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MEMORANDUM

EXPERIMENTAL INVESTIGATION OF EXPANDED DUCT SECTIONS AND SCREENS FOR REDUCING FLOW DISTORTIONS AT SUBSONIC FLOWS

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SUMMARY

An investigation of expanded duct sections and the effect of their design parameters on flow distortion over a duct Mach number range of 0.19 to 0.67 was conducted in the small tunnel facility of the Lewis Research Center.

The parameters investigated were: (1) entrance angle of expanded section, (2) length of expanded section, (3) area ratio of expanded section, (4) location of expanded section relative to the engine face, and (5) the use of screens of varying solidities and mesh.

Expansion half-angles of 5°, 15°, and 30° reduced the total-pressure distortions induced in the duct. The larger expansion angles reduced circumferential distortion more effectively than radial distortion. However, the half-angle of 15° appeared to be optimum for reducing both radial and circumferential distortions while still maintaining a high total-pressure recovery.

Increasing the expanded-section area ratio and increasing the expanded-section lengths with the 15° expansion half-angle led to less total-pressure distortion with no appreciable loss in pressure recovery. Screens incorporated in the expanded section indicated that 22.2-percent-solidity screens decreased distortion still further while 37.3-percent-solidity screens generally increased distortion above that of a constant-area duct incorporating the same solidity screen.

INTRODUCTION

Large total-pressure distortions entering the compressor of turbojet engines and the cooling passages of nuclear powerplants can cause adverse operational effects. Lower surge limits, locally increased turbine gas temperatures, and local heating in the nuclear reactor are examples.

Several methods of reducing total-pressure distortions are discussed in reference 1; these include screens, rotating blade rows, constant-area mixing lengths, accelerated flow, and internal bleed. All these methods help to reduce total-pressure distortions. Screens, however, when used at higher duct Mach numbers, increase the total-pressure losses (ref. 2).

In general, an airflow that is expanded and contracted back to the original area helps to reduce total-pressure distortion (ref. 3) by induced mixing. In addition, the low duct Mach number in the expanded section would indicate efficient incorporation of straightening screens. However, little work has been done in investigating these methods of reducing distortion. Such an investigation has, therefore, been undertaken, and the results are reported herein.

The test apparatus comprised a circular duct 5.5 inches in diameter and 65 inches long, through which ambient air was inducted at Mach numbers up to 0.67 at a simulated compressor face. The study included: (1) the effect of an expanded section on total-pressure distortion, (2) the importance of various expanded-section parameters, and (3) the effect of screens in the expanded section on total-pressure distortion and pressure recovery.

SYMBOLS

The following symbols are used in this report:

A	duct cross-sectional area
D	basic duct diameter, 5.5 in.
L	length
M	Mach number
P	total pressure
$\dfrac{P_{max} - P_{min}}{P_{av}}$	total-pressure distortion parameter based on maximum pressure variation across pressure rake divided by average total pressure at rake
p	static pressure
q	dynamic pressure, $\frac{\gamma}{2} pM^2$
R	duct radius
r	inner radius used in design of radial-distortion-inducing screens

β	angle used in design of circumferential-distortion-inducing screens (fig. 2)
γ	ratio of specific heats
θ	half-angle of expanded section
φ	screen solidity, total duct area minus total screen open area divided by total duct area (in percent)

Subscripts:

av	average
c	compressor rake station (measured from downstream end of expanded section)
e	reference to expanded section
i	reference to induced-distortion station, measured immediately downstream of induced-distortion screen
l	local
max	maximum
min	minimum
5,15,30	half-angles of expanded sections, deg

APPARATUS AND PROCEDURE

The apparatus used in this investigation was a bellmouth circular duct 5.5 inches in diameter and 65 inches long, through which air was inducted at Mach numbers up to 0.67 at a simulated compressor face. Segments of the duct were removed and replaced with expanded sections of various designs, a few of which are shown in figure 1. The expanded sections were investigated for half-angles of expansion of 5°, 15°, and 30°, area expansion ratios of 1.72 and 1.46, and various expanded lengths. Screens of 22.2- and 37.3-percent solidity and various mesh were incorporated at the end of the expanded section (fig. 2(a)). All the configurations investigated are summarized in table I.

A translating, simulated compressor face with survey rake (see fig. 1) was located downstream of the expanded section. Data for two positions of the rake, $L_c/D = 0$ and 2, are presented; other rake positions were investigated briefly. A hemispherical and an elliptic nose hub (major-to-minor axis ratio of 2.0) were interchanged to determine the effect of hub geometry on duct flow at high subsonic Mach numbers. The compressor-face hub-to-tip ratio was 0.4.

Induced Distortion

Distortion was induced into the flow 6 inches upstream of the expanded section by the screens shown in figure 2(b). The screens were designed to induce radial or circumferential distortions (as in ref. 4) of three magnitude levels: 3 to 15 (low), 3 to 20 (medium), and 5 to 40 percent (high). The amount of distortion that each screen induced at the compressor face was a function of the Mach number just ahead of the distortion-inducing screen, as shown in figure 3. All distortions were measured at the compressor face, with the rake mounted on the simulated compressor hub, over a compressor-face Mach number range of 0.19 to 0.67. Distortion data for the constant-area configuration incorporating 22.2- and 37.3-percent-solidity straightening screens were obtained but are not presented in figure 3; however, the data are included in the following figures of this report.

In figure 3, double values of distortion are plotted for the high-level radial and circumferential distortion screens because of the noted difference, as was expected in the induced distortion measured at the two locations of the compressor-face rake, $L_c/D = 0$ and 2 (39 and 59 in. from the bellmouth, respectively). This difference is negligible for the medium- and low-level distortions and is not presented.

Data Reduction

The average total pressure at the compressor face was computed from a mass flow measured at the bellmouth, a static pressure, and the area at the indicated station. This value was in close agreement with that obtained by area-weighting the total pressures of the compressor-face rake.

In computing distortion $\left(\frac{P_{max} - P_{min}}{P_{av}}\right)$, the maximum and minimum total pressures were measured values, while the average total pressure was the mass-derived value. Both radial and circumferential distortions were computed by this definition.

The total-pressure-recovery parameter P_c/P_i in this report is a ratio of the computed average total pressure at the compressor face, P_c, to the pressure just ahead of the expanded section but downstream of the distortion screen, P_i (fig. 1).

DISCUSSION OF RESULTS

Angle of Expansion

Three expansion half-angles of 5°, 15°, and 30° were investigated over a Mach number range of 0.19 to 0.67 for high, medium, and low radial and circumferential distortions. These expanded sections were investigated with an area ratio A_e/A of 1.72, a nominal expanded length L_e/D of 2.0 (ranging from 1.78 to 2.03), and straightening-screen solidities of 22.2 and 37.3 percent.

Figure 4 presents cross plots showing the effect of expansion half-angle and screen solidity with high radial and circumferential distortions for duct Mach numbers of 0.6, 0.5, and 0.3. For this figure the compressor-face station was located 2 duct diameters downstream of the expanded section.

The data of figure 4(a) for circumferential distortion indicate decreasing distortion with increasing half-angle of expansion θ except for the 37.3-percent-solidity screen (discussed in next paragraph). The same trends, however, are not indicated for the radial-type distortion: As the expansion half-angle was increased from 15° to 30°, an increase instead of a decrease in distortion was noted. This behavior is a consequence of the fact that the high-energy core of the radial distortion apparently passed through the θ_{30° expanded section relatively unexpanded and unmixed. As a result, the distortion is similar in magnitude to that measured in the constant-area duct (see fig. 4(b)). Circumferential distortion, however, has unequal pressure forces within the fluid itself that cause secondary flow and, therefore, strong mixing. Mixing in the expanded section will flatten the flow profile and result in the reduced distortion for θ_{30° in figure 4(a).

The 37.3-percent-solidity straightening screen produced such wake turbulence with both radial and circumferential flows that distortion was generally increased above that of a constant-area configuration incorporating the same solidity screen.

The higher the screen solidity, the greater was the reduction in screen and total-pressure losses with duct expansion. Once the duct was expanded, however, the angle of expansion had little effect on screen losses and pressure recovery.

For compressor-face Mach numbers of 0.5 and 0.3, figures 4(b) and (c) show the same trends for both the circumferential and radial distortions as discussed previously for Mach 0.6. Because of the low velocity in the duct (fig. 4(c)), the 37.3-percent-solidity screen produces less wake disturbance and no longer increases the distortion above that of a constant-area configuration.

The magnitude of the distortion entering the expanded section changes only slightly with the addition of straightening screens or changes in the expanded-section geometry; the maximum deviation of the entering distortion in comparing any two points is a maximum of ±2.7 percent of the average total pressure. If any two points with the same straightening screen solidity are compared, the maximum deviation of the entering distortion can be ±1.8 percent. Compressor-face total-pressure contours for the constant area and the θ_{15° and θ_{30° configurations discussed previously are presented in figure 5. The contours are plotted for the maximum compressor-face Mach number tested.

From figure 5(a) it is interesting to note that, in attempting to reduce circumferential distortion by increasing the expansion half-angle θ or the screen solidity φ, not only is the magnitude of the circumferential distortion reduced but the circumferential distortion takes on characteristics of a radial distortion. For the same change of variables, the magnitude of the radial distortion of figure 5(b) is reduced, but the distortion type remains radial.

Figure 6 is included to indicate the effects of expansion angle and distortion-straightening screens on pressure recovery and distortion when the induced distortion is of medium level (fig. 3). The data for low-level distortion indicated results similar to, but less significant than, those of figure 6 and are not presented.

Effect of Expanded-Section Area Ratio

Two area ratios of 1.72 and 1.46 were investigated with a 15° half-angle configuration and high circumferential distortion. The data are presented in figure 7 as a function of compressor-face Mach number.

With the compressor-face rake located 2 duct diameters downstream of the expanded section (fig. 7(a)), the larger area ratio indicated reduced distortions and equivalent pressure recoveries for 0-, 22.2-, and 37.3-percent-solidity straightening screens over the entire Mach number range. With the rake located at $L_c/D = 0$ (fig. 7(b)), the area ratios had no apparent effect on distortion for Mach numbers and screens tested.

Figure 7 shows that distortions are also reduced just by locating the expanded section 2 duct diameters upstream of the compressor face regardless of the geometry of the expanded section.

No significant change in total-pressure recovery was indicated either by the compressor location or by a change of expanded-section area ratio.

Effect of Length of Expanded Section

With high circumferential distortion and a 15° half-angle configuration three expanded-section lengths, $L_e/D = 1.1$, 1.5, and 2.0, were investigated with and without screens. The results are presented for compressor locations of $L_c/D = 2$ and 0 in figure 8.

With a compressor location of $L_c/D = 2$ (fig. 8(a)) for the no-screen case, the longer the expanded section, the greater was the reduction in distortion with no effect on pressure recovery. When the screen solidity was increased to 22.2 percent, the length of the section had much less effect on distortion. With the solidity increased to 37.3 percent, the length of the expanded section had no practical effect on distortion, and the screen itself produced greater distortion than that of a constant-area duct with the same solidity screen.

In figure 8(b), where the compressor is located at the end of the expanded section ($L_c/D = 0$), the length of the expanded section and the expanded section itself have very little effect in reducing distortion or improving pressure recovery. For the 22.2- and 37.3-percent-solidity screens, distortion was increased and pressure recovery improved.

Effect of Screen Mesh on Distortion

Distortion-straightening screens of 6, 8, 10, and 28 mesh and nominal solidity of 40 percent were tested with a 15° expanded section for effectiveness in reducing circumferential distortion. All screens were tested with an L_c/D of 2.0, and the data are presented in figure 9.

The results are similar to those found in reference 5, which shows that increased screen mesh resulted in reduced distortion. However, the effect is small, and it is concluded that screen mesh with 40-percent solidity is not an important design parameter in reducing distortion. The 6-mesh screen incurred the least total-pressure loss across the expanded section.

Comparison of Straight and Swept Screens

Swept screens have been proved beneficial for reducing distortions and total-pressure losses for a limited subsonic range of Mach numbers (refs. 2 and 6). For an extension of Mach range and for comparison purposes, data are presented in figure 10 for a straight screen, a single-swept screen, and a wedge or double-swept screen, all installed in a constant-area duct. Data for a $\theta_{15^{\circ}}$ expanded configuration with a straight screen incorporated in the expanded section are included. All screens were of 6 mesh, 22.2-percent solidity and were investigated for a high radial distortion and a compressor location of $L_c/D = 2$. The swept screens and the $\theta_{15^{\circ}}$ expanded section indicate higher pressure recoveries than the straight screen over the range of Mach numbers. At the higher Mach numbers, however, the swept screens were less effective in reducing total-pressure distortion than either the straight screens or the $\theta_{15^{\circ}}$ expanded section.

Effects of Hemispherical and Elliptic Compressor Hubs

The entire investigation of expanded-section design parameters was conducted with a hemispherical compressor hub. In an attempt to evaluate hub contour at high subsonic speeds, an elliptic hub was also investigated, and data were again taken with a $\theta_{15^{\circ}}$ configuration with radial and circumferential distortion. As shown in figure 11, a hemispherical hub is more effective in reducing radial distortion than an elliptic hub, while no major differences in performance were evident with the high circumferential distortion.

SUMMARY OF RESULTS

In an investigation of expanded duct sections and the effect of their design parameters on flow distortion over a simulated engine-face Mach number range of 0.19 to 0.67, the following results were obtained:

1. Expanded sections without distortion-straightening screens reduced circumferential distortion for increasing half-angles tested up to 30°. When the flow distortion was largely radial, a lower total-pressure distortion was obtained with a half-angle on the order of 15°. Little total-pressure loss was incurred in all cases without screens.

2. Screens of 22-percent solidity incorporated in an expanded section generally reduced distortion slightly more than comparable constant-area installations; however, the loss in total pressure was not as great. A 37.3-percent screen resulted in large improved total-pressure recoveries but increased the total-pressure distortions over a constant-area duct incorporating the same screen.

3. The farther the expanded section was upstream of the engine face, the greater was the reduction in total-pressure distortion and the greater were the effects of the expanded-section area ratio and length. With the compressor located at the end of the expanded section, increasing the expanded area ratio from 1.46 to 1.72 and the length from 1.1 to 2.0 had no significant effect in reducing total-pressure distortions or total-pressure losses.

4. Maintaining constant screen solidity of 40 percent in a 15° expanded-section screen mesh indicates little effect on total-pressure distortion. Six-mesh screens incurred the least total-pressure loss across the expanded section.

5. A 22.2-percent-solidity swept screen in a constant-area duct was slightly less effective than a normal screen in reducing distortion, but it incurred less total-pressure loss. A 15° half-angle expanded section with an identical screen section gave less total-pressure loss than either the swept or normal screens and improved the distortion results.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, October 14, 1958

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2. Wood, Charles C., and Knip, Gerald, Jr.: An Investigation of Screens for Removing Distortions in Ducted Flows at High Subsonic Speeds. NACA RM L57G08, 1957.

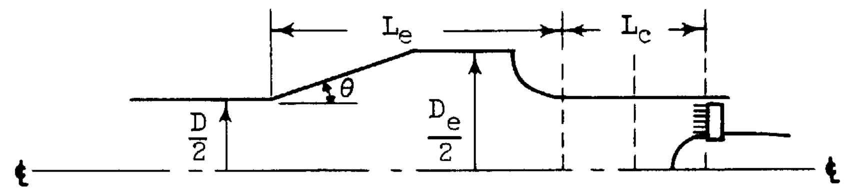
3. Piercy, Thomas G., and Klann, John L.: Experimental Investigation of Methods of Improving Diffuser-Exit Total-Pressure Profiles for a Side-Inlet Model at Mach Number 3.05. NACA RM E55F24, 1955.

4. Smith, Ivan D., Braithwaite, W. M., and Calvert, Howard F.: Effect of Inlet-Air-Flow Distortions on Steady-State Performance of J65-B-3 Turbojet Engine. NACA RM E55I09, 1956.

5. Klann, John L.: Experimental Evaluation of Methods for Improving Diffuser-Exit Total-Pressure Profiles for a Side-Inlet Model at Mach Number 1.91. NACA RM E56K05a, 1957.

6. Woollett, Richard R.: Preliminary Investigation of Short Two-Dimensional Subsonic Diffusers. NACA RM E56C02, 1956.

TABLE I. - CONFIGURATIONS AND PARAMETERS TESTED



Configuration	Type of induced distortion	Expansion area ratio, A_e/A	Length of expanded section, L_e/D (a)	Screen solidity, φ, percent	Screen mesh	Mach number at compressor, M_c	Compressor location, L_c/D
Constant-area duct	Natural Radial Circumferential	------	------	0 22.2 37.3 22.2 Swept	6	0.19 to 0.67	0, 1, 2
5° Half-angle expanded section, $\theta_{5^{\circ}}$	Radial Circumferential	1.72	2.03 2.34	0 22.2 37.3	6	0.19 to 0.67	0, 1, 2
15° Half-angle expanded section, $\theta_{15^{\circ}}$	Radial Circumferential	1.72 (1.46)	1.10 1.48 2.00 (1.65)	0 22.2 37.3	6 8 10 28 (6)	0.19 to 0.67	0, 1, 2
30° Half-angle expanded section, $\theta_{30^{\circ}}$	Radial Circumferential	1.72	1.52 1.78	0 22.2 37.3	6	0.19 to 0.67	0, 1, 2

[a]Duct diameter, D, 5.5 inches.

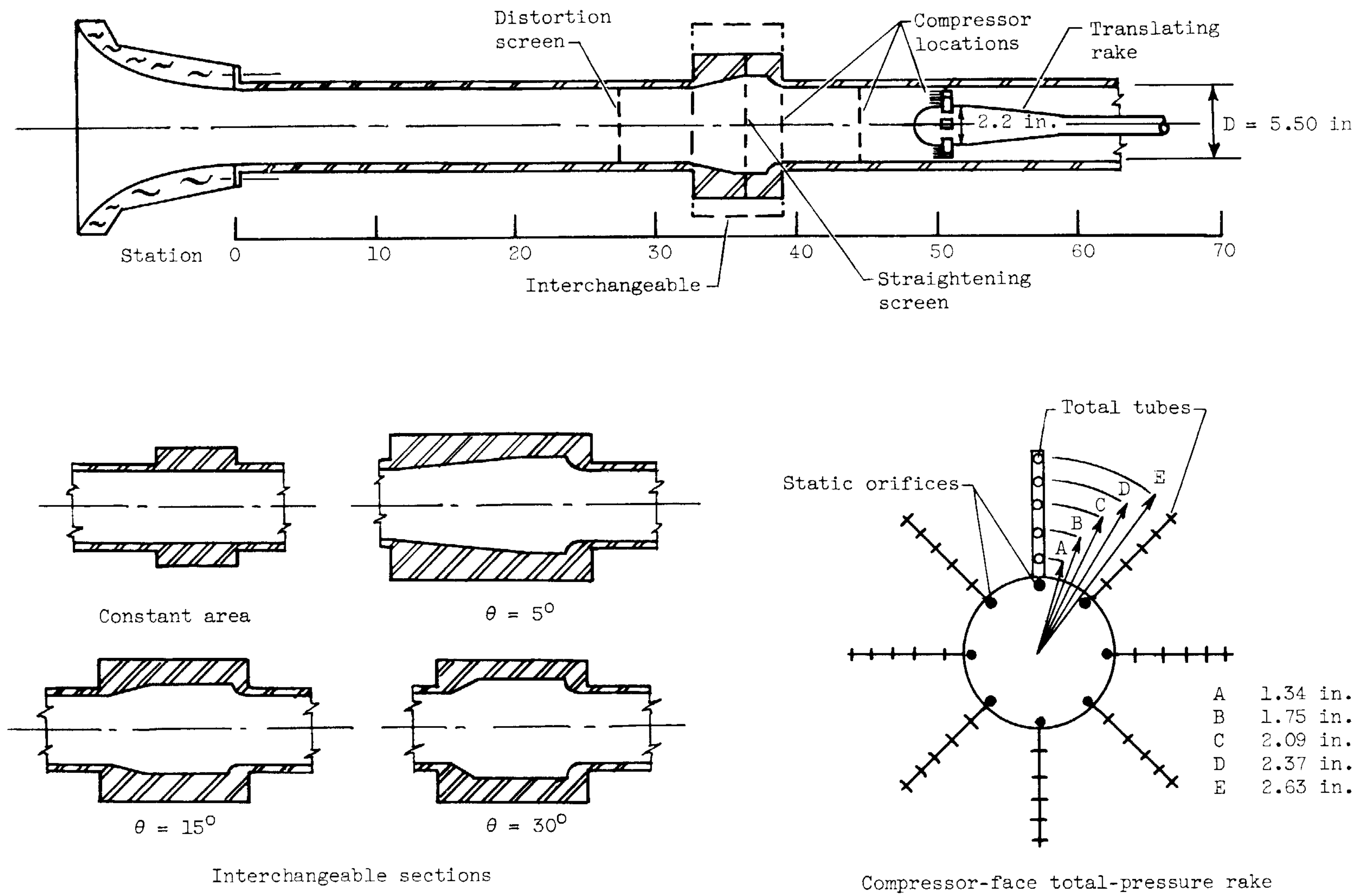
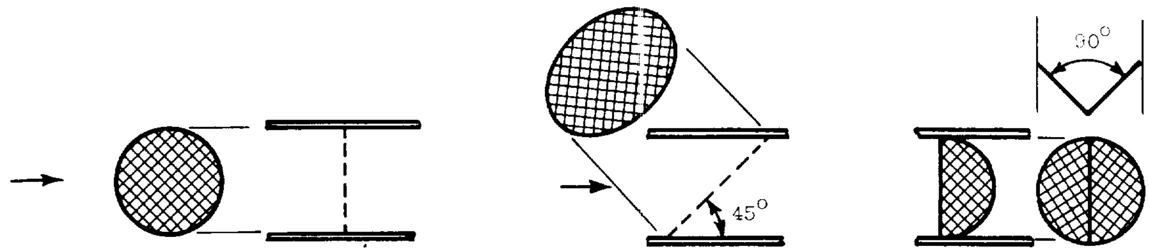


Figure 1. - Experimental setup and several configurations tested.



Vertical screen

Swept screen

Wedge (double-swept) screen

Screen type	Screen solidity	Mesh	Wire diameter, in.	Width of opening, in.
Vertical	0.222	6	0.020	0.147
	.373	6	.035	.132
	.376	28	.0075	.028
	.398	8	.028	.097
	.407	10	.023	.077
Swept	0.254	8	0.017	0.108
Wedge (double swept)	0.222	6	0.020	0.147

(a) Distortion-straightening screens.

Circumferential distortion					Radial distortion					Maximum distortion level at M_c = 0.6
Duct blockage (a)	Mesh	β, deg	Wire diam., in.	Width of opening, in.	Duct blockage (a)	Mesh	r/R (b)	Wire diam., in.	Width of opening, in.	
0.20	6	89	0.028	0.139	0.20	8	0.618	0.020	0.105	Low (15%)
.25	10	89	.023	.077	.30	10	.549	.023	.077	Med. (20%)
.36	12	86.5	.035	.048	.36	10	.600	.035	.059	High (40%)

[a]Duct closed area divided by duct open area.

[b]Duct radius, R, 2.75 inches.

(b) Distortion-inducing screens.

Figure 2. - Screen designs used for inducing and straightening total-pressure distortion.

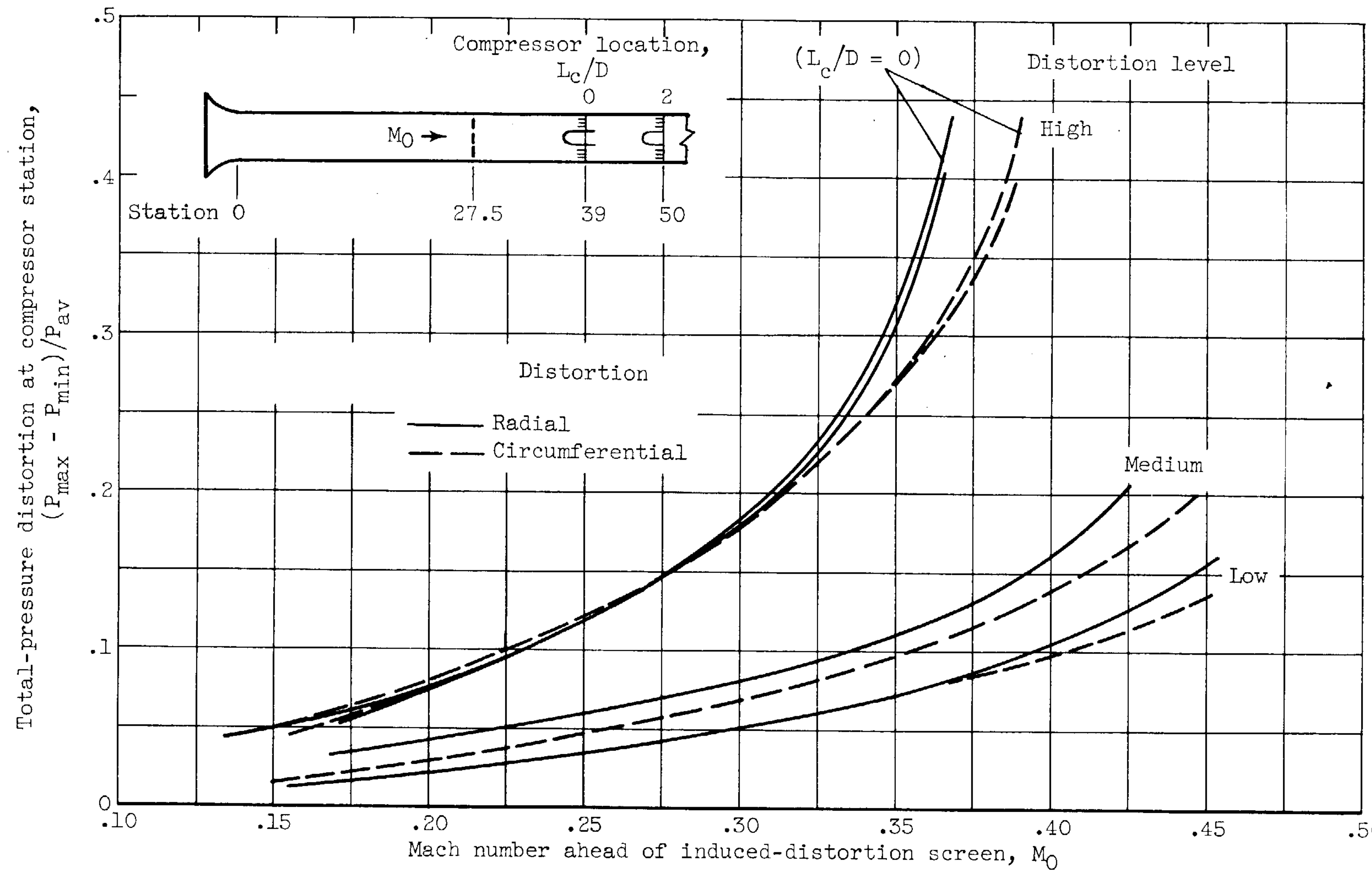
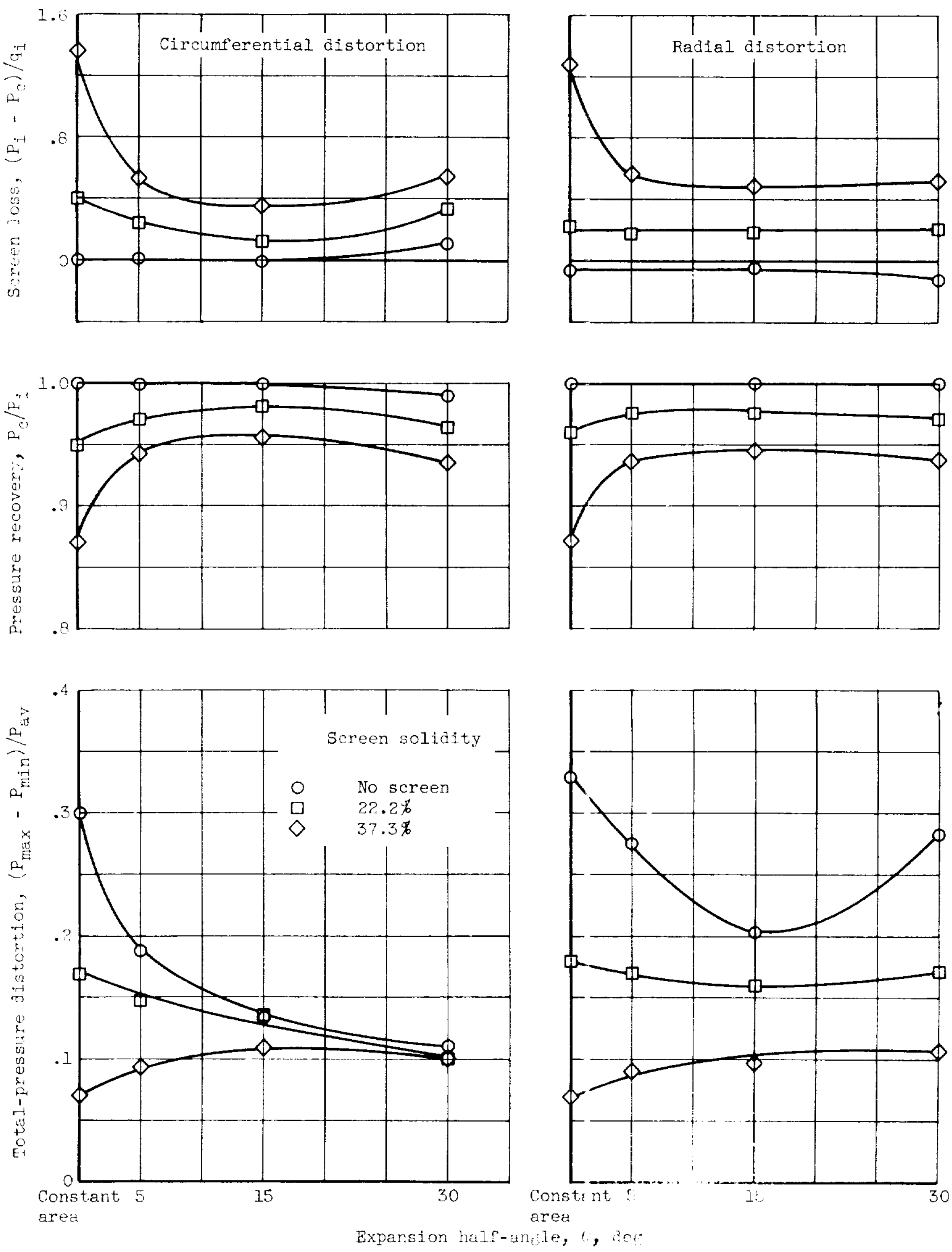
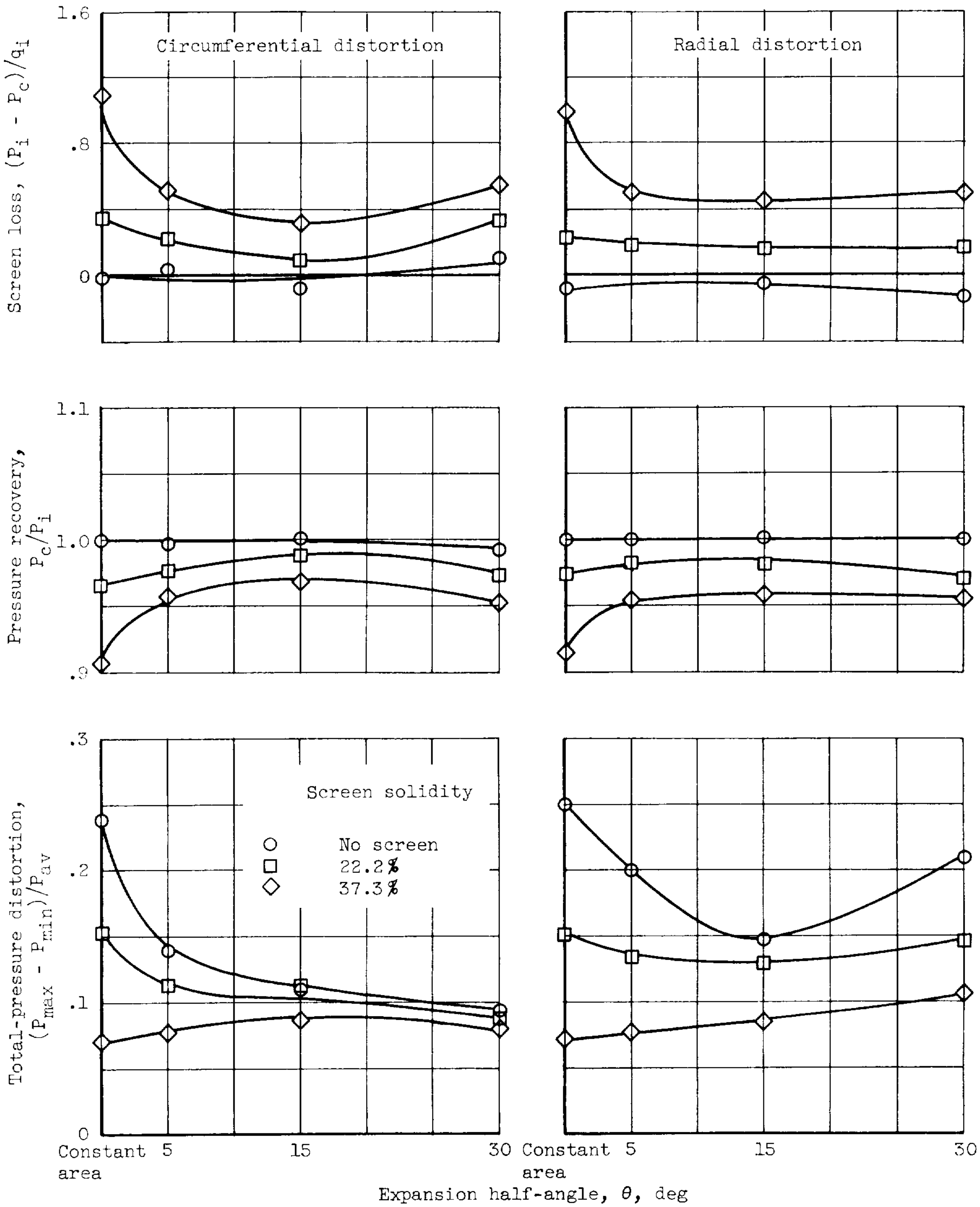


Figure 3. - Distortion induced in a 5.5-inch constant-area duct, measured 50 inches from rear of bellmouth ($L_c/D = 2.0$).



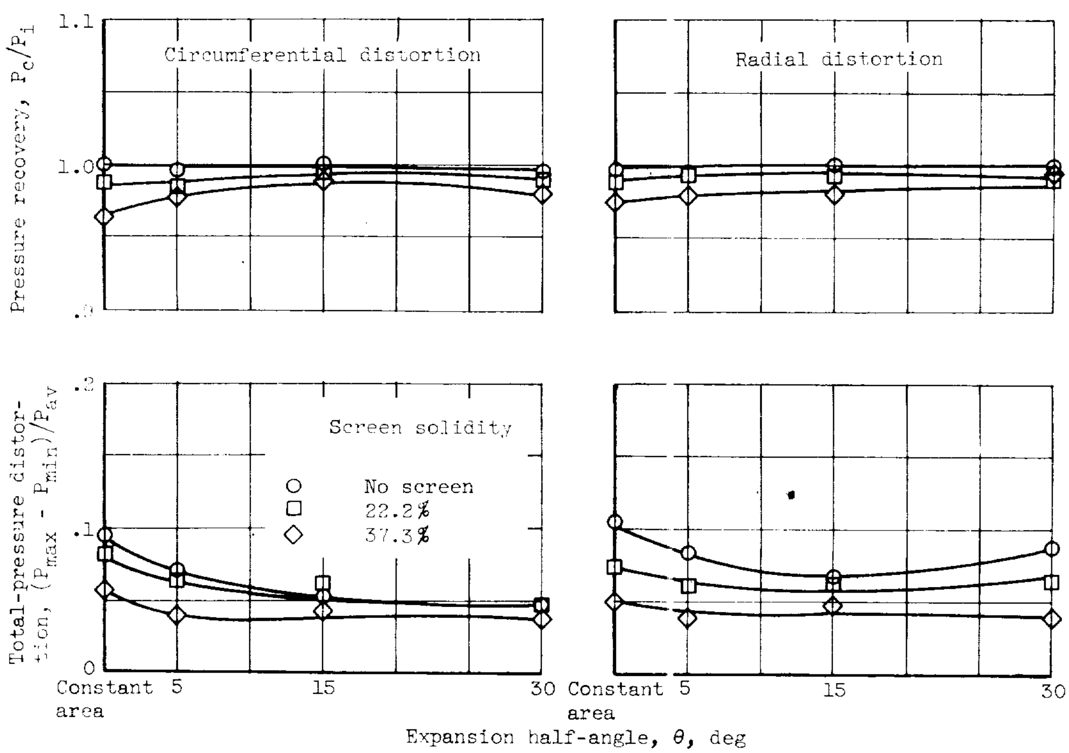
(a) Compressor-face Mach number, 0.6.

Figure 4. - Effects of expansion angle and screen solidity with high-magnitude distortions for $D_e/D = 1.31$, $L_e/D = 2.0$, and $L_c/D = 2.0$.



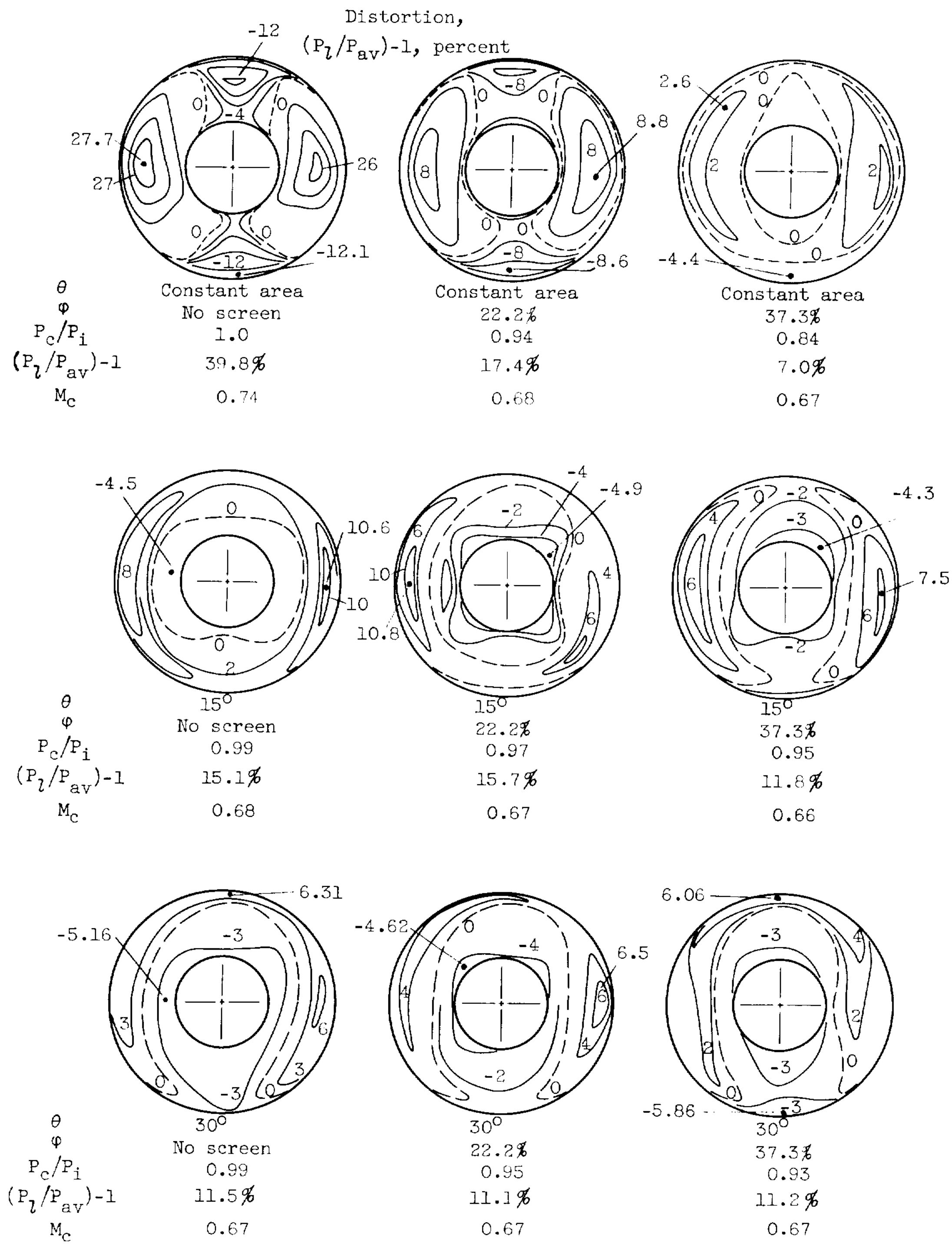
(b) Compressor-face Mach number, 0.5.

Figure 4. - Continued. Effects of expansion angle and screen solidity with high-magnitude distortions for $D_e/D = 1.31$, $L_e/D = 2.0$, and $L_c/D = 2.0$.



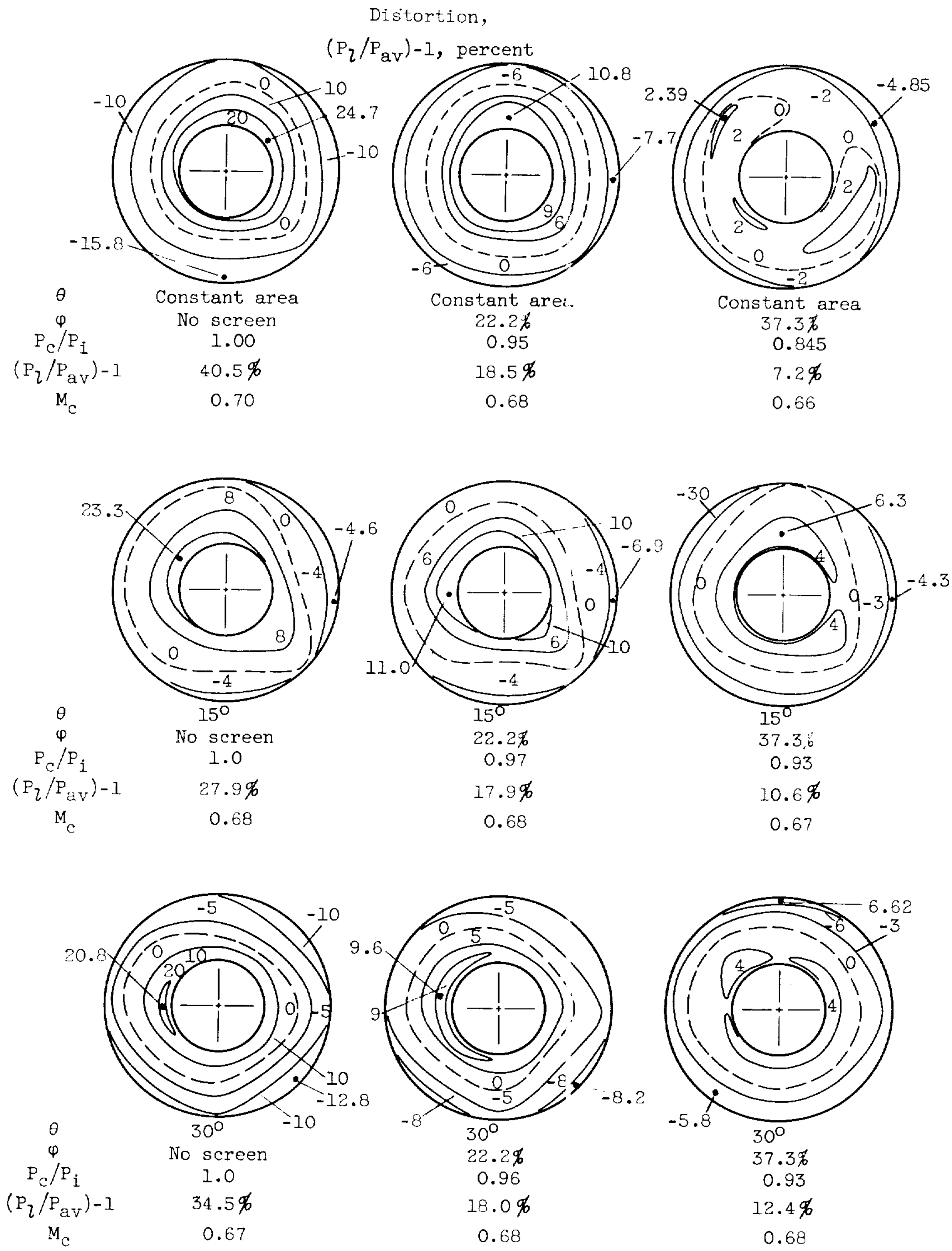
(c) Compressor-face Mach number, 0.3.

Figure 4. - Concluded. Effects of expansion angle and screen solidity with high-magnitude distortions for $D_e/D = 1.31$, $L_e/D = 2.0$, and $L_c/D = 2.0$.



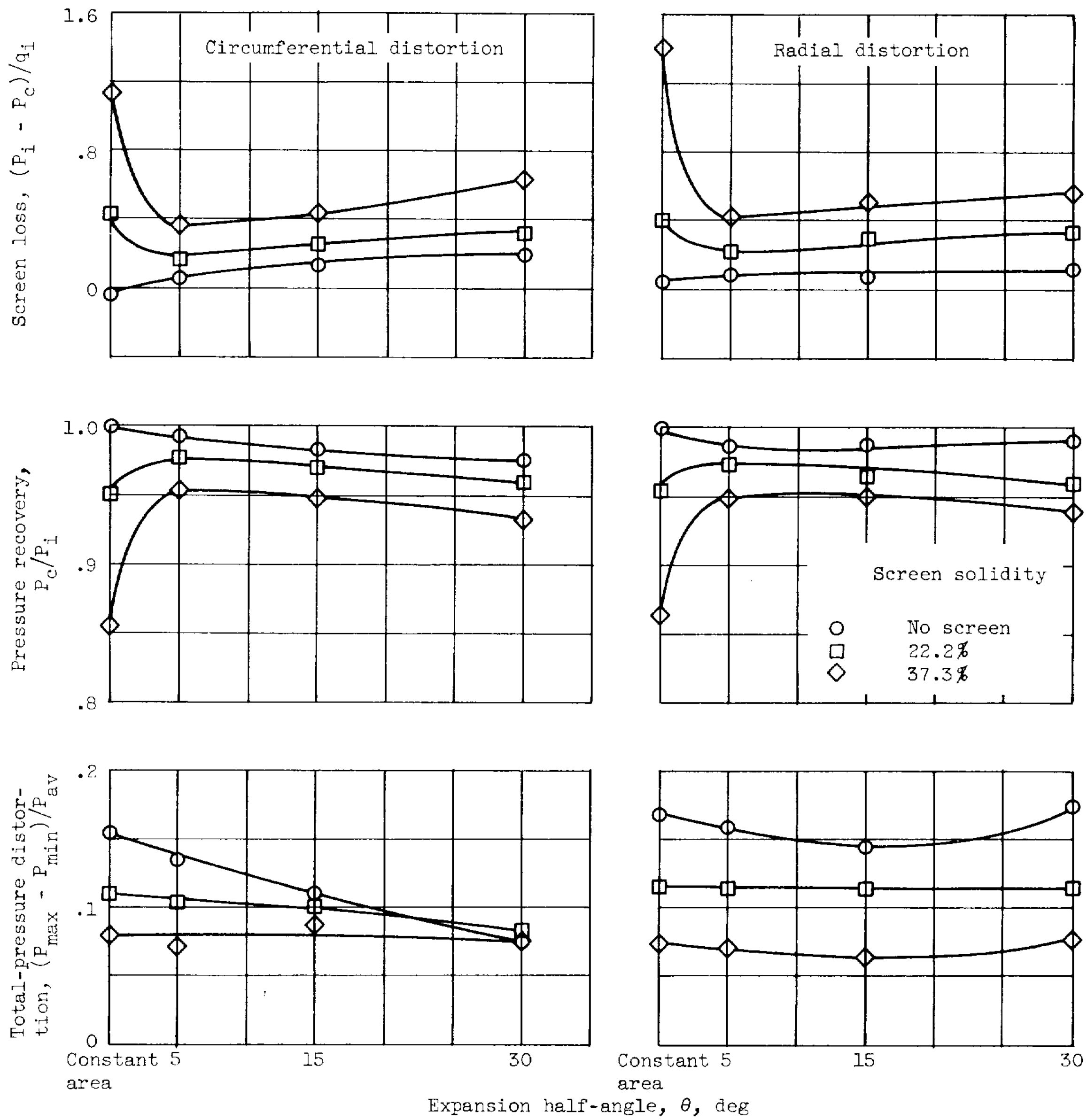
(a) High circumferential distortion.

Figure 5. - Effect of expansion angles and screens on compressor-face contours. $L_c/D = 2$; $A_e/A = 1.72$.



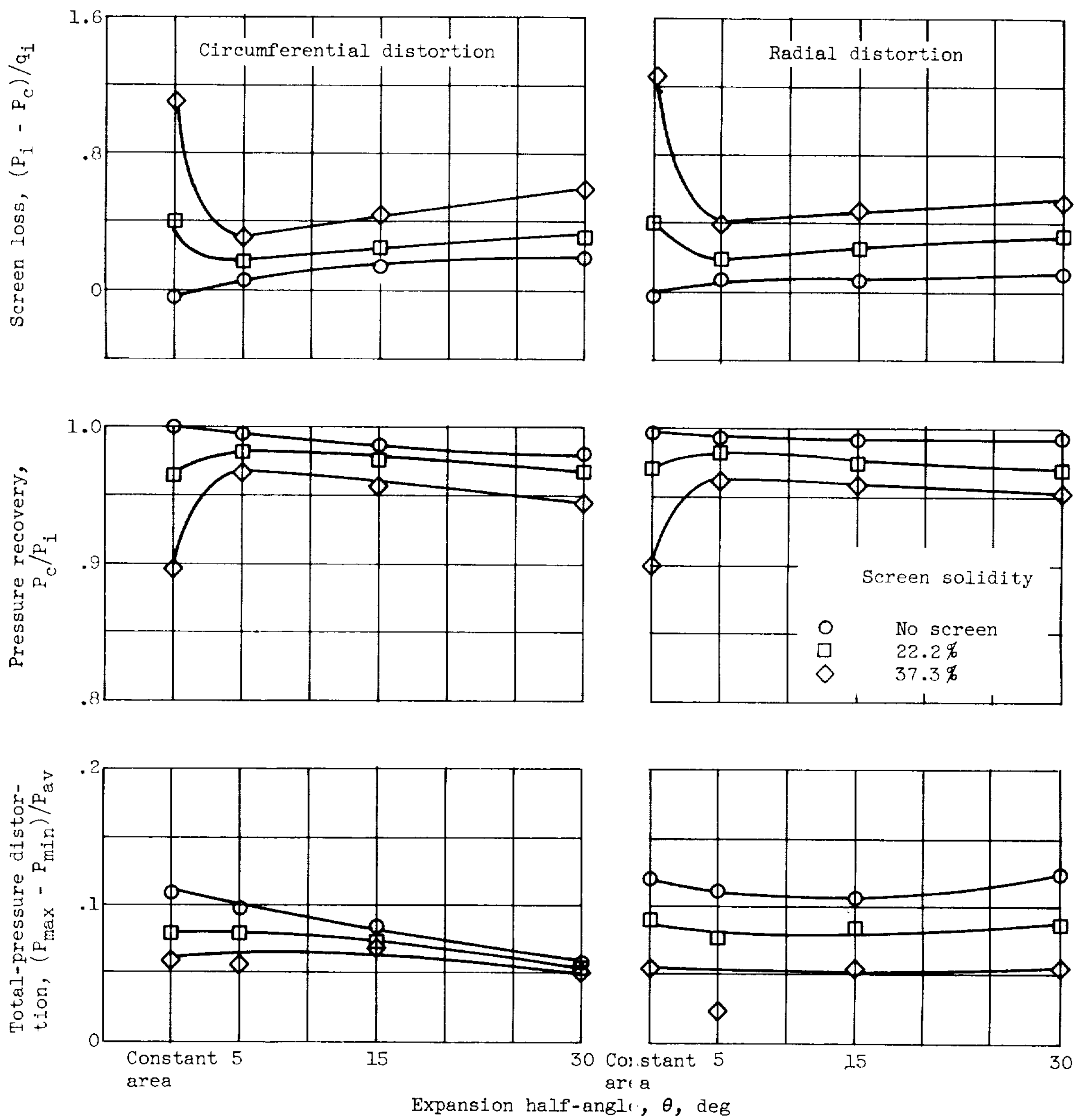
(b) High radial distortion.

Figure 5. - Concluded. Effect of expansion angles and screens on compressor-face contours. $L_c/D = 2$; $A_0/A = 1.72$.



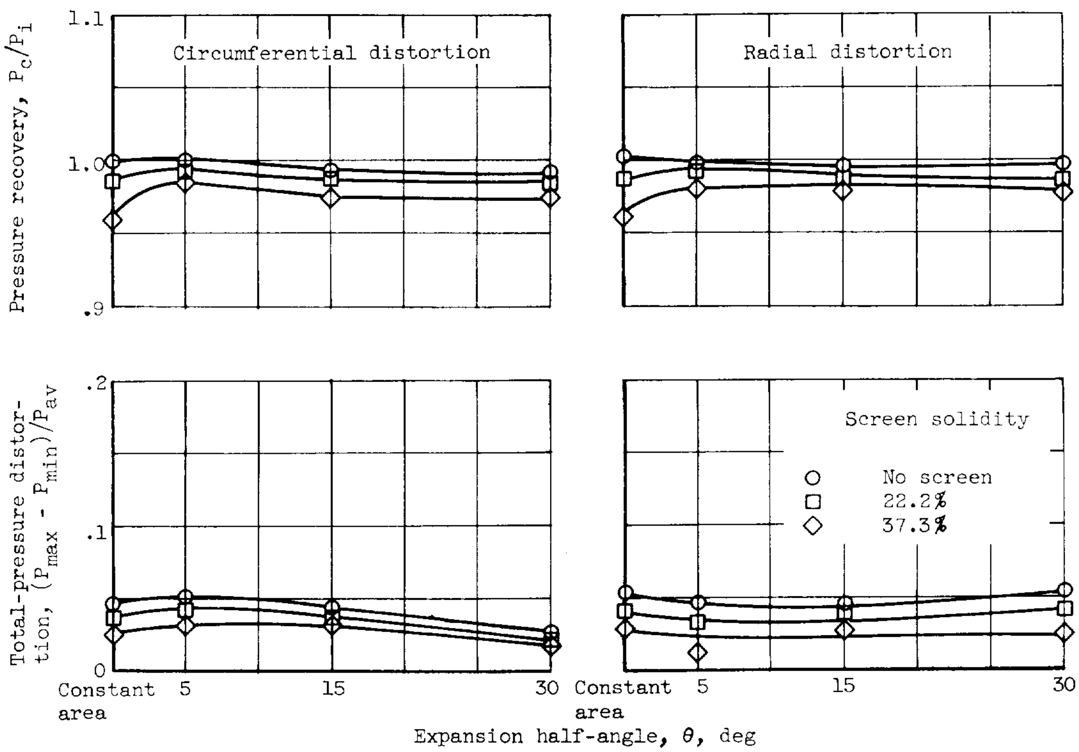
(a) Compressor-face Mach number, 0.6.

Figure 6. - Effects of expansion angle and screen solidity with medium-magnitude distortions for $A_e/A = 1.72$, $L_e/D = 2.0$, and $L_c/D = 2.0$.



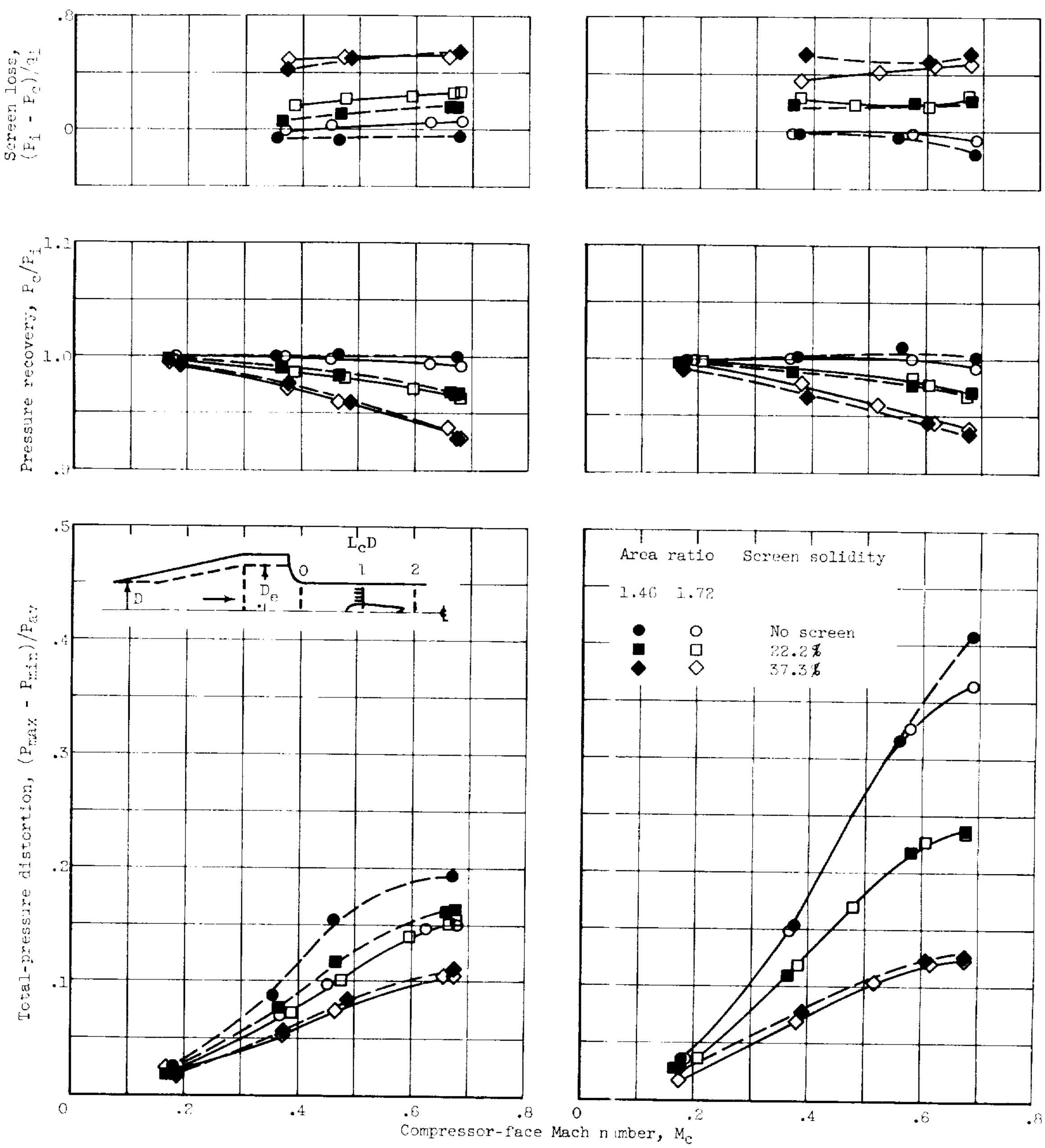
(b) Compressor-face Mach number, 0.5.

Figure 6. - Continued. Effects of expansion angle and screen solidity with medium-magnitude distortions for $A_e/A = 1.72$, $L_e/D = 2.0$, and $L_c/D = 2.0$.



(c) Compressor-face Mach number, 0.3.

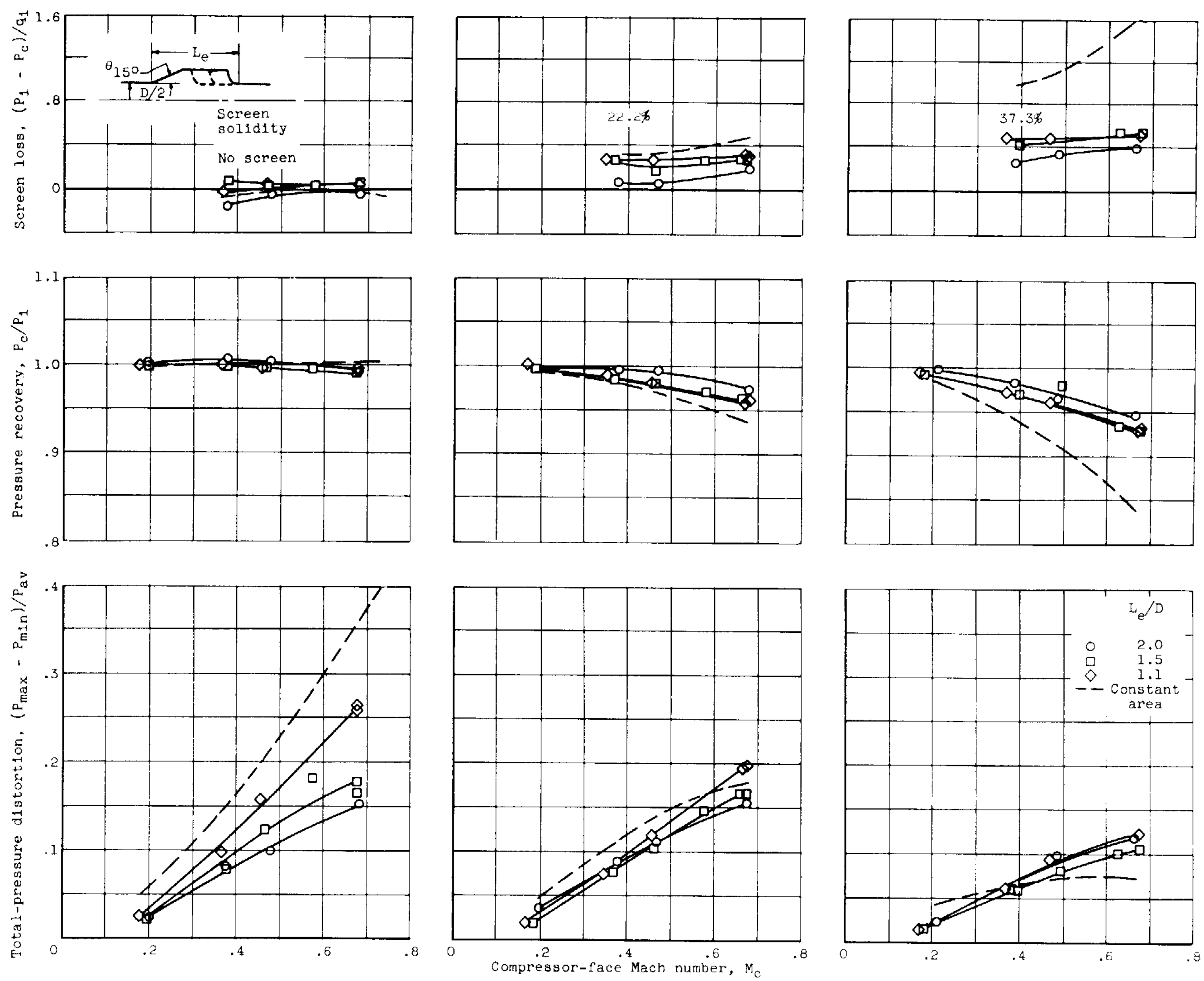
Figure 6. - Concluded. Effects of expansion angle and screen solidity with medium-magnitude distortions for $A_e/A = 1.72$, $L_e/D = 2.0$, and $L_c/D = 2.0$.



(a) Compressor face located 2 duct diameters downstream of expanded section ($L_c/D = 2$).

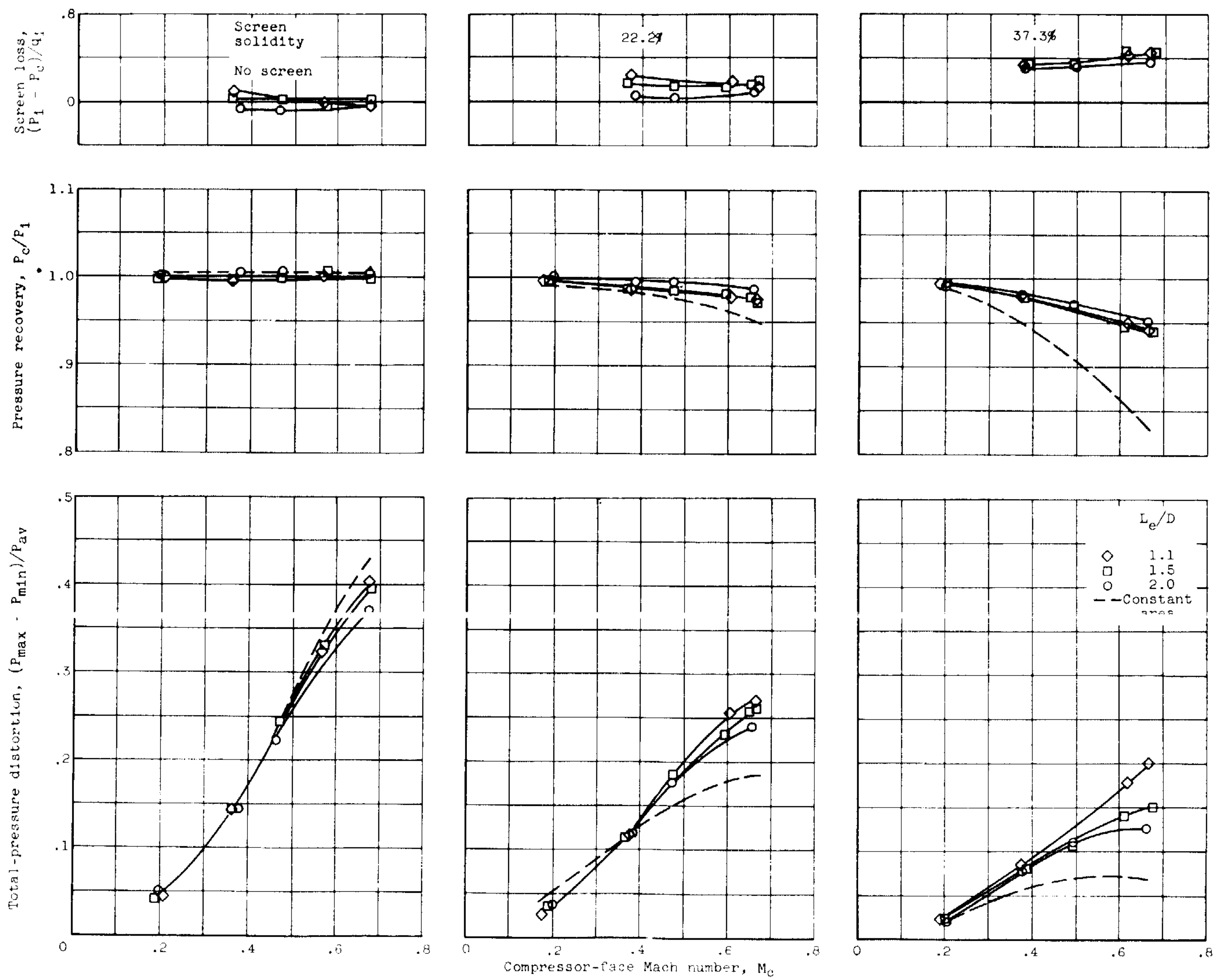
(b) Compressor face located at end of expanded section ($L_c/D = 0$).

Figure 7. - Effect of overexpansion diameter ratio with high circumferential distortion. Expansion half-angle, 15°.



(a) Compressor 2 diameters downstream of expanded section.

Figure 8. - Effect of length of expanded section with a 15° half-angle of expansion and high circumferential distortion. Area ratio, 1.72.



(b) Compressor at end of expanded section.

Figure 8. - Concluded. Effect of length of expanded section with a 15° half-angle of expansion and high circumferential distortion. Area ratio, 1.72.

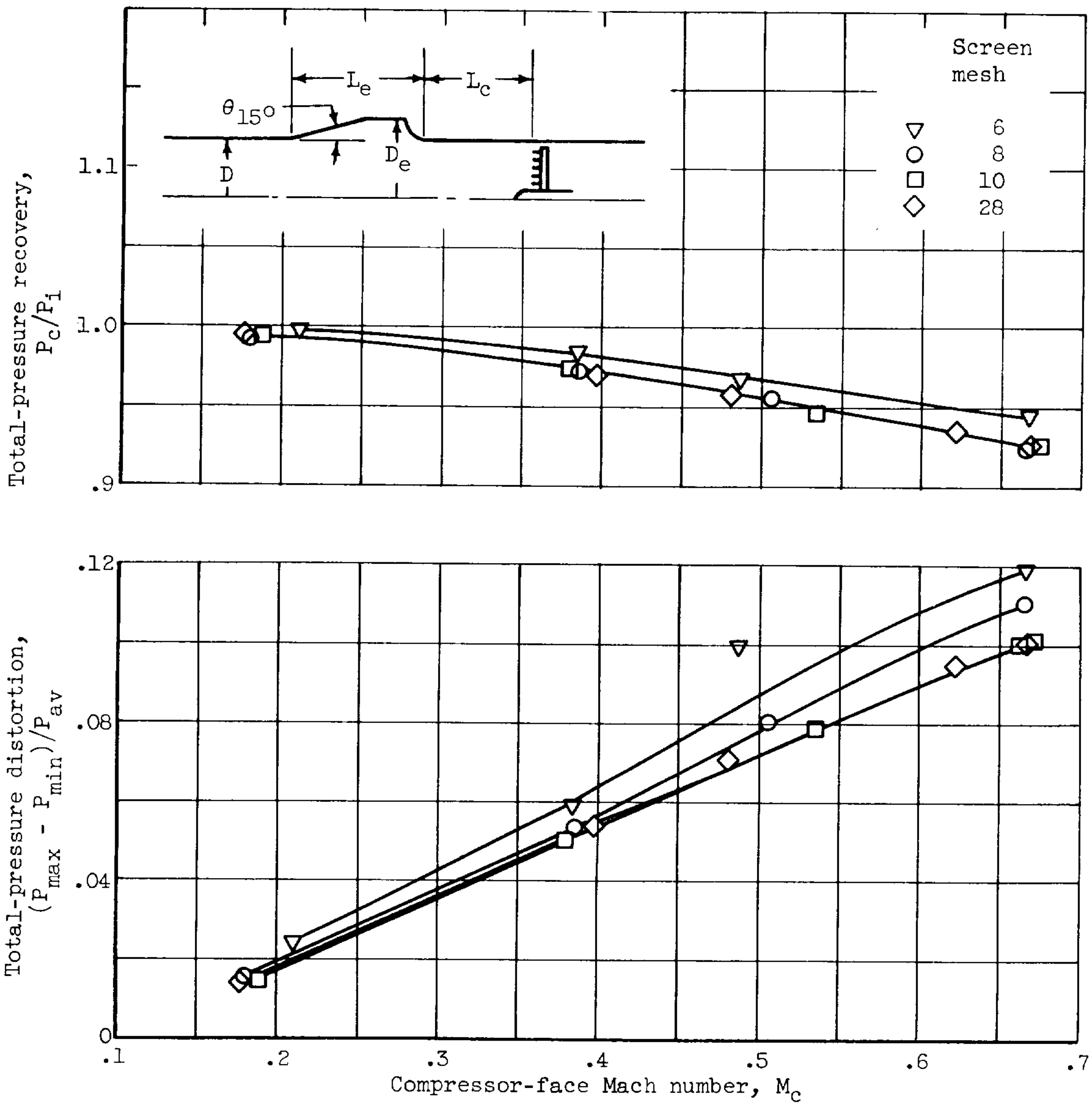


Figure 9. - Effect of screen mesh with high circumferential distortion in a 15° expanded diffuser section. Nominal solidity, 40 percent; $L_e/D = 2.0$; $L_c/D = 2.0$; $A_e/A = 1.72$.

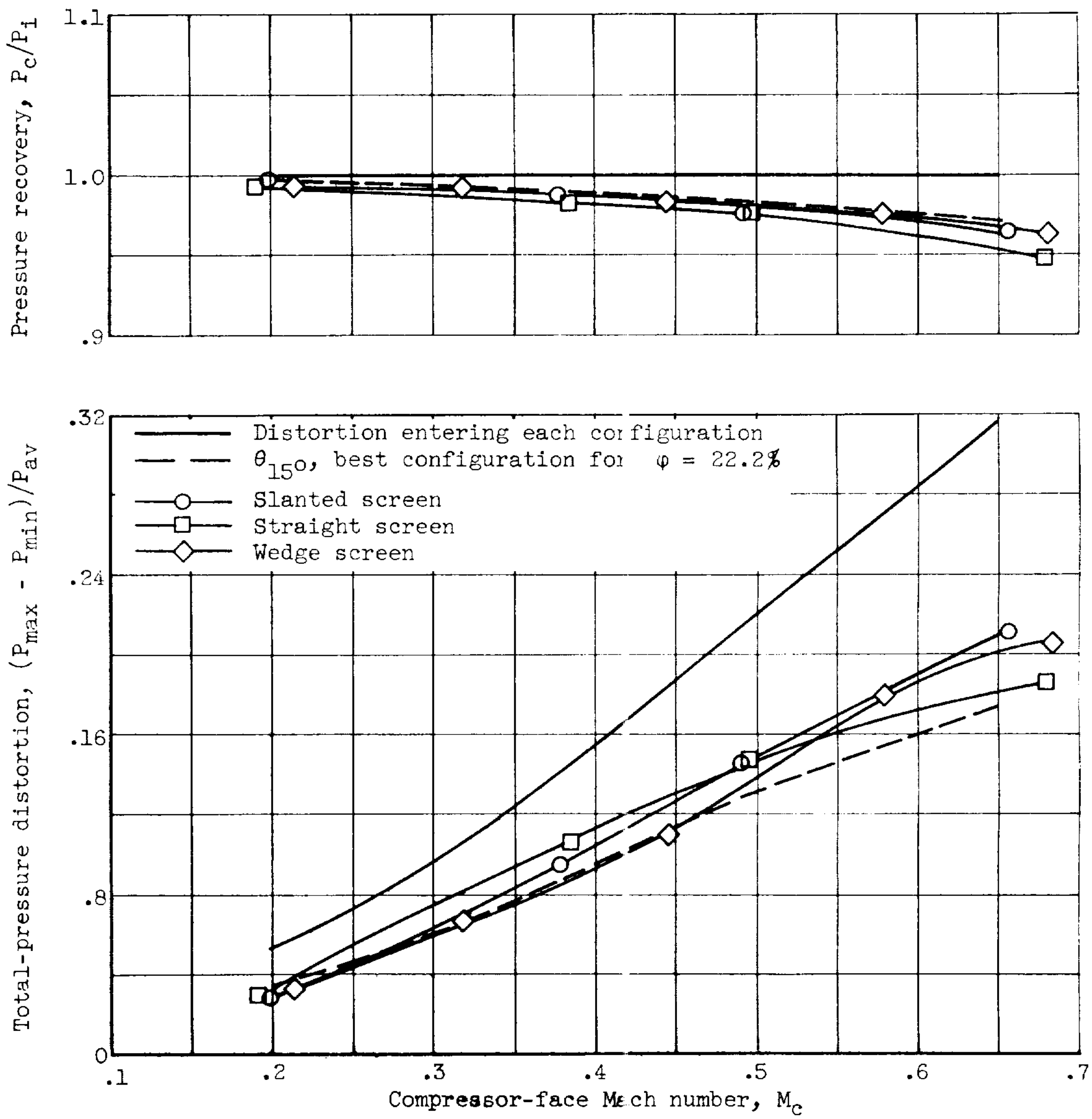
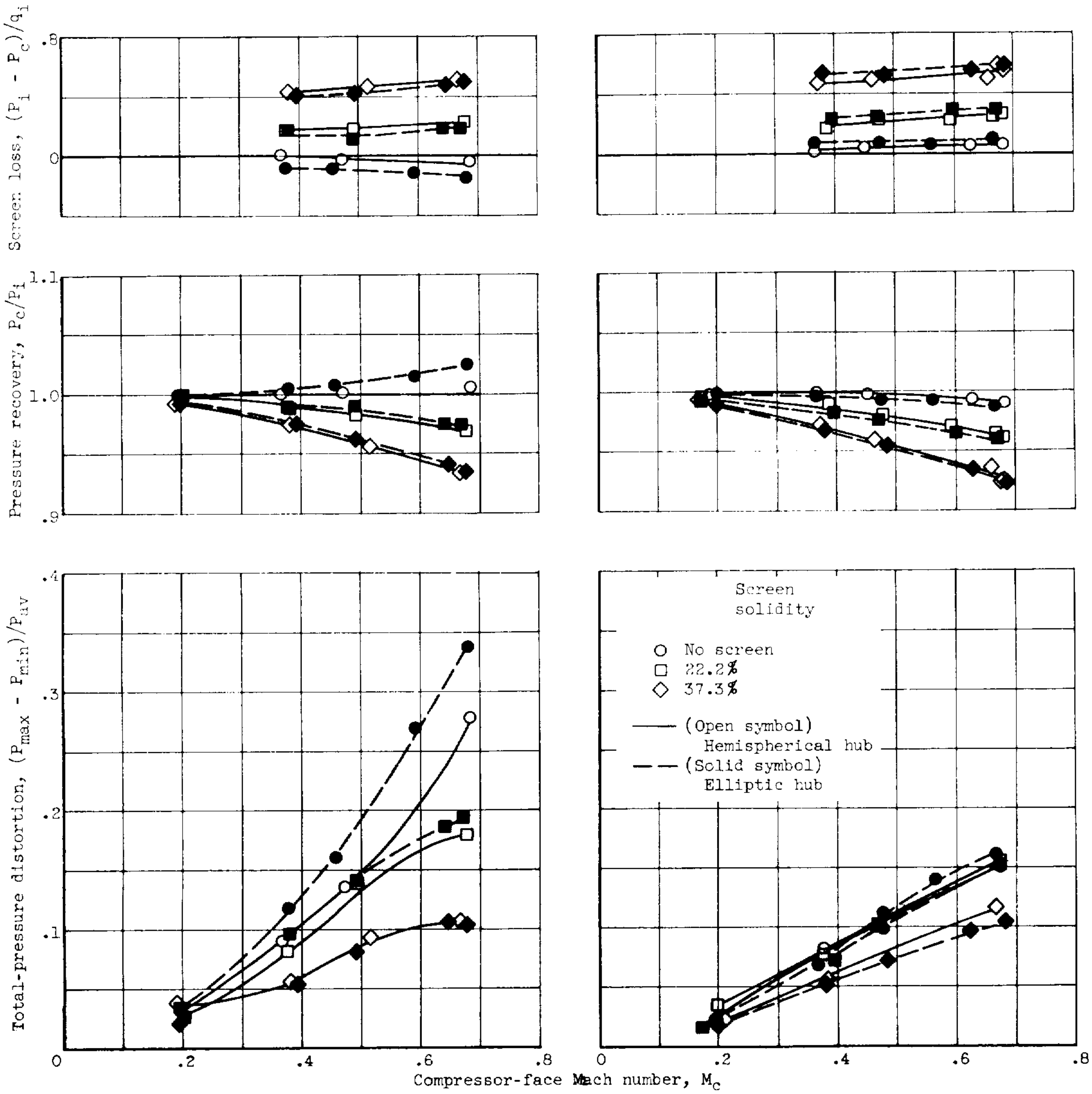


Figure 10. - Effect of straight, swept, and wedge-shaped screens in constant-area duct with high radial distortion. Solidity of screens, 22.2 percent.



(a) High radial distortion.

(b) High circumferential distortion.

Figure 11. - Effects of a hemispherical and an elliptic compressor-face hub 2 diameters downstream of expanded diffuser section. θ_{15°; $A_e/A = 1.72$.