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DESIGN AND PERFORMANCE OF STAGED STEAM EJECTORS WITH INTERSTAGE CONDENSERS

F. H. Smith, Jr.
ARO, Inc.

March 1966

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NOTICES

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FOREWORD

The work reported herein was done at the request of Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under System 921E/1461, Project SUPER, Project 9514, and Task 951411. The results were obtained by ARO, Inc. (a subsidiary of Sverdrup and Parcel, Inc.), contract operator of AEDC, Arnold Air Force Station, Tennessee, under Contract AF40(600)-1200. The report was prepared under ARO Project No. TW4355, and the manuscript was submitted for publication on November 10, 1965.

This technical report has been reviewed and is approved.

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ABSTRACT

One-dimensional analysis was used to design a staged steam ejector system. The system gives experimental results that are within the predicted performance envelope. The differences between the experimental results and theoretical predictions are critically examined. It was concluded (1) that the design of spray condensers between the ejector stages has an important influence on the overall performance of the system, (2) that the best system performance was obtained when the ejectors were operated at equal primary flow rates, and (3) that the effect of the Mach number of the secondary flow in the region of the ejector steam jet can have a great influence on ejector performance.

CONTENTS

ILLUSTRATIONS

NOMENCLATURE

A_D/A^*	Area ratio - diffuser to nozzle throat
A_{NE}/A^*	Area ratio - nozzle exit to nozzle throat
D^*	Diameter of nozzle throat
M_P	Molecular weight, primary steam
M_S	Molecular weight, secondary air
P_P	Total pressure of primary steam
P_{ex}	Total pressure at exit of exhauster stage
P_{in}	Total pressure at inlet of exhauster stage
PRR	Pressure rise ratio, P_{ex}/P_{in}
T_P	Absolute temperature, primary steam
T_S	Absolute temperature, secondary air
W_P	Flow rate of primary steam
W_S	Secondary airflow rate
ΔP	Pressure rise across the ejector, $P_{ex} - P_{in}$
ΔPRR	Change in pressure rise ratio

SECTION I
INTRODUCTION

In the ground testing of rocket engines under simulated altitude conditions, the requirement for maintaining a constant altitude pressure poses a problem, especially during rocket ignition and tailoff. A supersonic diffuser can be used to maintain a constant altitude pressure as long as the rocket chamber pressure is constant. However, during the ignition period when the rocket chamber pressure is rising and the diffuser has not started, there is a large increase in the cell pressure. This also occurs during rocket tailoff when the diffuser flow breaks down and there is backflow into the cell.

Auxiliary ejectors are used to evacuate test cells to the desired pressure altitude before rocket engines are ignited and to maintain this altitude after ignition. Since optimum design of auxiliary ejectors - and proper control of them during the firing and tailoff sequence - should contribute to greatly attenuating if not eliminating these pressure fluctuations, a study was made. For the experimental phase, development of an exhauster capability was required. Staged steam ejectors were considered for the exhauster system since the primary interest of the study was ejector performance. Practical experience in the design and performance of these ejectors was desirable because staged ejector systems have not been adequately discussed in the literature. This is especially true of nonisoenergetic systems employing interstage condensing.

A computer program, developed during a previous study (Ref. 1), was used in the design of the exhauster system. The actual performance of the system was compared with that theoretically predicted, and the differences noted were critically examined.

SECTION II
DESIGN CONSIDERATIONS

2.1 GENERAL

The staged ejector system was designed by using the one-dimensional, adiabatic, and frictionless ejector design program developed for another study. To allow for errors that might be introduced through the use of these assumptions, the program was "overdriven" by approximately eight

percent. This was accomplished by exhausting to a pressure of 16 psia rather than to atmospheric pressure. Condensing spray coolers were located between ejector stages to remove as much of the steam from the preceding stages as possible. Cooler efficiency was assumed to be 50 percent.

The input to the exhauster system was programmed as the output from the simulated rocket engine - that is, a cold-flow nozzle operating at 500-psia air pressure. The weight flow rate was 0.5 lb_m/sec at 500 psia and 530°R total temperature. The additional parameters to be considered in the design were the temperature of the condensing spray water, the temperature of the steam, the quality of the steam, and the number of stages of compression.

2.2 DETERMINATION OF NUMBER OF COMPRESSION STAGES

The altitude of the test cell was arbitrarily fixed at about 110,000 to 115,000 ft so that distinctive pressure transients could be obtained at simulated ignition and tail-off. The pressure rise of the cold-flow simulation nozzle was determined to be approximately 6 psia, assuming a 0.9 normal shock pressure recovery. The overall pressure rise was therefore approximately 9.5 psia. By using the relationship $PRR = \sqrt[N]{P_{ex}/P_{in}}$ as developed in Ref. 1, the number of stages, N, could be determined.

There is no optimum number of ejector stages for a given pumping job. The designer applies the law of diminishing returns in making a selection compatible with his cost factors. Figure 9 of Ref. 2 shows, for example, that steam savings of approximately 30 percent can be realized by increasing the number of pumping stages from two to three. A further increase from three to four, however, results in a steam reduction of 15 percent. In this study, the number of stages was limited to four. This gave the stage pressure rise ratio of $\sqrt[4]{2.67}$ or 1.278, which was used to compute the interstage pressures. Consequently, the first interstage pressure was 7.67 psia, the second 9.79 psia, and the third 12.52 psia.

2.3 SELECTION OF COOLING WATER TEMPERATURE

The temperature of the spray water used for steam condensation has a two-fold effect upon the system. When the initial temperature difference between the steam and the water is large, the initial heat transfer and potential heat content of the water is greater than for a smaller temperature difference. Thus less water is required as is indicated in Ref. 1. However, a more important effect is the vapor

pressure of the water. Water at 50°F has a vapor pressure of 0.178 psia, whereas water at 80°F has a vapor pressure of 0.507 psia. These pressures directly affect the water content of the gas stream being pumped and therefore the amount of pumping that is required in the succeeding stage. Since the cooling water temperature at AEDC varies seasonally from approximately 45 to 80°F, the higher figure was selected. This gives the exhauster system an all-season capability at design performance with a potential performance bonus to be realized during periods of cooler water temperatures. The size of the system did not pose any problem in the quantity of water required at the higher temperature.

2.4 STEAM PRESSURE, TEMPERATURE, AND QUALITY

The Central Steam Plant generates steam at 200 psia and saturation. Conditions of the steam at the user's site vary greatly, however, depending upon the load, the season of the year, and the distance from the plant. Because of the favorable location of the exhauster system in relation to the steam plant, a steam pressure of 150 psia at saturated conditions was selected for the design. This allowed a pressure drop of 50 psi in line losses and lower initial pressures which might be caused by large steam demands. No provisions were made for the determination of steam quality.

2.5 COMPUTER SPECIFIED DESIGN

The previously determined values were put in the program, and a computer run was made to obtain design values for the ejector units. The program was written to solve the one-dimensional equations of flow under adiabatic conditions. The assumptions made in their solution are listed below:

1. The Mach number of the secondary or pumped flow is 0.3 at the plane of the steam nozzle.

2. All steam from the ejectors is condensed in the succeeding cooler.

3. The secondary flow leaves the coolers in a saturated condition at a temperature 20°F higher than the inlet temperature of the cooling water.

The following design values were obtained from the computer program:

<u>First Jet Pumping Stage (holding ejector)</u>

Steam flow rate, 0.21 lb_m/sec
Mixing duct diameter, 0.309 ft

<u>First Interstage Condenser</u>

Water flow rate, 182.1 gal/min
Condenser diameter, 3.870 ft

<u>Second Jet Pumping Stage</u>

Steam flow rate, 0.18 lb_m/sec
Mixing duct diameter, 0.246 ft

<u>Second Interstage Condenser</u>

Water flow rate, 154.7 gal/min
Condenser diameter, 3.665 ft

<u>Third Jet Pumping Stage</u>

Steam flow rate, 0.18 lb_m/sec
Mixing duct diameter, 0.216 ft

<u>Third Interstage Condenser</u>

Water flow rate, 155.0 gal/min
Condenser diameter, 3.667 ft

<u>Fourth Jet Pumping Stage</u>

Steam flow rate, 0.18 lb_m/sec
Mixing duct diameter, 0.190 ft

The steam flow rate of the first ejector was greater than that of the succeeding ejectors because of the greater specific volume of the secondary airflow because of its temperature. It was considered that the air from the simulated rocket would be heated to keep it above its liquefaction temperature during the expansion process. The temperature of the air after recovery through the diffusion process was therefore greater than the air temperature entering the succeeding ejectors. The computer program was run for this higher temperature at the first ejector. The assumption that the flow leaving the coolers is saturated had the effect of making the water content of the flow a function of pressure only.

2.6 DESIGN OF EJECTORS

The flow rates specified by the computer were arbitrarily increased to be conservative. The first, or holding, ejector flow rate was increased to 0.25 lb_m/sec, and the remaining ejector flow rates were increased to 0.20 lb_m/sec. These flow rates and the properties of the assumed supply steam

were used to determine the nozzle throat areas. The diffusers for all of the ejectors were made from 3-in. Sch 40 pipe. This gave the first unit a 31-percent-undersized diffuser, the second unit was eight-percent oversized, the third 40-percent oversized, and the fourth 81-percent oversized. A better sizing could have been obtained by using different sizes and strengths of pipe. However, because of the many other unknowns involved in this design, the ejectors were standardized at the 3.068-in. diffuser diameter.

A length-to-diameter ratio of 7.5 was selected for all diffusers. An inlet nozzle and subsonic diffuser were installed on each cylindrical supersonic diffuser. The subsonic diffusers had an entrance diameter equal to the inside diameter of the supersonic diffuser. The exit diameter was 6 in. with a total divergence angle of $11^{\circ}25'$. The subsonic nozzles had an inlet diameter of 6 in. and an exit diameter equal to the diameter of the supersonic diffuser. The nozzle total convergence angle was 24 deg.

The A_D/A^* value for the holding ejector was 63.51, and the remaining three had an A_D/A^* value of 79.07. The steam nozzles were designed with an exit diameter of 1.34 in. This gave an A_{NE}/A^* ratio of 12.15 for the holding ejector and 15.12 for the remaining three. The nozzles were machined from 17-4-PH stainless steel. They all had a faired inlet bellmouth and an 18-deg half angle of divergence. A typical nozzle detail is shown in Fig. 1.

The steam nozzles were axially located in the subsonic nozzles with the exit plane of the nozzles located in the inlet plane of the supersonic diffuser. The nozzles were supported by the 3/4-in. steam supply line which was welded into the side of the inlet section. Figure 2 shows the configuration of the ejector assembly.

2.7 DESIGN OF THE SPRAY CONDENSERS

The design of the condensers from the computer data presented a difficult problem. The computer program solves for the condensers through an assumed process. Little information is available, however, to substantiate the validity of this process. The assumptions made for the computer design program represent ideal conditions. A spray density of 40 gpm/ft^2 of cross-sectional area, which may or may not be a valid figure, was assumed.

The greatest deviation from the specified design was made in the condenser design. Diameters were specified that were between 3 and 4 ft. Fabrication costs and material availability dictated a diameter of 2 ft. The

length was increased to 4 ft in an attempt to compensate for the reduced diameter. The 2-ft diameter resulted in a condenser with a cross-sectional area 73 percent less than specified for the maximum case. The water was sprayed into the condenser with a Spraying Systems Co. 1-7G25 nozzle obtained from the Rocket Test Facility (RTF), AEDC. This nozzle has a flow rate of 52.5 gpm at 90-psi water pressure. This gave a spray density of 16.7 gpm/ft^2 in the condensers, or approximately 40 percent of the specified spray density. The spray nozzle was axially located in the cooler 4 in. from the entrance flange, spraying in a downstream direction. The nozzle was supported by a 1-in. supply line welded in the condenser wall. A 3-in. drain line was provided to carry off the spray water and steam condensate.

Since the pressure level in the condensers was at all times less than atmospheric, a barometric leg had to be provided to allow gravity draining. A vertical drop of 24.5 ft was obtained by utilizing an existing valve vault, which allowed a first cooler pressure level of 4 psia. A separate drain line from each condenser had to be run to the well because of the difference in pressure levels at each condenser. All drain lines were terminated in a 55-gal drum to provide the water seal and the volume of water required to fill the drain line to the level corresponding to the condenser pressure. Figure 3 shows the configuration of the condenser assembly.

2.8 DESIGN OF THE ROCKET SIMULATION NOZZLE AND CELL

A simulated rocket was desired that could pump the cell down to a pressure corresponding to an altitude of 110,000 to 115,000 ft. A supersonic diffuser was required with the simulated rocket so that the flow could diffuse back up to the desired pressure level of 6 psia at the inlet to the ejector exhauster system. High pressure air to drive the simulated rocket is available from the von Kármán Facility (VKF), AEDC, high pressure supply. The desired flow rate of 0.5 lb_m/sec at a supply pressure around 500 psia is well within the capability of the air supply system. Design parameters of an A_D/A^* ratio of 145 and a supersonic diffuser length-to-diameter ratio of 7.5 were selected after the available literature on this particular design (Refs. 3 and 4) had been consulted.

As no condensing was needed between the exit of the simulated rocket diffuser and the first ejector, they could be directly connected, and it was convenient to make them of the same size pipe. Consequently, the nozzle throat area was fixed, and only the selection of a driving pressure remained to be made. Calculations indicated that approximately

600 psia driving pressure would satisfy both the altitude and the pressure recovery requirements. Since this pressure exceeded the maximum specified flow rate, the throat area was reduced, resulting in an A_D/A^* value of 176.1. The simulated rocket nozzle was made with a conical contour at a half angle of divergence of 18 deg. The nozzle expansion ratio of A_{NE}/A^* was 56.1. The A_D/A_{NE} ratio was 3.14.

Calculations have indicated that the rate of the pressure fluctuations are a function of the volume of the test cell. The cell was therefore made small enough so that it would have no large damping effect upon the pressure changes. It was fabricated from 14-in. pipe with a volume of approximately 1 ft^3.

2.9 DESIGN OF THE ATMOSPHERIC FLOW ORIFICES

Since it was desirable to determine the performance of the exhauster system before operating the simulated rocket nozzle, an alternate method of loading the system was devised. A set of three ASME nozzles were fabricated from aluminum and installed in the front plate of the test cell. Two nozzles were made to pass 0.10 lb_m/sec and one to pass 0.05 lb_m/sec at standard atmospheric pressure and temperature. The flow could be varied from 0.05 lb_m/sec to 0.25 lb_m/sec by holding a critical pressure ratio across the desired nozzles.

The nozzles were designed according to the recommendations of the ASME for long radius flow nozzles with low β* values (see Chapter 4, Part 5 of Supplement to Power Test Code, the American Society of Mechanical Engineers, Second Edition 1959, and ASME Paper No. 63-WA-25, "Flow Nozzles with Zero Beta Ratio.")

SECTION III
INSTALLATION

The ejector exhauster system was installed with the rocket simulation cell inside the Propulsion Wind Tunnel Facility (PWT), AEDC, transonic tunnel area. This location was selected for the following reasons:

1. The area was already the site of an ESF project, and manpower, the control room, and instrumentation could be shared.

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*Diameter of the nozzle/diameter of the plenum upstream of the nozzle.

2. The area is adjacent to the VKF high pressure air line.

3. It is adjacent to high pressure steam.

4. It has adequate water supply and drainage provisions.

The cell was located on a concrete valve vault horizontal to and at a centerline distance of 5 ft from the ground. The cooler and ejector units were supported by pipe stands. The cell was supported by a fabricated brace which was designed to cancel out any thrust from the system. The steam line was extended from the PWT steam heater supply line to the exhauster system. The line was insulated along its full length to minimize heat loss. The high pressure air line was extended along the transonic tunnel to the site of the exhauster system. It was then branched to supply both the supersonic compressor test stand and the steam ejector test. A high pressure regulator was installed at the initial point of the line extension and set to deliver a 1500-psia pressure. The 1500-psia air was regulated to the desired pressure through separate regulators at each of the test installations.

When the installation was completed, the last ejector and the drain lines were flanged off, and all water and steam supply lines were valved off. The system was then evacuated by using a 5-hp Kinney vacuum pump, and all the leaks that could be found were sealed. The system leak rate was checked periodically during the sealing period. The system was considered to be adequately sealed for this type of testing when a leak rate of less than 0.001 lb_m/sec was obtained. The completed installation is shown in Fig. 4.

SECTION IV
INSTRUMENTATION

For instrumentation purposes the ejector system was treated as four individual ejectors because the computer program analyzed each ejector separately. Each ejector was therefore instrumented separately and identically to the others.

4.1 PRESSURE

The following pressures were required for comparing the actual ejector performance with the predicted performances: (1) steam pressure at the ejector nozzle, (2) total pressure of the secondary flow upstream of the ejector, and (3) total pressure downstream of the ejector. In addition to this

instrumentation required for the ejectors, it was also necessary to have the pressure of the cooling water supplied to the condensers. The aerodynamic pressures were measured on 0- to 100-in.-Hg Kollman gages with the exception of the cell pressure, which was measured on a 0- to 15-psia Heiss gage. The steam and cooling water pressures were measured on automatic synchronizer gages to avoid high pressure fluids being introduced into the control room. When the high pressure air system is made operational, the air pressure will also be measured on an automatic synchronizer gage.

4.2 TRANSIENTS

Provisions were made for the recording of pressure transients when the ignition and tailoff cell pressure fluctuation investigation is made. A Consolidated Electrodynamics Corporation 18-channel oscillograph recorder was installed for this purpose. Transient pressures to be recorded include: (1) cell pressure, (2) air pressure to the simulated rocket nozzle, and (3) steam pressure to the holding ejector. These pressures will be converted to a recorder signal by means of strain-gage transducers.

4.3 TEMPERATURE

The following temperatures were required for the ejector performance analysis: (1) steam temperature and (2) atmospheric temperature. Additional temperature instrumentation was installed, however, to give a better understanding of the condenser performance. These temperatures were: (1) cooling water in, (2) drain water out, (3) secondary flow into the condenser, (4) and secondary flow out of the cooler. All temperatures were measured with iron-constantan (type J) thermocouples and read out on Sym-pli-trol indicators. The type J thermocouple was used because of its higher millivolt output than other standard thermocouples at low temperatures.

SECTION V
PROCEDURES

The ejector system was started from rear to front and was shut down from front to rear. This means that the fourth, or last, ejector was brought on the line, then the third condenser, the third ejector, and on up to the first ejector. The shutdown was just the reverse, beginning with the first ejector. In all cases the condenser was turned on before its associated ejector was turned on, and the ejector was turned off before the condenser was turned off. This prevented filling the system with steam, which condensed out in the

pressure lines. The zero flow runs were made by varying the steam pressure uniformly on all ejectors from 30 psi to maximum. The condensers were initially run at 80-psi water pressure. A comparison made at 40-psi water pressure, however, showed no reduction in performance; therefore 40 psi was set on all subsequent runs. The runs with secondary flow were set up in the same way as the zero flow runs, and then the secondary flow rate was set by removing nozzle plugs. The flow was increased until 0.25 lb_m/sec was reached or until the flow measuring nozzle did not have a critical pressure ratio across it. When either happened, the steam pressure was increased, and the secondary flows were again varied from 0 to 0.25 lb_m/sec. The steam pressure could be varied between the level necessary to maintain a critical pressure ratio across the orifice and the maximum available.

On each run the temperature and pressure data for each ejector stage were recorded. The atmospheric pressure and temperature were recorded for each group of runs.

SECTION VI
RESULTS

The performance data for the ejector system using the atmospheric flow orifices are presented in three ways. The performance with zero secondary flow is presented in the manner of Barton and Taylor (Ref. 3), and the pressure difference across the ejector is presented as a function of steam flow. The data on secondary flow performance were treated in a different manner. The pressure rise ratio of the ejector was shown as a function of primary-to-secondary weight flow ratio. The holding ejector was considered separately because of its larger throat diameter, and the performance of the remaining three ejectors was presented together because they are identical. The secondary flow data are presented for weight flows of 0.05, 0.10, 0.15, 0.20, and 0.25 lb_m/sec. All the experimental data are presented along with two computer predicted performance lines which show the maximum and mimimum performance, depending upon the inlet pressure level of the secondary flow. More detailed information about this, as well as the zero flow case, is presented in Ref. 5.

6.1 ZERO FLOW PERFORMANCE

Figure 5 shows the performance of the holding ejector on the Barton-Taylor plot of reciprocal nozzle pressure ratio as a function of the reciprocal driving pressure ratio. No attempt was made to "start" the ejector, and the results are presented in this plot for comparison with previous data.

Figure 6 shows the performance of the first of the three pumping ejectors presented on the same plot. The holding ejector pumped to a pressure rise ratio slightly greater than 2.5 at its best point. The geometry of this ejector is such that it would have to reach a pressure rise ratio of 18 before it would start. The second ejector reached a pressure rise ratio of about 2 at its best point. A pressure rise ratio of about 20 would be necessary to start this ejector. These plots are presented for purposes of comparison only since these ejectors were not designed for this type of operation.

Figures 7a and b show the performance of the holding ejector and the pumping ejectors as a function of steam flow. The experimental data for the holding ejector are almost all above the upper performance line. The data on the remaining ejectors have some points above the upper performance line, but most of the points fall between the lines. Data on, or close to the lower line, are in almost all cases for the fourth ejector. This is as expected because of the higher inlet total pressure of the secondary flow to this ejector.

6.2 SECONDARY FLOW PERFORMANCE OF THE HOLDING EJECTOR

The secondary flow data on the ejectors are again treated separately because of the differences in throat diameters. Figure 8a shows the performance of the holding ejector for a secondary flow rate of 0.05 lb_m/sec. The performance is better than predicted for three points and within the prediction for the remaining five. One would expect the data to lie near the upper curve because the secondary flow inlet total pressure on the holding ejector is the lowest in the system. Figure 8b shows the holding ejector performance for 0.10 lb_m/sec. The performance is not as good as with 0.05 lb_m/sec, with only one point falling above the upper performance line. The data are generally closest to the performance line for low secondary inlet pressure. Holding ejector performance for 0.15 lb_m/sec is shown in Fig. 8c. All of the data now fall within the performance curves. The data are obviously becoming more vertical in alignment. For a constant secondary flow rate, relatively large increases in pressure rise ratio can be obtained with a small increase in primary steam flow. Figure 8d is for a flow rate of 0.20 lb_m/sec. All data are within the predicted performance, but they are more centered between the curves rather than being close to either one. It should be noted also that the performance lines come closer together and more nearly vertical as the secondary flow rate increases. Figure 8e shows performance for 0.25 lb_m/sec. The performance is within predictions but is less efficient than for previous cases based on the relative location of the points to the performance lines.

6.3 SECONDARY FLOW PERFORMANCE OF JET PUMPING EJECTORS

All the jet pumping data are presented in the curves of constant secondary flow rate. Figure 9a shows the performance for 0.05 lb_m/sec. Approximately 20 percent of the data fall below the lower line of predicted performance. The remainder of the points are in the lower half of the performance envelope. Examination of the data shows three separate lines moving generally parallel to the performance lines. The upper line is for the second ejector, the middle line is for the third ejector, and the lower line is for the fourth and last ejector. The relative positioning of the data is as expected because of the inlet total pressure effect. Figure 9b shows performance for the 0.10-lb_m/sec secondary flow rate. The fourth ejector has about the same percentage of points outside of the performance envelope as the 0.05-lb_m/sec curve. The data from the second and third ejectors are grouped closer together, however, and cannot be as readily distinguished. Figures 9c, d, and e show the ejector performance for secondary flow rates of 0.15, 0.20, and 0.25 lb_m/sec, respectively. The performance shown here follows the same trend as previously indicated, with the data approaching the lower performance line more closely with increasing flow. In Figure 9e the data are clustered around the lower line. In Figure 9e, also, the W_p/W_s ratio is less than one for all cases. The measured pressure rise ratio of all points is also less than the design pressure rise ratio of 1.278, which is shown on Figs. 8 and 9 by a star symbol.

SECTION VII
DISCUSSION

The results obtained were much as expected. The zero flow performance for both the holding ejector and the jet pumping ejectors correlates well with the one-dimensional isentropic calculation. The performance for secondary flow rates of 0.05 and 0.10 lb_m/sec (1/10 and 1/5 design) is generally better than predicted. The holding ejector data for flow rates of 0.15, 0.20, and 0.25 lb_m/sec fall within the predicted performance envelope. The data on the jet pumping ejectors, however, show that performance was less than predicted from the very low flow rate of 0.05 lb_m/sec up through 0.25 lb_m/sec.

An explanation was sought because these three physically identical ejectors have identical predicted performance. Also the distinctive alignment of the individual ejector data in Fig. 9a was puzzling. Although the effect of

secondary inlet total pressure might account for the distinctive alignment, this effect should not have been great enough to move the data below the performance envelope.

There were two likely causes for this performance: the design deviations of the ejectors and the spray coolers. The ejectors are felt to exert primary influence because of their controlling function on the operational performance. Referring to Section 2.7, the last two ejectors were 40 and 81-percent oversized, respectively. A check made on this system using an off-design ejector program (Ref. 5) that was not available at the time the ejectors were designed indicates that there is not sufficient steam pressure available to raise the performance of these oversized units up to the design point. This fact is considered to be the prime reason for the degenerate performance with each additional stage.

The spray condensers were also checked for any contribution they might be making to the substandard performance. Since the holding ejector does not have an upstream condenser, its performance would be comparable to that of the other ejectors if the condensers were performing as it was assumed that they would. The effect of the condensers upon the performance was evaluated by operating the last three ejectors both with and without the first cooler. The results of this check are shown in Fig. 10 in which ΔP attributable to the cooler is a function of secondary flow rate only. The effect on the first ejector is negligible at 0.05 lb_m/sec but increases from a two-percent variation at 0.10 lb_m/sec to six percent at 0.20 lb_m/sec. Figure 10 was replotted in terms of ΔPR in Fig. 11 so that the results could be directly applied to the performance plots. Figure 11 shows performance (ΔP) falling off directly with increasing secondary flow.

This effect can be the result of two conditions that may have been present. If the efficiency of the condensers is such that all of the steam from the preceding stage is not condensed out, the steam carry-over would cause a greater load requirement on the succeeding ejector. This would be a cumulative effect; and the last ejector would be operating under the worst conditions, as the data indicate.

Also since the condensers were not sized to the diameter recommended by the computer program, the velocity of the flow through them is larger than optimum. This could result in spray water being carried through the condenser and into the next ejector stage, where it would have a detrimental effect. These results indicate that no correction should be made to the 0.05 lb_m/sec data. However, these data apply to one condenser and one ejector only, whereas the performance of the last ejector may be affected by three condensers if their

effects are cumulative. Consequently, there could be a correction for the third and fourth ejectors that would not show up in this check of one condenser and ejector unit.

The flow velocity through the condensers is calculated for the different flow rates at the design pressure and exit temperature. The results of these calculations are shown in Fig. 12 and indicate that the effect of spray water carryover should be greatest in the first condenser. If the observed changes in pressure rise ratio are related to velocity through the condenser and the resulting corrections then applied to the data, the effect would be to increase the spread among the individual ejector data rather than to reduce it. The cooler effects must therefore be in some manner additive. The effects of the first cooler are not only felt in the second ejector but also in the third and fourth ejectors. This would also be true with the effects of the second condenser being felt in the third and fourth ejectors. The performance of the second ejector would therefore be best even though it apparently has the worst velocity condition in its preceding cooler.

SECTION VIII
CONCLUSIONS

One-dimensional analysis was used to design a staged steam ejector system. The system gives experimental results that are generally within the predicted performance envelope. In the design of jet pumps the design data should be adhered to as closely as possible. If deviations must be made, indications are such that the deviation should be toward undersizing rather than oversizing the unit. The spray condensers used between the steam ejector stages may also have an important influence upon the overall performance of the system and should be designed for low gas velocities. The best system performance is obtained when the ejectors are operated at equal primary flow rates.

The design of spray condensers may be a critical factor in the performance of staged steam ejectors, and investigations should be made in this area. The condensers were apparently operating at a greater efficiency than predicted, but they may have a performance influence which is felt downstream throughout the system.

The effect of the Mach number of the secondary flow in the region of the ejector steam jet is potentially of great influence upon ejector performance and should be evaluated.

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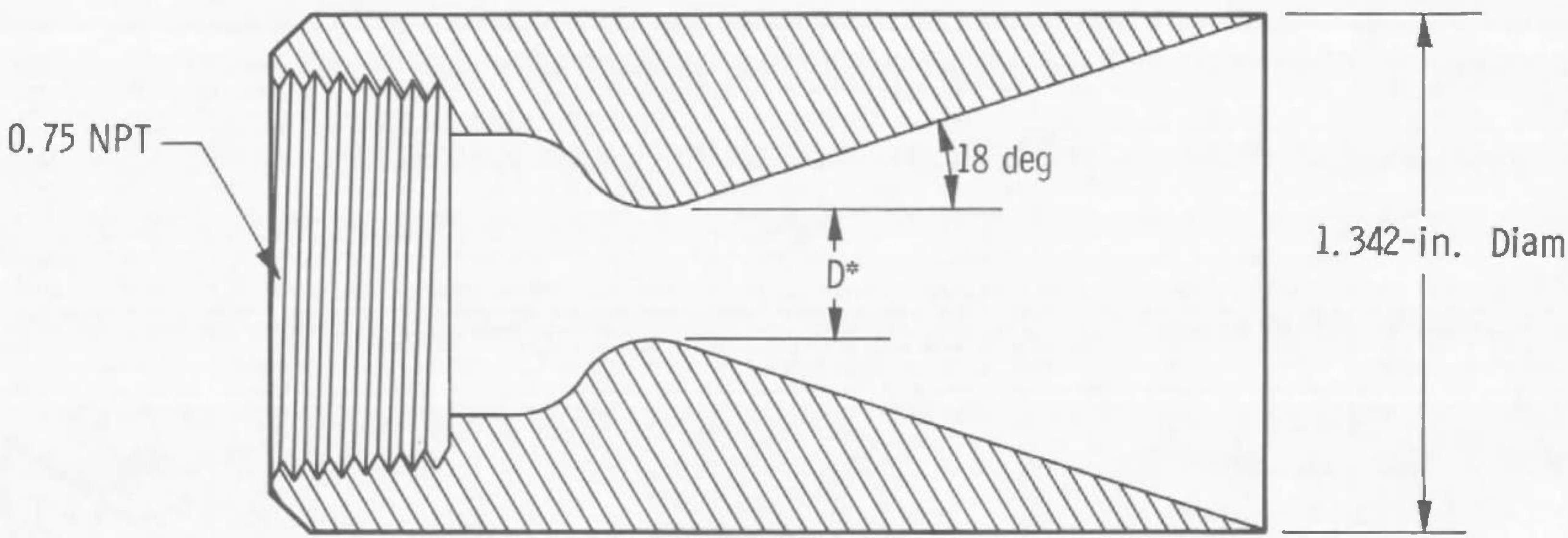


	D*
Holding Ejector	0.385
Jet Pumping Ejectors	0.345

Fig. 1 Steam Nozzle Detail

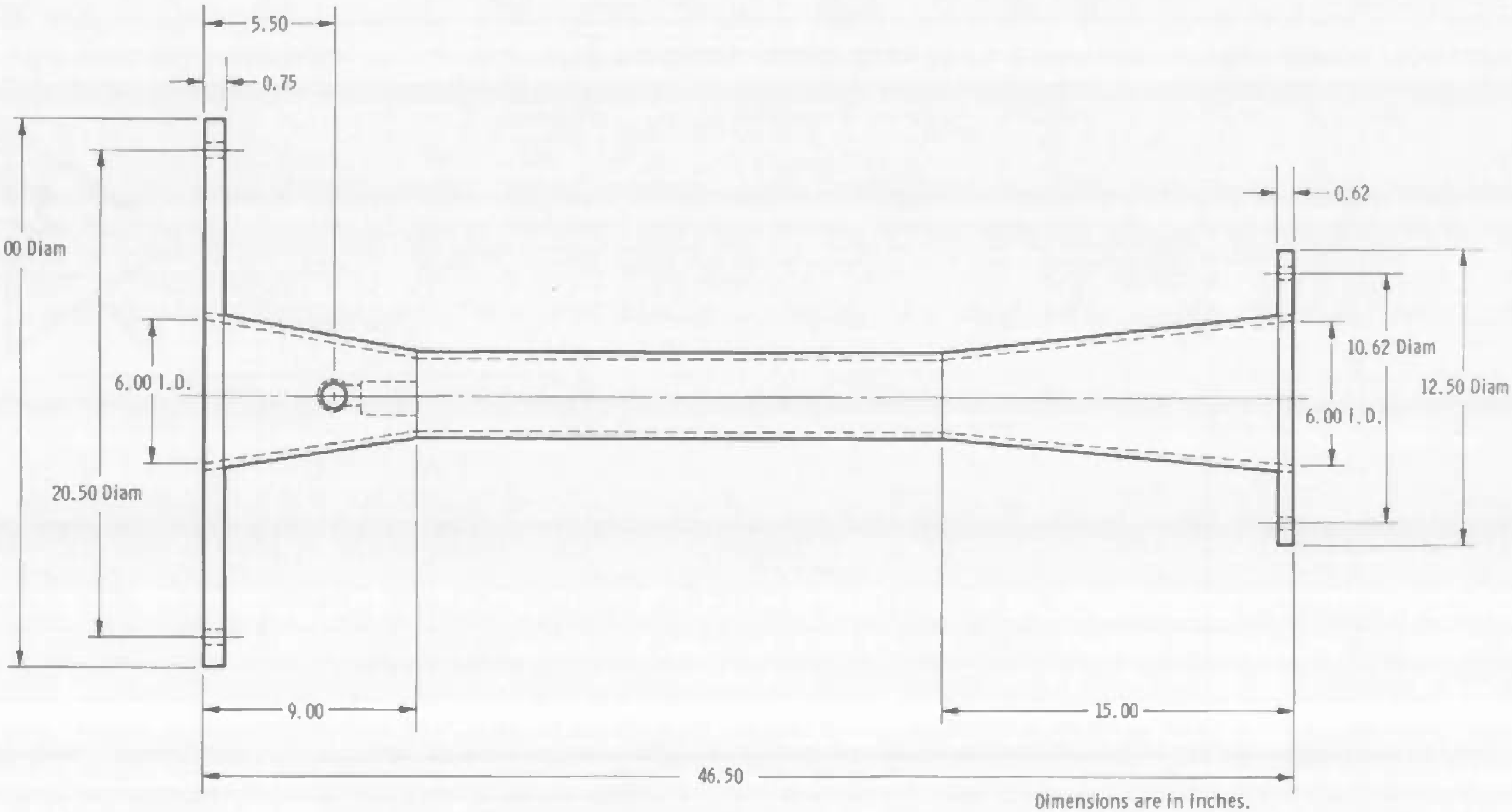


Fig. 2 Ejector Assembly

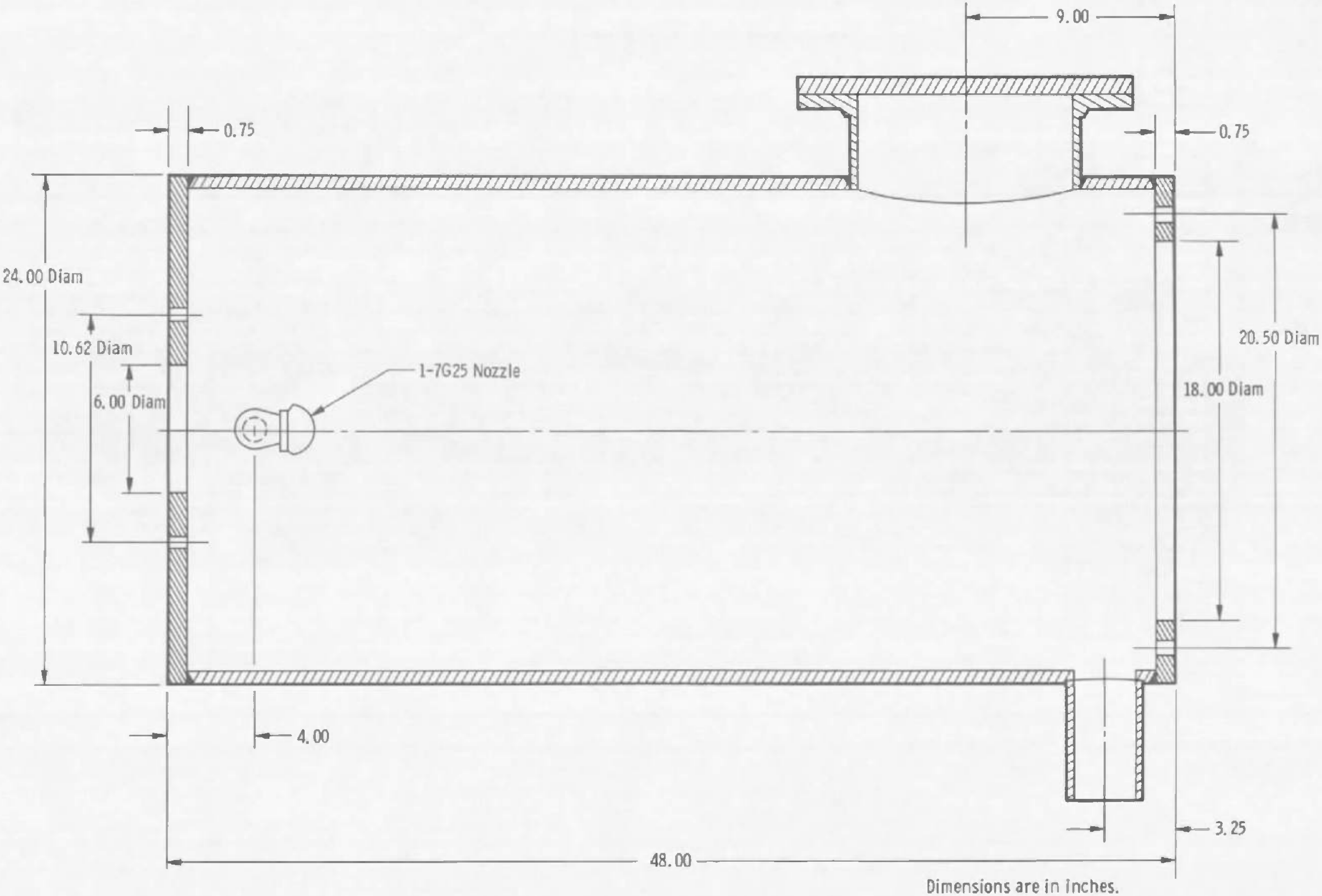


Fig. 3 Condenser Assembly

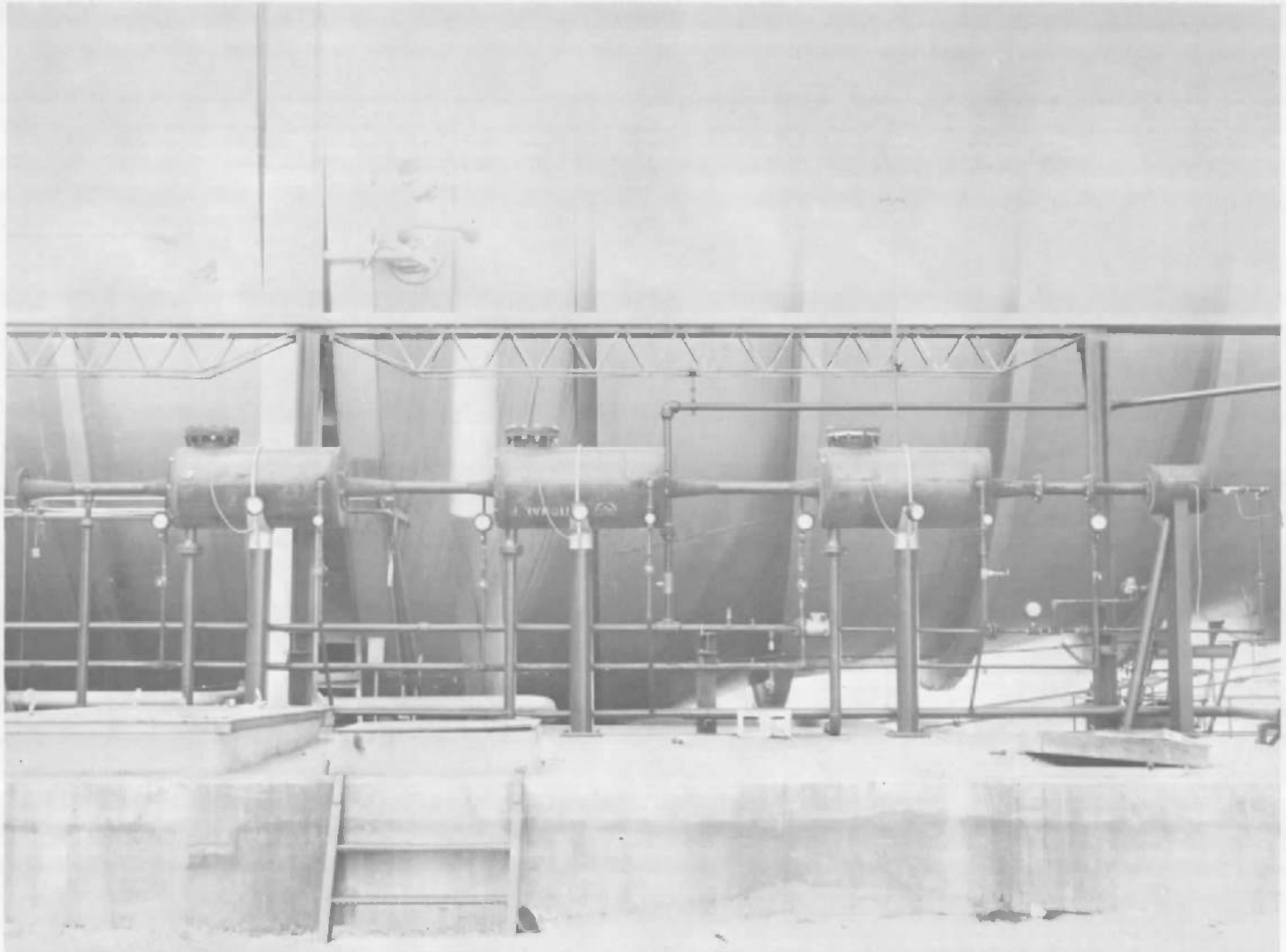


Fig. 4 Steam Ejector Test Installation

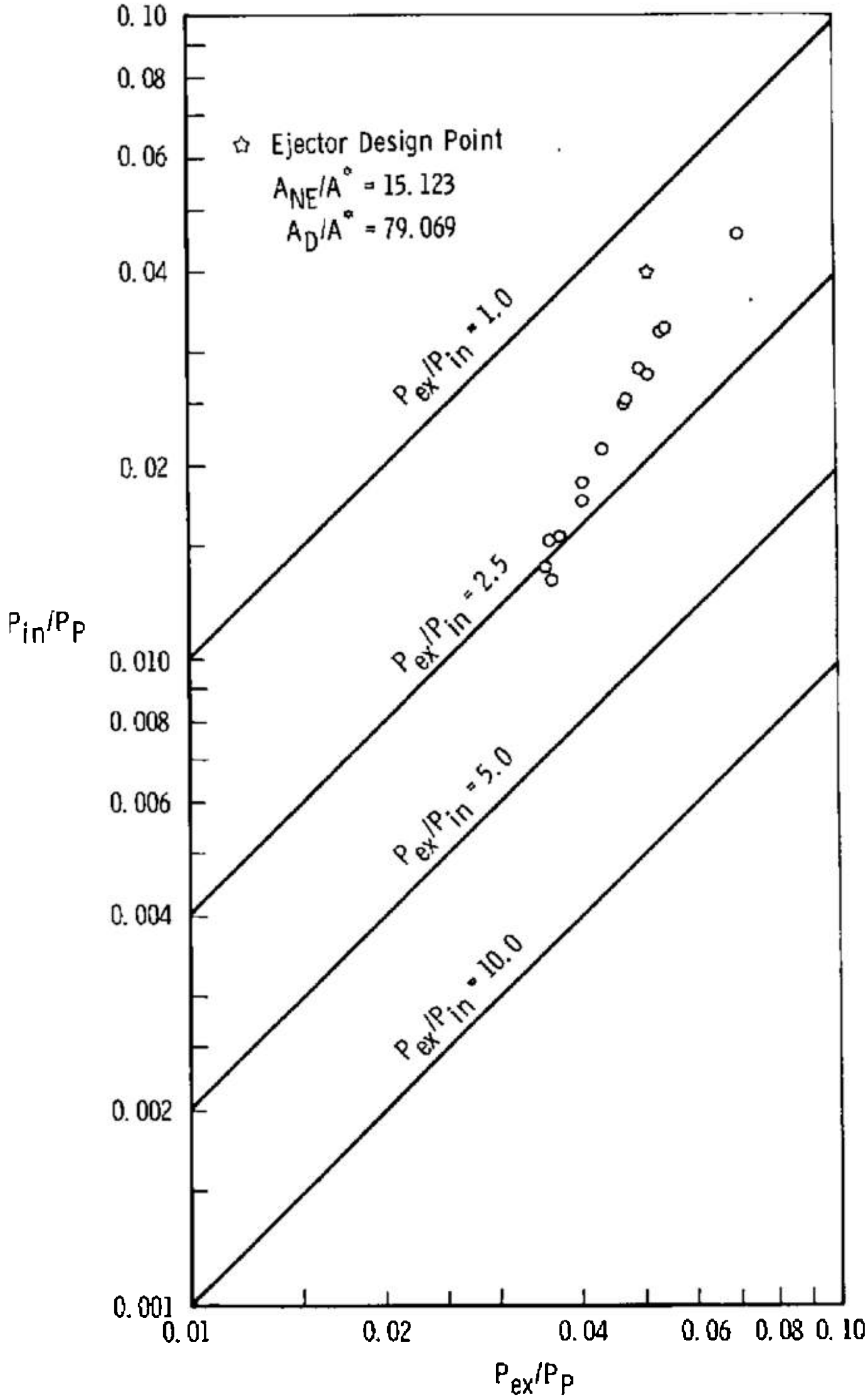


Fig. 5 Zero Flow Performance of First Ejector

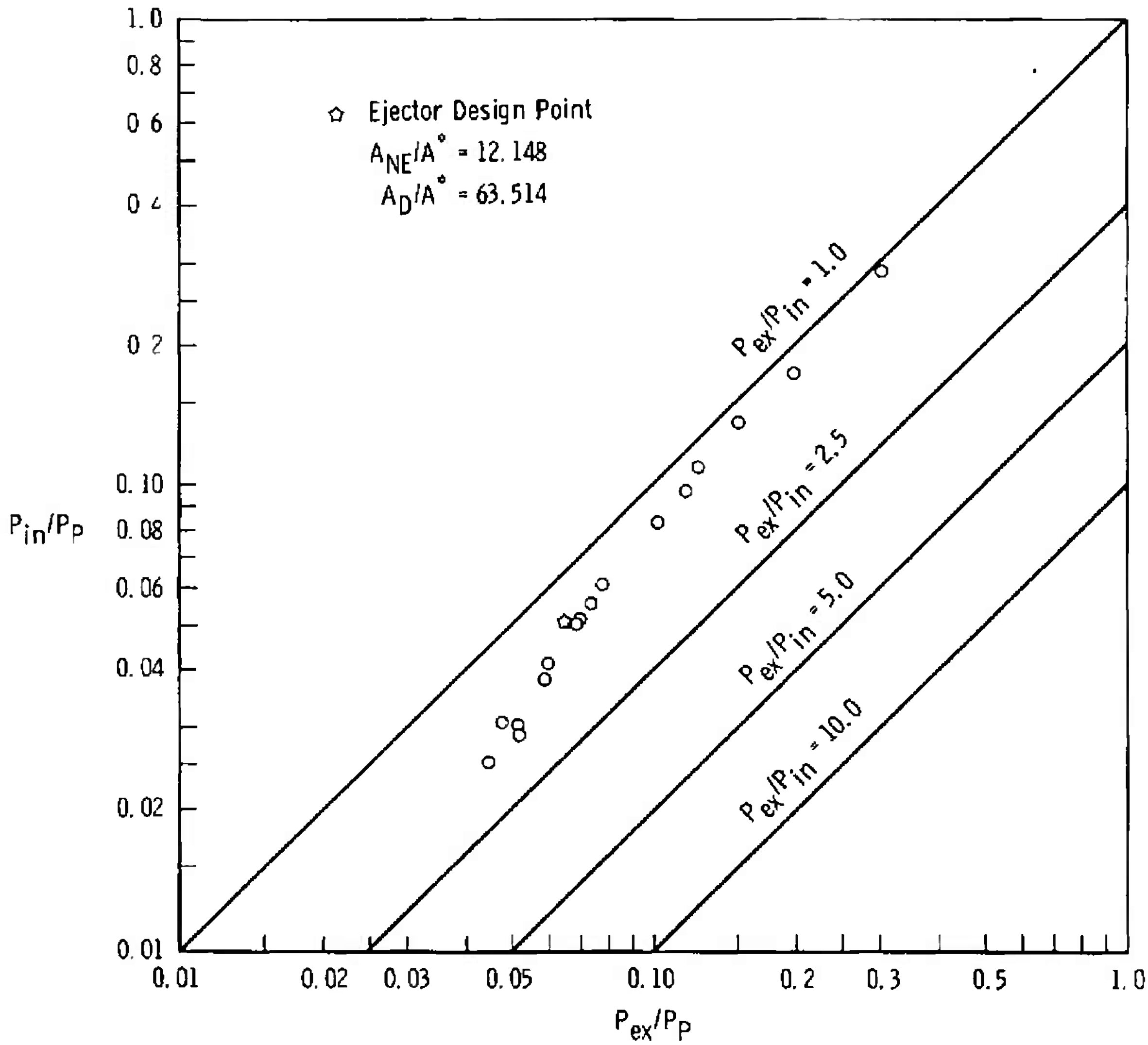
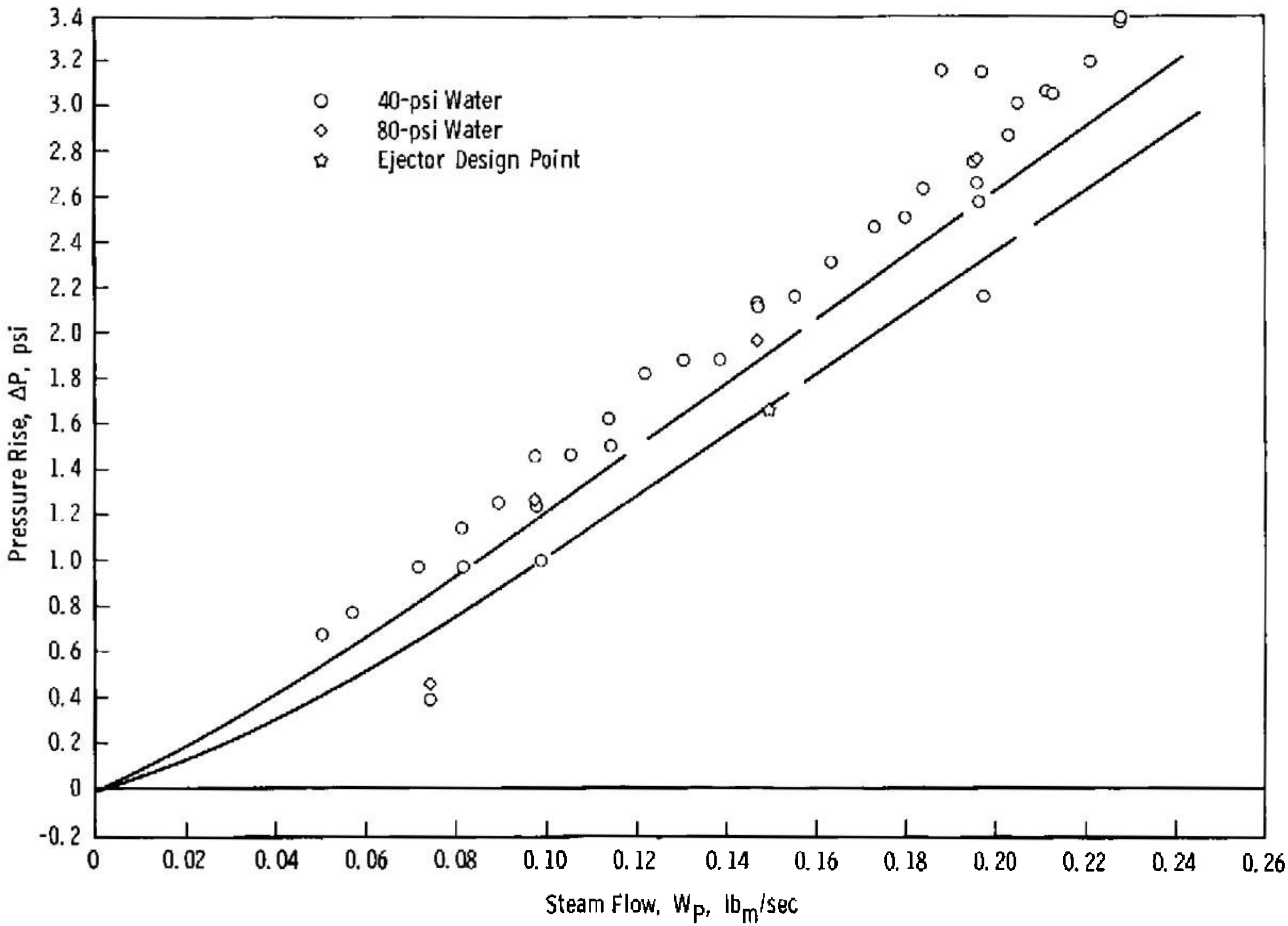
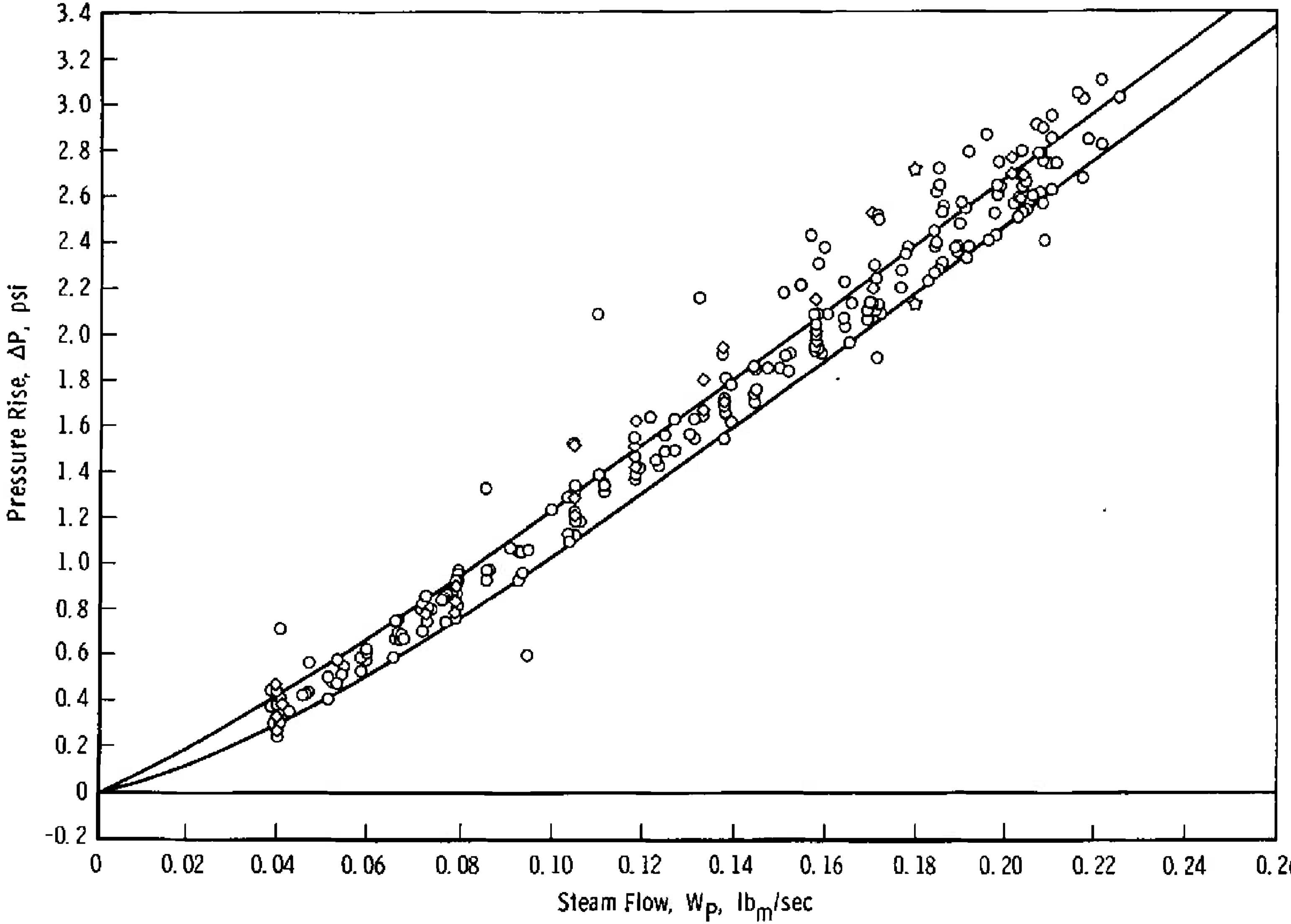


Fig. 6 Zero Flow Performance of Second Ejector



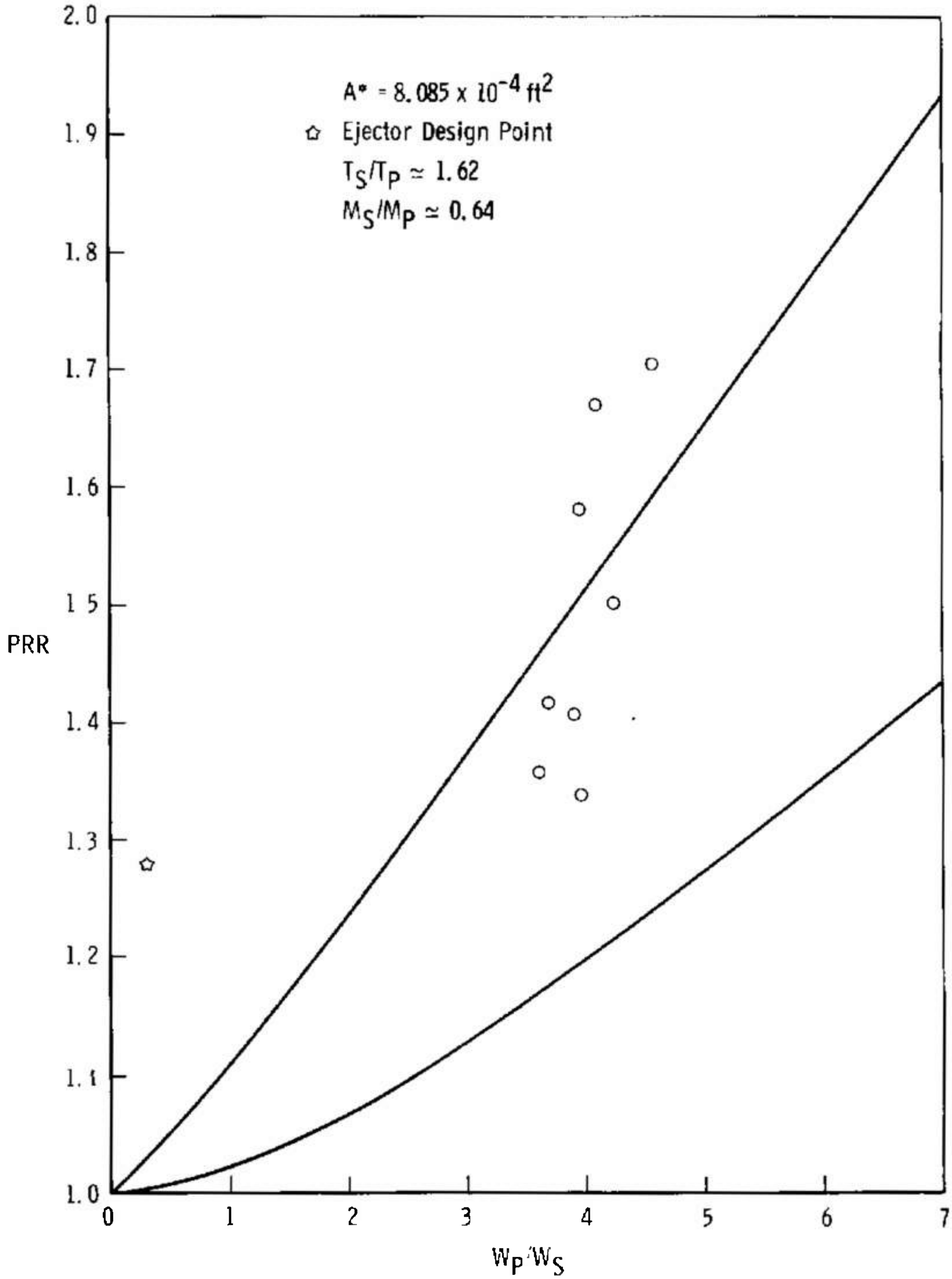
a. First Ejector

Fig. 7 ΔP Rise at Zero Flow



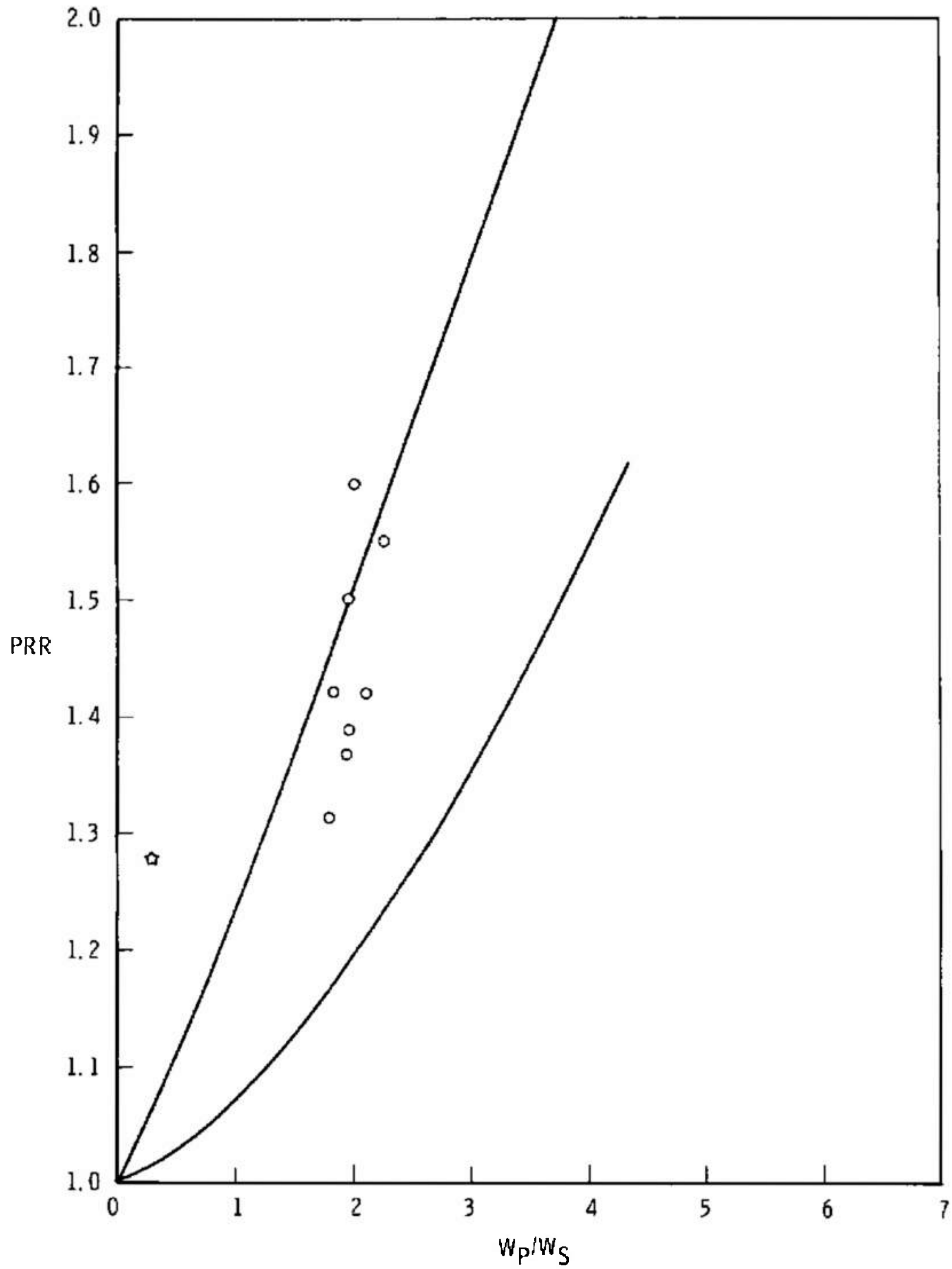
b. Second Ejector

Fig. 7 Concluded



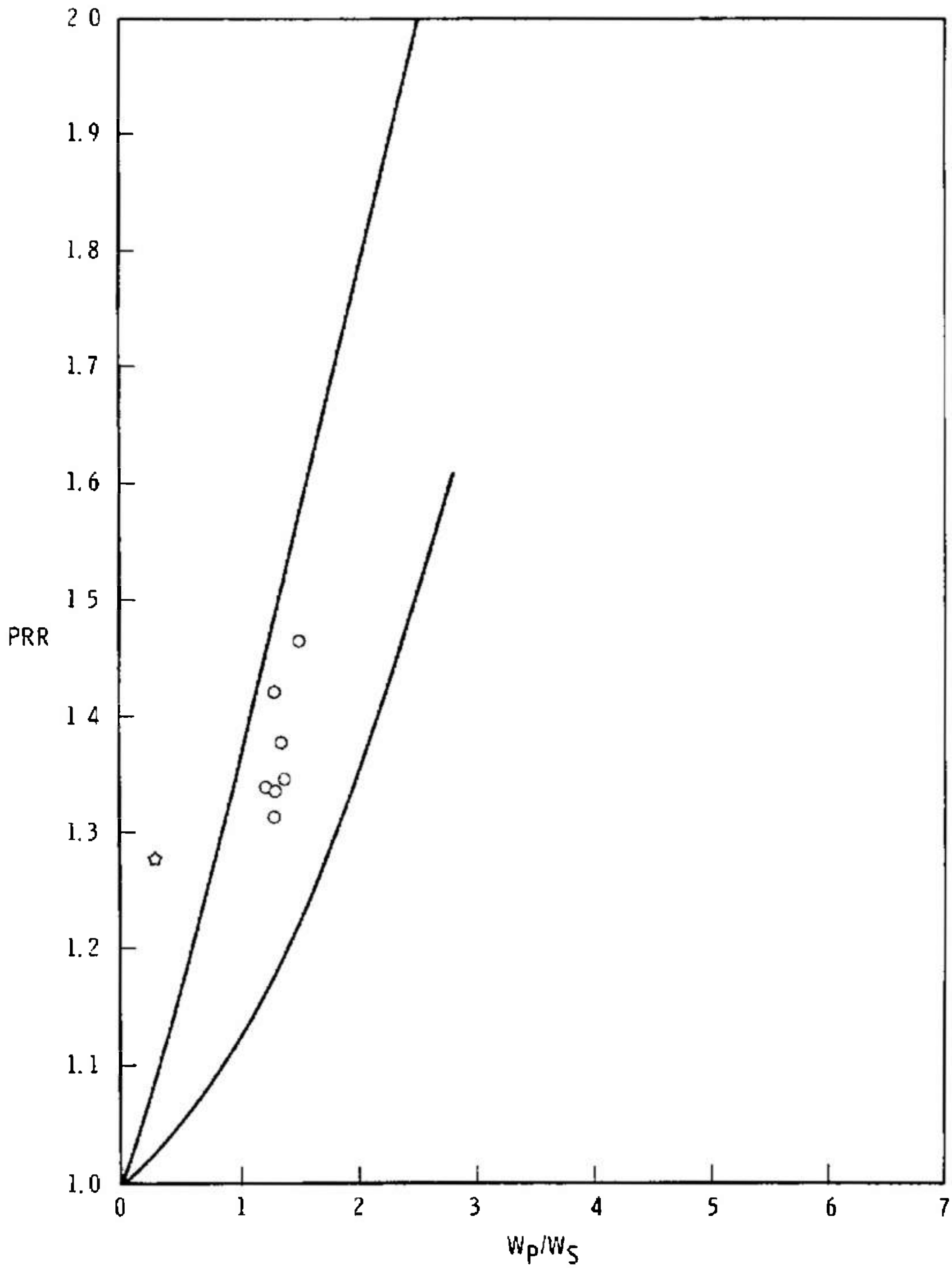
a. 0.05 lb_m/sec

Fig. 8 First Ejector Performance with Secondary Flow



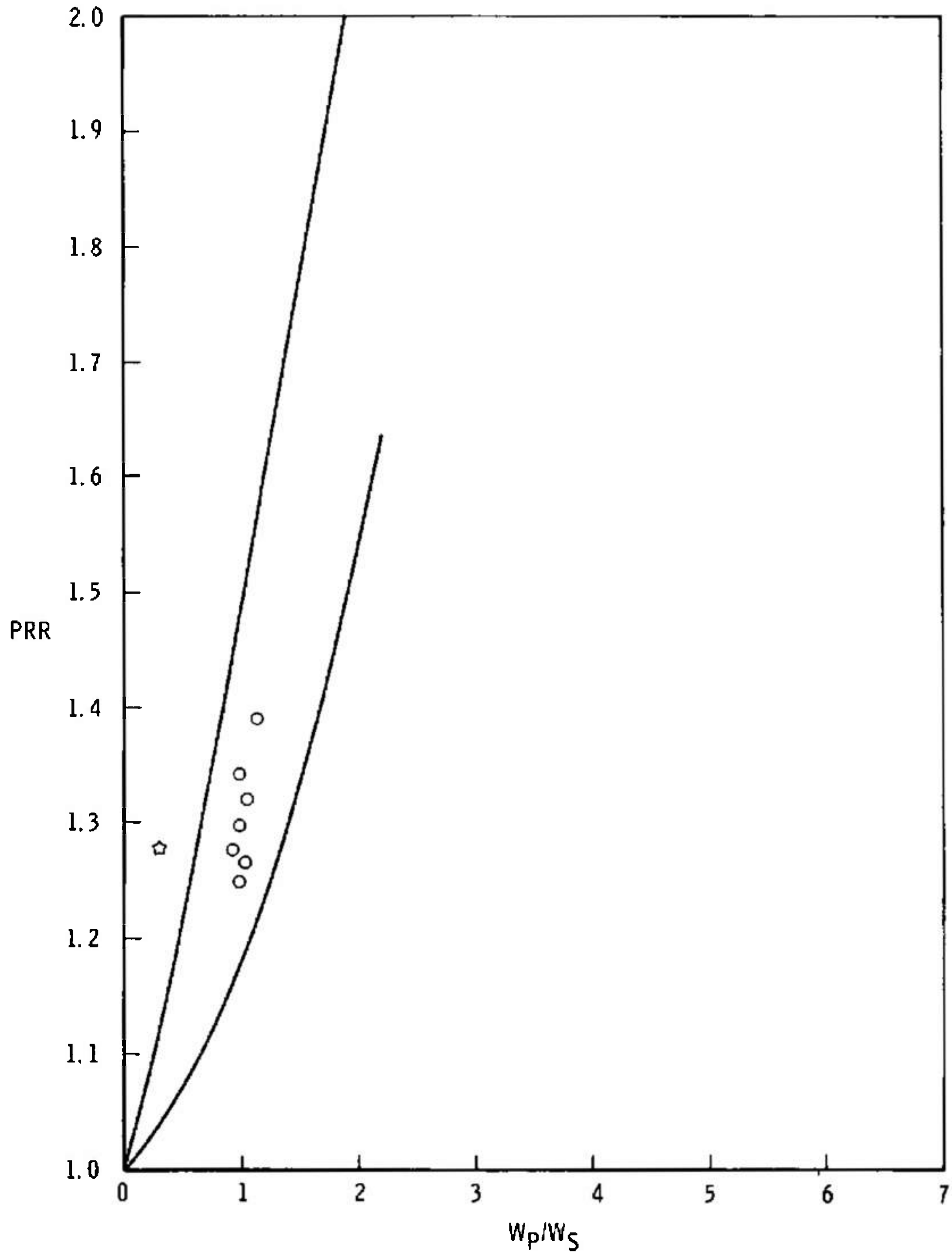
b. 0.10 lb_m/sec

Fig. 8 Continued



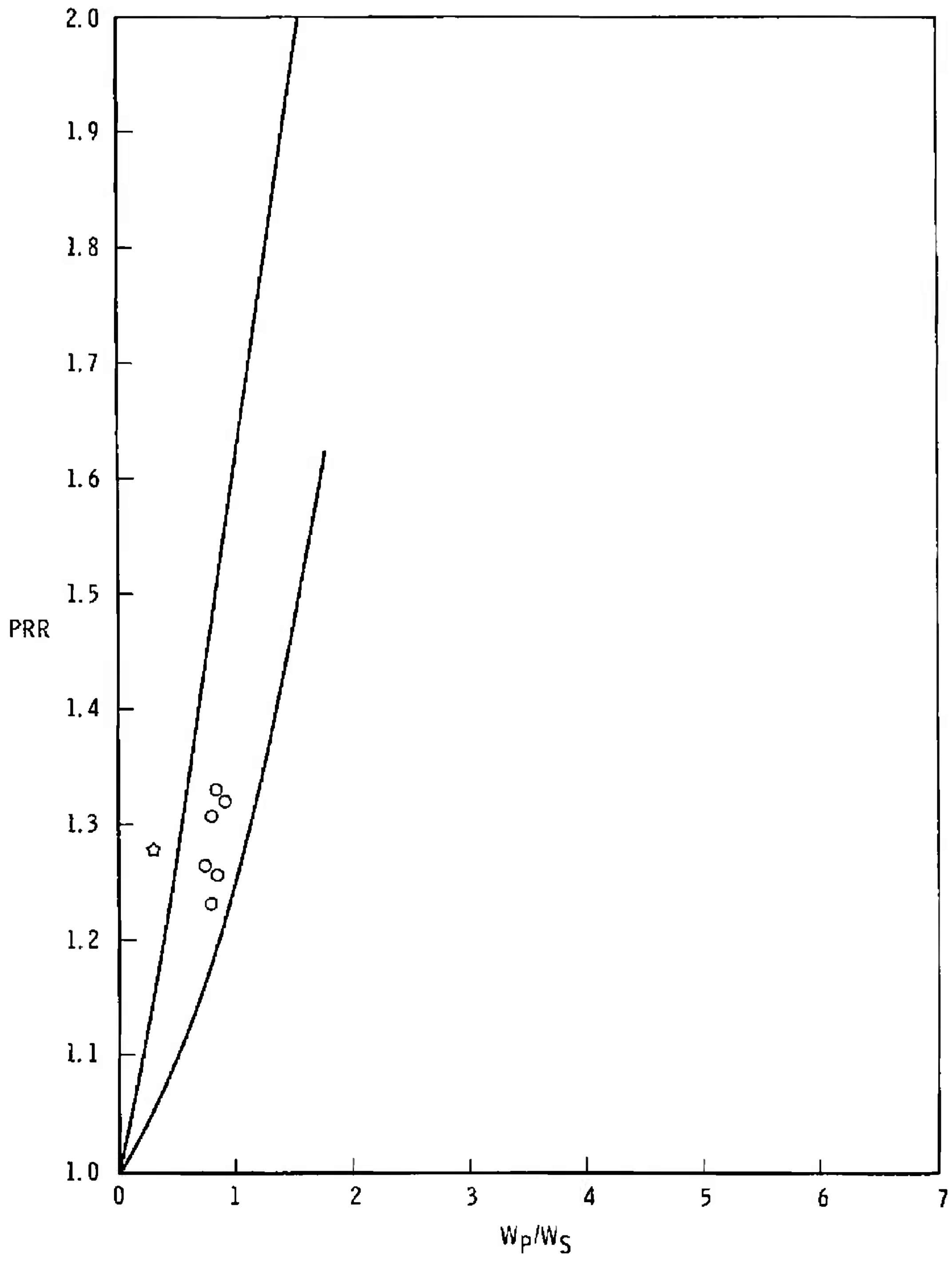
c. 0.15 lb_m/sec

Fig. 8 Continued



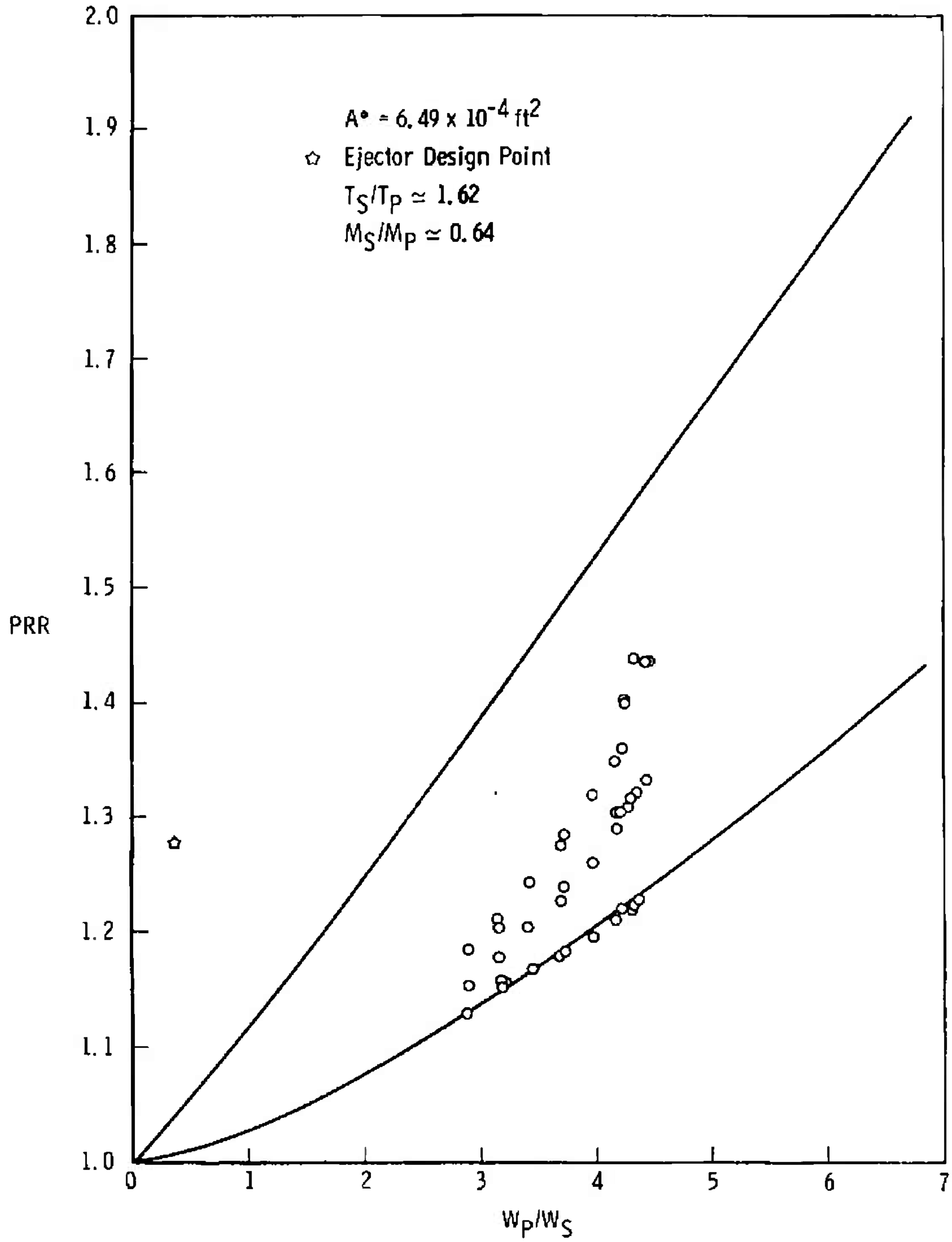
d. 0.20 lb_m/sec

Fig. 8 Continued



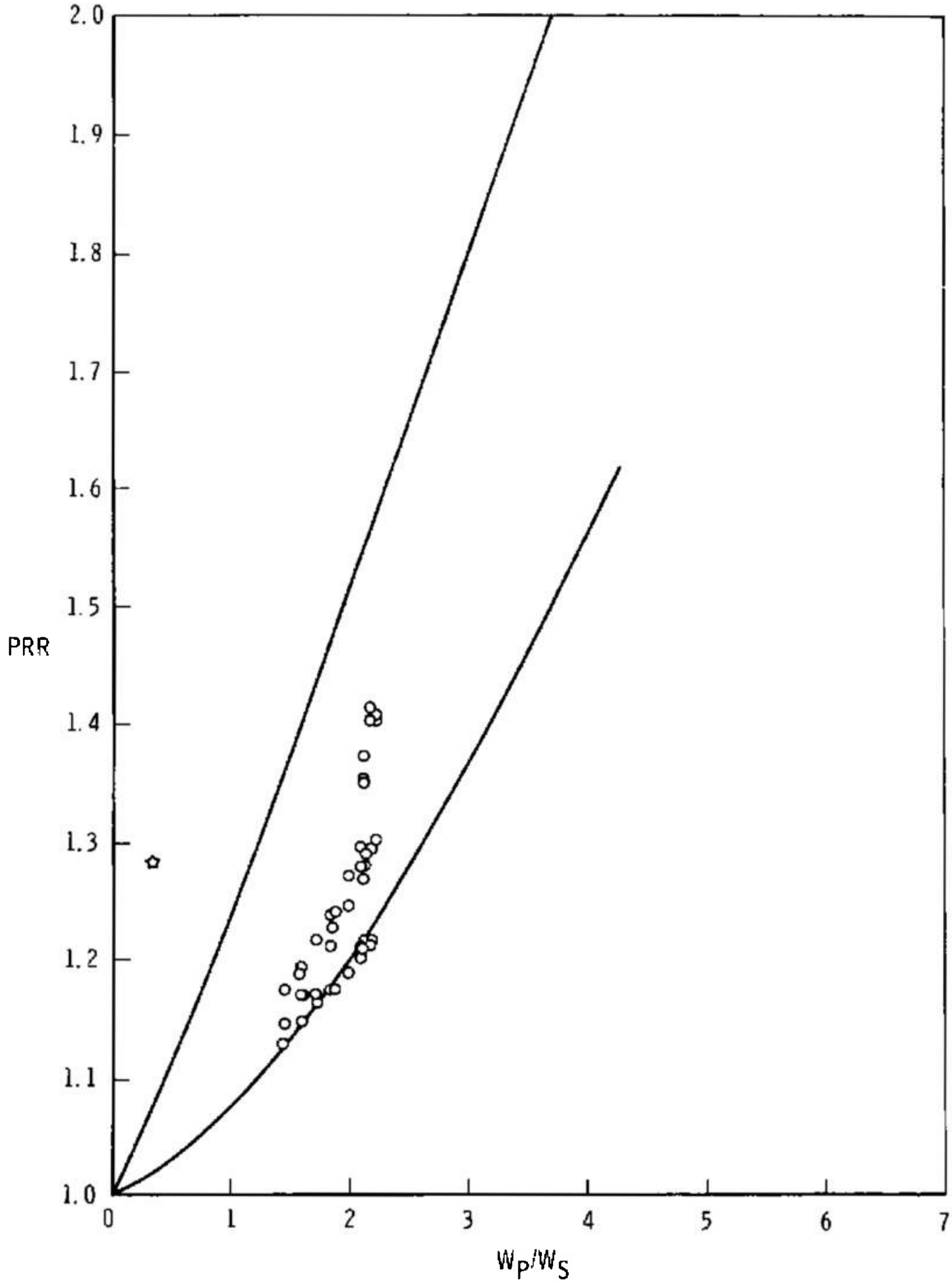
e. 0.25 lb_m/sec

Fig. 8 Concluded



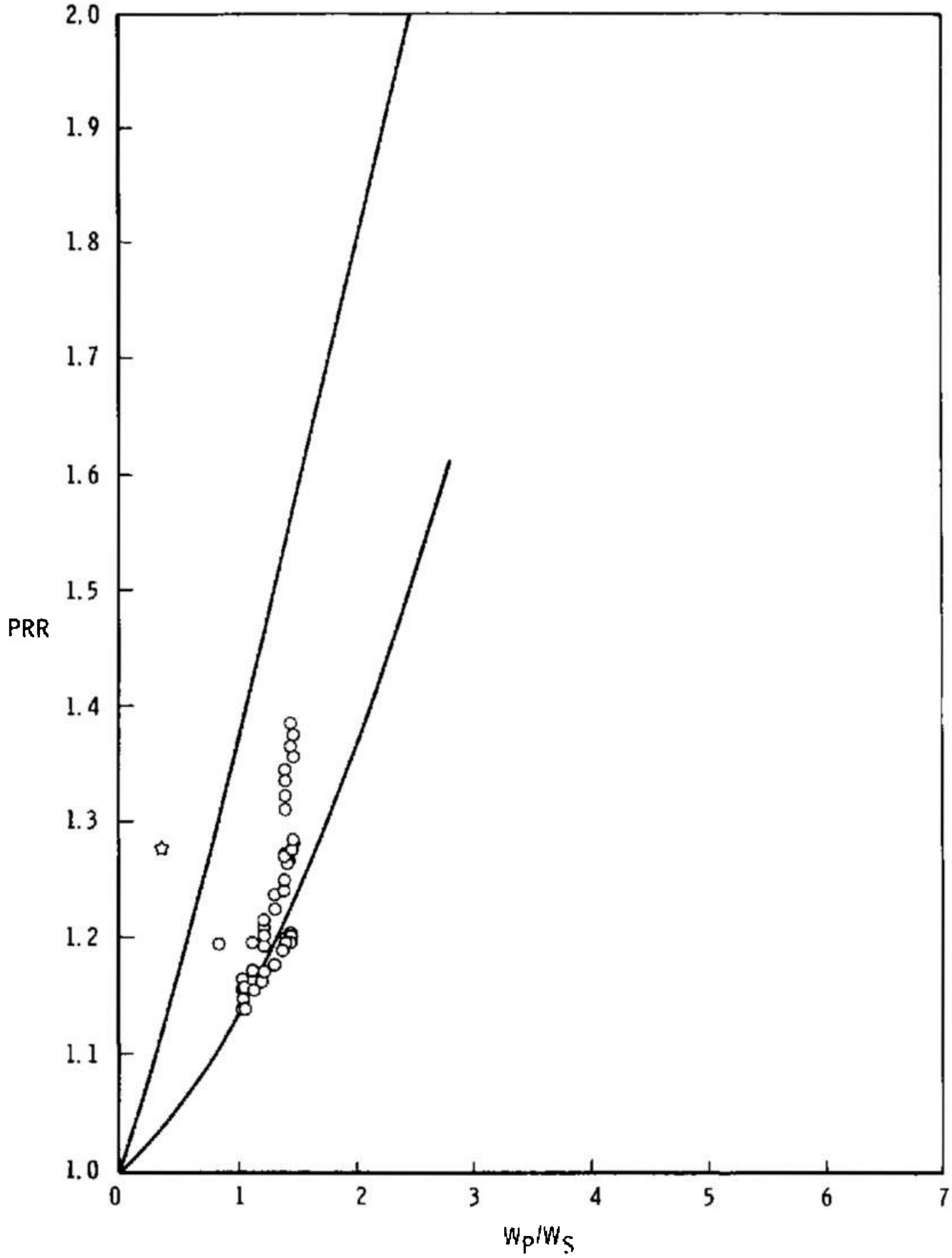
a. 0.05 lb_m/sec

Fig. 9 Second, Third, and Fourth Ejector Performance with Secondary Flow



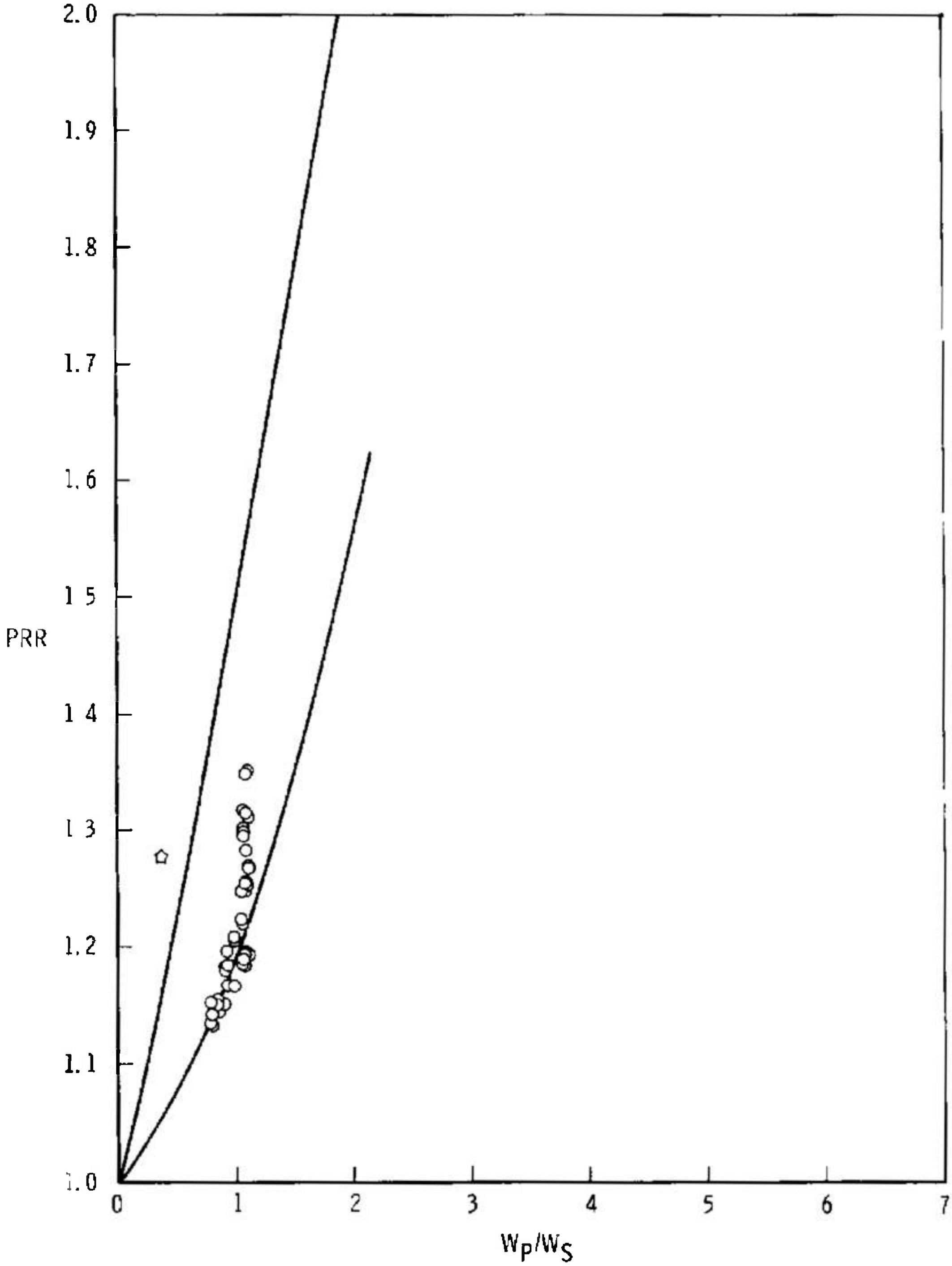
b. 0.10 lb_m/sec

Fig. 9 Continued



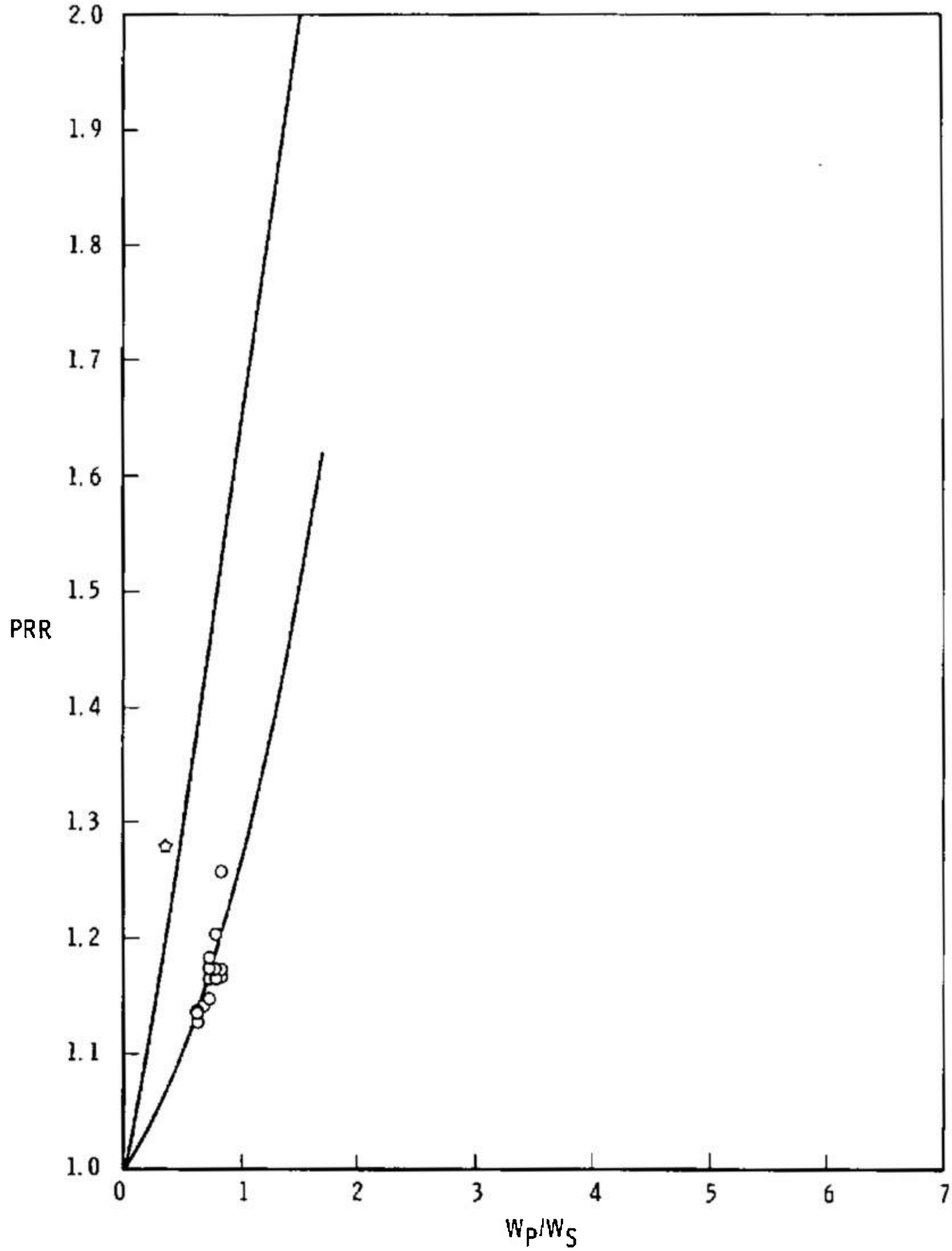
c. 0.15 lb_m/sec

Fig. 9 Continued



d. 0.20 lb_m/sec

Fig. 9 Continued



e. 0.25 lb_m/sec

Fig. 9 Concluded

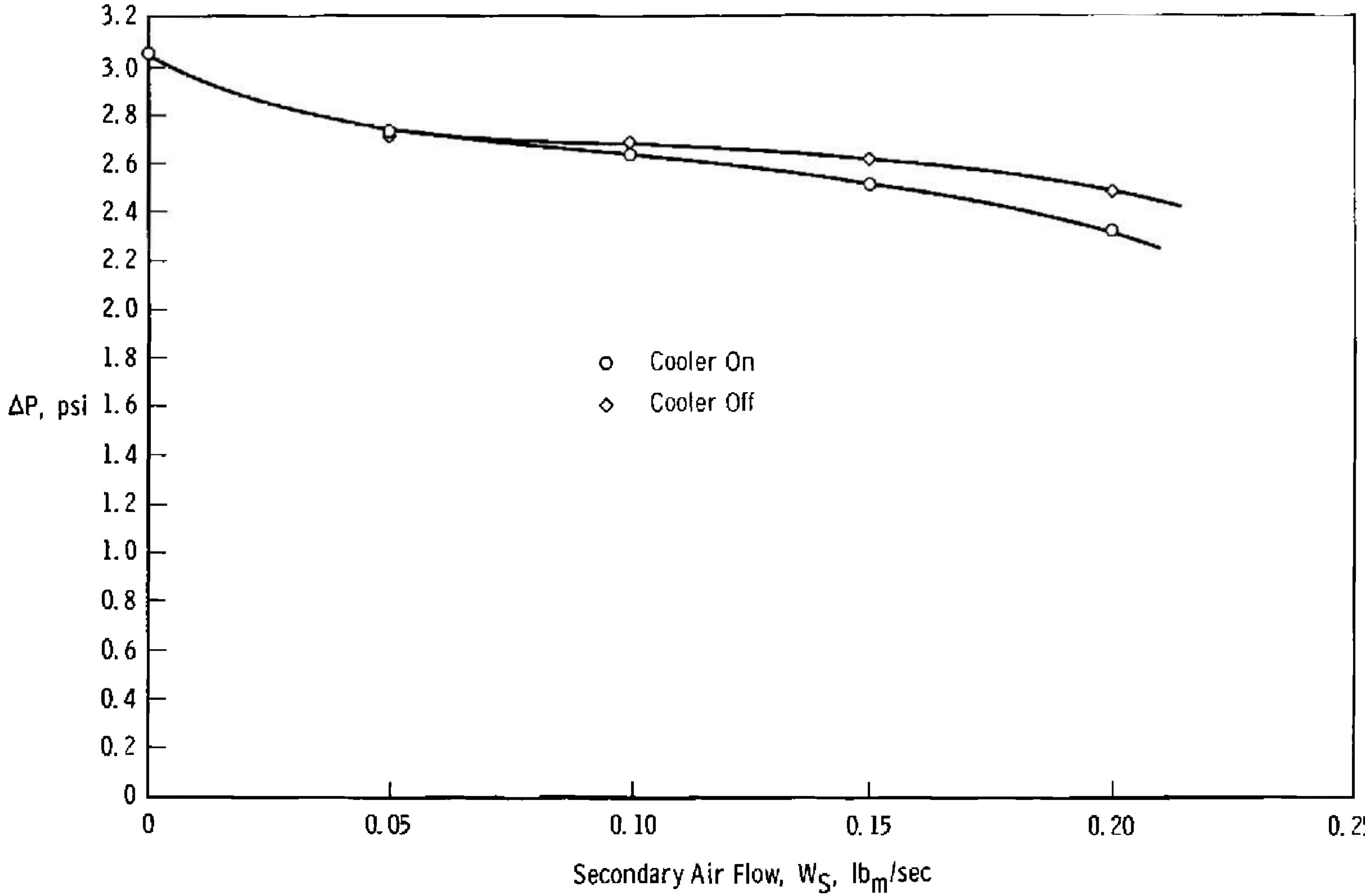


Fig. 10 Effect of Cooler on Pressure Rise of Second Ejector

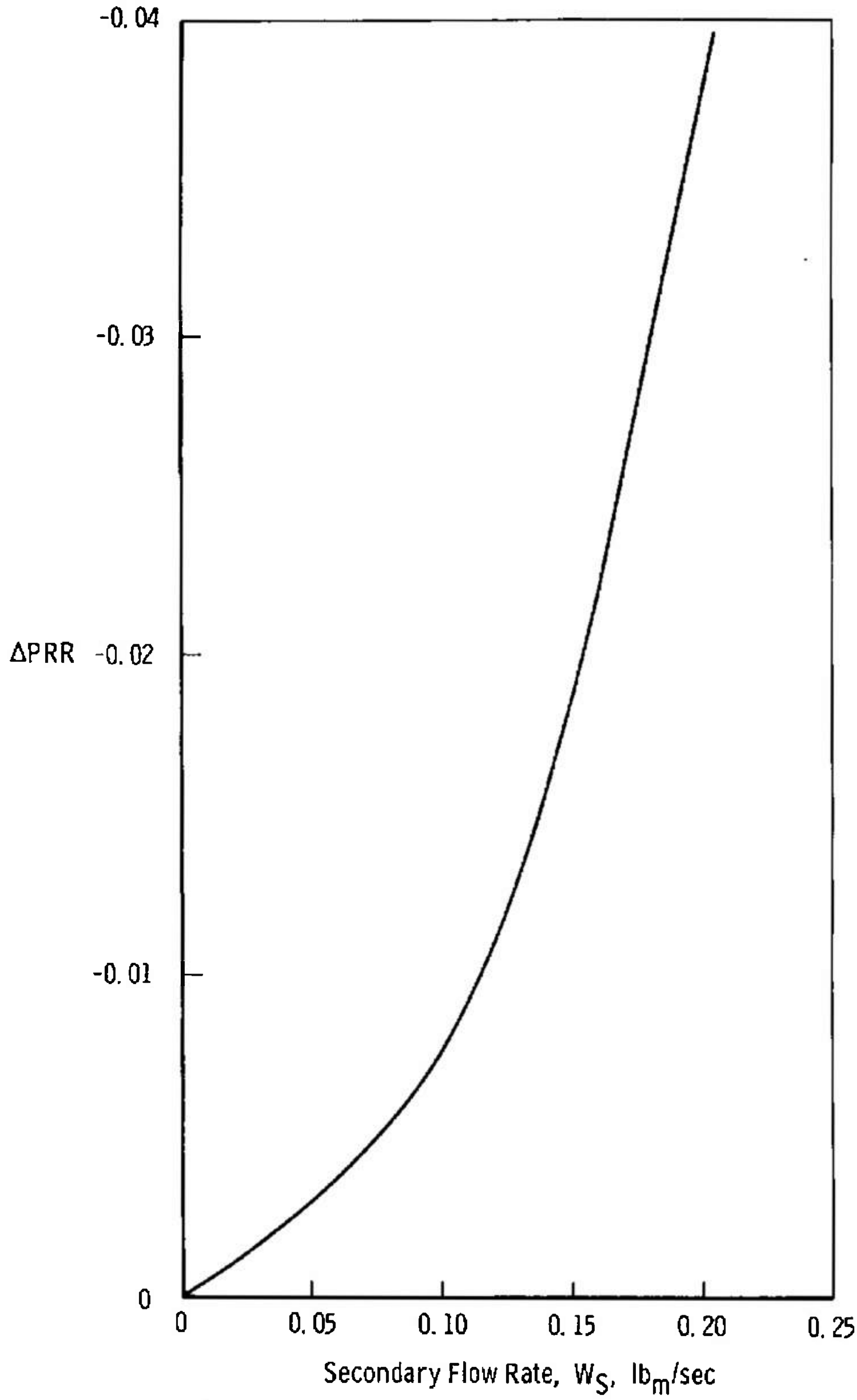


Fig. 11 Effect of Cooler on Pressure Rise Ratio of Second Ejector

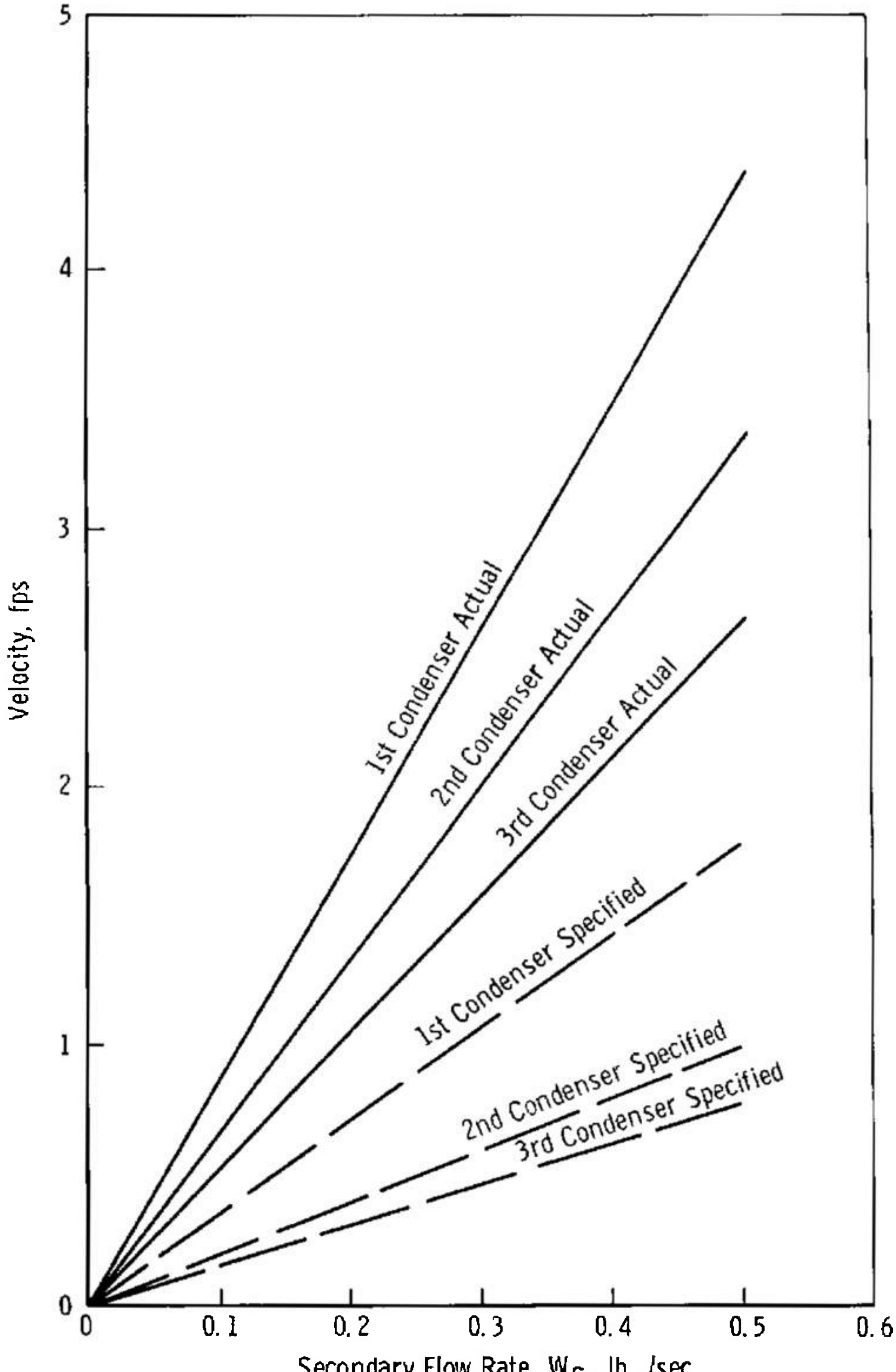


Fig. 12 Actual and Predicted Secondary Flow Velocity through Condensers

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4 DESCRIPTIVE NOTES (Type of report and inclusive dates)

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5 AUTHOR(S) (Last name, first name, initial)

F. H. Smith, Jr., ARO, Inc.

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13 ABSTRACT

One-dimensional analysis was used to design a staged steam ejector system. The system gives experimental results that are within the predicted performance envelope. The differences between the experimental results and theoretical predictions are critically examined. It was concluded (1) that the design of spray condensers between the ejector stages has an important influence on the overall performance of the system, (2) that the best system performance was obtained when the ejectors were operated at equal primary flow rates, and (3) that the effect of the Mach number of the secondary flow in the region of the ejector steam jet can have a great influence on ejector performance.

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Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
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Ejectors						
Staged Steam Ejectors						
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