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EXPERIMENTAL EVALUATION OF ROCKET EXHAUST DIFFUSERS FOR ALTITUDE SIMULATION

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SUMMARY

An experimental investigation of exhaust diffusers has been conducted to evaluate various methods of minimizing the overall pressure ratio (from chamber to ambient pressure) required to establish and maintain full expansion of the nozzle flow (altitude simulation). Exhaust-diffuser configurations investigated were (1) cylindrical diffusers, (2) diffusers with contraction, and (3) diffusers including a right-angle turn. Cylindrical diffusers were evaluated with primary nozzles of various area ratios and types, as well as two clustered configurations; the other diffusers were evaluated with individual nozzles of constant area ratio and varied type. Air was the working fluid, except for two check points obtained with JP-4 fuel and liquid-oxygen rocket engines and cylindrical diffusers.

The minimum length-diameter ratio of cylindrical diffusers was about 6 for minimum pressure-ratio requirements. With cylindrical diffusers of adequate length, the pressure-ratio requirements were primarily a function of the ratio of diffuser to nozzle-throat areas and were essentially independent of primary-nozzle type (including two clustered configurations) or area ratio. The two check points obtained with rocket engines indicated the pressure-ratio requirements at given ratios of diffuser to nozzle-throat areas were lowered, as compared with the requirements with air, as a result of the reduced ratio of specific heats.

The minimum length-diameter ratio of the contraction throat of convergent-divergent diffusers was also about 6 for minimum pressure-ratio requirements. With adequate contraction-throat length, the pressure-ratio requirements of such diffusers were appreciably below those of comparable cylindrical diffusers when used with conical and cutoff-isentropic nozzles, but not when used with a bell nozzle.

Minimum pressure-ratio requirements of a diffuser including a simple long-radius right-angle turn at maximum diffuser area, obtained with the center of radius of the turn a minimum of 2 diffuser diameters downstream of the nozzle exit, were not appreciably above those of a comparable optimum cylindrical diffuser. A diffuser including a long-radius right-angle turn at a contraction minimum area had somewhat lower pressure-ratio requirements than the aforementioned simple turn.

INTRODUCTION

For the upper stages of multistage space vehicles, rocket engines with large-area-ratio exhaust nozzles are desirable to take advantage of the high specific-impulse potential. In the development process, such engines must be operated under conditions that permit full expansion of the flow in the exhaust nozzle. To accomplish such operation at sea level, it is necessary to provide some means of reducing the pressure into which the flow from the exhaust nozzle discharges. Conventional altitude facilities may be used for this purpose, but these are limited in physical capabilities for handling large engines, as well as in number and location. It has been proposed that exhaust diffusers be used so as to utilize the energy of the rocket exhaust to establish and maintain a static-pressure rise in the diffuser and thus to provide a reduced pressure surrounding the exit of the exhaust nozzle. The process is similar to that in diffusers of supersonic tunnels. Exhaust diffusers have been used to extend the useful altitude range of conventional facilities in tests of turbojet and ramjet engines (ref. 1); similar application to tests of rocket engines was discussed in reference 2. The use of exhaust diffusers as the only means of providing altitude simulation for rocket performance evaluations has been reported (e.g., ref. 3), and the validity of the technique for this application has been established. Experimental evaluations of exhaust-diffuser (or ejector) design variables are reported in references 4 and 5.

The experimental investigation of exhaust diffusers reported herein was conducted at the NASA Lewis Research Center to evaluate various methods of minimizing the overall pressure ratio (from chamber to ambient pressure) required to establish and maintain full expansion of the nozzle flow (altitude simulation). This program used larger-scale configurations to check and extend the range of the investigations of references 4 and 5. Exhaust-diffuser configurations investigated were (1) cylindrical diffusers, (2) diffusers with contraction, and (3) diffusers including a right-angle turn. Primary-nozzle configurations included (a) an area-ratio range from 5.5 to 62.9, (b) conical, cutoff-isentropic, bell (ref. 6), and full-isentropic types, and (c) single- and clustered-nozzle installations. Air was the working fluid, except for two check points obtained with JP-4 fuel and liquid-oxygen rocket engines and cylindrical diffusers to indicate the influence of the ratio of specific heats on pressure-ratio requirements. Cylindrical diffusers were evaluated in conjunction with all nozzle configurations; the overall range of the ratio of diffuser to nozzle-throat areas was from 9.3 to 100.9. The other diffuser configurations were investigated with conical, cutoff-isentropic, and bell nozzles that had an area ratio of 25; the maximum ratio of diffuser to nozzle-throat areas was 28.9.

SYMBOLS

A	area
d	diameter
l	length
M	design Mach number
P	total pressure
p	static pressure
s	spacing from primary-nozzle exit
γ	ratio of specific heats

Subscripts:

a	ambient surrounding exhaust-diffuser exit
c	chamber
d	basic diffuser
e	exit of primary nozzle
r	upstream face of right-angle turn
s	start of contraction
t	throat of contraction
w	wall

Superscript:

*	throat of primary exhaust nozzle

APPARATUS

Cold-Flow-Air Primary Nozzles and Exhaust Diffusers

Installation and instrumentation. - A sketch of the cold-flow-air installation used in evaluating various exhaust-diffuser configurations is presented in figure 1. The assembly included an inlet-air duct, a primary (simulated rocket) nozzle, and an exhaust diffuser mounted in a 10-foot-diameter altitude test chamber. Dry air at a temperature of about 70° F was the working fluid. Inlet total pressure P_c of 55 to 70 pounds per square inch absolute was available. The exhaust diffuser discharged to ambient pressures p_a as low as 0.35 pound per square inch absolute in the altitude test chamber. Thus, a maximum pressure ratio P_c/p_a of 200 was available.

The location of pressure instrumentation is also indicated in figure 1. The primary measurements were: (a) inlet total pressure P_c (corresponding to rocket-chamber pressure), (b) primary-nozzle-exit wall static pressure p_e, and (c) ambient static pressure p_a in the altitude test chamber. Additional wall static pressures were measured along the divergent section of the primary nozzles and along the length of the exhaust diffusers. Steady-state pressure measurements were recorded by means of a digital automatic pressure-recording system.

<u>Primary nozzles</u>. - The nozzle configurations are summarized in table I. Most of the configurations included a single nozzle, but two multiple-nozzle configurations were also used. An area-ratio range from 5.5 to 50.0 was provided with conical nozzles. The two multiple-nozzle configurations used clusters of two and four conical nozzles, each with an area ratio of 17.3. Conical, cutoff-isentropic, and bell (Rao's method, ref. 6) nozzles with an area ratio of 25.0 were utilized, and the contours of these nozzles are presented for comparison in figure 2.

In addition, two full-isentropic nozzles were used, and the contours of these nozzles are presented in figure 3. The area ratios were 27.3 and 62.9, and the design Mach numbers were 5.018 and 6.00, respectively. These configurations were more representative of nozzles for supersonic tunnels than for rocket engines because of their length, but were included to extend the range of nozzle type and area ratio. The nozzle with an area ratio of 62.9 was appreciably larger than other configurations used and was tested in a separate altitude facility. The inlet and ambient pressures were similar to those previously described, and the inlet temperature was about 800° F.

<u>Exhaust diffusers</u>. - The following configurations were investigated: (1) cylindrical diffusers, (2) diffusers with contraction (area reduction), and (3) diffusers including a right-angle turn.

Cylindrical exhaust-diffuser configurations are summarized in table II and illustrated in figure 4. Cylindrical diffusers were evaluated with all primary-nozzle configurations, including single and clustered nozzles, as illustrated in figures 4(a) and (b), respectively. Standard pipes of selected diameters were used for the diffusers. For

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convenience, diffusers used with the shorter nozzles were attached at the nozzle inlet, whereas those used with the full-isentropic nozzles were attached in the plane of the nozzle exit, as illustrated in figure 4(a). Diffuser variables evaluated included area ratio A_d/A^* and length-diameter ratio, l_d/d_d.

Exhaust diffusers with contraction are summarized in table III and illustrated in figure 5. Two types were investigated: (1) cylindrical diffusers containing conical contraction and (2) convergent-divergent diffusers. Primary nozzles of varied type but constant area ratio (25.0) were used, and the basic diffuser area ratio A_d/A^* was held constant (28.9). In the case of cylindrical diffusers containing conical contraction, the variables include contraction ratio A_t/A_d, spacing ratio s_s/d_d, contraction semiangle, and overall length-diameter ratio l_d/d_d. In the case of convergent-divergent diffusers, the variables include spacing ratio s_s/d_d and contraction-throat length-diameter ratio l_t/d_t (and thus overall l_d/d_d); contraction ratio was held constant, and the exit area of the divergent section was equal to the basic diffuser area A_d.

Exhaust diffusers including a right-angle turn are summarized in table IV and illustrated in figure 6. The configurations evaluated were (1) a simple long-radius turn at the basic diffuser diameter, with the turn spacing ratio s_r/d_d a variable (fig. 6(a)); (2) the aforementioned simple turn including conical contraction with $s_r/d_d = 1.0$ (fig. 6(b)); and (3) a simple long-radius turn at a contraction minimum area ($A_t/A_d = 0.60$, fig. 6(c)). Primary-nozzle and basic diffuser area ratios, A_e/A^* and A_d/A^*, were held constant at 25.0 and 28.9, respectively.

Rocket and Cylindrical Exhaust Diffusers

A sketch of the rocket installation used in evaluating two exhaust-diffuser configurations is presented in figure 7. The rocket engine provided a nominal thrust of 1000 pounds at a combustion-chamber pressure of 600 pounds per square inch absolute; JP-4 fuel and liquid oxygen were used as the propellant combination. The engine assembly, including the thrust system, was totally enclosed in a capsule, which consisted of a semicylindrical cover that was clamped to the engine mounting stand. The capsule isolated the rocket assembly from ambient-pressure forces and prevented any secondary flow into the system. Water-cooled cylindrical exhaust diffusers were bolted to the capsule. Two configurations of conical engine exhaust nozzle (table I) and cylindrical exhaust diffuser (table II) were evaluated; nozzle area ratio A_e/A^* and the associated diffuser area ratio A_d/A^* were the primary variables.

PROCEDURE

Tests of each configuration began with maximum chamber pressure P_c and a low ambient pressure p_a. At constant chamber pressure, the ambient pressure was slowly increased until a sudden rise in the nozzle-exit pressure p_e was observed. The minimum overall pressure ratio P_c/p_a for which the primary-nozzle-exit pressure was not affected is termed the breakdown pressure ratio. Then, starting from a condition of constant chamber pressure but an ambient pressure high enough that the nozzle-exit pressure was also high, the ambient pressure was slowly decreased until the nozzle-exit pressure returned to its minimum value, indicating full expansion of the flow through the nozzle. The overall pressure ratio P_c/p_a at the point where the nozzle-exit pressure just reached its minimum value is termed the starting pressure ratio. The starting and breakdown pressure ratios are discussed further in the following section.

RESULTS AND DISCUSSION

The principle in the application of exhaust diffusers to the testing of rocket engines is that of accomplishing supersonic compression of the exhaust gases and thus using the energy of the exhaust to provide and maintain a static-pressure rise in the diffuser in the manner of diffusers of supersonic tunnels. If this compression is accomplished satisfactorily, the design pressure ratio of the exhaust nozzle P_c/p_e will be provided, while the overall pressure ratio P_c/p_a will be much less than P_c/p_e because of the pressure rise in the diffuser. Exhaust-diffuser design variables will affect the efficiency of the supersonic compression process and thus the overall pressure-ratio requirements.

Supersonic compression is accomplished through a shock system. A discussion of supersonic compression in cylindrical ducts is given in reference 7, wherein the compression is indicated to be basically a normal-shock process. However, the compression shock is not a planar discontinuity, because interaction between the shock system and the boundary layer results in backflow and separation. The main stream separates from the wall and alternately passes through a series of accelerations and shocks until subsonic flow is obtained. The flow then diverges and fills the diffuser again. A substantial diffuser length is required to establish the complete shock system.

Illustrative Diffuser Performance

Typical cylindrical-exhaust-diffuser characteristics are presented in figure 8. The configuration included a conical primary nozzle with an area ratio A_e/A^* of 25 and a cylindrical exhaust diffuser with an area ratio A_d/A^* of 28.9 and a length-diameter ratio l_d/d_d of 12. The wall static-pressure distribution, presented as p_w/P_c, along the divergent section of the nozzle and the length of the diffuser is shown in figure 8(a) for four values of overall pressure ratio P_c/p_a. At high overall pressure ratio, supersonic flow existed in the nozzle divergent section and several diffuser diameters into the diffuser. Thereafter, a compression-shock system increased the pressure in the diffuser to approximately ambient pressure at the diffuser exit. As the overall pressure ratio was decreased, the shock system in the diffuser moved upstream toward the nozzle. When the overall pressure ratio was reduced below a minimum value of about 23, the shock system moved into the nozzle and thus affected the expansion process in the nozzle. It can be observed that, at overall pressure ratios for which the expansion process in the primary nozzle was not affected, the "altitude" pressure in the diffuser at the plane of the nozzle exit was less than the nozzle-exit pressure. Thus, the primary nozzle was operating underexpanded, and the flow expanded further in filling the diffuser.

To illustrate further the aforementioned minimum overall pressure ratio, primary-nozzle pressure ratio, presented as p_e/P_c, is shown as a function of overall pressure ratio P_c/p_a in figure 8(b). At overall pressure ratios above the minimum value of about 23, the nozzle pressure ratio was constant at a minimum value, and the expansion process in the nozzle was unaffected. As overall pressure ratio was reduced below the minimum value, the nozzle pressure ratio increased rapidly. For the case illustrated, starting and breakdown pressure ratios (as defined in PROCEDURE) were equal; for some configurations to be discussed, this was not true.

Cylindrical Exhaust Diffusers

Diffuser length-diameter ratio. - The effect of overall diffuser length-diameter ratio l_d/d_d on the minimum overall starting and breakdown pressure ratios P_c/p_a of typical cylindrical-diffuser configurations is shown in figure 9. Data are presented for three diffuser area ratios. Primary-nozzle area ratio was varied with diffuser area ratio; and, at one nozzle area ratio, data are presented for three nozzle types.

The minimum diffuser length-diameter ratio l_d/d_d was about 6 for minimum pressure-ratio P_c/p_a requirements for the range of diffuser area ratio investigated. At values of diffuser l_d/d_d of 6 or greater, starting and breakdown pressure ratios were equal and were relatively unaffected by diffuser l_d/d_d or primary-nozzle type. As diffuser l_d/d_d was decreased below 6, the pressure-ratio requirements rapidly increased and were influenced by primary-nozzle type. Also, starting and breakdown pressure ratios were no longer equal. There is a trend for minimum pressure-ratio requirements to increase with diffuser area ratio.

It was observed in reference 5 that the minimum overall starting pressure ratios of cylindrical diffusers, with and without a subsonic diffuser with an area ratio of 2, occurred at overall diffuser length-diameter ratios between 8 and 10 for all configurations investigated. Because of the relative insensitivity of pressure-ratio requirements to diffuser length-diameter ratio at values of 6 or greater, there is general agreement in the results of the two investigations.

Diffuser area ratio. - The variation of minimum overall starting and breakdown pressure ratios P_c/p_a with diffuser area ratios A_d/A^* is presented in figure 10(a) for the primary-nozzle and cylindrical-diffuser configurations investigated with air as the working fluid. Diffuser overall length-diameter ratio l_d/d_d was 6 or greater in all cases. Two theoretical curves of normal-shock pressure ratios as functions of area ratio, based on one-dimensional theory, are presented for comparison with the experimental results. Normal-shock total- to static-pressure ratio represents theory for the constant-area ducts as tested, whereas normal-shock total-pressure ratio represents theory for subsonic diffusion to zero velocity.

As expected, the experimental minimum pressure ratios increased as diffuser area ratio was increased. A single curve represents with reasonable accuracy experimental data from all configurations investigated. The primary-nozzle configurations included (1) a range of area ratios A_e/A^* from 5.5 to 62.9, (2) a range of types from the simple conical to the full-isentropic, and (3) single- and clustered-nozzle installations. The cylindrical-diffuser configurations included (1) diffuser area ratios A_d/A^* greater than primary-nozzle area ratio A_e/A^* in all cases, (2) a range of diffuser area ratios at constant primary-nozzle area ratio with each of three conical nozzles (A_e/A^*, 5.5, 11.7, and 25.0) and the largest-area-ratio full-isentropic nozzle, and (3) a total diffuser-area-ratio range from 9.3 to 100.9.

The experimental results of figure 10(a) show that the minimum pressure-ratio requirements of cylindrical-exhaust-diffuser configurations were primarily a function of diffuser area ratio and essentially independent of primary-nozzle area ratio or type. Within limitations of available overall pressure ratio, a wide range of diffuser area ratios can be used with a given primary-nozzle area ratio. Minimum pressure-ratio requirements, however, would be obtained as diffuser area approached nozzle-exit area. The primary influence of nozzle area ratio, then, is that it approximately determined the minimum usable diffuser area ratio. It is necessary, however, that the diffuser area be somewhat greater than that of the nozzle exit to prevent nozzle-diffuser interactions; two examples of this follow. In the present investigation, attempts were made to operate a full-isentropic nozzle, $A_e/A^* = 27.3$, while using a cylindrical diffuser of equal area ratio (configuration noted in table II); however, it was not possible to establish full expansion of the nozzle flow at overall pressure ratios as high as 188. With the same nozzle but with a diffuser area ratio of 43.5 (not intended to be optimum), the starting pressure ratio was 37 and agreed reasonably well with the trend of the other data of figure 10(a). In another investigation of a particular nozzle-diffuser combination, comparative pressure-ratio requirements were determined for two cases: (1) There was a normal step increase in area from the primary-nozzle exit to the diffuser, and (2) the step at the primary-nozzle exit was filled so as to extend the original conical nozzle to the particular diffuser area. The pressure ratio required to establish full expansion of the original nozzle flow was observed to increase when the step was filled.

Two configurations were investigated that included clusters of either four or two conical primary nozzles, each with an area ratio of 17.3, contained within a single cylindrical exhaust diffuser. Based on the ratio of diffuser area to the sum of the nozzle-throat areas, the diffuser area ratios A_d/A^* for the four- and two-nozzle cluster configurations were 28.9 and 57.8, respectively. The experimental pressure-ratio requirements of these configurations, which are included in figure 10(a), correlate well with the single-nozzle requirements on the basis of the aforementioned definition of diffuser area ratio.

The experimental cold-flow-air pressure-ratio requirements, as represented by the curve of figure 10(a), were higher than normal-shock total- to static-pressure ratios by from about 13 percent at very low diffuser area ratio to about 5 percent at high diffuser area ratios. The agreement is such as to substantiate the theory that the compression in cylindrical diffusers is basically a normal-shock process. The addition of subsonic diffusers to the cylindrical diffusers was not evaluated in the present investigation, but the potential reductions in pressure-ratio requirements are indicated by the differences between the curves of normal-shock total- to static-pressure ratio and total-pressure ratio.

The experimental minimum pressure-ratio requirements of the two configurations, in which cylindrical exhaust diffusers were used in conjunction with JP-4 fuel and liquid-oxygen rocket engines, are presented in figure 10(b). The faired cold-flow-air results (fig. 10(a)) and normal-shock pressure ratios for a ratio of specific heats γ of 1.2 are included for comparative purposes. The experimental minimum pressure ratios increased with diffuser area ratio as did the cold-flow-air results, but were lower than the cold-flow-air minimum pressure ratios at given diffuser area ratios because of the reduced ratio of specific heats. The two data points agree well with normal-shock total-to static-pressure ratios for $\gamma = 1.2$.

Cold-flow starting-pressure-ratio data from reference 5 for cylindrical diffusers are presented in figure 11 and compared with the faired results from the present investigation. Data are included for cylindrical diffusers with and without a subsonic diffuser with an area ratio of 2. The results from reference 5 agree well with those of the present investigation and indicate small reductions (5 to 9 percent) in pressure-ratio requirements through use of the added subsonic diffusion. E-395

Exhaust Diffusers with Contraction

Because the diffuser pressure recovery is basically a normal-shock process, as was indicated, area reduction to reduce the stream Mach number at which the main shock system initiates would be expected to improve the diffuser pressure recovery and reduce the overall pressure-ratio requirements. Two types of exhaust diffuser with contraction (area reduction) were investigated. These were described previously and included (1) the cylindrical diffuser containing conical contraction (fig. 5(a)), and (2) the convergent-divergent diffuser (fig. 5(b)). The convergent-divergent diffuser with a length of constant-area contraction throat was more in keeping with the theory of the multishock pressure-recovery system.

Nozzle-to-contraction spacing. - It was observed early in the investigation of exhaust diffusers with contraction that the spacing between the primary-nozzle exit and the contraction influenced pressure-ratio requirements. This influence is shown in figure 12, where starting pressure ratios P_c/p_a are shown as functions of the contraction spacing ratio s_s/d_d. In general, the starting pressure ratio decreased somewhat as the contraction spacing ratio was reduced. When using contracted diffusers in conjunction with the conical primary nozzle, it was observed that the nozzle could not be started for contraction spacing ratios investigated below 0.5 nor above 1.5. With the cutoff-isentropic nozzle and the convergent-divergent diffuser, however, it was possible to reduce the contraction spacing ratio to 0.125; lower spacing ratios were not evaluated, but it appeared that flow separation would have been encountered. It is believed that the exit wall angle (or exit flow angle) of the primary nozzle affects the minimum permissible contraction spacing ratio. For higher nozzle-exit wall angles (e.g., the conical nozzle as compared with the cutoff-isentropic nozzle), the flow must negotiate a turn through a greater angle to enter the contraction and thus requires a larger contraction spacing ratio to permit full expansion of the flow. For the convergent-divergent diffuser, there is a trend for starting pressure ratio to decrease as the length-diameter ratio of the contraction throat l_t/d_t is increased.

In the investigation of reference 5, a contraction spacing ratio of zero could be used to start all configurations investigated, and the only starting limitation occurred at maximum spacing ratios. The maximum spacing ratio varied from 0.2 to about 2.68 and was dependent on primary-nozzle type as well as the amount and angle of contraction. A spacing ratio of 0.2 was satisfactory for all configurations and was used for those evaluated in detail. The reason for the discrepancy between the results of the two investigations relative to contraction spacing ratio is not known.

In the present investigation, most of the experimental data from exhaust diffusers with contraction were obtained with a contraction spacing ratio of 0.5; all results presented hereafter are for this spacing ratio.

Cylindrical diffusers containing conical contraction. - The performance of cylindrical exhaust diffusers containing conical contraction is presented in figure 13 as the variation of starting and breakdown pressure ratios P_c/p_a with overall diffuser length-diameter ratio l_d/d_d. Data are included for a range of contraction ratios and two contraction angles. Therefore, a shaded band has been used to show the trend of the experimental results. For comparative purposes, the curve for cylindrical diffusers without contraction is included in the figure. Minimum overall diffuser length-diameter ratio was again about 6 for minimum pressure-ratio requirements. Starting and breakdown pressure ratios were equal over the range of diffuser l_d/d_d for the configurations investigated. It is apparent that the contained conical contraction produced only small reductions in pressure-ratio requirements as compared with the cylindrical-diffuser configuration.

Convergent-divergent diffusers. - The performance of convergent-divergent exhaust diffusers with a conical primary nozzle is presented in figure 14 in terms of the variation of starting and breakdown pressure ratios with contraction-throat length-diameter ratio l_t/d_t and thus with overall diffuser length-diameter ratio l_d/d_d. Available data from the use of the longest convergent-divergent diffuser with two other nozzle types are also presented. The starting-pressure-ratio curve for cylindrical diffusers used with the conical primary nozzle is included for comparative purposes.

The minimum starting pressure ratio of the particular conical primary nozzle was reduced from 23 to 14, about 39 percent, by replacing the cylindrical diffuser with the longest convergent-divergent diffuser

from one-dimensional theory.

investigated. Thus, the latter diffuser type offers significant potential performance gains relative to the simple cylindrical diffuser. Minimum contraction-throat length-diameter ratio for minimum pressure-ratio requirements associated with the conical primary nozzle was of the order of 6. For the particular diffuser design investigated, this contraction-throat length-diameter ratio corresponded to an overall length-diameter ratio of about 9 (as compared with 6 for the simple cylindrical diffuser). In the investigation of reference 5, using a conical primary nozzle, minimum starting and breakdown pressure ratios were obtained with minimum contraction-throat length-diameter ratios of 5 to 7 and 9 to 10, respectively.

Trade-offs can be made to minimize the overall length of convergent-divergent diffusers. In the present investigation, the semiangles of contraction and subsonic divergence were both 3.75°. In the investigation of reference 5, contraction semiangles of 3°, 6°, and 15° were evaluated, and 6° was found to be best on the basis of length and pressure-ratio requirements; the subsonic divergence semiangle was 8°. In general, the overall length of optimum convergent-divergent diffusers may be longer than that of optimum cylindrical diffusers, but the pressure-ratio requirements will be lower.

It is significant to note in figure 14 that primary-nozzle type appreciably influenced the starting-pressure-ratio reductions available through use of the longest convergent-divergent diffuser investigated. In going from the cylindrical diffuser to the convergent-divergent diffuser, (1) the starting pressure ratio of the bell nozzle was reduced only from 23 to 21.2 as compared with reductions for the conical and cutoff-isentropic nozzles from about 23 to 14 or 15; however, (2) the breakdown pressure ratios of the three nozzles were reduced from about 23 to 12.5 or 14. From the investigation of reference 5, it was observed that (1) going from a cylindrical to a convergent-divergent diffuser produced less reduction in starting pressure ratio for a bell primary nozzle than for a conical nozzle, and (2) the starting pressure ratios with a bell nozzle were not improved as much with the addition of contraction-throat length as were those of a conical nozzle. The relatively high starting pressure ratio of the bell nozzle with the convergent-divergent type diffuser is probably attributable to higher total-pressure losses during the off-design operation of starting than for the conical or cutoff-isentropic nozzles. If this is the case, it is quite possible that less contraction would be more nearly optimum for use with the bell nozzle. Other investigations, including reference 5, indicated that less contraction could be used with a bell nozzle than with conical nozzles.

<u>Contraction ratio</u>. - Experimental minimum starting pressure ratios P_c/p_a are presented as functions of contraction ratio A_t/A_d in figure 15 for both selected cylindrical diffusers containing conical contraction and for the available long convergent-divergent diffusers.

Two theoretical curves of normal-shock pressure ratios as functions of area ratio (assumed equal to $A_t/A^* = (A_d/A^*)(A_t/A_d)$), based on one-dimensional theory, are presented for comparison with the experimental results. Normal-shock total- to static-pressure ratio represents theory for the diffusers tested with subsonic diffusion to an area equal to A_d, whereas normal-shock total-pressure ratio represents theory for subsonic diffusion to zero velocity.

As pointed out previously, only small reductions in pressure-ratio requirements were obtained through use of cylindrical diffusers containing conical contraction. It is observed that the starting pressure ratios of such configurations were well above the normal-shock pressure ratios. In the case of the long convergent-divergent diffusers, the use of contraction provided significant reductions in starting-pressure-ratio requirements associated with two primary-nozzle types. For these configurations, the trend of starting pressure ratio with contraction ratio appears to parallel the normal-shock total-pressure ratios but diverges percentagewise from theory as contraction ratio is reduced. Though basically a normal-shock process is indicated, pressure losses ahead of the contraction throat presumably increased as contraction ratio was decreased.

Minimum contraction ratios were not determined in the present investigation. In reference 5 for a conical primary nozzle and a convergent-divergent diffuser comparable with those of figure 15, successful starts were obtained with a contraction ratio A_t/A_d as low as 0.467 but could not be obtained with a contraction ratio of 0.431. The region between the two aforementioned contraction ratios has been shaded in figure 15 to indicate the approximate minimum contraction ratio associated with at least the conical primary nozzle and probably also the cutoff-isentropic nozzle. As pointed out previously from reference 5, the minimum contraction ratio was higher with a bell nozzle than with the conical nozzle; with the bell nozzle, successful starts were obtained with a contraction ratio of 0.602 but could not be obtained with a contraction ratio of 0.544. Reference 5 also indicates the effect of diffuser area ratio (or Mach number) on contraction ratio.

If it were assumed that a normal shock occurred at the maximum diffuser area A_d during the starting process, and the Mach number was 1.0 at the minimum contraction area A_t, then the minimum contraction ratio from one-dimensional theory would be 0.646 for the diffuser area ratio A_d/A^* of figure 15. Since diffuser configurations with contraction ratios appreciably less than this were used, the effective diffuser flow area was less than A_d, and therefore the shock occurred at a Mach number lower than that predicted by diffuser area ratio A_d/A^* from one-dimensional theory.

Comparison of Cylindrical and Convergent-Divergent Exhaust Diffusers

An effort was made to generalize approximately the starting-pressure-ratio data from optimum cylindrical (contraction ratio of 1.0) and convergent-divergent diffusers. For this purpose, starting-pressure-ratio data for convergent-divergent diffusers are presented in figure 16 as a function of the ratio of minimum diffuser area to primary-nozzle-throat area A_t/A^*. The faired experimental curve from figure 10(a) for cylindrical diffusers is included for comparison. Convergent-divergent diffuser data are included from figure 15 and from reference 5. The available data provide a range of contraction ratios A_t/A_d used with diffuser area ratios A_d/A^* of 28.9-30.0 and 57. Dashed lines are shown for the two diffuser area ratios, with the lines extending from the data points to the respective contraction ratio of 1.0 as defined by the faired curve for cylindrical diffusers. It is apparent that there is not exact agreement of results for convergent-divergent and cylindrical diffusers when compared on this basis. It does appear, however, that the method provides a first-order approximation of starting-pressure-ratio requirements associated with the two diffuser types when used with conical and cutoff-isentropic primary nozzles. It also appears that the minimum pressure-ratio requirements of convergent-divergent diffusers used with these nozzles were primarily a function of A_t/A^*. Pressure-ratio requirements associated with diffusers used with the bell-type nozzle were not appreciably reduced through use of contraction for the contraction ratio evaluated, as previously discussed. Caution must be followed in the use of a general curve such as figure 16, in that the figure does not indicate minimum or optimum contraction ratios of convergent-divergent diffusers. The minimum A_t/A^* data points for the two examples represent the approximate minimum contraction ratios of the particular configurations.

Exhaust Diffusers Including Right-Angle Turn

In previous discussion, it was shown that relatively long exhaust diffusers were required to provide minimum pressure-ratio requirements. For rockets that must be fired in a vertical installation, clearance limitations may prevent use of long axial exhaust diffusers. In an effort to reduce the required axial length along the nozzle centerline, a few exhaust diffusers that included a right-angle turn were evaluated. The performance of these configurations is presented in figure 17. The configurations included a conical primary nozzle with an area ratio A_e/A^* of 25 and exhaust diffusers with an area ratio A_d/A^* of 28.9.

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The performance of exhaust-diffuser configurations including a simple long-radius right-angle turn at maximum diffuser area is presented in figure 17(a) as a function of the right-angle-turn spacing ratio s_r/d_d. The pressure-ratio requirements were reduced as the spacing ratio was increased for the three cases evaluated. The minimum experimental starting and breakdown pressure ratio was 24 at $s_r/d_d = 3$ as compared with 23 for the comparable nozzle and optimum cylindrical-diffuser configuration. Minimum turn spacing ratio for minimum pressure-ratio requirements was perhaps 2. Thus, the axial length along the nozzle centerline could be reduced from about 6 d_d for the cylindrical diffuser to about 3.5 d_d for the diffuser with a simple turn (turn radius of 1.5 d_d).

The performance of configurations including a long-radius right-angle turn and using contraction is presented in figure 17(b) as a function of contraction ratio A_t/A_d. The contraction was spaced 0.5 d_d downstream of the primary-nozzle exit in accordance with practice followed with axial diffusers. Data are presented for the simple turn spaced 1.0 d_d from the nozzle exit with and without contained conical contraction, and for the turn at a contraction minimum area. Contained conical contraction provided small reductions in pressure-ratio or length requirements; the configurations tested had an axial length along the nozzle centerline of 2.5 d_d. Check points (not presented) indicated that primary-nozzle type did not significantly influence the pressure-ratio requirements of such configurations. The configuration with the turn at a contraction minimum area provided somewhat lower pressure-ratio requirements than the other configurations tested, and had an axial length along the nozzle centerline of 3.4 d_d. The latter configuration did not include a subsonic divergence downstream of the turn; the indicated minimum exit Mach number was about 0.7. It was estimated that use of subsonic divergence to a diffuser-exit area equal to A_d would reduce the required pressure ratio of this latter configuration from 22 to about 18 to 20, as compared with about 15 for an optimum convergent-divergent diffuser of equal contraction ratio.

The type of configuration with a right-angle turn at a contraction minimum area would appear to offer minimum pressure-ratio requirements. Trade-offs could be made to reduce either the axial-length or pressure-ratio requirements of such configurations. The configuration investigated used a contraction semiangle of 3.75°; it was previously mentioned that reference 5 found a contraction semiangle of 6° to be more nearly optimum than either 3° or 15° from considerations of length and pressure-ratio requirements of axial convergent-divergent diffusers. From the results of figure 17(a) relative to the simple turn without contraction, it might be expected that the use of 2 to 3 contraction-throat diameters of length upstream of a turn at a contraction minimum area might significantly reduce pressure-ratio requirements with attendant sacrifice in increased axial length. In general, the axial length of an optimum configuration with a right-angle turn at a contraction minimum area may be greater than that of a configuration with a simple turn and no contraction, but the pressure-ratio requirements will be lower.

SUMMARY OF RESULTS

An experimental investigation of exhaust diffusers has been conducted to evaluate various methods of minimizing the overall pressure ratio (from chamber to ambient pressure) required to establish and maintain full expansion of the nozzle flow (altitude simulation). Exhaust-diffuser configurations investigated were (1) cylindrical diffusers, (2) diffusers with contraction, and (3) diffusers including a right-angle turn. Primary-nozzle configurations included (a) an area-ratio range from 5.5 to 62.9, (b) conical, cutoff-isentropic, bell, and full-isentropic types, and (c) single- and clustered-nozzle installations. Air was the working fluid, except for two check points obtained with JP-4 fuel and liquid-oxygen rocket engines and cylindrical diffusers. Cylindrical diffusers were evaluated in conjunction with all nozzle configurations; the overall range of the ratio of diffuser to nozzle-throat areas was from 9.3 to 100.9. The other diffuser configurations were investigated with conical, cutoff-isentropic, and bell nozzles that had an area ratio of 25; the maximum ratio of diffuser to nozzle-throat areas was 28.9.

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Results of the investigation are summarized relative to the three basic diffuser configurations.

Cylindrical Exhaust Diffusers

1. The minimum length-diameter ratio of cylindrical diffusers was about 6 for minimum pressure-ratio requirements. With cylindrical diffusers of adequate length, the pressure-ratio requirements were primarily a function of the ratio of diffuser to nozzle-throat areas and essentially independent of primary-nozzle type or area ratio. A diffuser area somewhat greater than that of the nozzle exit was required to prevent nozzle-diffuser interaction. These results agree, in general, with those of reference 5 and extend the range of variables investigated.

2. The pressure-ratio requirements of two clustered-nozzle configurations correlated with single-nozzle requirements on the basis of the ratio of diffuser area to the sum of primary-nozzle-throat areas.

3. The two check points obtained with rocket engines indicated the pressure-ratio requirements at given ratios of diffuser to nozzle-throat

areas were lowered, as compared with the requirements with air, as a result of the reduced ratio of specific heats.

4. The agreement of minimum required pressure ratios with normal-shock pressure ratios was such as to substantiate the theory that the compression is basically a normal-shock process.

Exhaust Diffusers with Contraction

1. The minimum length-diameter ratio of the contraction throat of convergent-divergent diffusers was also about 6 for minimum pressure-ratio requirements. With adequate contraction-throat length, the pressure-ratio requirements of convergent-divergent diffusers were appreciably below those of comparable cylindrical diffusers when used with conical and cutoff-isentropic nozzles, but not when used with a bell nozzle. With the first two nozzle types, the minimum pressure-ratio requirements were primarily a function of the ratio of contraction-throat area to nozzle-throat area.

2. The minimum pressure-ratio requirements of cylindrical diffusers containing conical contraction were not appreciably below those of comparable cylindrical diffusers.

3. The axial spacing between the primary-nozzle exit and the initiation of contraction was found to be critical. In the present investigation, both minimum and maximum spacings were encountered beyond which the nozzle flow would not fully expand.

4. The aforementioned results agree in general with those of reference 5 with one exception: The investigation reported therein observed only maximum spacings between the nozzle exit and the initiation of contraction as starting limitations.

Exhaust Diffusers Including Right-Angle Turn

1. Minimum pressure-ratio requirements of a diffuser with a simple long-radius right-angle turn at maximum diffuser area were obtained with the center of radius of the turn a minimum of 2 diffuser diameters downstream of the primary-nozzle exit. The pressure-ratio requirements were not appreciably above those of a comparable optimum cylindrical diffuser.

2. Contained conical contraction provided small reductions in pressure-ratio or length requirements relative to the aforementioned simple turn.

3. A diffuser including a long-radius right-angle turn at a contraction minimum area had somewhat lower pressure-ratio requirements than the aforementioned configurations with turns. Further optimization of this type of configuration would be required to evaluate trade-offs to be made in reducing pressure-ratio or length requirements.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, April 22, 1960

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2. Goethert, Bernhard H.: Some Selected Problems in Engine Altitude Testing. AGARDograph No. 37, Advanced Aero Engine Testing, Pergamon Press, 1959, pp. 33-78.

3. Fortini, Anthony, Hendrix, Charles D., and Huff, Vearl N.: Experimental Altitude Performance of JP-4 Fuel and Liquid-Oxygen Rocket Engine with an Area Ratio of 48. NASA MEMO 5-14-59E, 1959.

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TABLE I. - PRIMARY NOZZLES

Type	Area ratio, A_e/A^*	Throat diam., d^*, in.	Exit diam., d_e, in.	Exit wall angle, deg
Cold-flow air				
Conical	5.5 11.7 [a]17.3 25.0 50.0	2.65 1.75 .75 1.50 1.64	6.22 6.00 3.12 7.50 11.61	19.5 15 ↓
Cutoff isentropic	25.0	1.50	7.50	9.5
Bell (Rao's method)	25.0	1.50	7.50	9.78
Full isentropic	27.3 62.9	1.542 3.485	8.06 27.62	≈0 ≈0
Rocket				
Conical	25.0 50.2	1.20 1.20	6.00 8.50	15 15

[a]Used in two- and four-nozzle clusters.

TABLE II. - CYLINDRICAL EXHAUST DIFFUSERS

Nozzle		Diffuser	
Type	Area ratio, A_e/A^*	Area ratio, A_d/A^*	l_d/d_d
Cold-flow air			
Conical	5.5	9.3	19.0
		14.7	15.0
		20.5	12.5
	11.7	21.2	4 to 19
		33.8	15.0
		47.8	12.5
	[a]17.3	[a]23.9	7.8
	[b]17.3	[b]57.8	7.8
	25.0	23.9	2 to 18
		46.1	14.0
		64.1	10.0
	50.0	53.5	4 to 8
Cutoff isentropic	25.0	23.9	2 to 10
Bell (Rao's method)	25.0	23.9	6.5
Full isentropic	27.3	27.3	7 to 18.5
		43.5	10.0
	62.9	69.3	8.0
		100.9	10.0
Rocket			
Conical	25.0	23.4	6.6
	50.2	56.3	10.1

[a]Four-nozzle cluster.
[b]Two-nozzle cluster.
} Diffuser area ratio based on sum of nozzle throat areas.

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TABLE III. - EXHAUST DIFFUSERS WITH CONTRACTION

[Cold-flow air.]

Nozzle		Diffuser					
Type	Area ratio, A_e/A^*	Area ratio, A_d/A^*	Contraction ratio, A_t/A_d	Spacing ratio, s_s/d_d	Contraction semiangle, deg	Contraction-throat l_t/d_t	Overall l_d/d_d
Cylindrical diffusers containing conical contraction							
Conical	25.0	28.9	0.70 .65 .55 .55 .50	0.5 0.25 to 1.5 .5 .5 0.25 to 2.0	7.5 7.5 7.5 3.75 3.75	0 ↓	6 and 18 6 and 18 2 and 3 4 4 and 6
Cutoff isentropic	25.0	28.9	0.55	0.5	3.75	0	6
Bell (Rao's method)	25.0	28.9	0.55	0.5	3.75	0	6.5
Convergent-divergent diffusers							
Conical	25.0	28.9	0.55	0.25 to 1.0 .5	3.75 3.75	3 and 4 0.18 to 9.8	6.4 to 7.9 4.6 to 11.7
Cutoff isentropic	25.0	28.9	0.55	0.125 to 1.0	3.75	9.8	11.3 to 12.2
Bell (Rao's method)	25.0	28.9	0.55	0.5	3.75	9.8	11.7

TABLE IV. - EXHAUST DIFFUSERS INCLUDING RIGHT-ANGLE TURN

[Cold-flow air.]

Nozzle		Diffuser				
Type	Area ratio, A_e/A^*	Area ratio, A_d/A^*	Turn spacing ratio, s_r/d_d	Contraction ratio, A_t/A_d	Contraction spacing ratio, s_s/d_d	Contraction semiangle, deg
Simple turn						
Conical	25.0	28.9	0 to 3	1.0	---	---
Simple turn including conical contraction						
Conical	25.0	28.9	1.0	0.63 and 0.70	0.5	7.5
Cutoff isentropic	25.0	28.9	1.0	0.63	0.5	7.5
Bell (Rao's method)	25.0	28.9	1.0	0.63	0.5	7.5
Simple turn at contraction minimum area						
Conical	25.0	28.9	---	0.60	0.5	3.75

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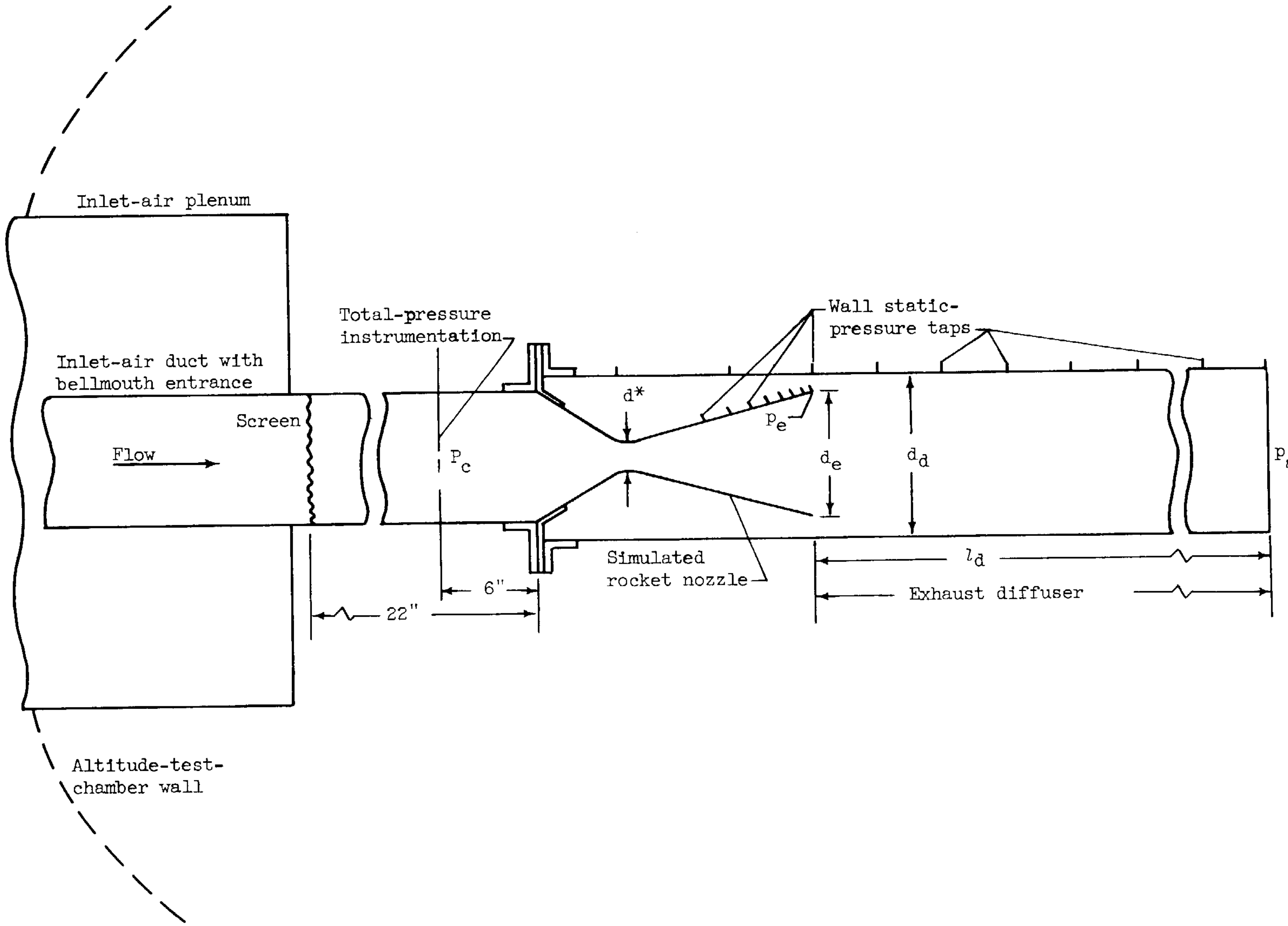


Figure 1. - Installation of cold-flow-air primary nozzles and exhaust diffusers.

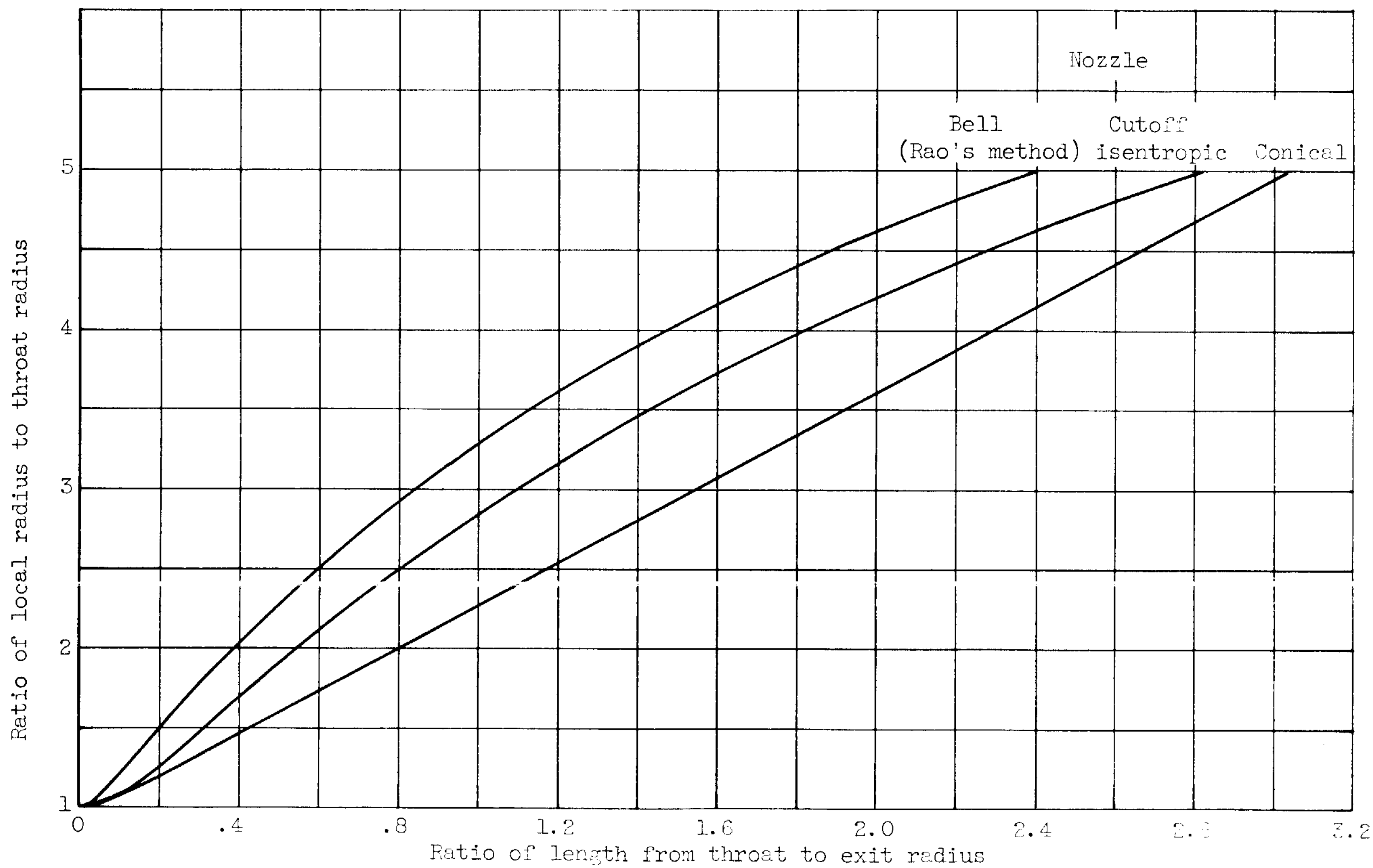


Figure 2. - Contours of primary nozzles with area ratio A_e/A^* of 25.

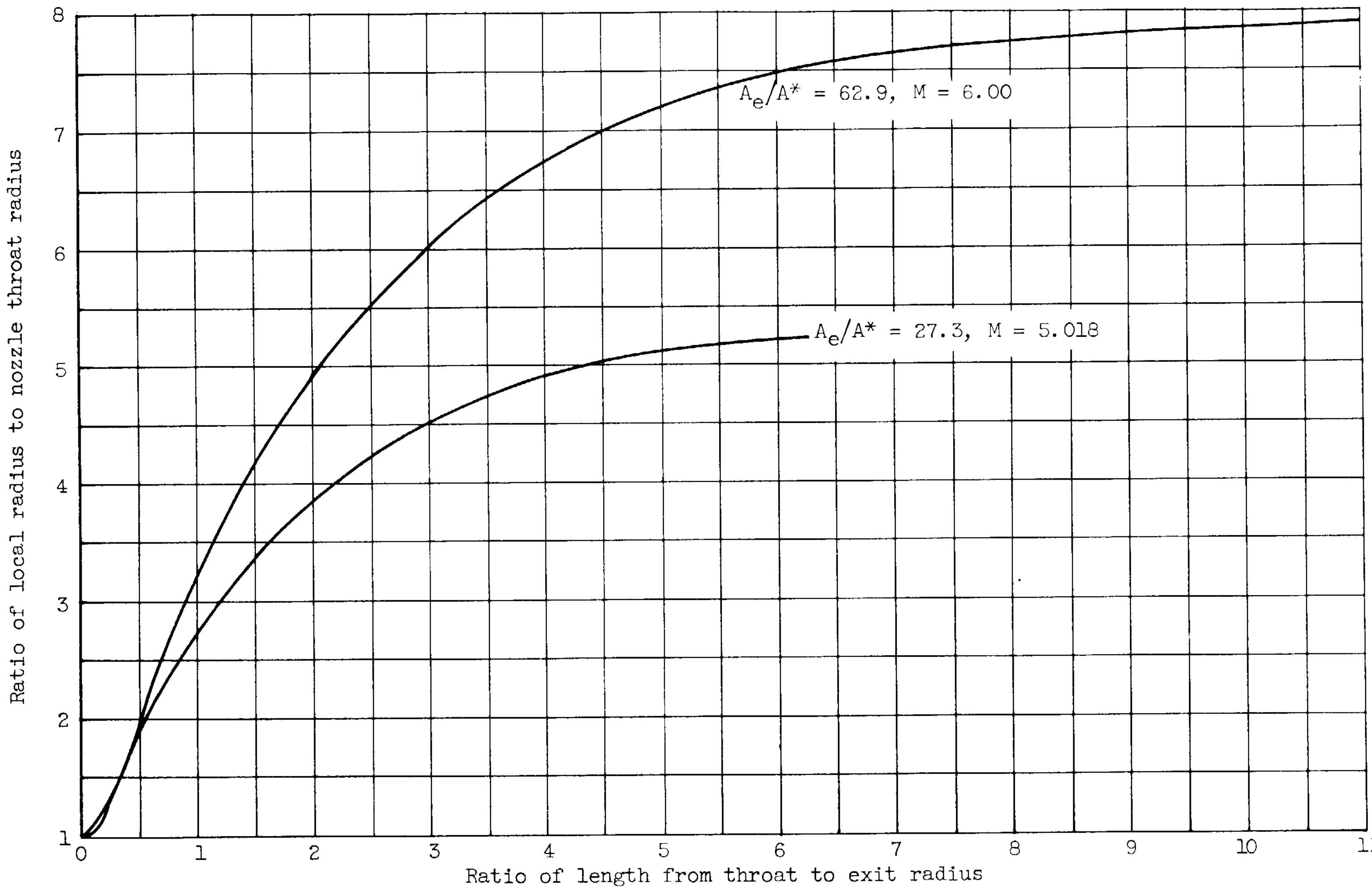
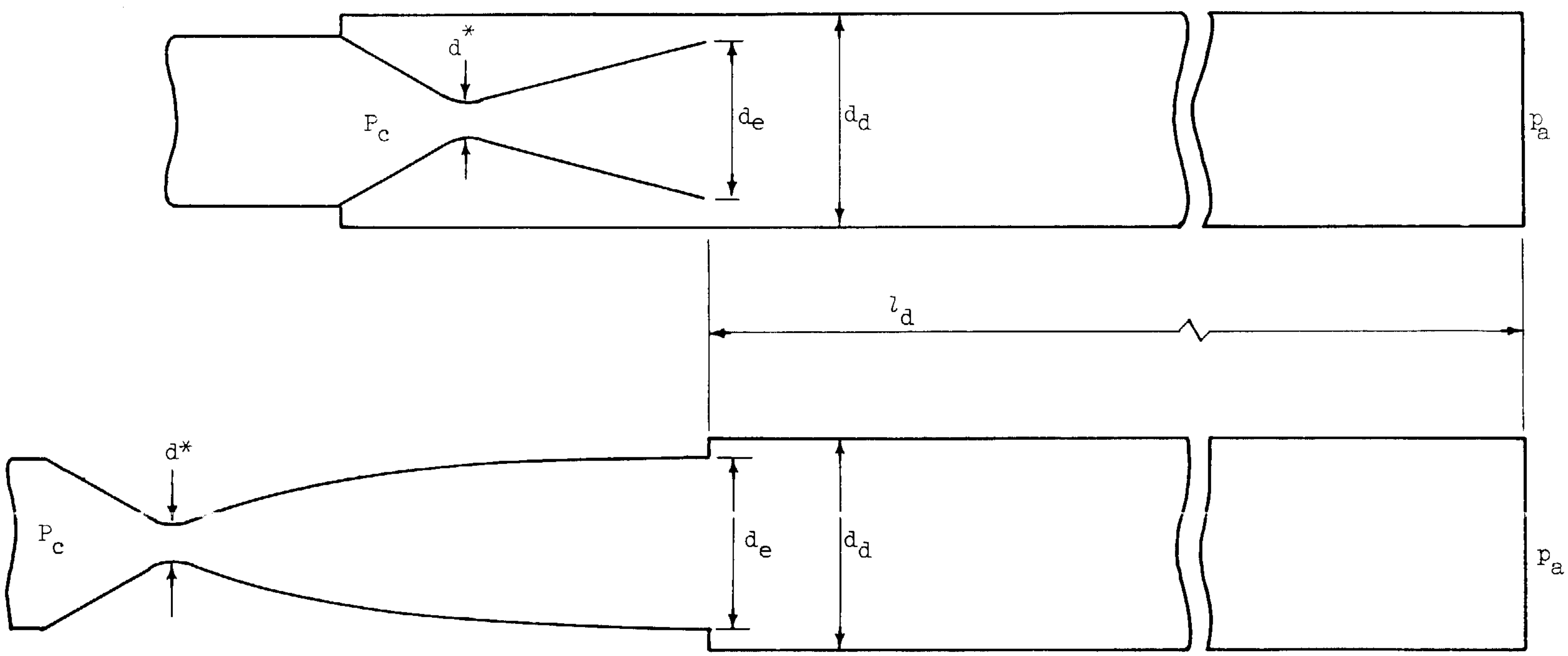
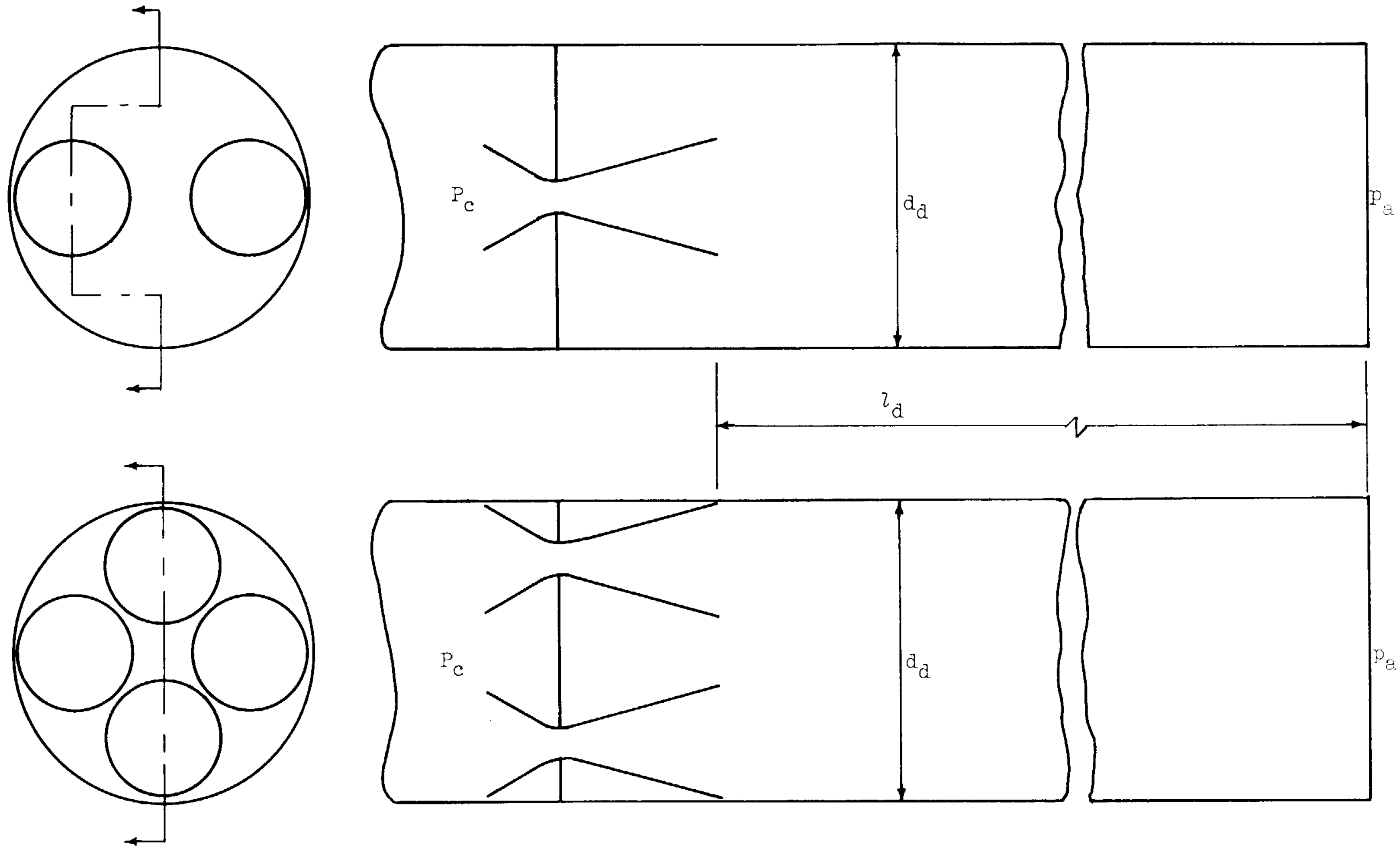


Figure 3. - Contours of full-isentropic primary nozzles.



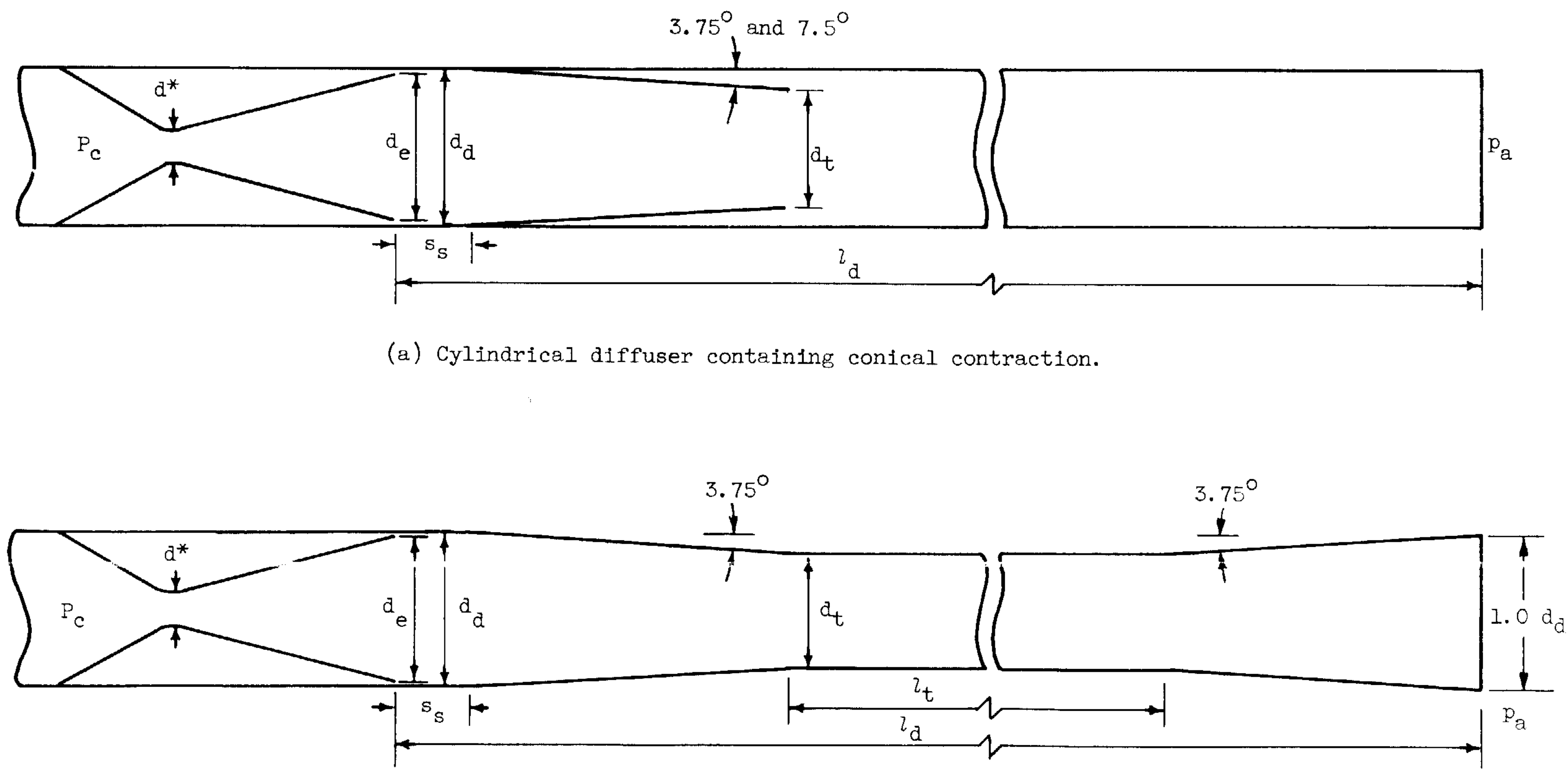
(a) Single primary nozzles.

Figure 4. - Cylindrical exhaust diffusers; cold-flow air.



(b) Clusters of two and four primary nozzles.

Figure 4. - Concluded. Cylindrical exhaust diffusers; cold-flow air.



(a) Cylindrical diffuser containing conical contraction.

(b) Convergent-divergent diffuser.

Figure 5. - Exhaust diffusers with contraction; cold-flow air.

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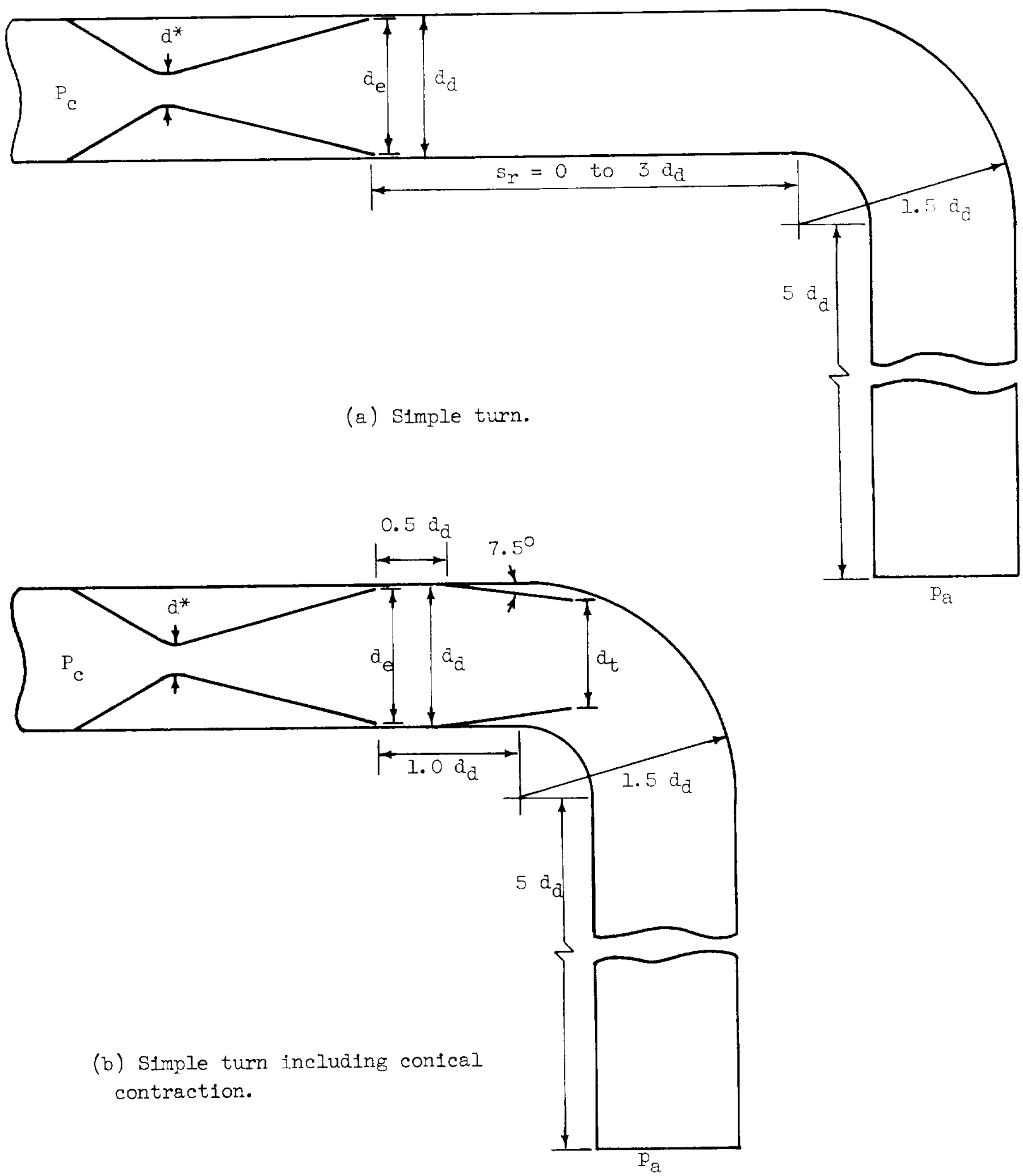

(a) Simple turn.

(b) Simple turn including conical contraction.

Figure 6. - Exhaust diffusers including right-angle turn; cold-flow air.

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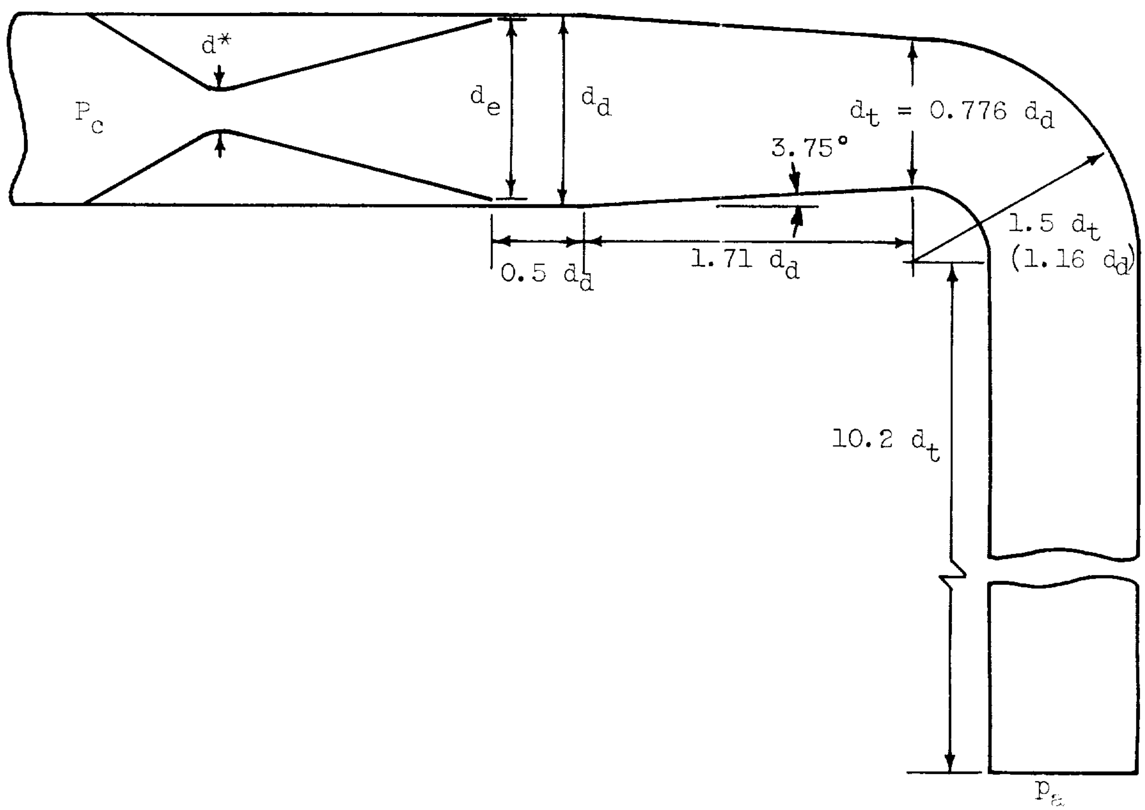


(c) Simple turn at contraction minimum area.

Figure 6. - Concluded. Exhaust diffusers including right-angle turn; cold-flow air.

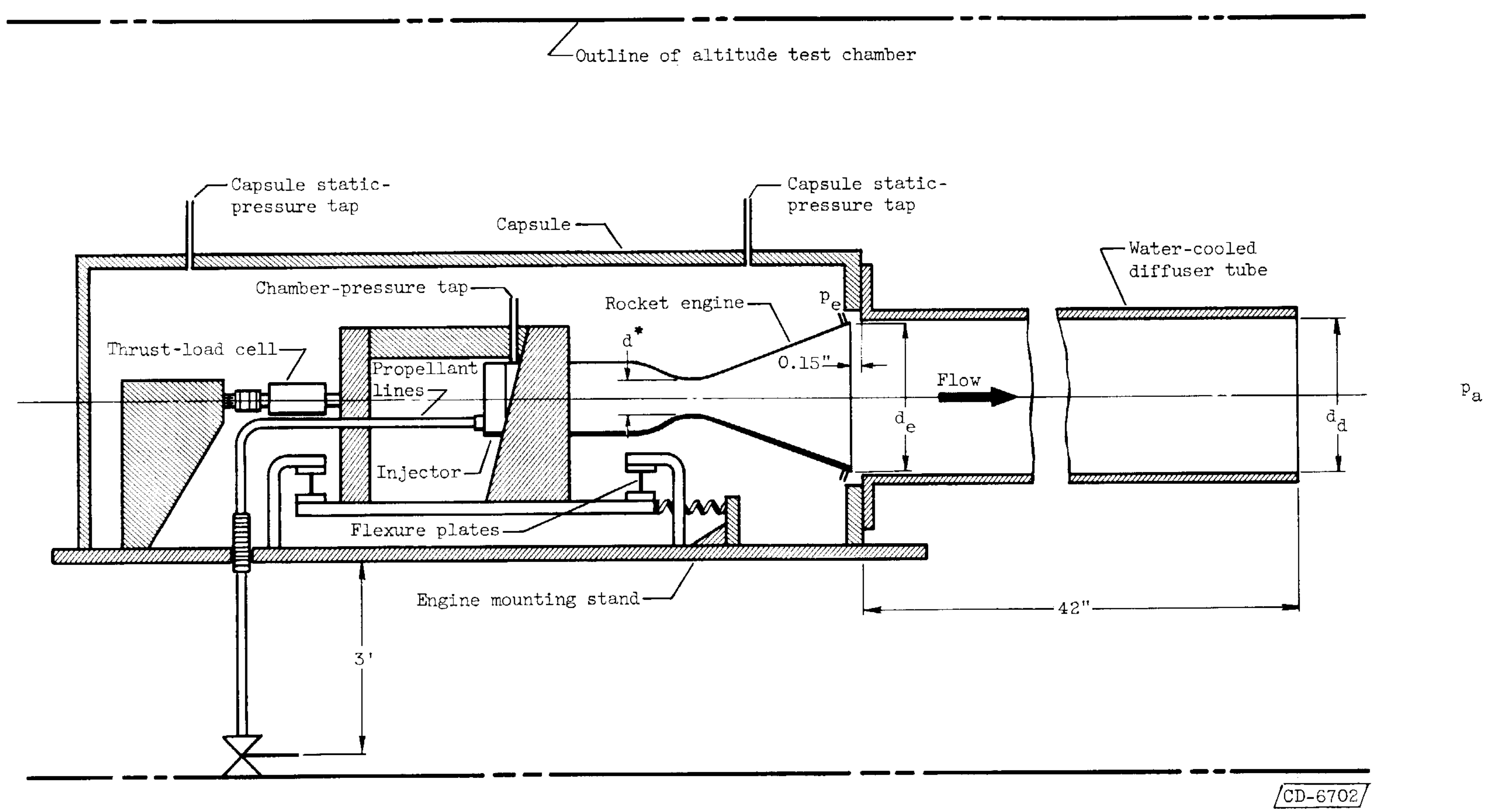
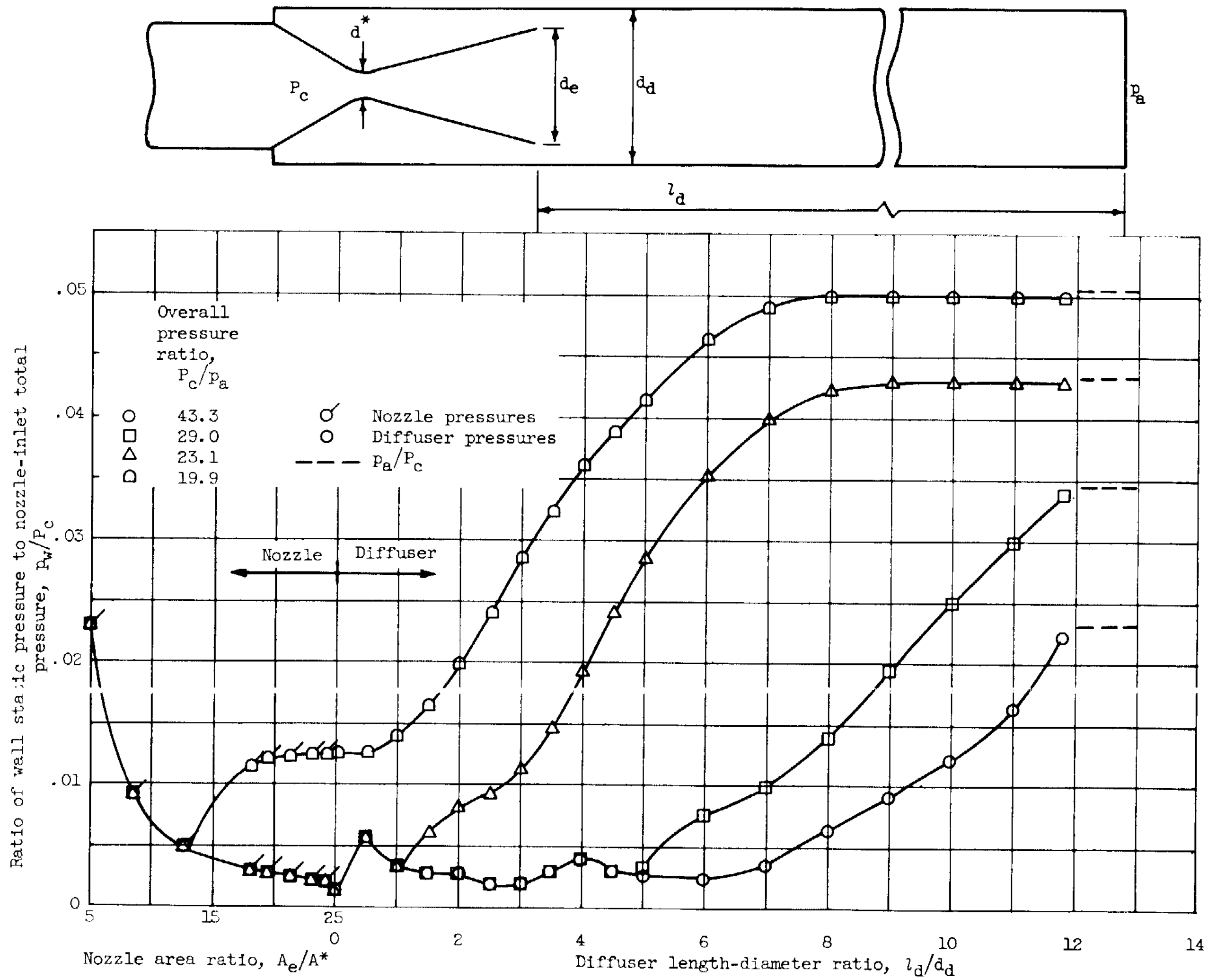
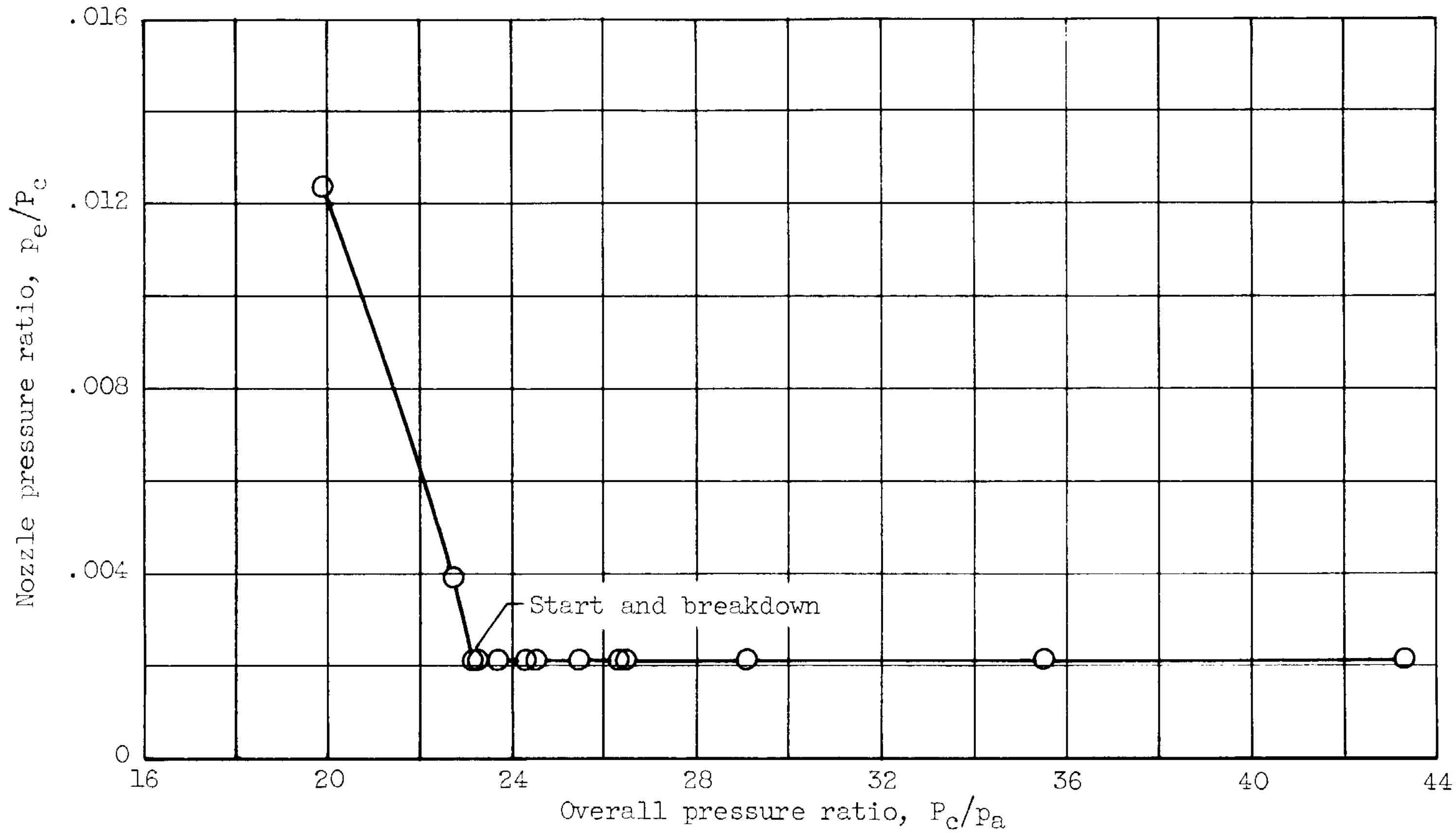


Figure 7. - Schematic diagram of rocket installation showing cylindrical exhaust diffuser and thrust system.



(a) Wall static-pressure distribution.

Figure 8. - Typical cylindrical-exhaust-diffuser performance. Diffuser overall length-diameter ratio, l_d/d_d, 12.



(b) Nozzle pressure ratio as affected by overall pressure ratio.

Figure 8. - Concluded. Typical cylindrical-exhaust-diffuser performance. Diffuser overall length-diameter ratio, l_d/d_d, 12.

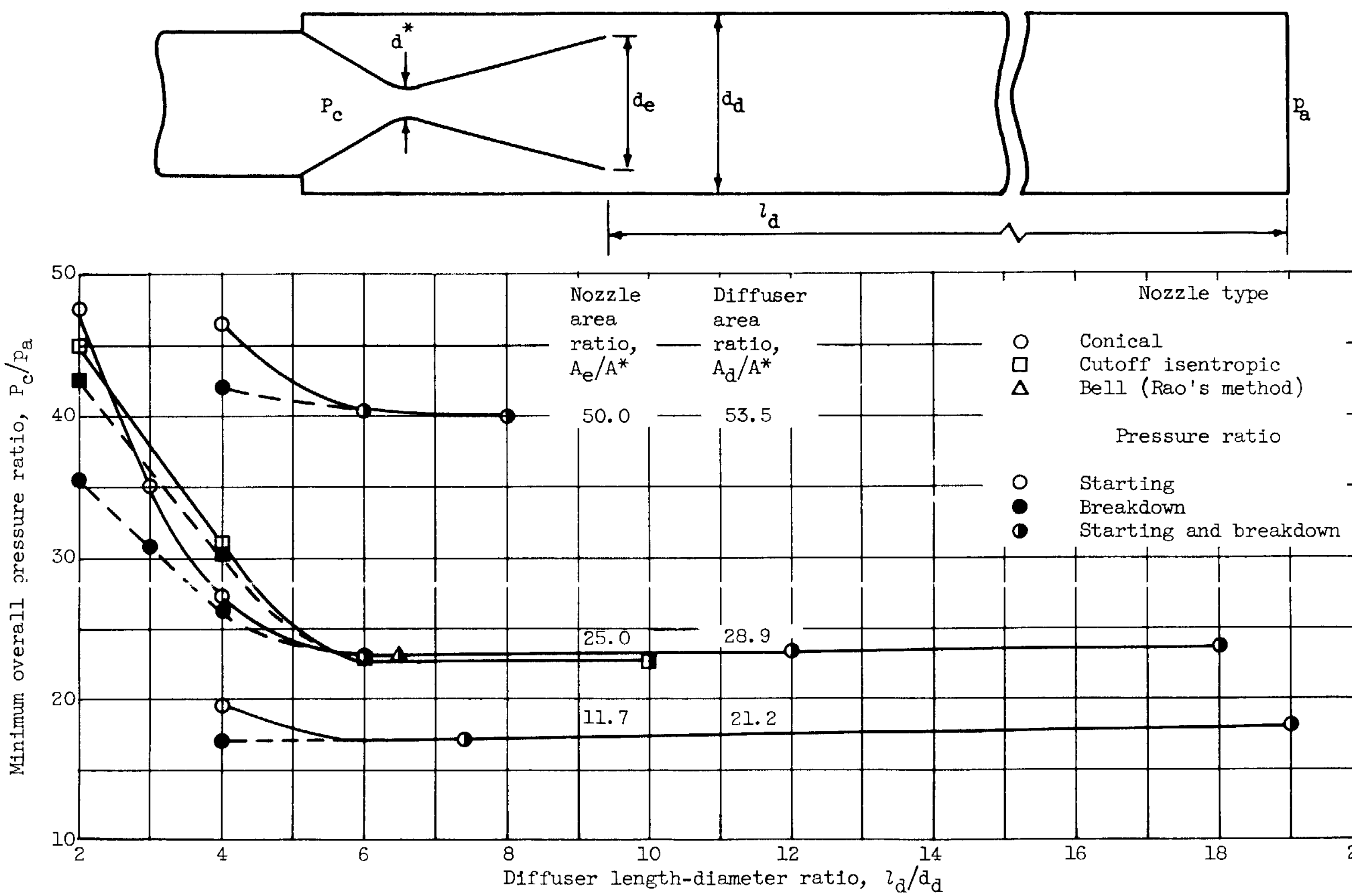


Figure 9. - Cylindrical-exhaust-diffuser performance as affected by diffuser length-diameter ratio.

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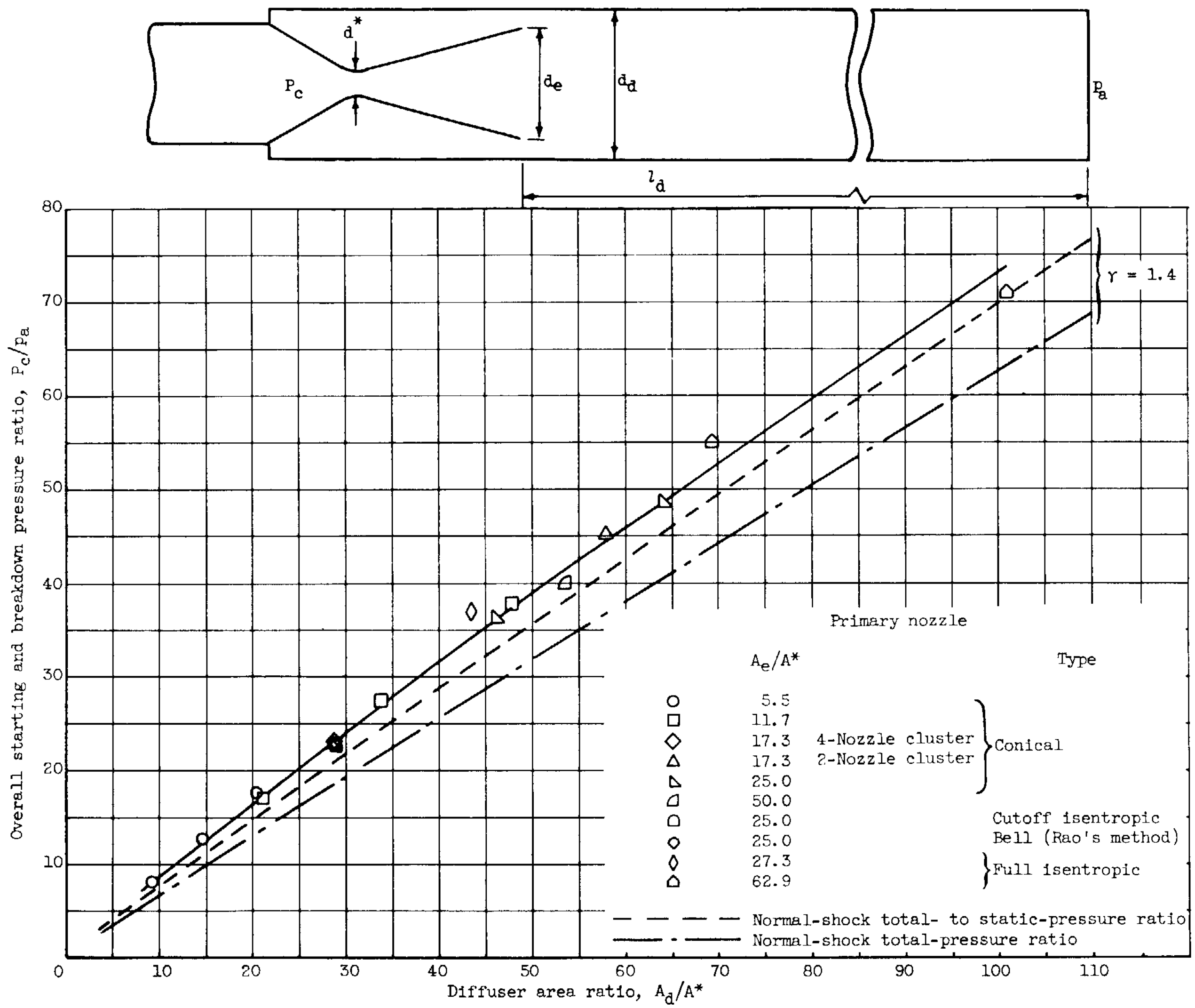
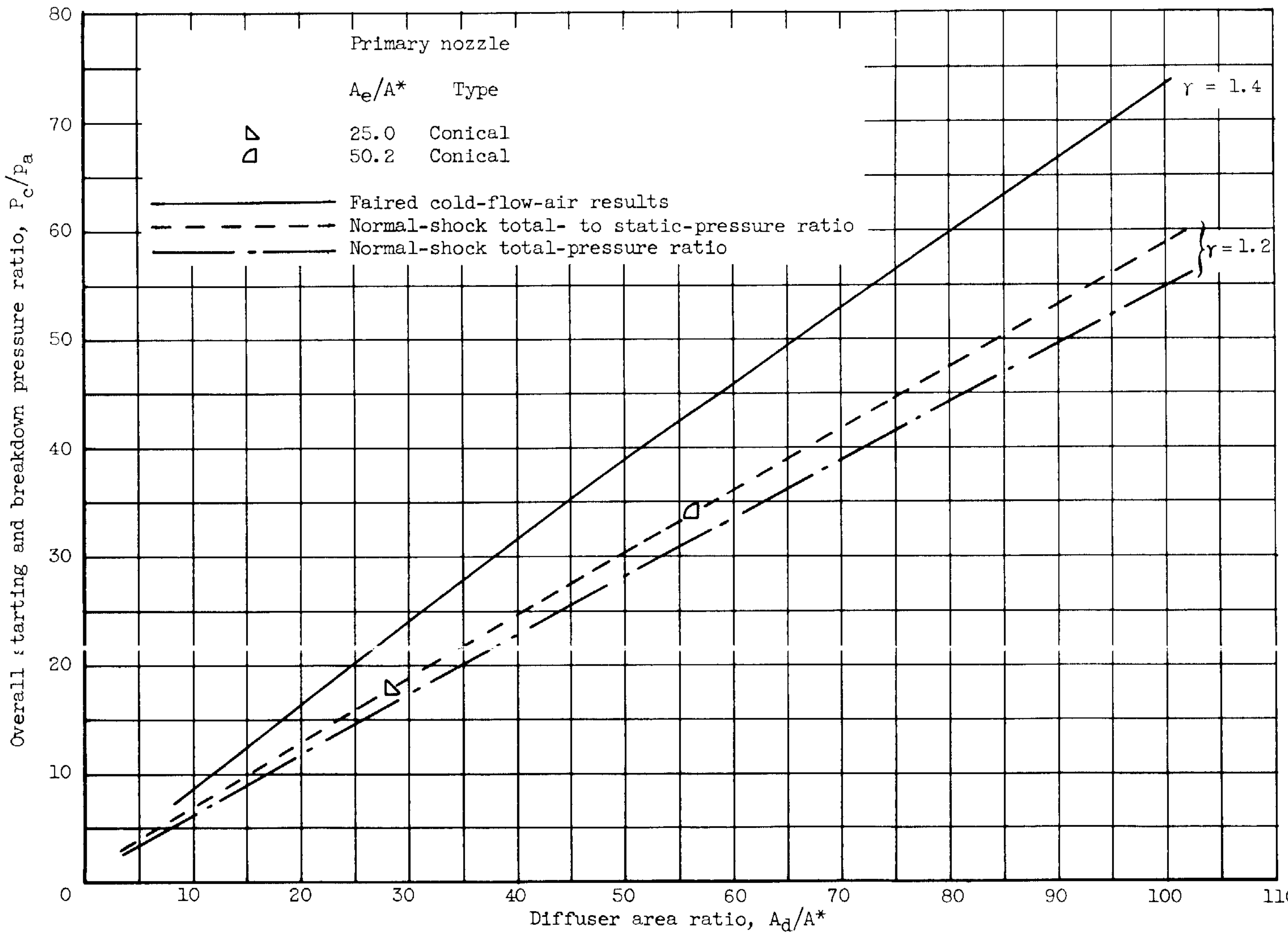


(a) Cold-flow-air data.

Figure 10. - Cylindrical-exhaust-diffuser performance as affected by diffuser area ratio.



(b) Hot-flow rocket data.

Figure 10. - Concluded. Cylindrical-exhaust-diffuser performance as affected by diffuser area ratio.

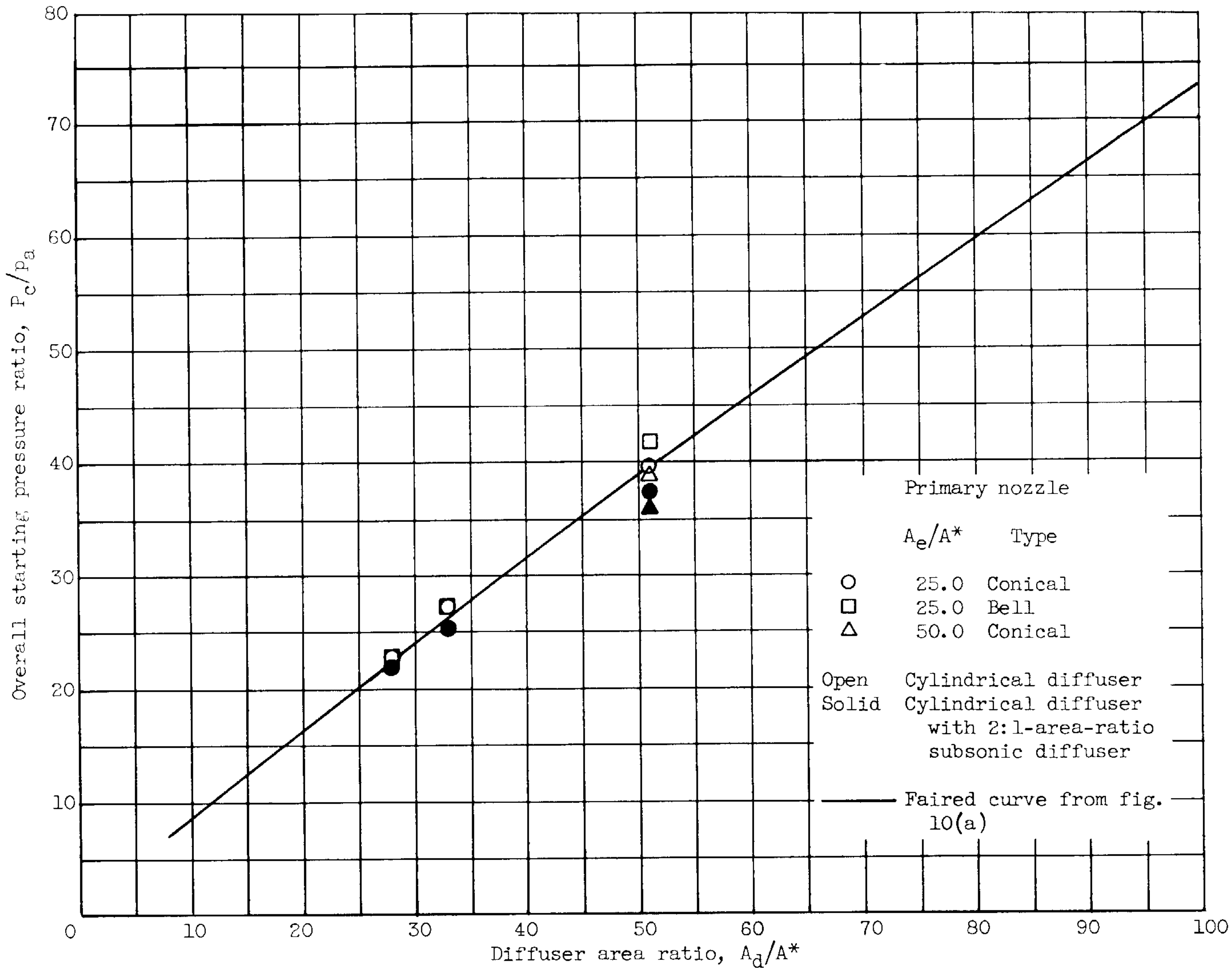


Figure 11. - Cylindrical-exhaust-diffuser performance from reference 5 compared with faired results of present investigation; cold-flow data.

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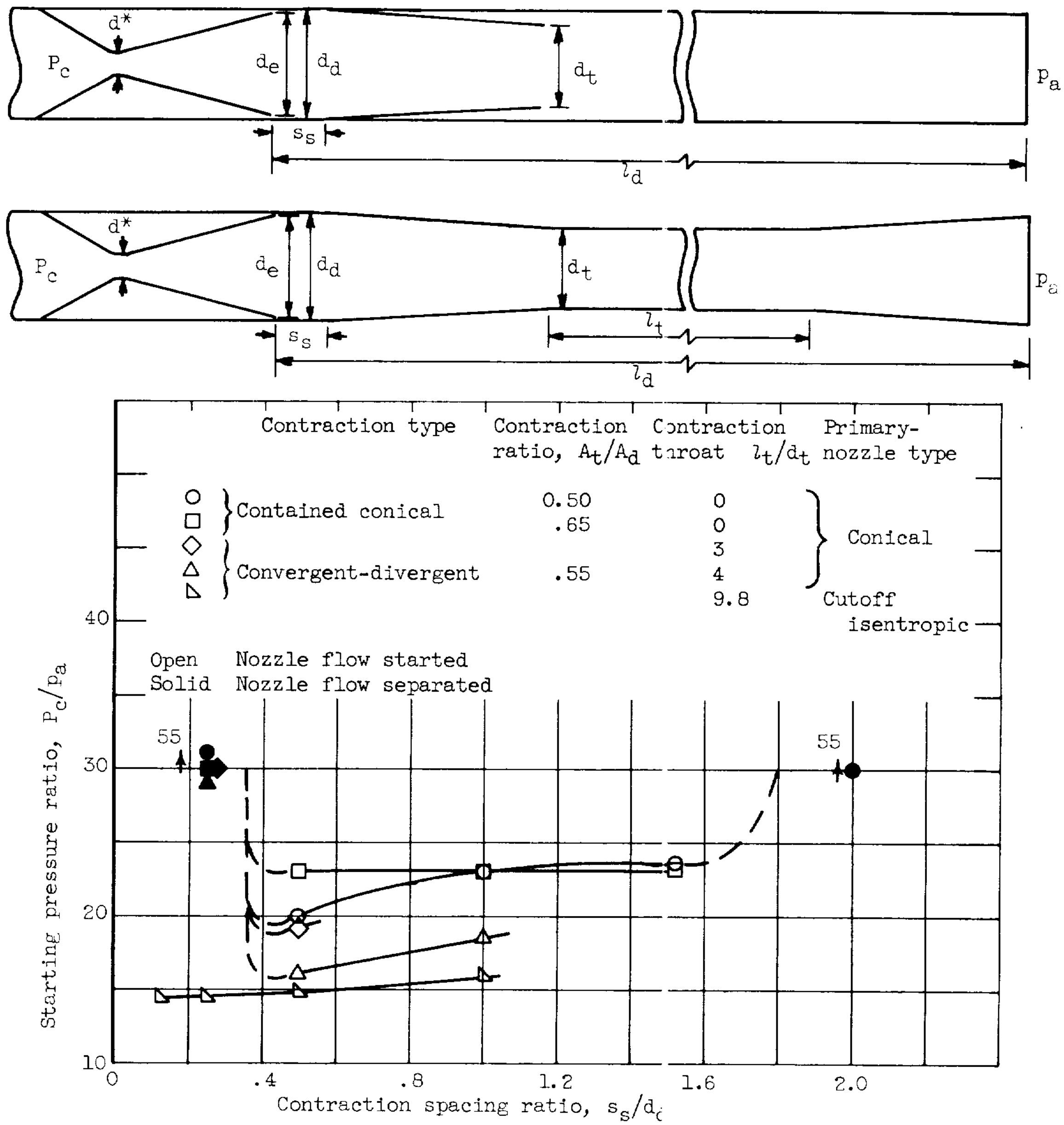

Figure 12. - Effect of contraction spacing on exhaust-diffuser performance. Primary-nozzle area ratio, A_e/A^*, 25; diffuser area ratio, A_d/A^*, 28.9.

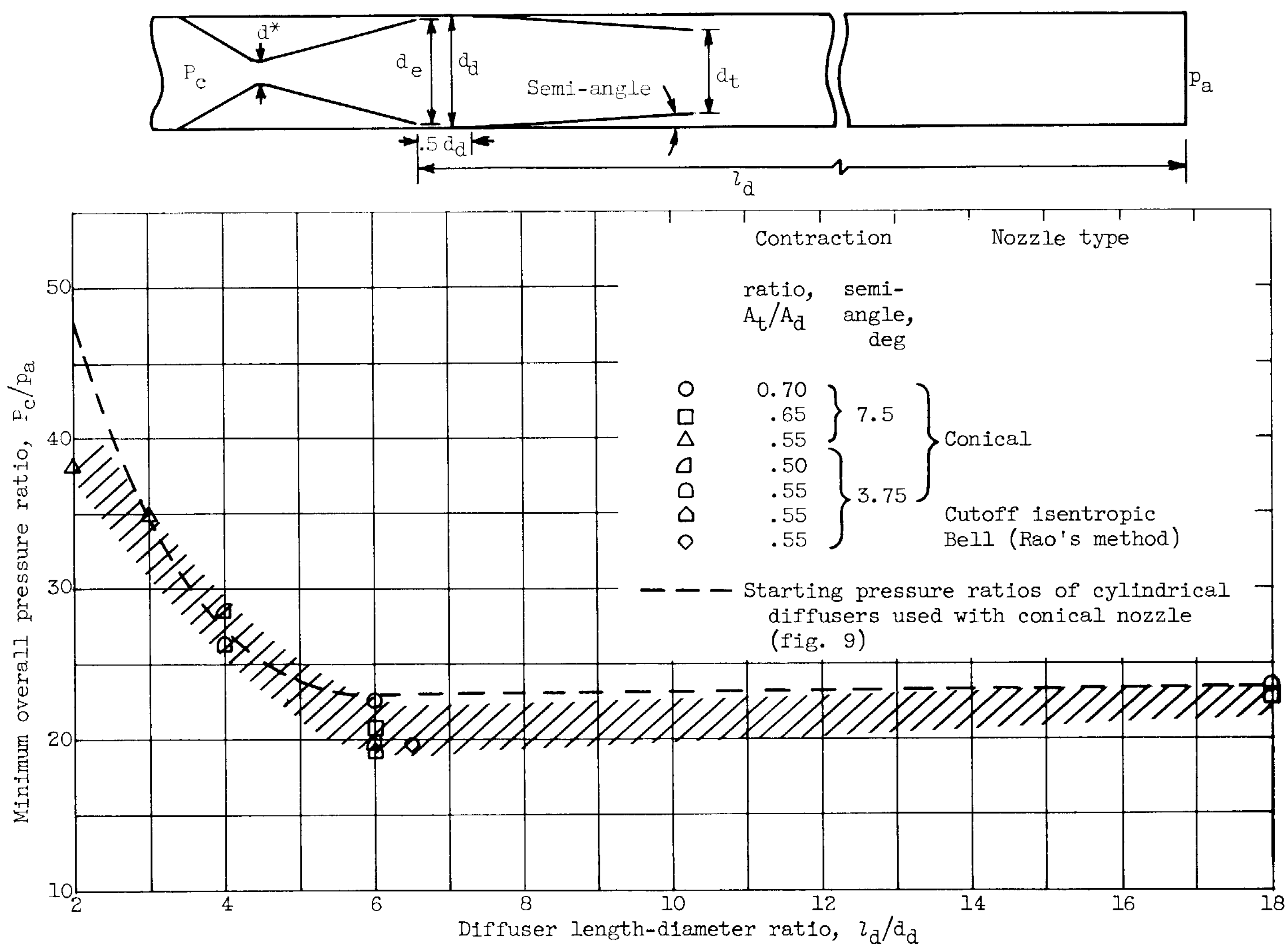

Figure 13. - Performance of cylindrical exhaust diffusers containing conical contraction. Primary-nozzle area ratio, A_e/A^*, 25.0; diffuser area ratio, A_d/A^*, 28.9.

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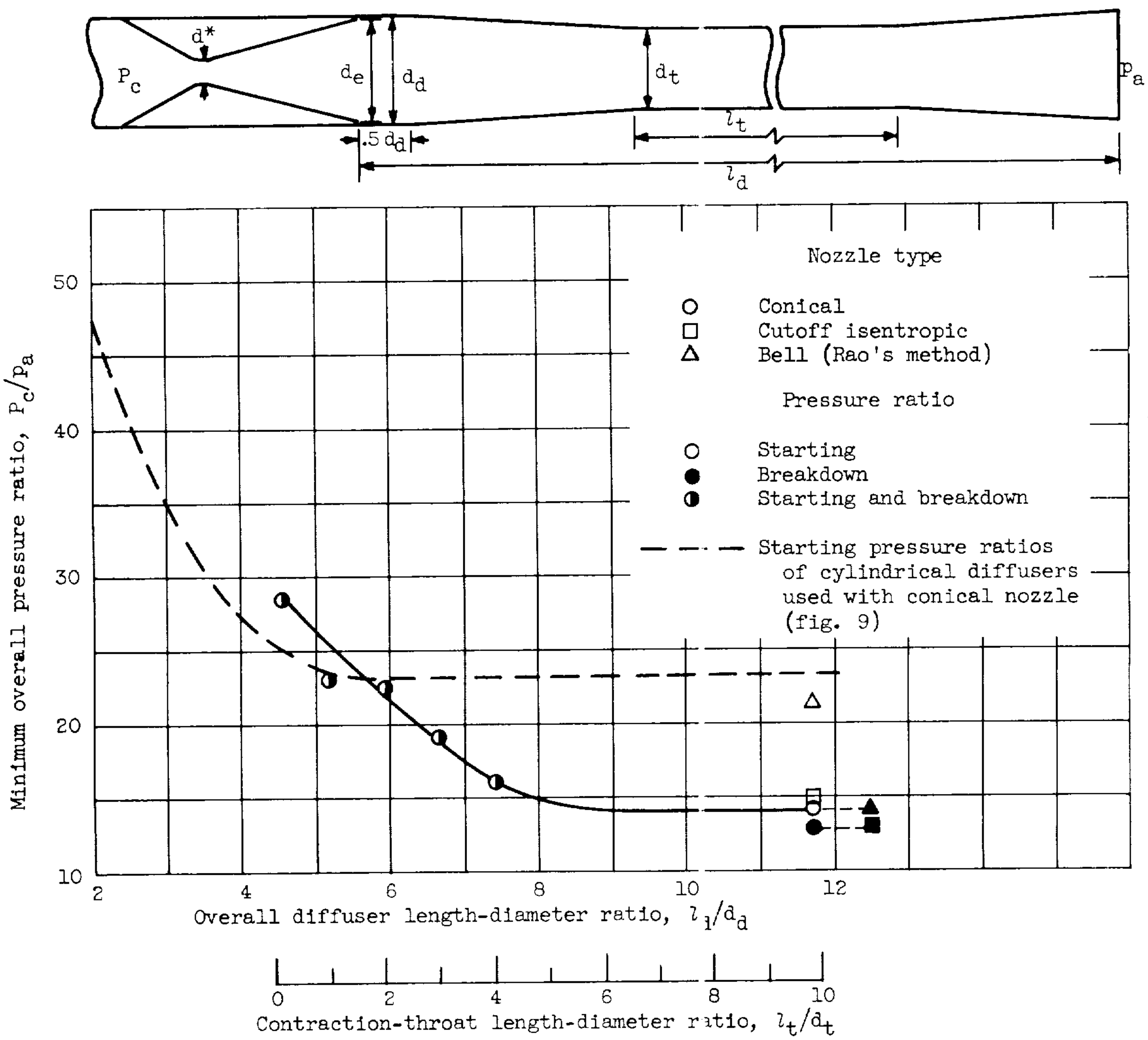

Figure 14. - Performance of convergent-divergent exhaust diffusers. Primary-nozzle area ratio, A_e/A^*, 25.0; diffuser area ratio, A_d/A^*, 28.9; contraction ratio, A_t/A_d, 0.55.

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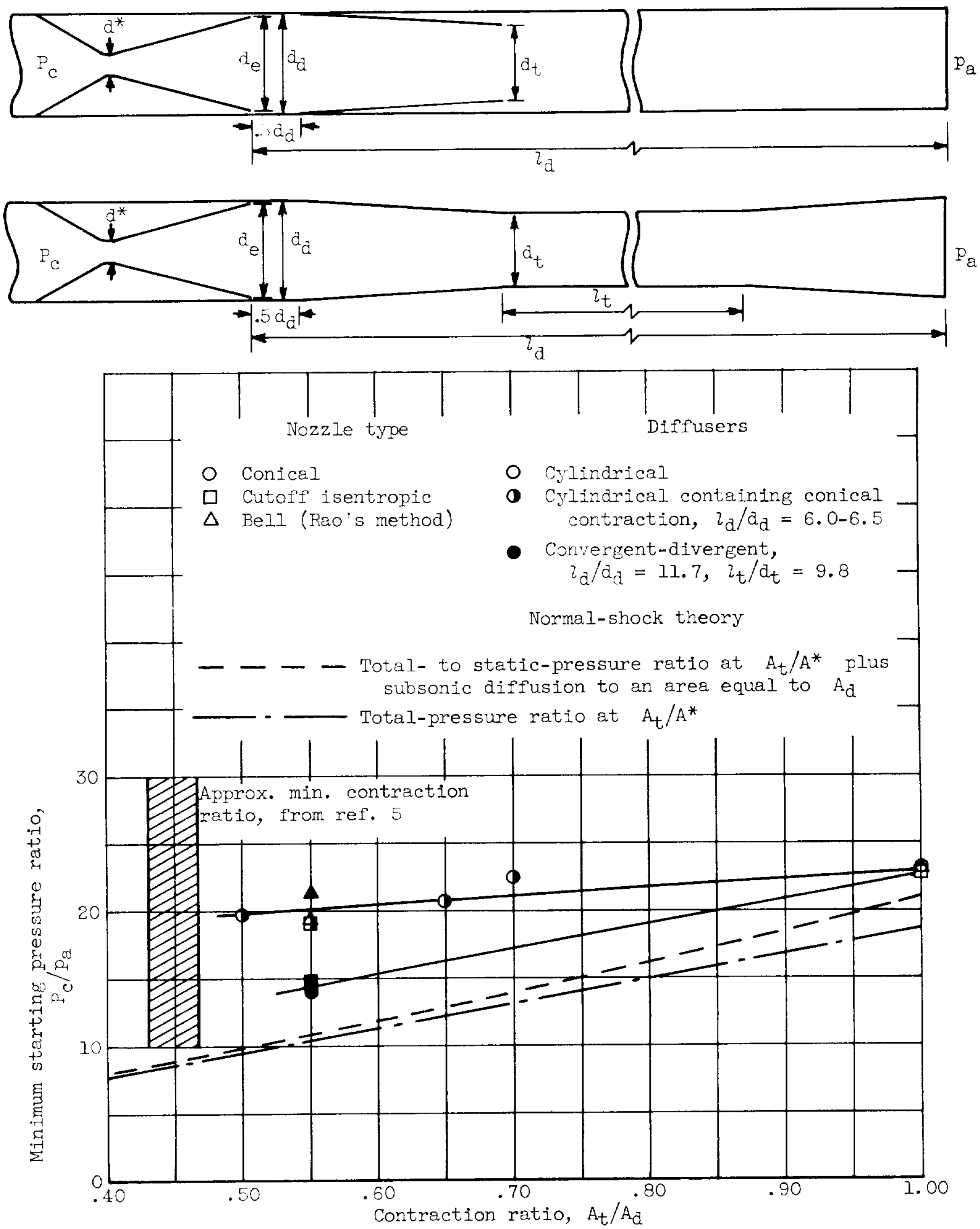


Figure 15. - Effect of contraction on exhaust-diffuser performance. Primary-nozzle area ratio, A_e/A^*, 25.0; exhaust-diffuser area ratio, A_d/A^*, 28.9.

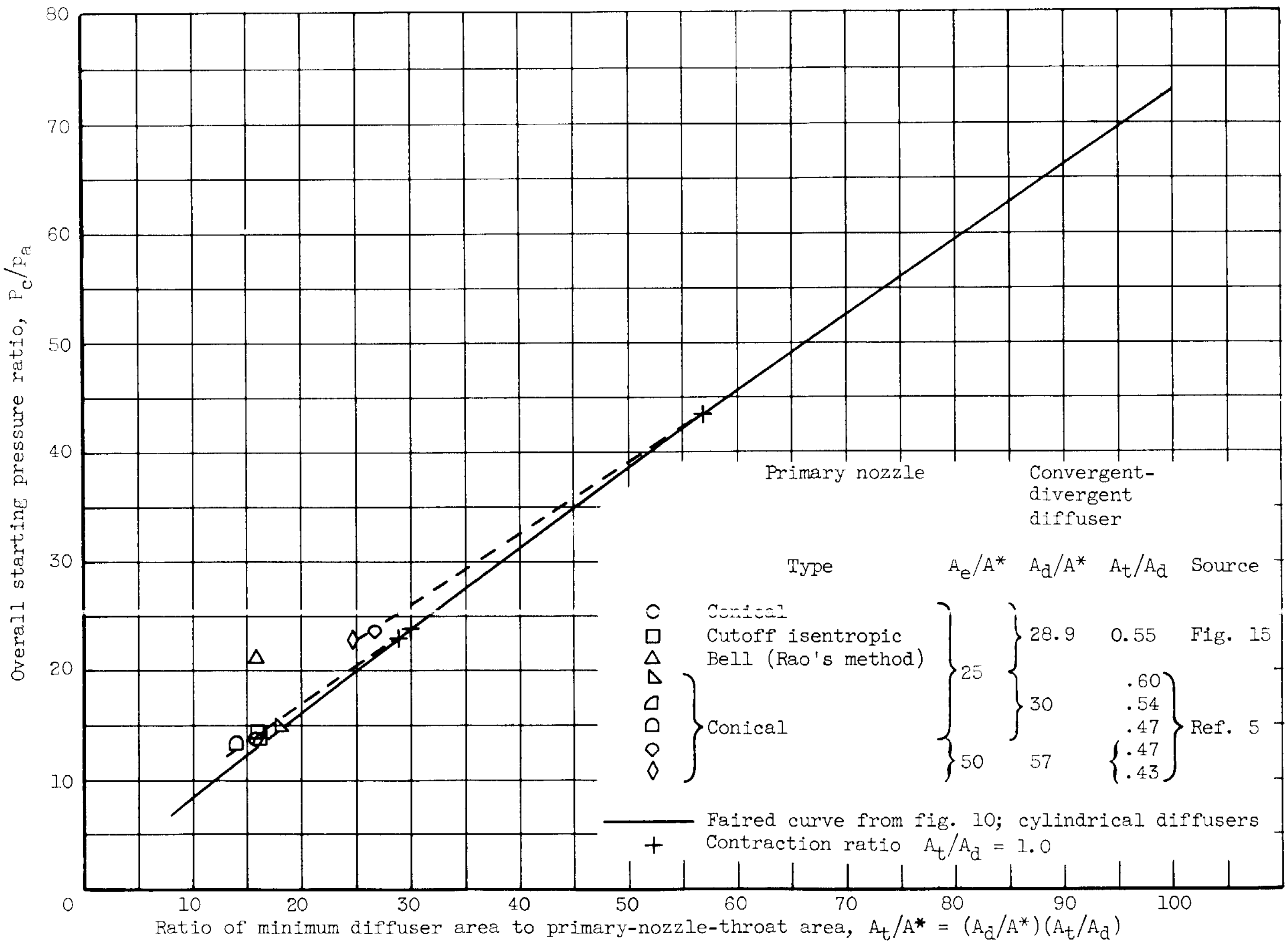
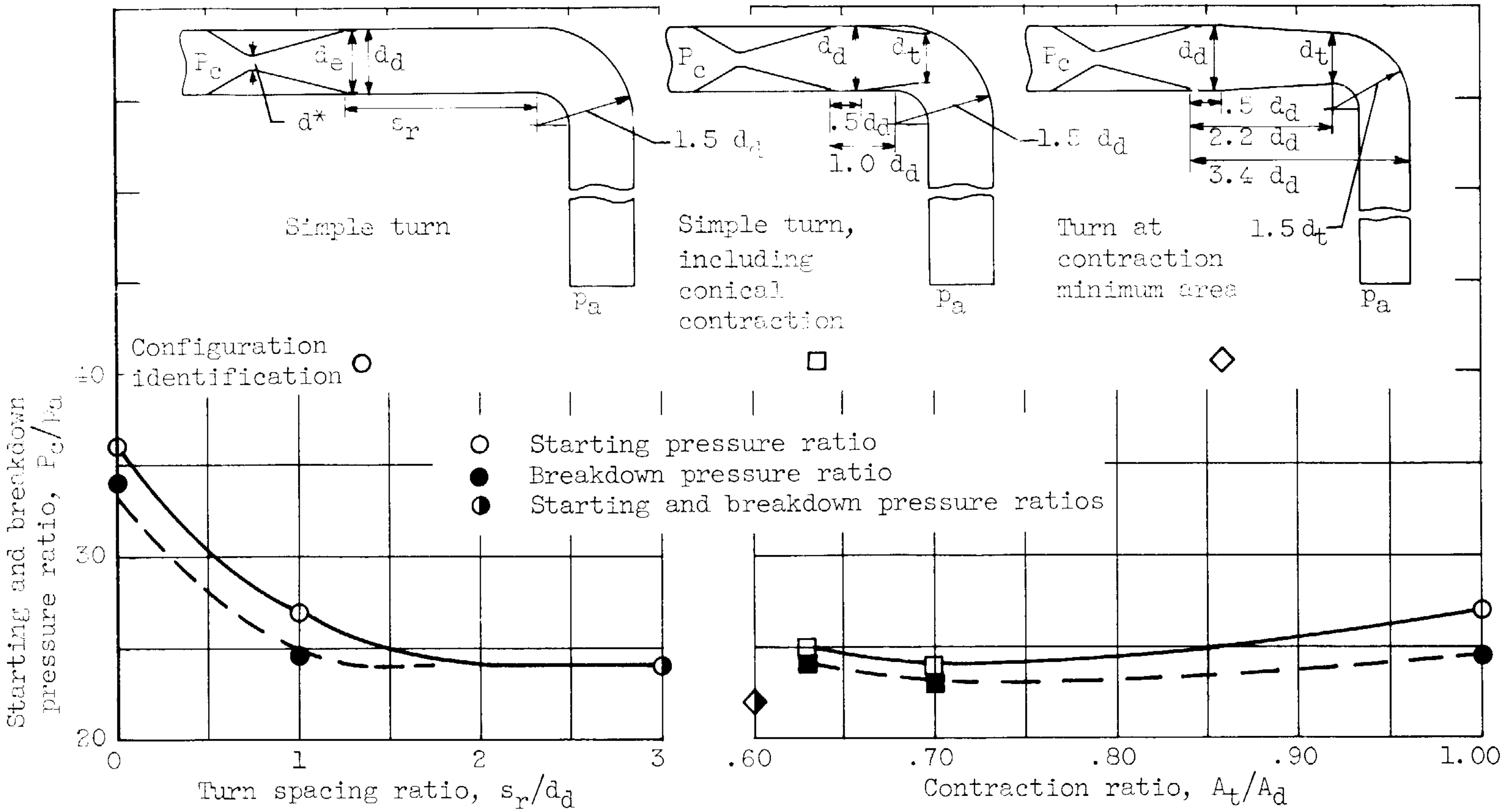


Figure 16. - Comparison of performance of convergent-divergent and cylindrical exhaust diffusers; cold-flow data.



(a) Simple turn.

(b) Turn using contraction.

Figure 17. - Performance of exhaust diffusers including right-angle turn with conical primary nozzle. Nozzle area ratio, A_c/A^*, 25; exhaust-diffuser area ratio, A_d/A^*, 28.9.