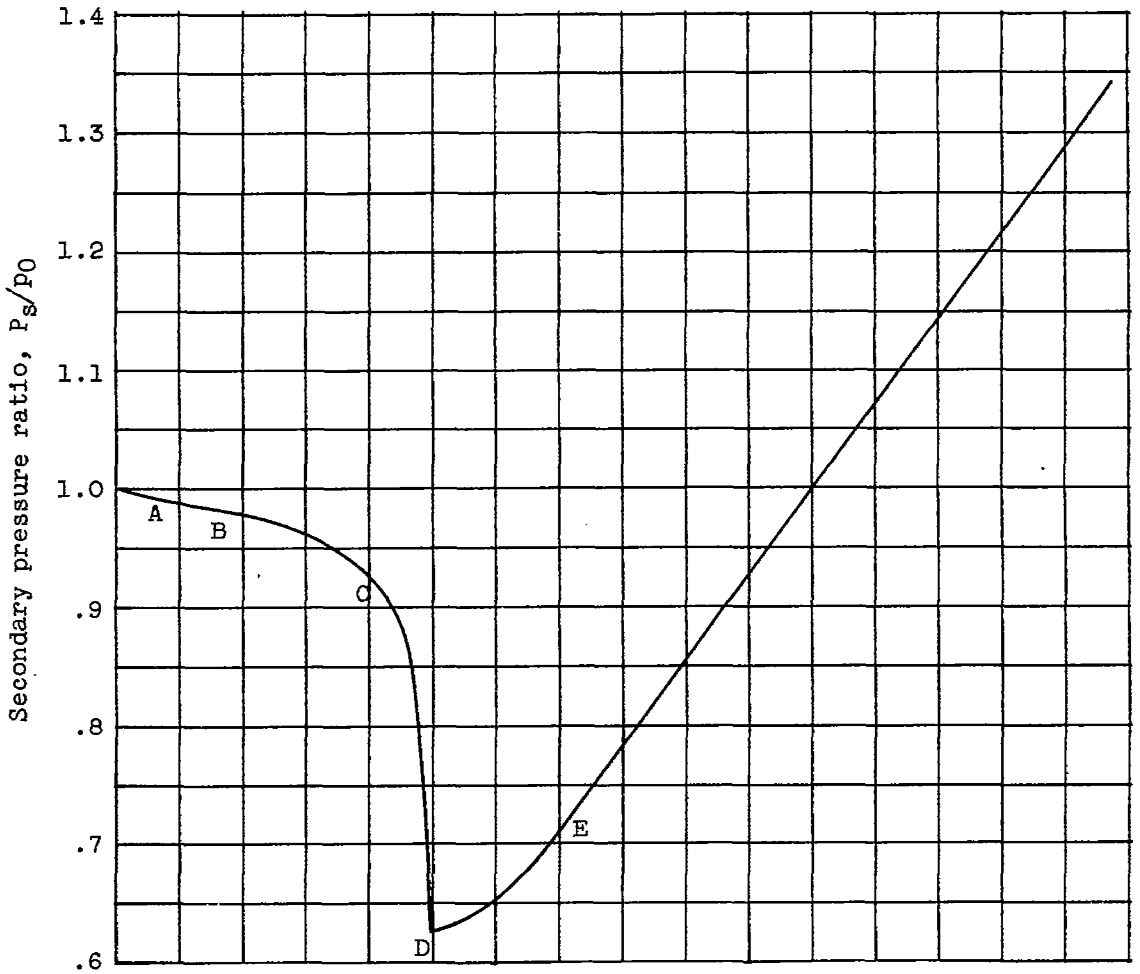
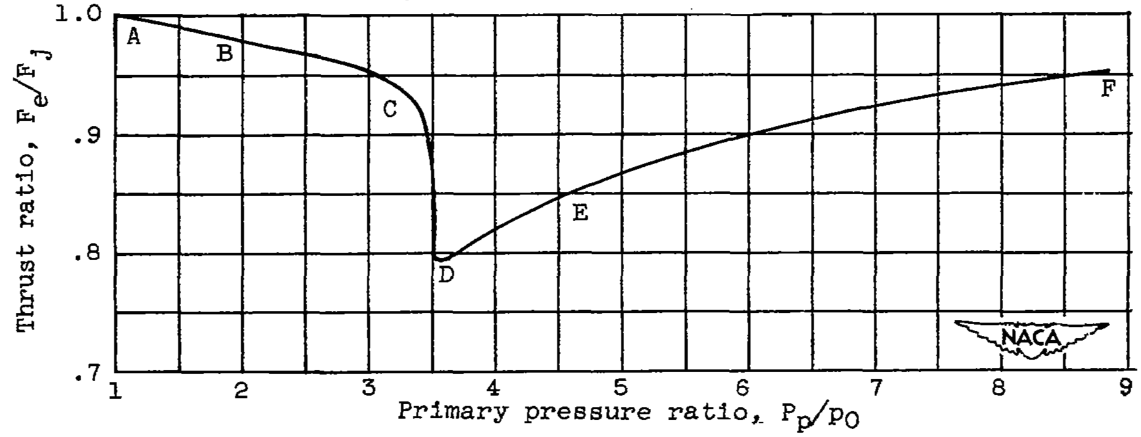


(a) Secondary pressure ratio.



(b) Thrust ratio.

Figure 2. - Typical effect of primary pressure ratio on performance of conical cooling-air ejector.

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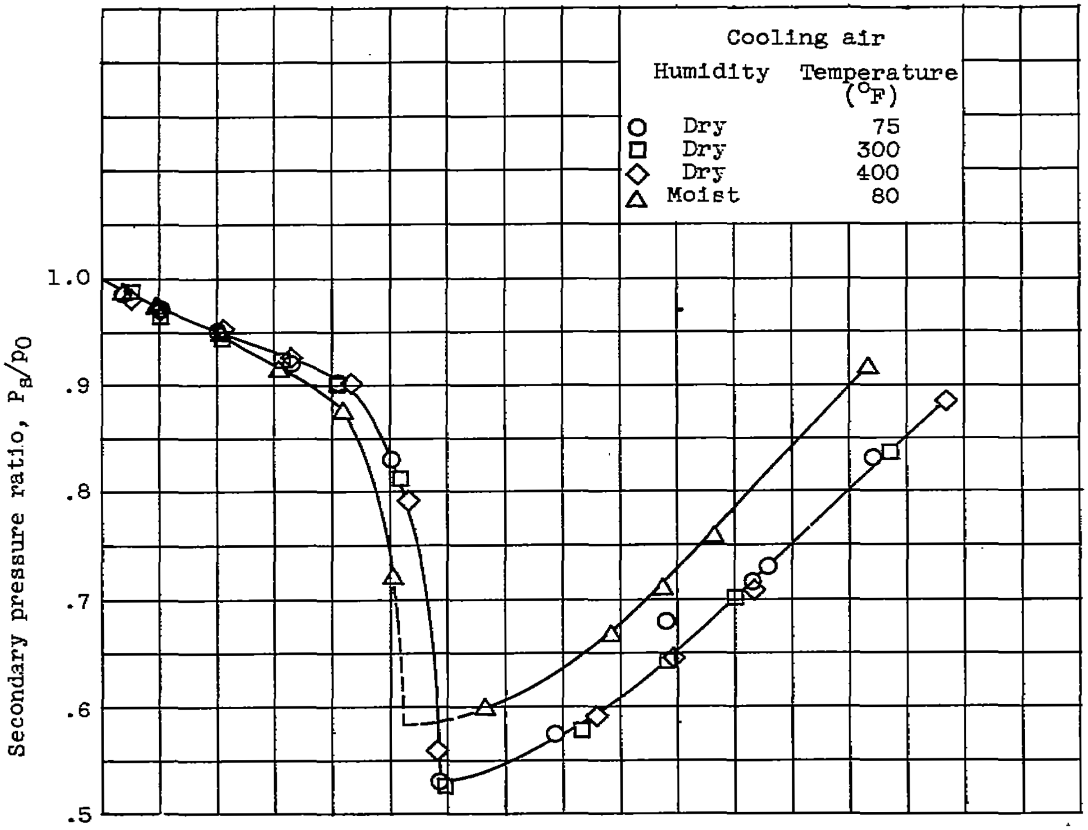
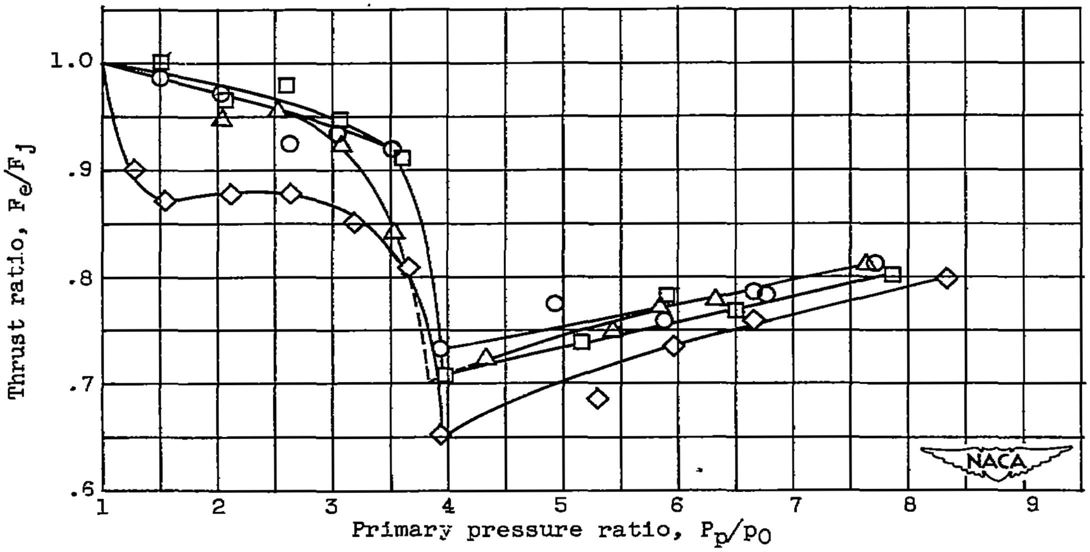


(a) Secondary pressure ratio.



(b) Thrust ratio.

Figure 3. - Effect of primary jet humidity on ejector performance.

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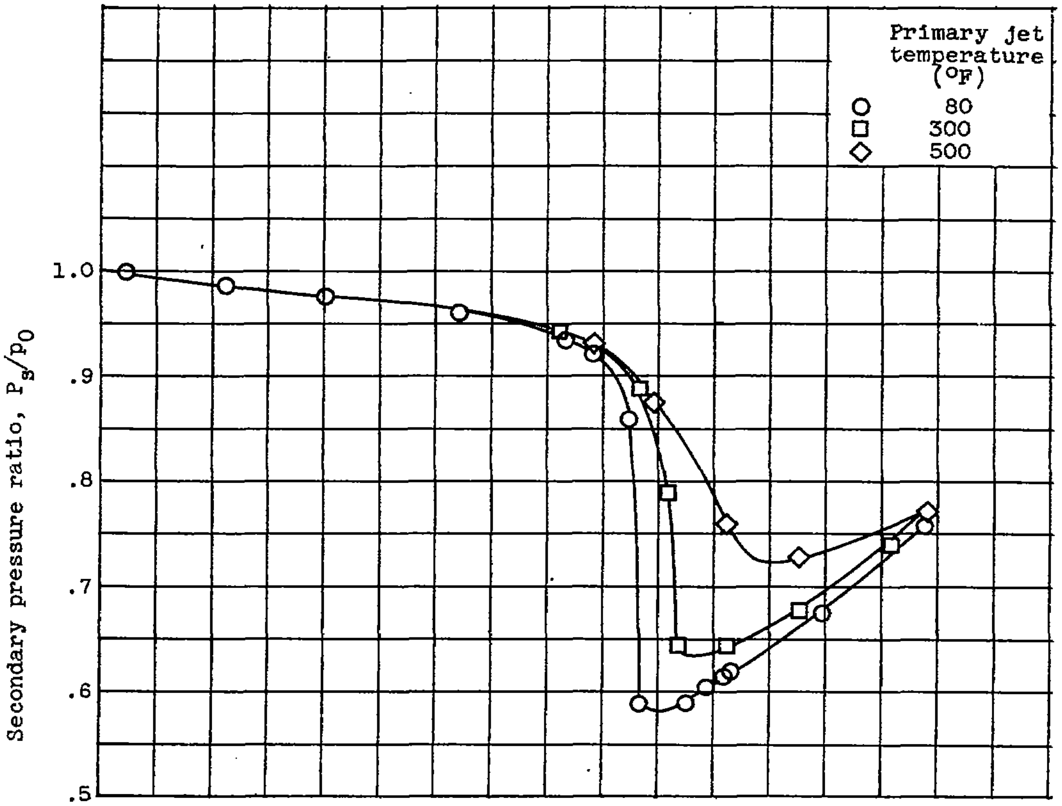
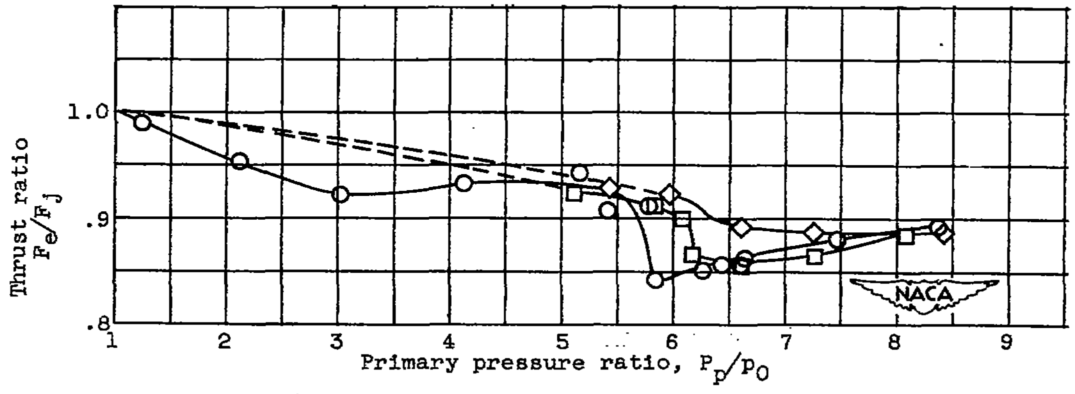
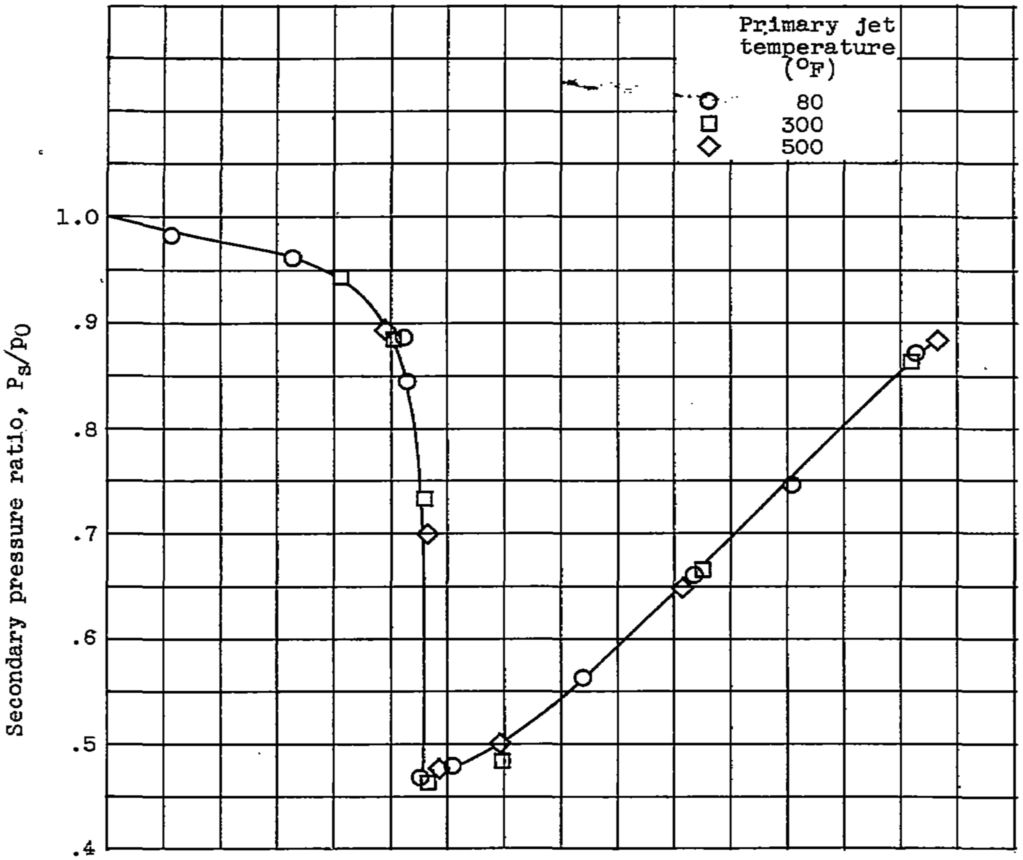


(a) Secondary pressure ratio; spacing ratio, 0.68.

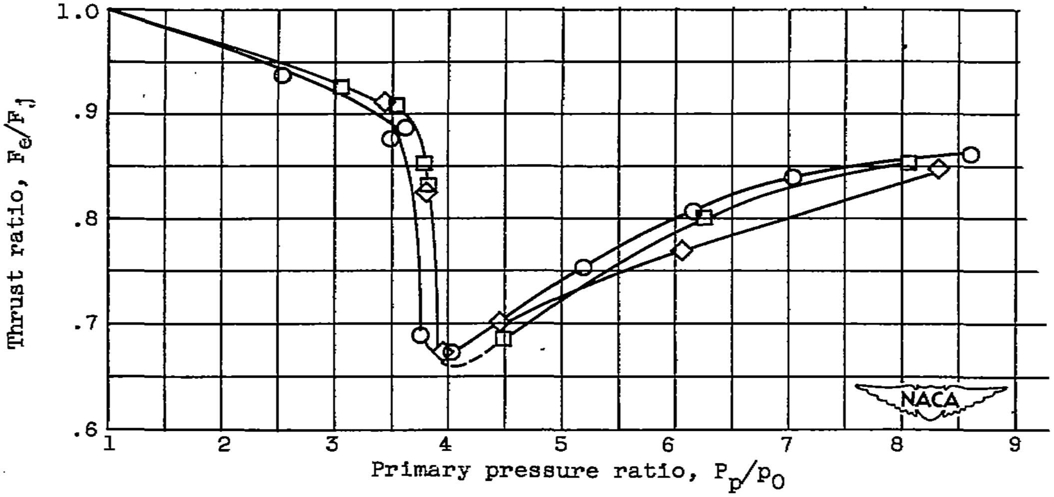


(b) Thrust ratio; spacing ratio, 0.68.

Figure 4. - Effect of primary jet temperature on ejector performance; diameter ratio, D_s/D_p, 1.58.



(c) Secondary pressure ratio; spacing ratio, 1.32.



(d) Thrust ratio; spacing ratio, 1.32.

Figure 4. - Concluded. Effect of primary jet temperature on ejector performance; diameter ratio, D_s/D_p, 1.58.

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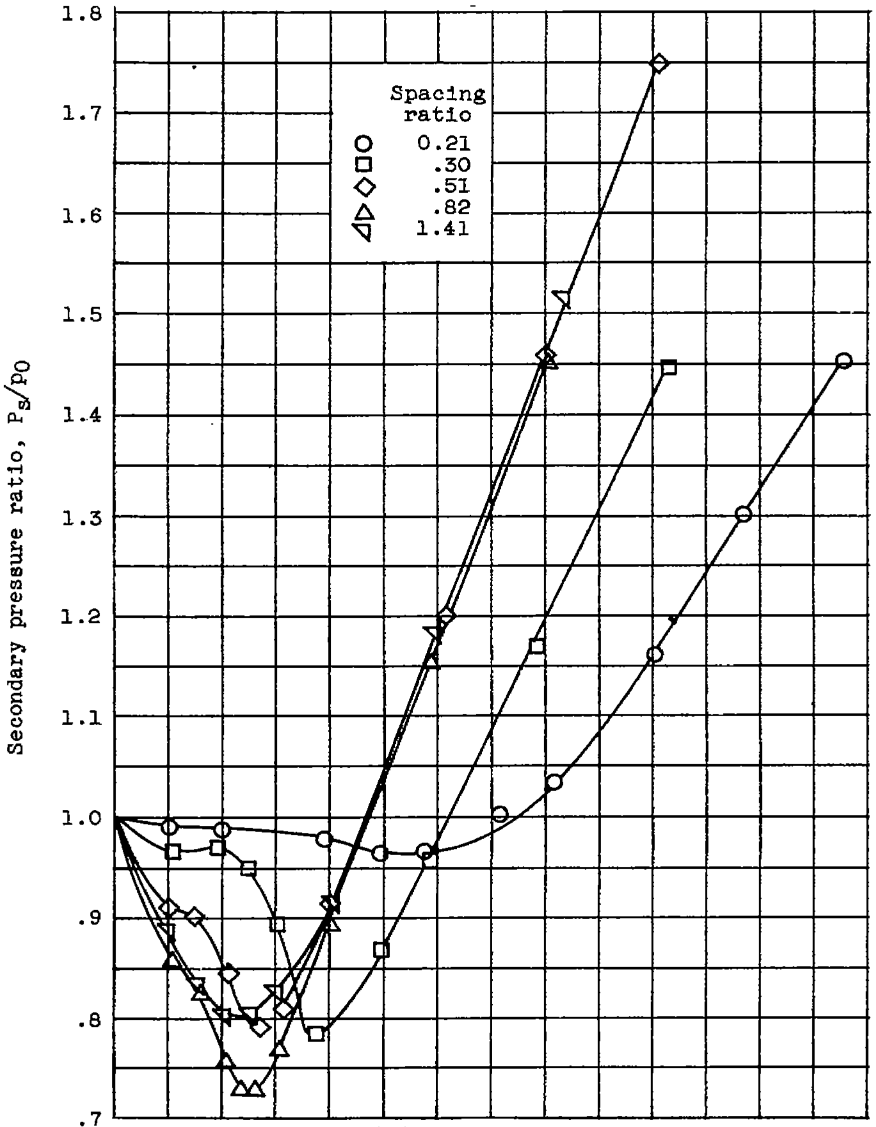
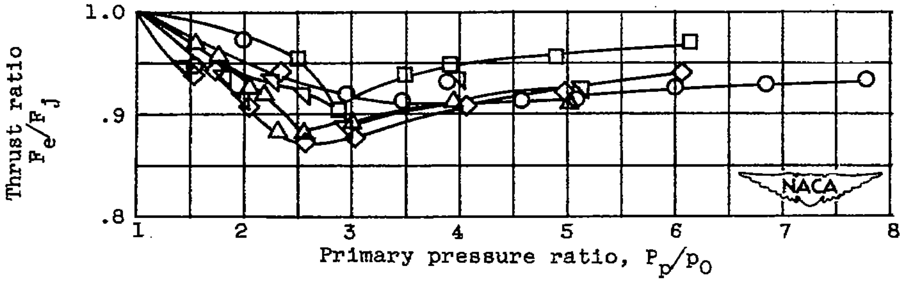


(a) Secondary pressure ratio.



(b) Thrust ratio.

Figure 5. - Effect of spacing ratio on ejector performance. Primary air temperature, 300° F; diameter ratio, D_s/D_p, 1.10.

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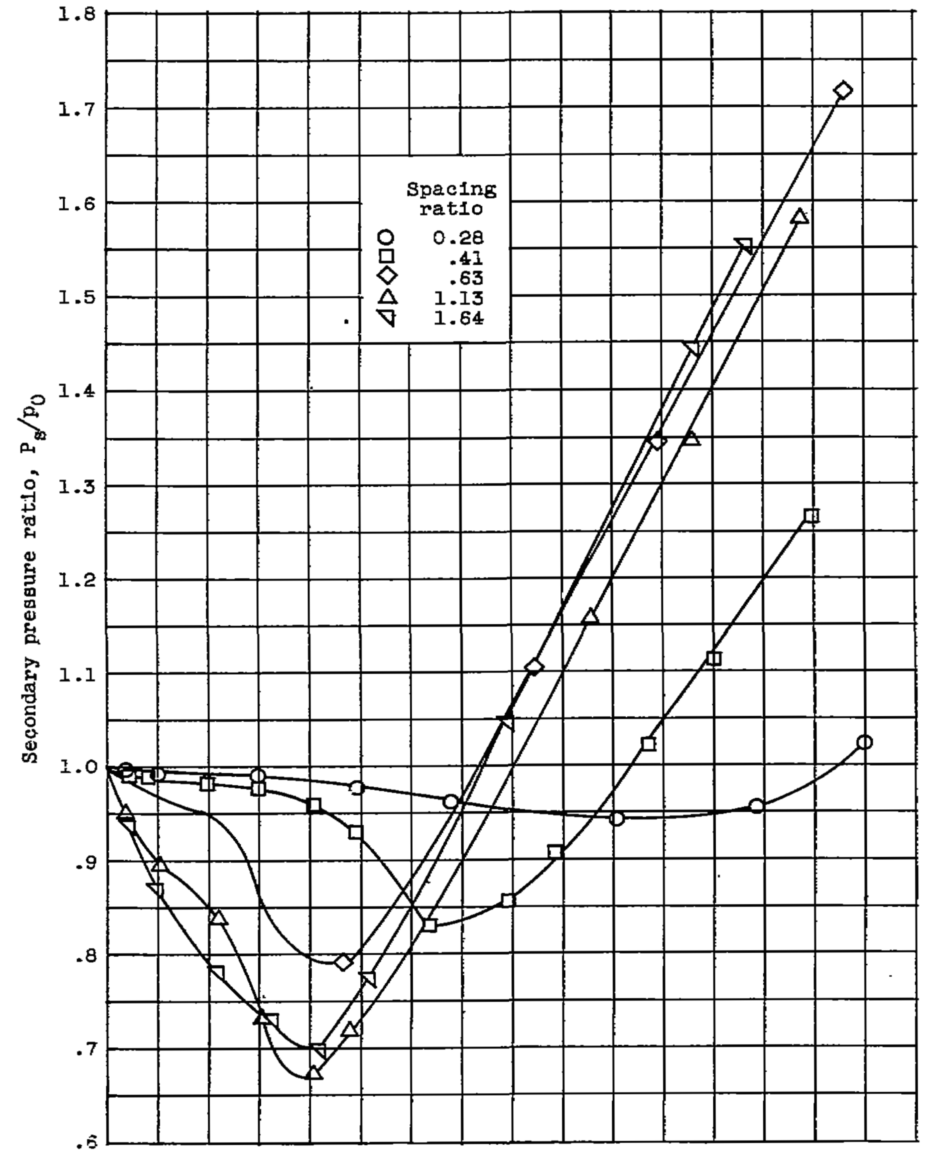
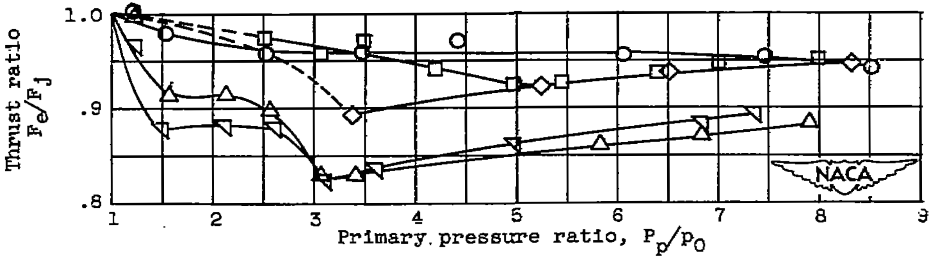


(a) Secondary pressure ratio.



(b) Thrust ratio.

Figure 6. - Effect of spacing ratio on ejector performance. Primary air temperature, 300° F; diameter ratio, D_s/D_p, 1.21.

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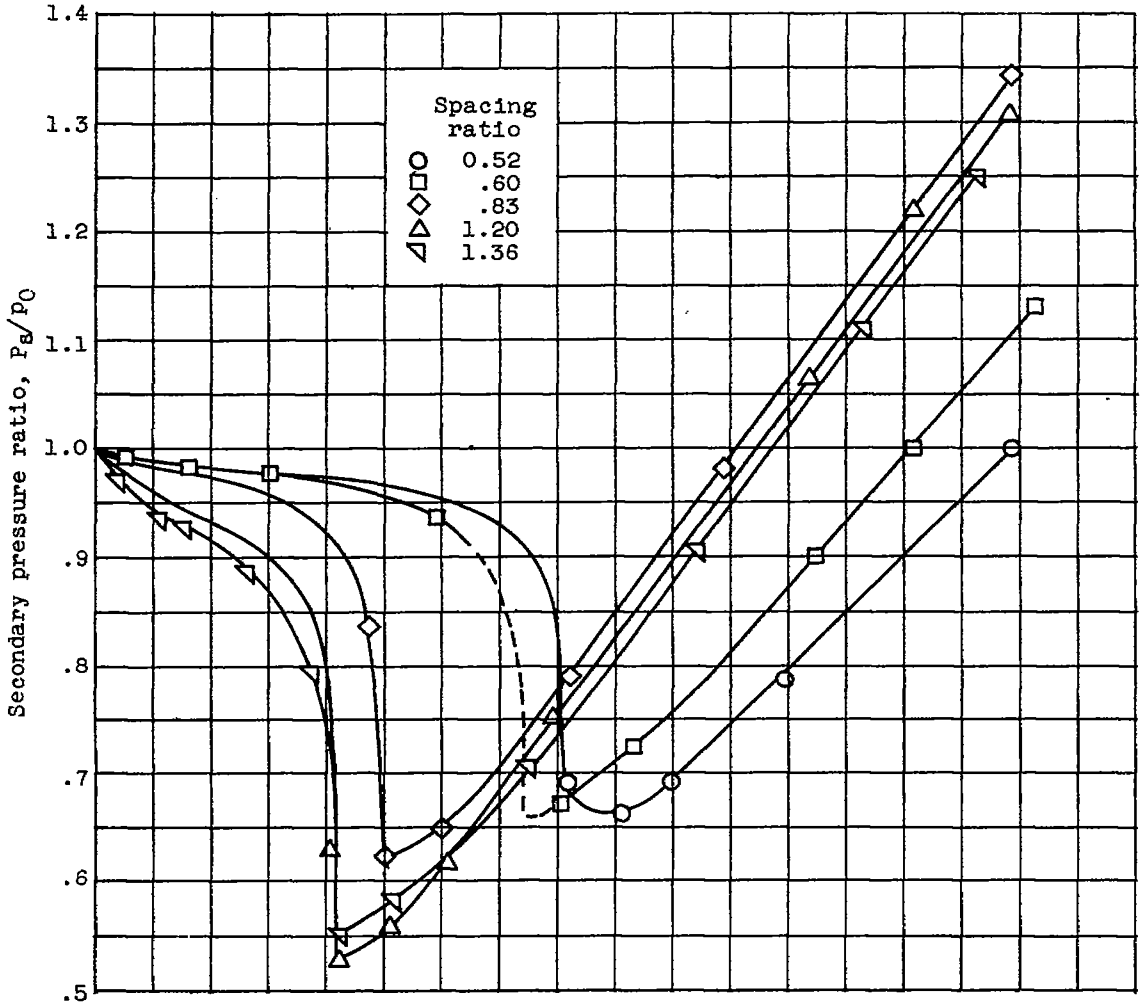
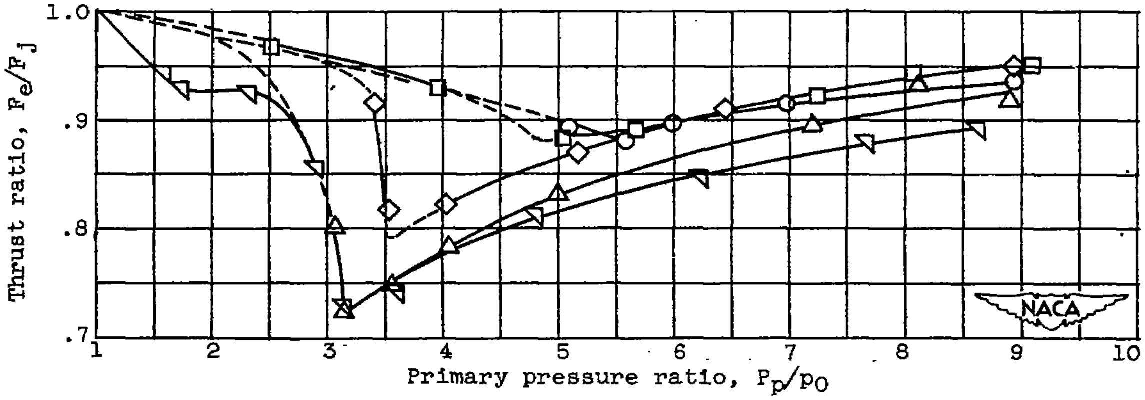


(a) Secondary pressure ratio.



(b) Thrust ratio.

Figure 7. - Effect of spacing ratio on ejector performance. Primary air temperature, 300° F, diameter ratio; D_s/D_p, 1.39.

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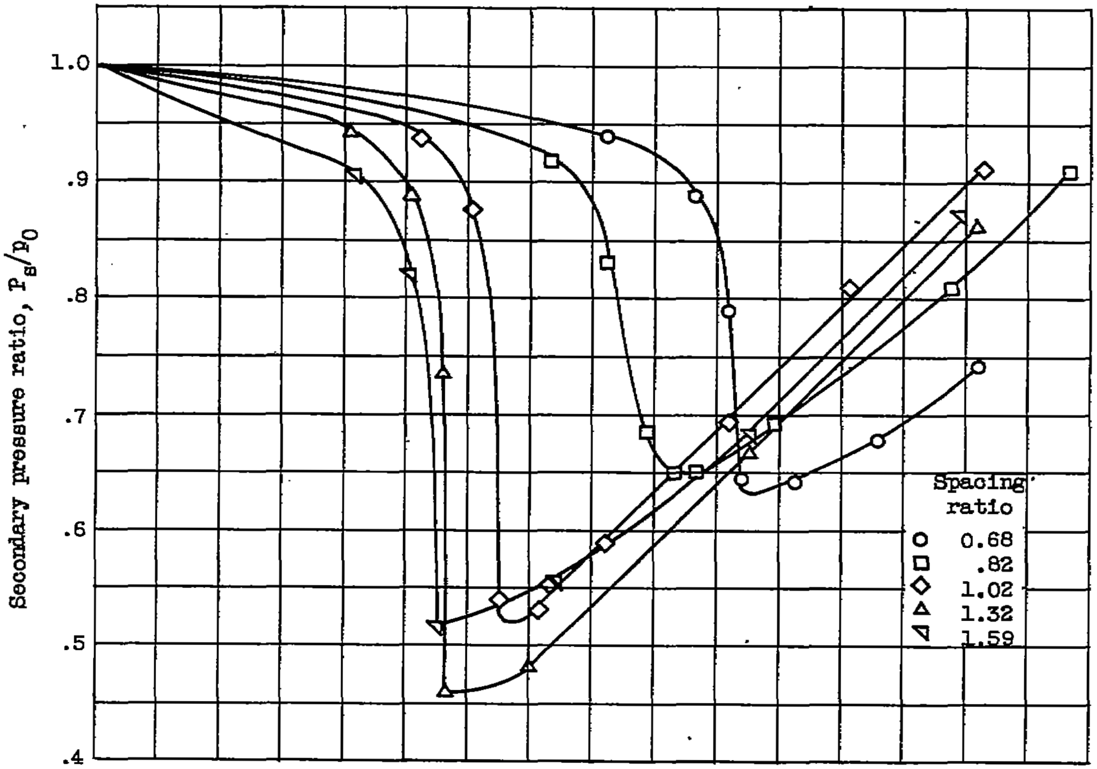
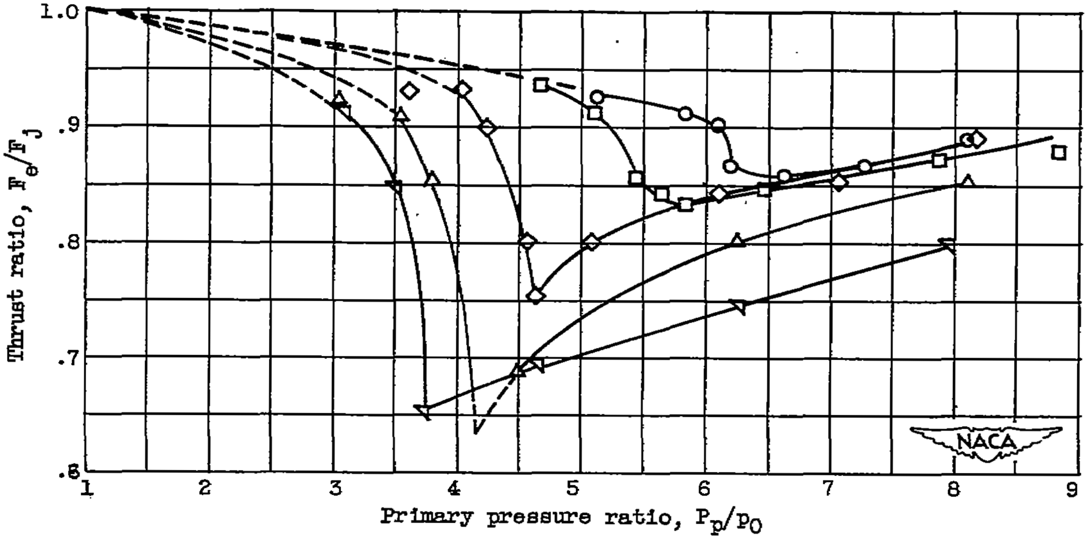


(a) Secondary pressure ratio.



(b) Thrust ratio.

Figure 8. - Effect of spacing ratio on ejector performance. Primary air temperature, 300° F; diameter ratio, D_s/D_p, 1.58.

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