NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM

No. 1214

JET DIFFUSION IN PROXIMITY OF A WALL

By D. Küchemann

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SUMMARY

When auxiliary jet engines are installed on airframes, as well as in some new designs, the jet engines are mounted in such a way that the jet stream exhausts in close proximity to the fuselage. This report deals with the behavior of the jet in close proximity to a two-dimensional surface. The experiments were made to find out whether the axially symmetric stream tends to approach the flat surface. This report is the last of a series of four partial test reports of the Göttingen program for the installation of jet engines, dated October 12, 1943. This report is the complement of the report on intake in close proximity to a wall.

I. INTRODUCTION

Considerable confusion still attends the installation of turbojet engines as regards the discharging jet, especially when it comes near other parts of the airplane and interference phenomena are possible. If the engine is mounted near to the fuselage, there is apprehension that the jet will adhere to it with consequent undesirable heating and possibly also drag increase. The purpose of the present report is to treat these problems in somewhat greater detail.

The feared jet processes are caused by the nearness of the wall. In order to secure more general and fundamental data, all special wall forms were disregarded and the jet was measured in the proximity of a flat wall. This precluded the processes which depend on the particular pressure distribution at the wall and in the surrounding space. Furthermore, the work was done on a cold jet, principally on account of experimental facility. The extent to which fundamental phenomena were suppressed by it must be left

*"Strahlausbreitung in Wandnähe." Zentrale für Wissenschaftliches Berichtswessen der Luftfahrtforschung des Generalluftzeugmeisters (ZWB) Berlin-Adlershof, Untersuchungen und Mitteilungen Nr. 3057, December 31, 1943.

to future experiments.[1] As variable parameters there remain the velocity of the jet, for which as criterion the mean velocity v_A in the exit of the engine model is chosen, and the outer flow velocity v_o; and indeed it suggests itself to once consider the difference $v_A - v_o$ and then the quotient v_A/v_o as significant. Another parameter is the distance a of the exit cone from the wall (that is, the distance of the point of exit closest to the wall from the wall), and lastly the design of the fairing between engine and wall will also play a part. In every case, the three-dimensional variation of the jet downstream from the exit must be measured.

II. CONVERSION TO OTHER OPERATING CONDITIONS

In view of the multiplicity of potential variations, it is desirable to establish simplifying connections. For practical purposes it would be more advantageous to be able to use easily made static tests (without stream flow) and to compute all phases with stream flow from it. Such a process is described in the following:

It is assumed that the general state of flow (v) results, in first approximation, from the superposition of the stream flow (v_o) with the jet flow (v'):

$$v = v' + v_o \tag{1}$$

This implies that the jet diffusion is to depend only on the difference of the velocity in the jet (v_A) and outside of the jet (v_o), so that the velocity v in the form $(v - v_o)/(v_A - v_o)$ for fixed particles is independent of the operating condition. A certain difficulty is involved in the finding of the location of these particles, that is, to pass from the velocity transformation (1) to the related transformation of the coordinates. A rectangular system of body axes (x, y, z) is used with x in the flow direction and the time coordinate t, with $x = 0$ (plane of exit) for $t = 0$. The space coordinates of the particles are functions of the time. Thus for equal time intervals t we get a relation between the coordinates x,y,z of the particle in the general flow ($v_o \neq 0$) and the coordinates x',y',z' of the flow without stream flow ($v_o = 0$).

[1]The problems of model similarity and reproduction of the hot-jet in wind-tunnel tests are discussed in reference 1.

It further is assumed that transverse flows can be disregarded, hence that the velocity has the direction of the x-axis, so that $y = y'$ and $z = z'$. This leaves the connection between x and t and x' and t to be determined.

$$v = \frac{dx}{dt}; \; v' = \frac{dx'}{dt} \tag{2}$$

the velocity relation (1) then reads

$$\frac{dx}{dt} = \frac{dx'}{dt} + v_o \tag{3}$$

which, integrated, gives

$$x(t) = x'(t) + v_o t \tag{4}$$

In this equation t is yet to be eliminated and to be replaced with the aid of (2) by means of the velocity $v' = v'(x',y,z)$, which is accessible to measurement:

$$t = \int_0^{x'} \frac{dx'}{v'(x',y,z)} \tag{5}$$

In this manner the desired transformation of the coordinates

$$\frac{x}{d} = \frac{x'}{d} + \frac{1}{\frac{v_A}{v_o} - 1} \int_0^{x'/d} \frac{d(x'/d)}{\frac{v'(x',y,z)}{v_A'}} \tag{6}$$

follows from (4), made dimensionless with the diameter d of the exit nozzle and the average velocity $v_A' = v_A - v_o$ in the exit nozzle. This transformation states that planes normal to the x-axis are not maintained, but that according to the velocity distribution $v'(x',y,z)$ the x displacement for the faster particles is less than for the slower ones. In practice v'/v_A' would be measured, the integration carried out, and the x corresponding to x' caluclated by (6). There the area of small velocity would cause difficulties, especially for the points $x = 0, \sqrt{y^2 + z^2} > d/2$, since v' with $x \to 0$ must approach zero in a certain way in order that the integral may exist. Moreover, the numerical evaluation in this area requires extreme accuracy of measurement.

A detailed check of the practicability of these assumptions was outside the scope of the present report. A thorough discussion - with consideration of the transverse motions must be the object of a special investigation. For the present, these assumptions were, after several other simplifications, simply used as basis for the test program. Since the potential core with its high dynamic pressures and presumably high temperatures is of particular interest in the application, $v' =$ constant was taken equal to $v_A' = v_A - v_o$. Therefore,

$$\frac{x}{d} = \frac{x'}{d} \frac{v_A/v_o}{v_A/v_o - 1} \tag{7}$$

This assumption is, of course, justified only for the region around the jet axis up to the dissolution of the potential core; however, in this region alone is the assumption of velocity parallel to the x-axis satisfied. In view of the mixing motion, it would physically be more logical if a mean velocity within the actual mixing zone were regarded as characteristic. The transformation (7) has the advantage of always permitting measurement in planes where $x =$ constant.

III. EXPERIMENTAL PROGRAM

In all tests, the difference $v_A - v_o$ was kept constant (= 33 m/s). The first operating condition with zero stream velocity was:

State I: $v_o = 0$; $v_A = 33$ m/s; $v_A/v_o = \infty$; $x = x'$,

the second, with comparatively low stream velocity:

State II: $v_o = 11$ m/s; $v_A = 44$ m/s; $v_A/v_o = 4$; $x = 1.33\, x'$

and the third, with greater stream velocity:

State III: $v_o = 33$ m/s; $v_A = 66$ m/s; $v_A/v_o = 2$; $x = 2x'$.

It was found during the measurements that the states I and III were in most cases sufficient for explaining the principal processes.

The wall distances themselves were limited to a few values, to $a = d$ (large distance) and $a = d/2$ (small distance); for comparative purposes, data with the jet motor were also measured without a wall ($a = \infty$).

The lining between engine and wall was kept especially slender in several cases, since Kunze's tests had shown the importance of adequate ventilation between jet and wall. As contrast to this "good" fairing, a particularly "poor" fairing was used (fig. 1). These cowlings all terminated with the exit plane of the power unit. In one instance, the good version was shifted backward by 2d and cylindrically cut out toward the jet, creating a type of "tunnel."

A model engine with installed blower was used. The measurements, made in tunnel No. 2, included total pressure and static pressure in y and z direction through the jet axis at various distances x from the exit nozzle.

IV. RESULTS

It is found that our knowledge of turbulent diffusion processes is in no way sufficient to explain definitely the individual phenomena.

1. Without Wall

Figures 2 to 4 represent the velocity distributions in the jet at various distances from the exit nozzle for the three operating conditions. It portrays the conventional pattern of jet diffusion and it must be conceded that the foregoing simplifying assumptions hold only very roughly. For the gradual decrease in the potential core with increasing distance the given transformation is practical, but greater differences occur in the transformation of the mixing zone, which is in general smaller than the assumption stipulates. If the coordinate relation (6) were more accurately taken into account and thus the greater values of x ascribed to the areas of lower velocity, the agreement would be better. Such agreement would then be obtained in the boundary zone if the mean velocity in the mixing zone were used as basis, while the deviations in the potential core would become greater. It is readily apparent that exact agreement is attained in no instance, hence that other physical processes must also play a part. These are due in part to the boundary layer on the outer engine surface which is particularly plain in state III and by which the jet is initially enveloped by a cushion of retarded air; but with it the entire past history of the outside flow is involved, so that more general predictions are rendered extremely difficult. Moreover, even for reasons of pure potential theory, a different jet seems to form with stream flow than without it. While in state I a rectangular velocity distribution exists in the exit cone and a jet contraction is scarcely noticeable, the latter is plainly evident in state III as a velocity increase in the potential core. This geometrical jet deformation could be induced by the shape of the outer contour which (in adhering flow) gives the velocity at the edge of the nozzle an inwardly directed radial component. The jet deformed by the approach flow gives, of course, a different basis for the mixing of the jet.

2. Large Wall Distance

In this instance, the fairing with its boundary layer and the boundary layer at the wall itself are involved. For comparison, the velocity distribution in the boundary layer at the wall in the unaffected state was plotted in the same manner as in the diagrams of figure 5.

In analyzing the results with the good fairing in figures 6 and 7 the section parallel to the wall (y direction) discloses practically no deviations from the corresponding states without wall. Only the planes normal to the wall (z direction) manifest at greater distance from the nozzle minor differences which reveal a slight travel of the jet toward the wall when no outside flow is present. But in state III just the opposite occurs: The maximum of the velocity distribution travels perceptibly away from the wall. The wake flow of the fairing is scarcely noticeable and the boundary layer at the wall also appears to experience no substantial variation by the flow.

On the poor fairing (figs. 8 and 9) the conditions are different. While in state I the jet still seems to move a little nearer to the wall than with the good fairing, with stream flow it ceases to move away from the wall and moves into the dead-air region introduced by the fairing.

To get some idea of the form of the jet in the various fairings, figure 10 represents the lines of equal velocity in a section normal to the flow, as well as was possible according to the measurements. The good as well as the bad fairing shows a form no longer axially symmetrical, which, however, is flattened out at the wall side in the first case and ovally pulled toward the wall in the other. The movement of the velocity maximum in different directions is plainly visible. According to this, it might be suspected that the good ventilation of the space between engine and wall with the good fairing forms a definite air cushion which pushes the jet away from the wall. This concept is supported by the conditions in a horizontal section through the jet in figure 11.

However, in spite of these dissimilarities, the effects are comparatively small. In the proximity of a flat wall, the possibility of a ventilation from the sides is so great as to preclude the existence of jet adherence even with an extremely poor fairing.

3. Short-Wall Distance

One noteworthy fact is that the aforementioned processes are repeated with the short wall distance, hence are not limited to the comparatively large distance from the wall. As with the good fairing, there is a slight movement toward the wall in the absence of stream flow and a movement away from it with increasing stream flow (figs. 12 and 13).

The fairing with tunnel extending backward beyond the afterbody of the engine unit is of practical interest for the reason that in many cases it is the only way to obtain a sufficiently elongated form. This fairing likewise exhibits no markedly unfavorable behavior. The jet naturally adheres in this case at the tunnel (figs. 14 and 15). This tunnel surface was therefore to have no projected area in the flight direction for reasons of resistance. Since, however, the tunnel must be adapted to the form of the jet, and this is not known at once for the different engine units, difficulties may arise, so that, if at all possible, such a tunnel fairing should be avoided.

It is perhaps not immediately comprehensible why in these measurements only these few generalized types of fairings were investigated and the form of the fairing not further varied, to establish, for example, which form could be still designated as good. According to the cited results, however, the solution of such a problem does not appear possible at once, since it was seen that geometrical conditions such as the form of the afterbody of the engine unit or the past history of the outer flow have some effect on the phenomena, so that a separation of these problems from the others for the installation of given conditions seems hardly correct, and the Reynolds number and the temperature conditions would then also have to be taken into account: Hence the limitation to basic experiments. That the conditions in an installed jet-propulsion unit are similar in the fundamental phenomena is shown by the wind-tunnel tests on an auxiliary turbojet unit model mounted below the fuselage on the Heinkel 219 (reference 2). So, in order to be absolutely certain about the jet diffusion for a specific design, a test on the total model is probably unavoidable, and judged by past experiences, a water-channel test is best suited for this purpose.

Translation by J. Vanier
National Advisory Committee
for Aeronautics

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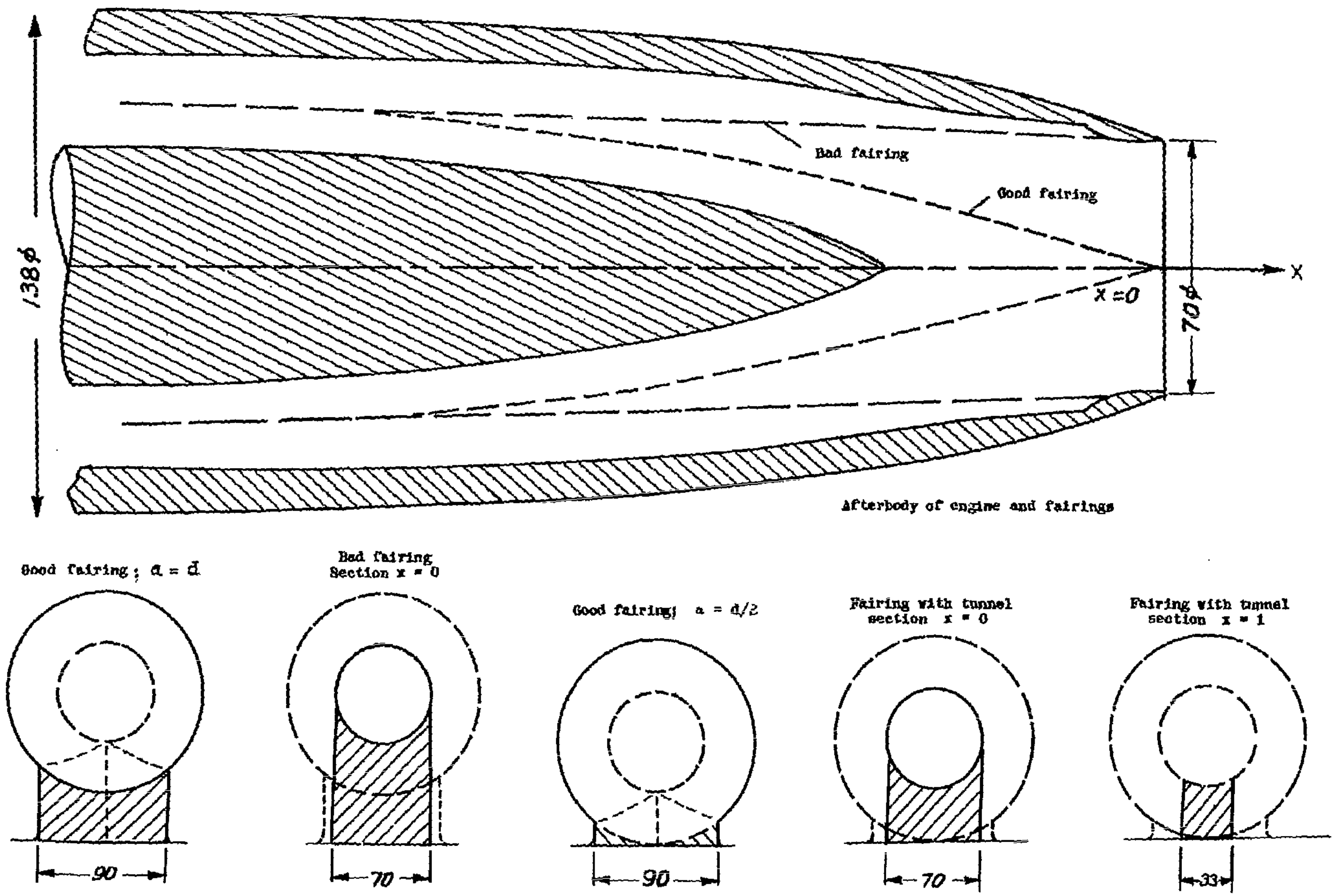
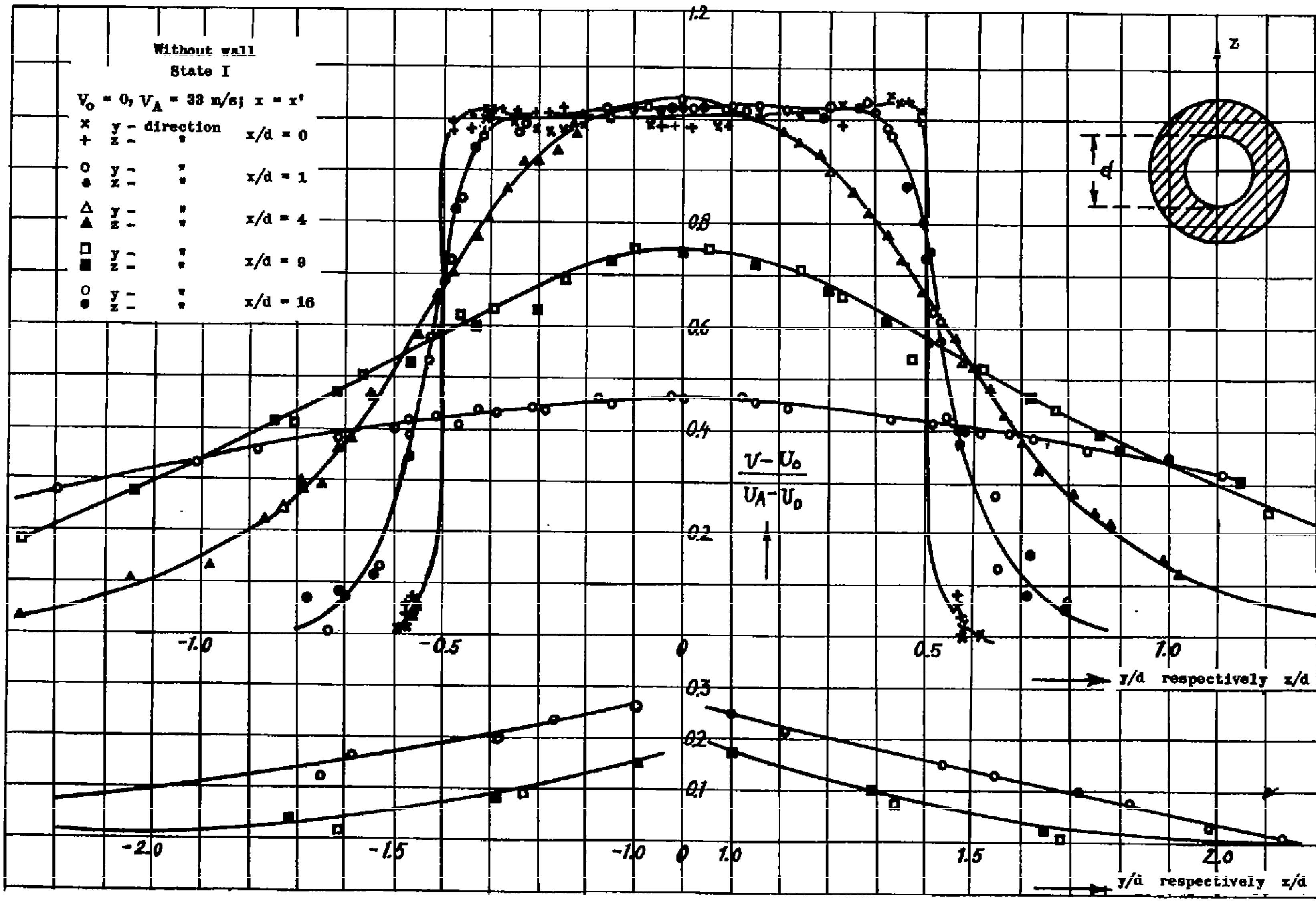

Bad fairing
Good fairing
138φ
70φ
x = 0
X
Afterbody of engine and fairings
Good fairing; a = d
Bad fairing
Section x = 0
Good fairing; a = d/2
Fairing with tunnel
section x = 0
Fairing with tunnel
section x = 1
90
70
90
70
33

Figure 1.



Without wall
State I
V0 = 0, VA = 33 m/s; x = x'
y - direction x/d = 0
z -
y - x/d = 1
z -
y - x/d = 4
z -
y - x/d = 9
z -
y - x/d = 16
z -
1.2
0.8
0.6
0.4
0.2
V - U0 / UA - U0
-1.0
-0.5
0
0.5
1.0
y/d respectively z/d
0.3
0.2
0.1
-2.0
-1.5
-1.0
0
1.0
1.5
2.0
y/d respectively z/d
z
y
d

Figure 2.

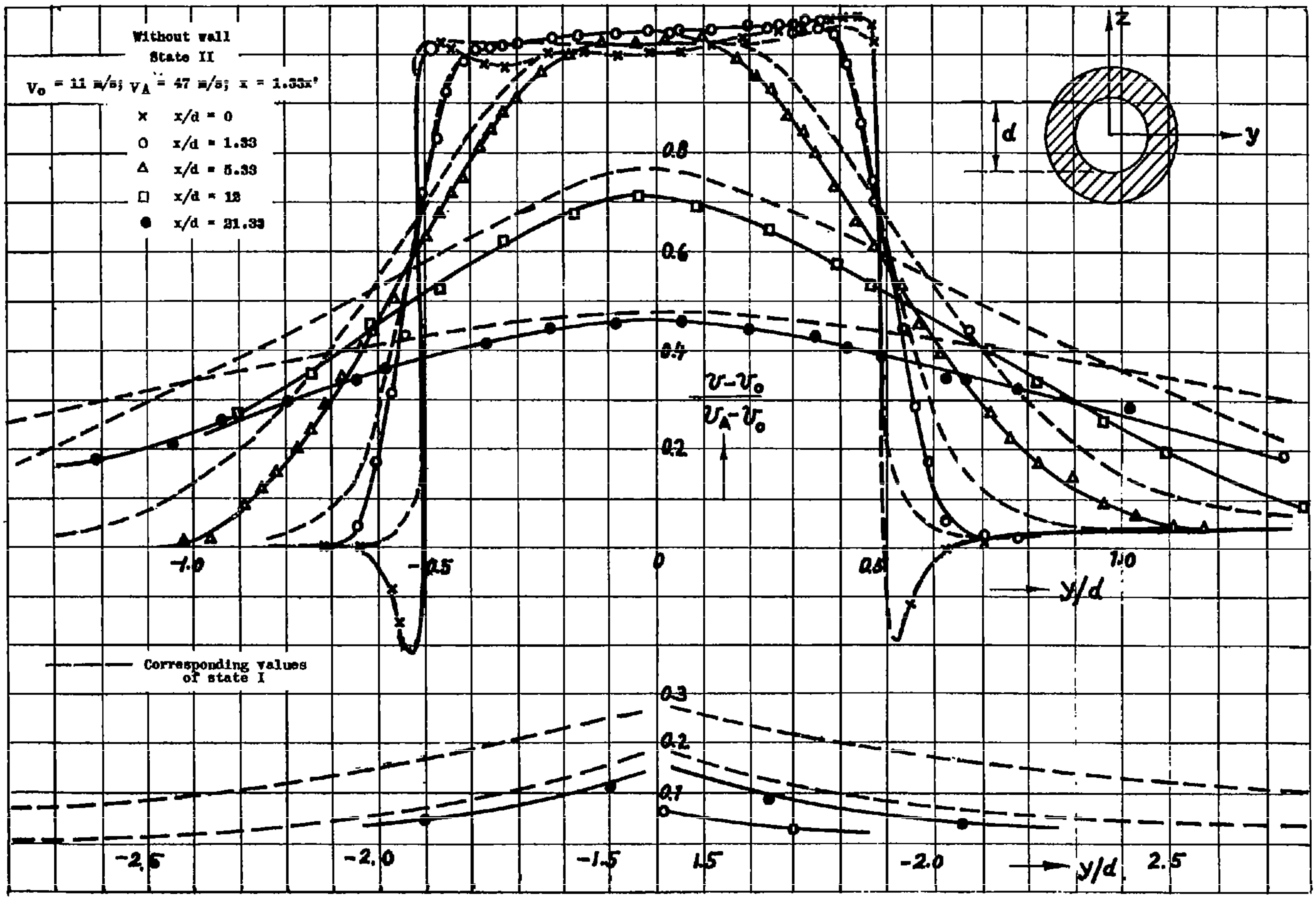

Without wall
State II
V_o = 11 m/s; V_A = 47 m/s; x = 1.33x'
× x/d = 0
○ x/d = 1.33
△ x/d = 5.33
□ x/d = 13
● x/d = 21.33
Corresponding values of state I
$\frac{v-v_o}{v_A-v_o}$
0.8
0.6
0.4
0.2
0.3
0.2
0.1
-1.0
-0.5
0
0.5
1.0
y/d
-2.5
-2.0
-1.5
1.5
-2.0
2.5
z
y
d

Figure 3.

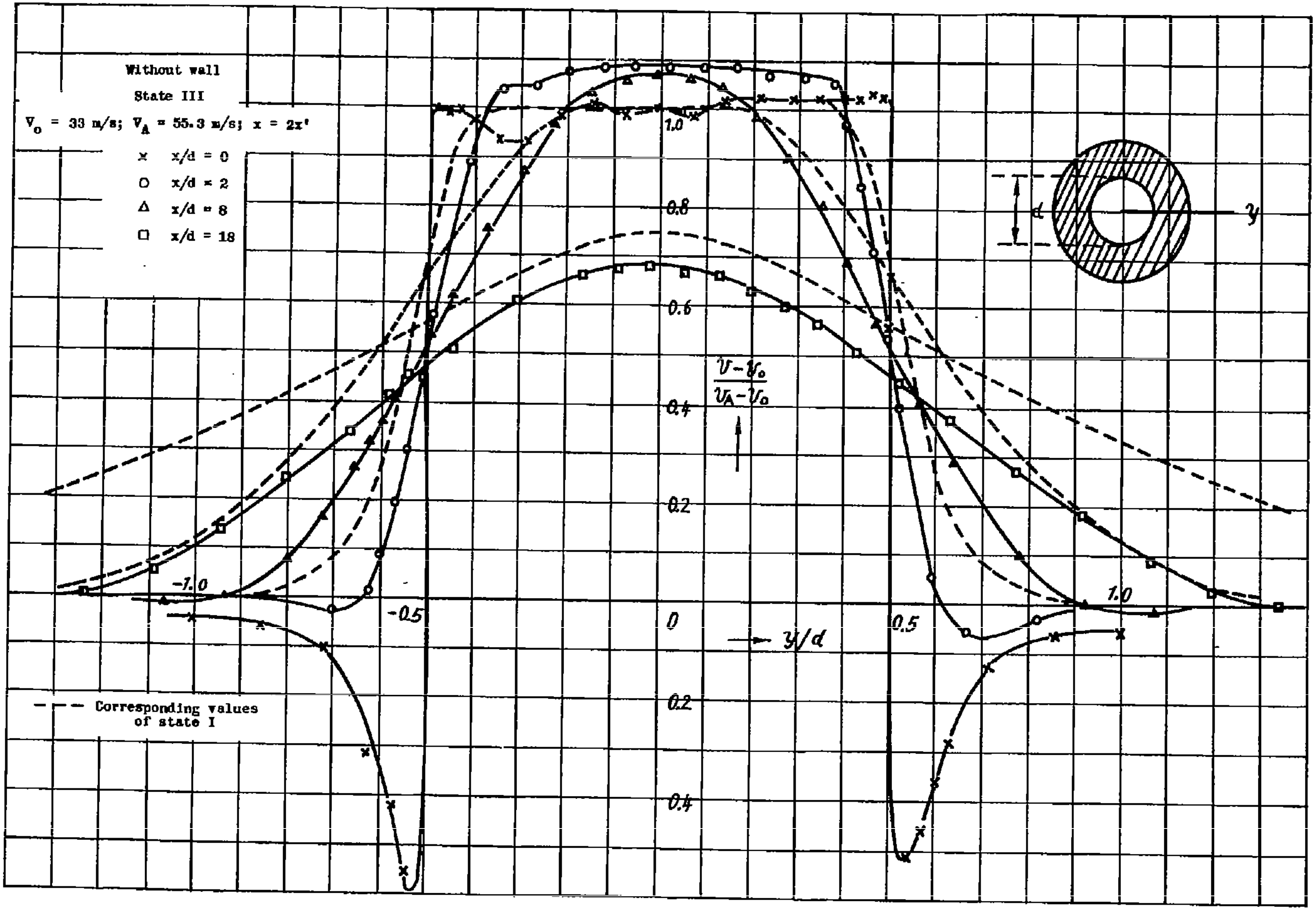
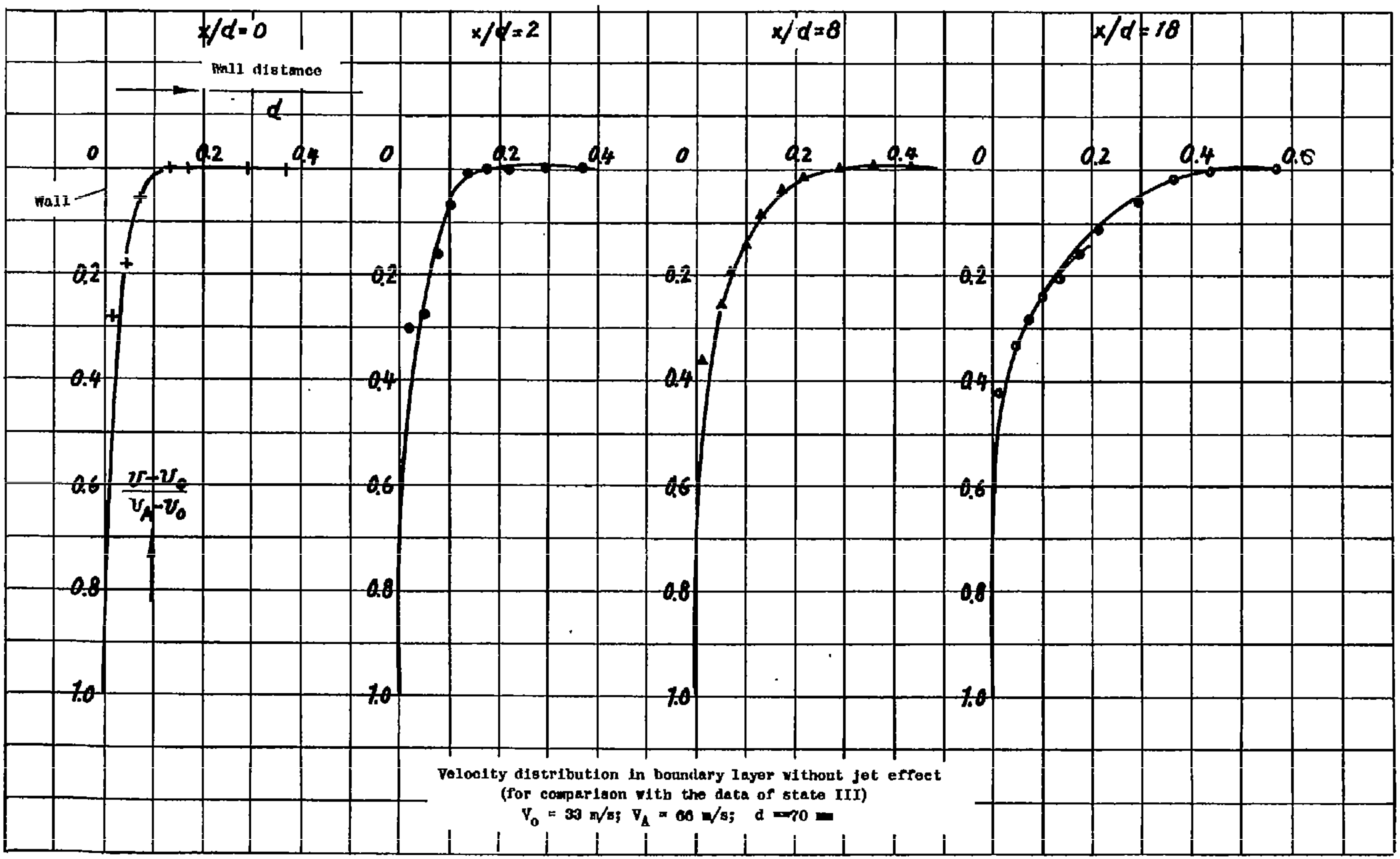

Without wall
State III
V_o = 33 m/s; V_A = 55.3 m/s; x = 2x'
× x/d = 0
○ x/d = 2
△ x/d = 8
□ x/d = 18
Corresponding values of state I
$\frac{V-V_o}{V_A-V_o}$
y/d
-1.0
-0.5
0
0.5
1.0
0.2
0.4
0.6
0.8
d
y

Figure 4.



Velocity distribution in boundary layer without jet effect
(for comparison with the data of state III)
V_0 = 33 m/s; V_A = 66 m/s; d = 70 mm

Figure 5.

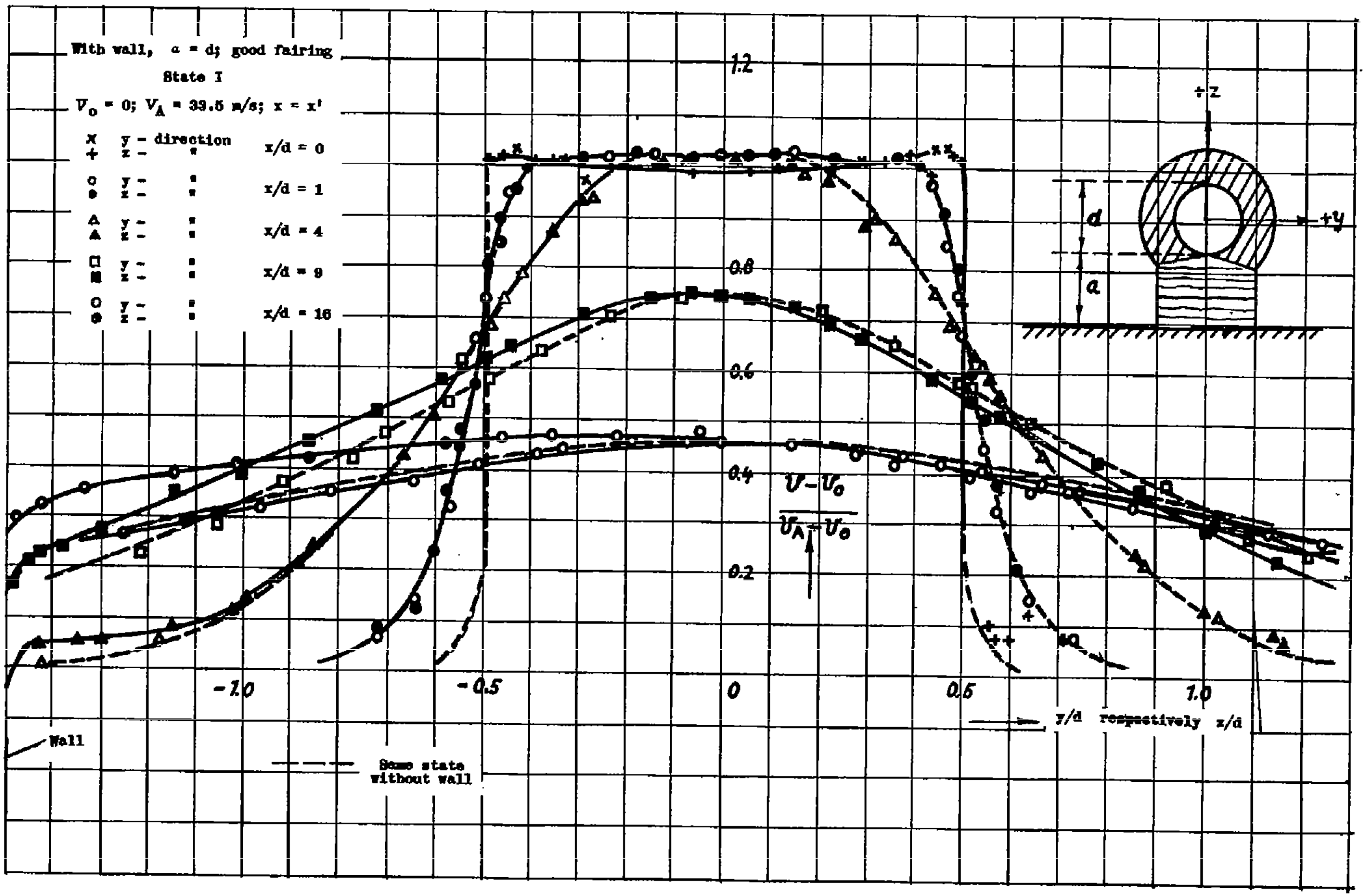
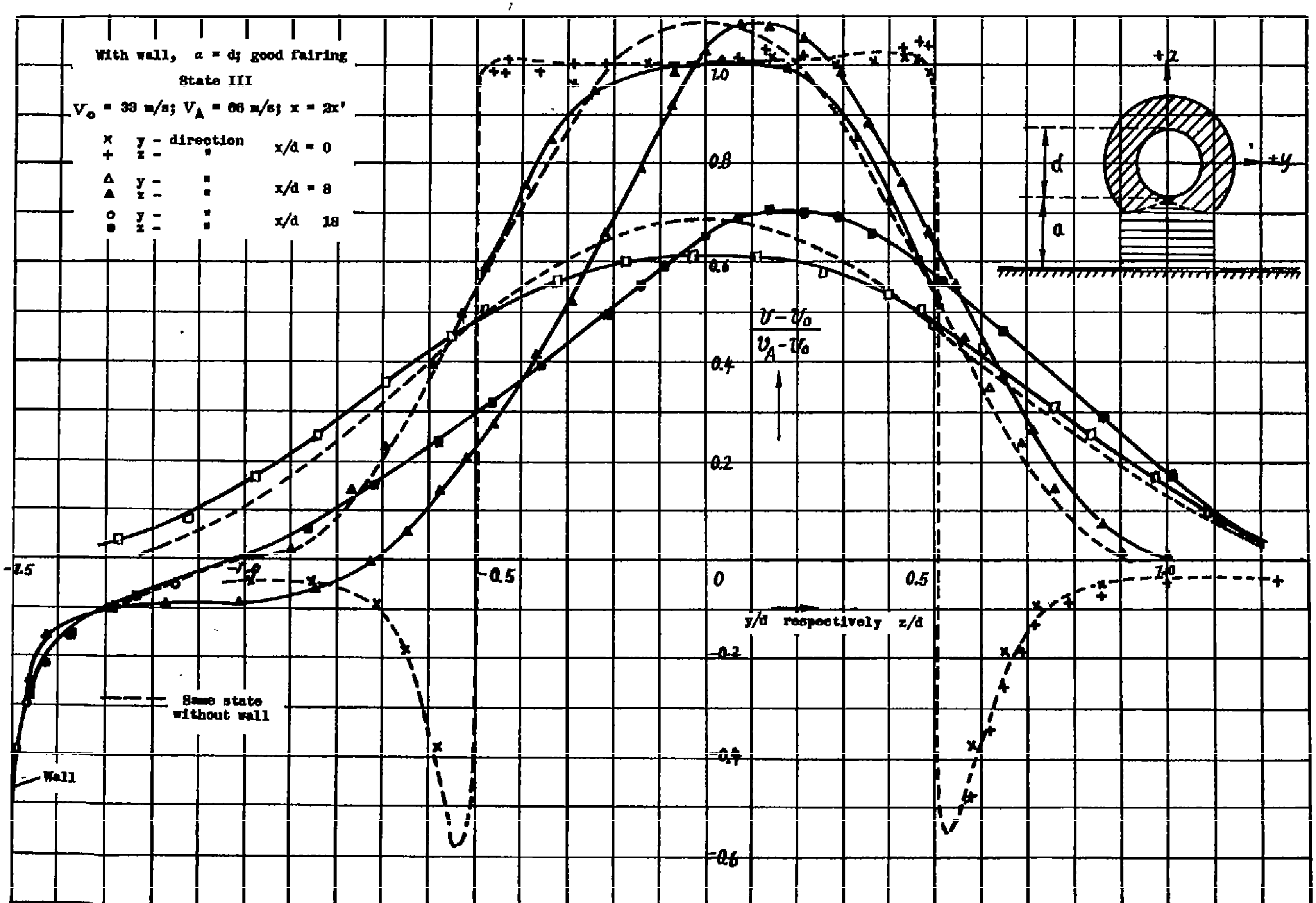
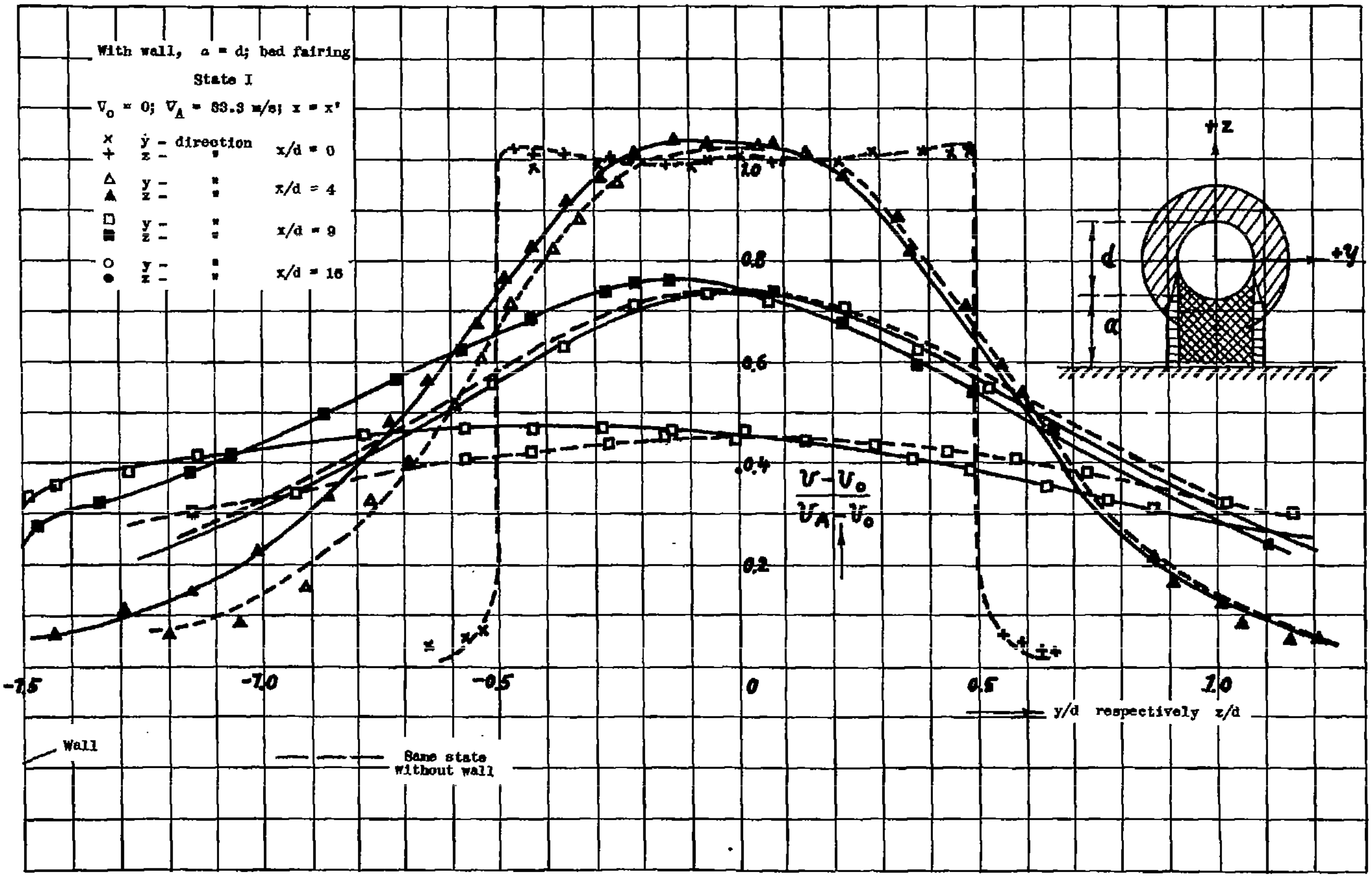

With wall, a = d; good fairing
State I
V_0 = 0; V_A = 39.5 m/s; x = x'
y - direction x/d = 0
y - x/d = 1
y - x/d = 4
y - x/d = 9
y - x/d = 16
1.2
0.8
0.6
0.4
0.2
$\frac{U - U_0}{U_A - U_0}$
-1.0
-0.5
0
0.5
1.0
y/d respectively z/d
Wall
Same state without wall
+z
+y
d
a

Figure 6.



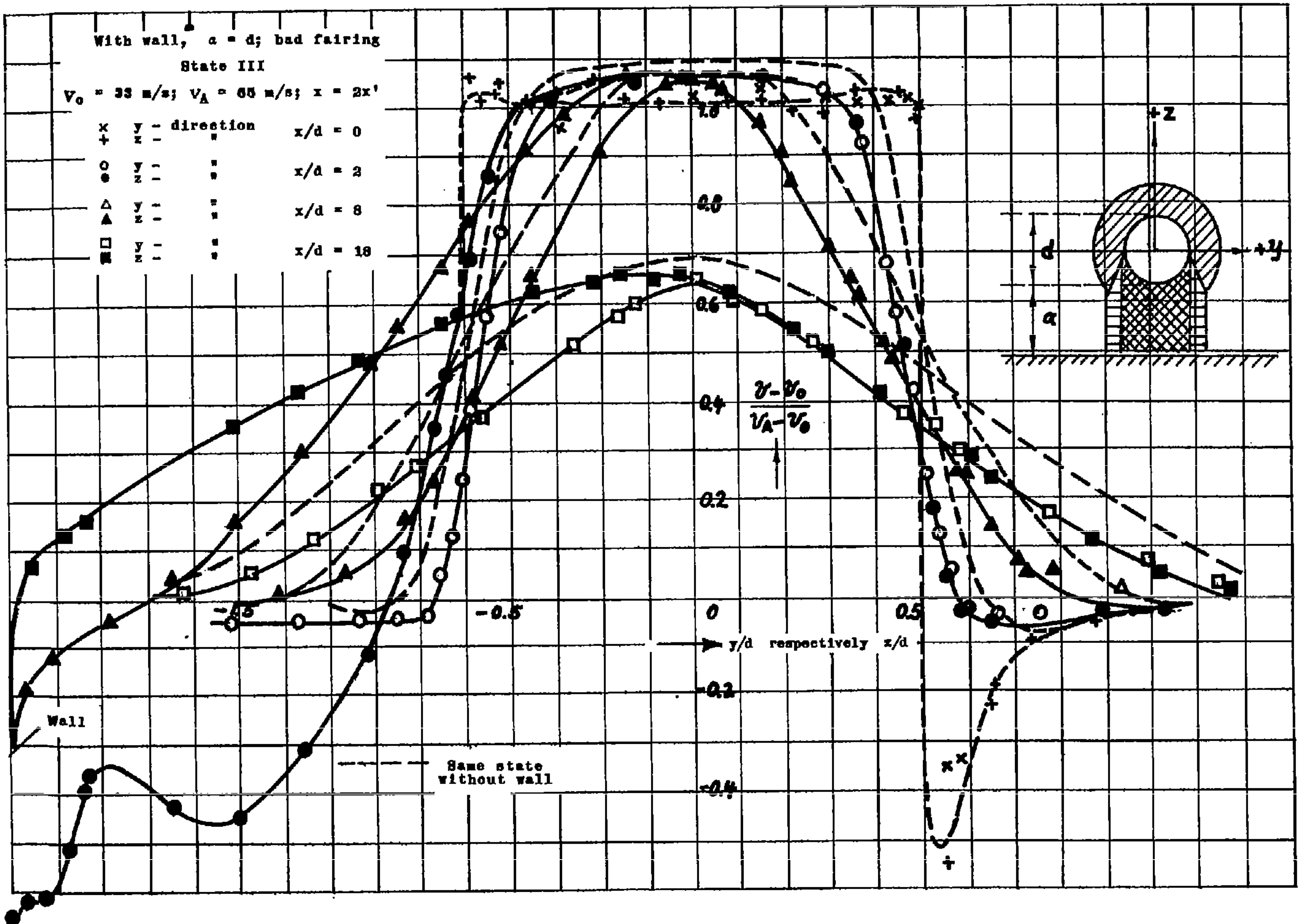
With wall, a = d; good fairing
State III
V₀ = 33 m/s; V_A = 66 m/s; x = 2x'
× y - direction x/d = 0
+ z - "
△ y - " x/d = 8
▲ z - "
○ y - " x/d 16
● z - "
Same state without wall
Wall
v - v₀ / v_A - v₀
y/d respectively z/d
1.0
0.8
0.6
0.4
0.2
-0.2
-0.4
-0.6
-1.5
-1.0
-0.5
0
0.5
1.0
+z
+y
d
a

Figure 7.



With wall, a = d; bed fairing
State I
V0 = 0; VA = 83.3 m/s; x = x'
y - direction
z - "
x/d = 0
y - "
z - "
x/d = 4
y - "
z - "
x/d = 9
y - "
z - "
x/d = 16
1.0
0.8
0.6
0.4
0.2
V-Vo / VA-Vo
+z
+y
d
a
-1.5
-1.0
-0.5
0
0.5
1.0
y/d respectively z/d
Wall
Same state without wall

Figure 8.



With wall, a = d; bad fairing
State III
V_0 = 33 m/s; V_A = 65 m/s; x = 2x'
× y - direction x/d = 0
+ z - "
○ y - " x/d = 2
● z - "
△ y - " x/d = 8
▲ z - "
□ y - " x/d = 18
■ z - "
$\frac{v-v_0}{v_A-v_0}$
y/d respectively z/d
Wall
Same state without wall
+z
+y
d
a

Figure 9.

Lines of equal velocity in jet
(y,z - plane normal to approved flow)

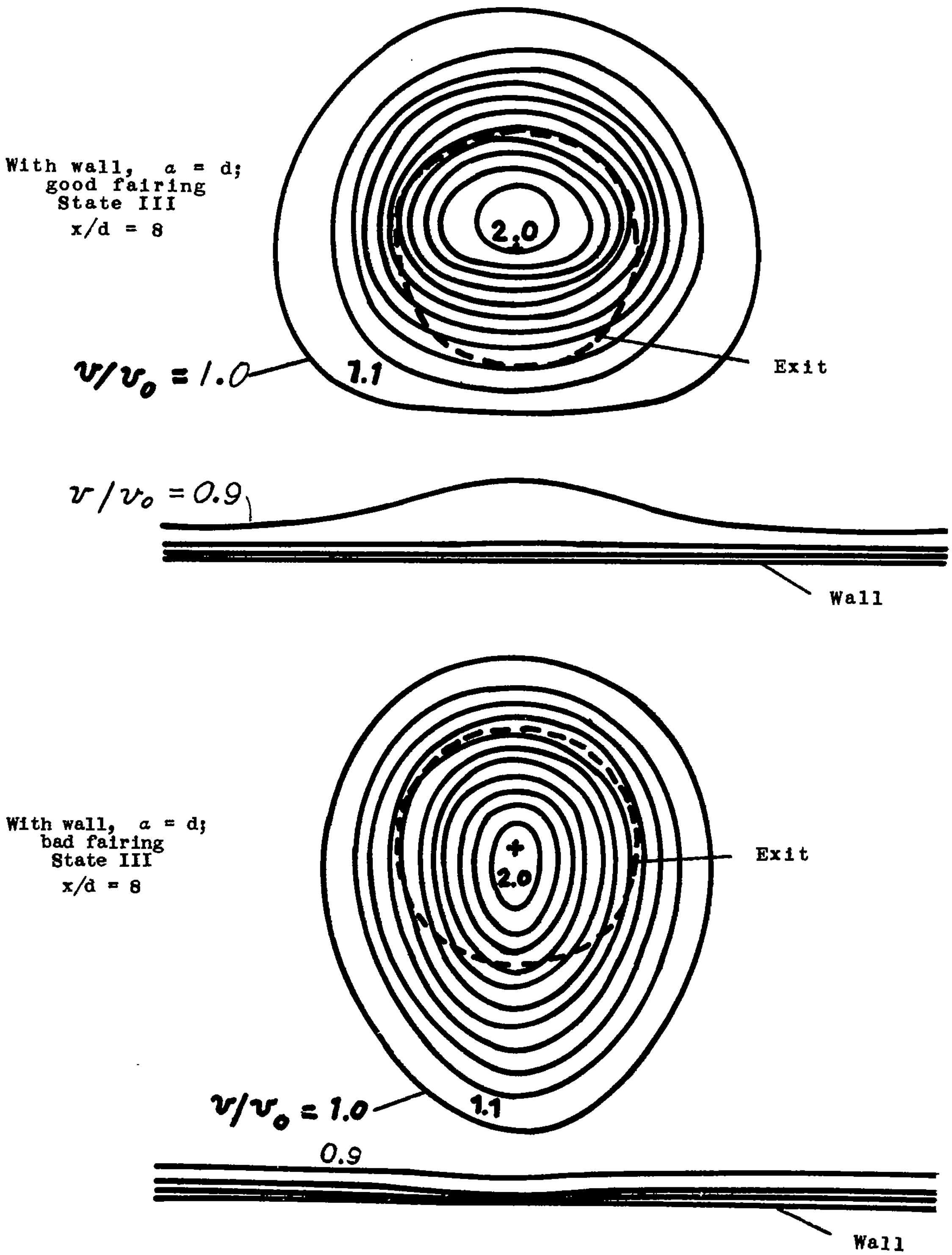
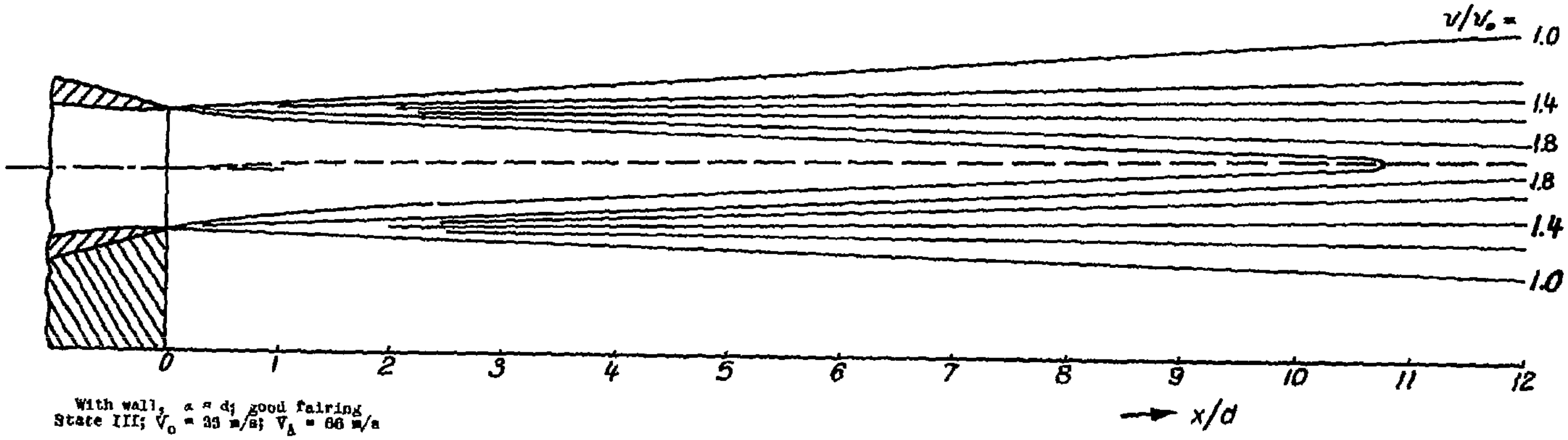
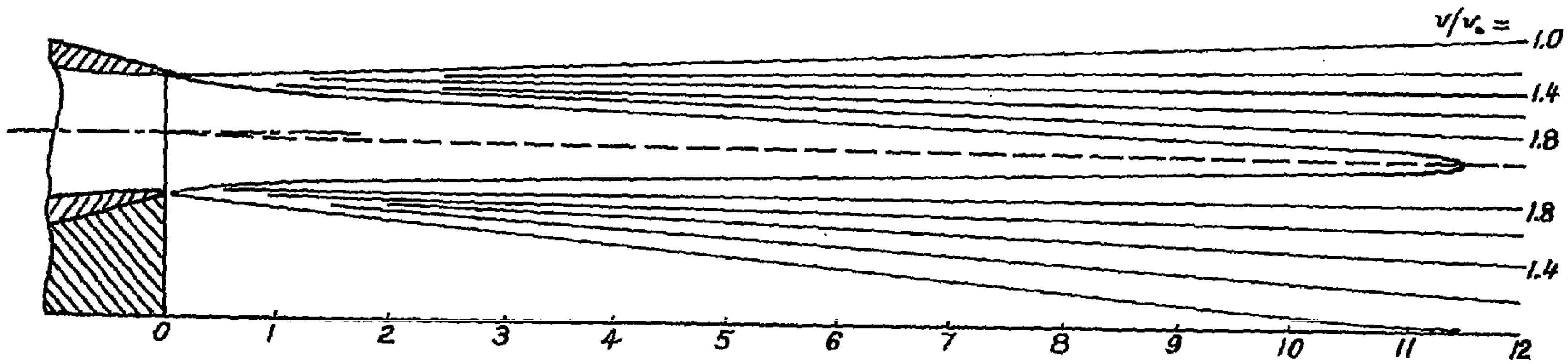


Figure 10.

Lines of equal velocity in the jet
(x,z - plane in flow direction)



With wall, $a = d$; good fairing
State III; V_0 = 33 m/s; V_A = 66 m/s



With wall, $a = d$; bad fairing
State III; V_0 = 33 m/s; V_A = 65 m/s

Figure 11.

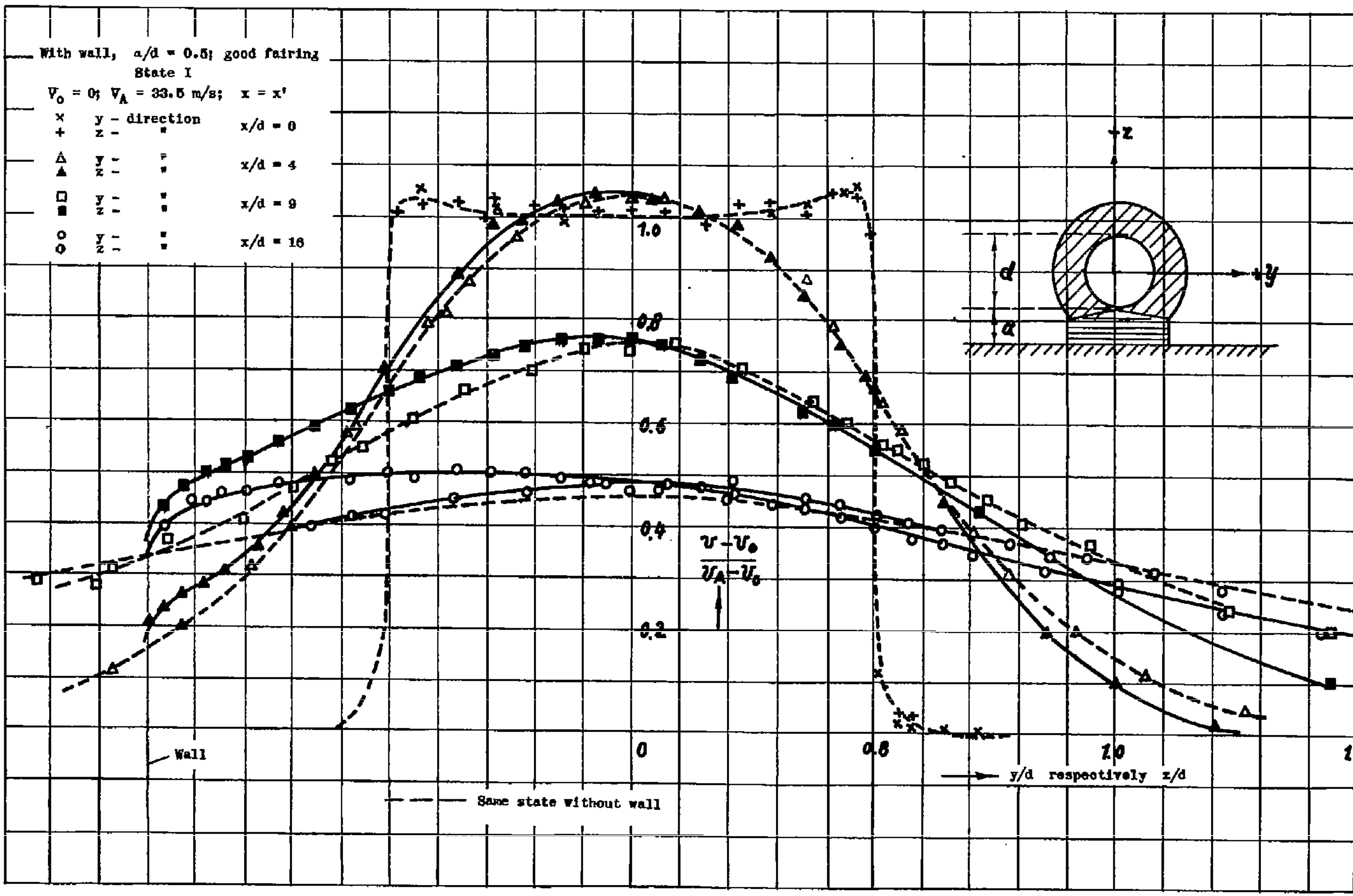

With wall, a/d = 0.5; good fairing
State I
V_0 = 0; V_A = 33.5 m/s; x = x'
y - direction x/d = 0
z - " "
y - " x/d = 4
z - "
y - " x/d = 9
z - "
y - " x/d = 16
z - "
1.0
0.8
0.6
0.4
0.2
$\frac{v-v_0}{v_A-v_0}$
Wall
0
0.5
1.0
1.5
y/d respectively z/d
Same state without wall
+z
+y
d
a

Figure 12.

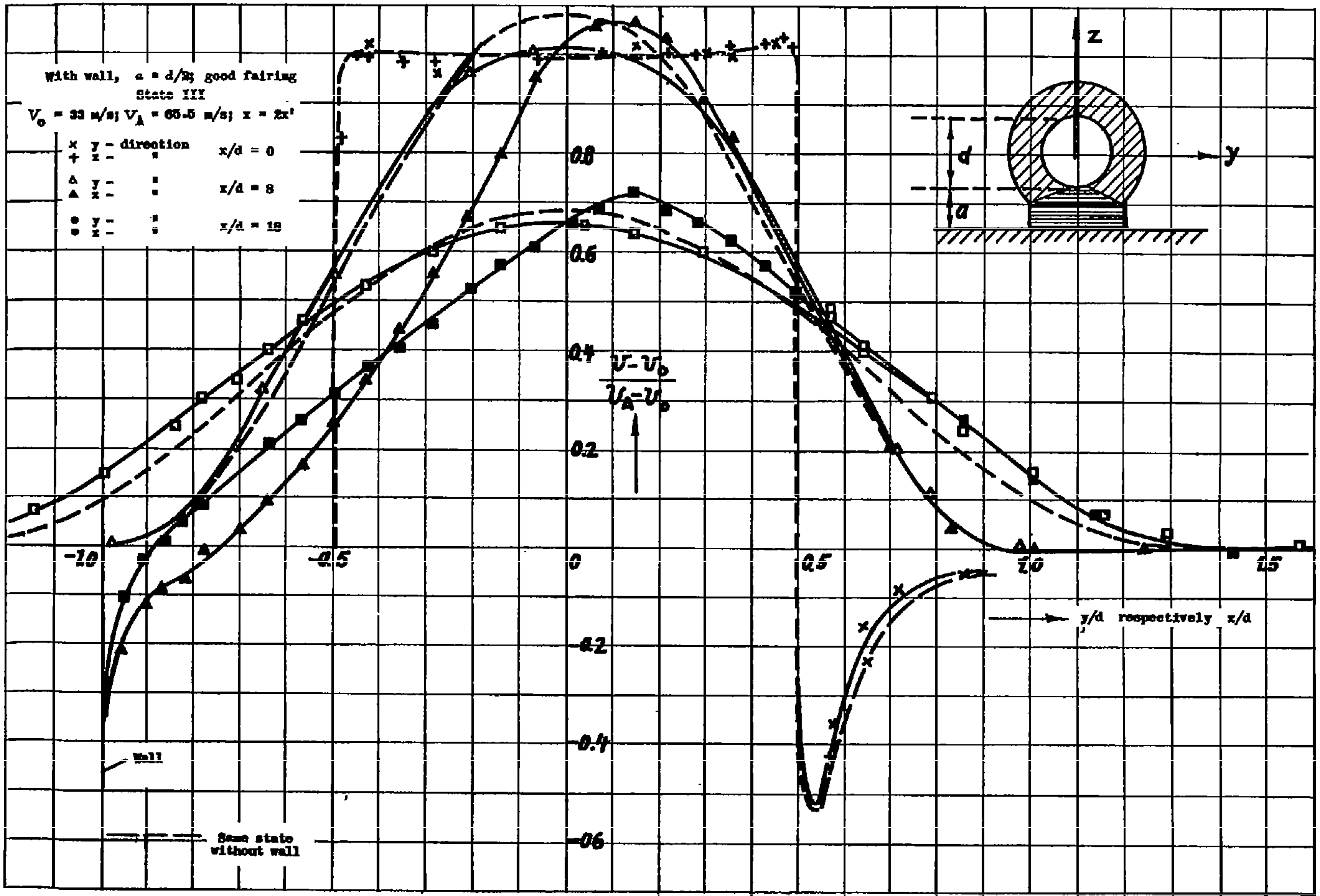

With wall, a = d/2; good fairing
State III
V_0 = 33 m/s; V_A = 65.5 m/s; x = 2x'
y - direction
z - "
x/d = 0
y - "
z - "
x/d = 8
y - "
z - "
x/d = 18
0.8
0.6
0.4
0.2
-0.2
-0.4
-0.6
$\frac{V-V_0}{V_A-V_0}$
-1.0
-0.5
0
0.5
1.0
1.5
y/d respectively x/d
Wall
Same state without wall
z
y
d
a

Figure 13.

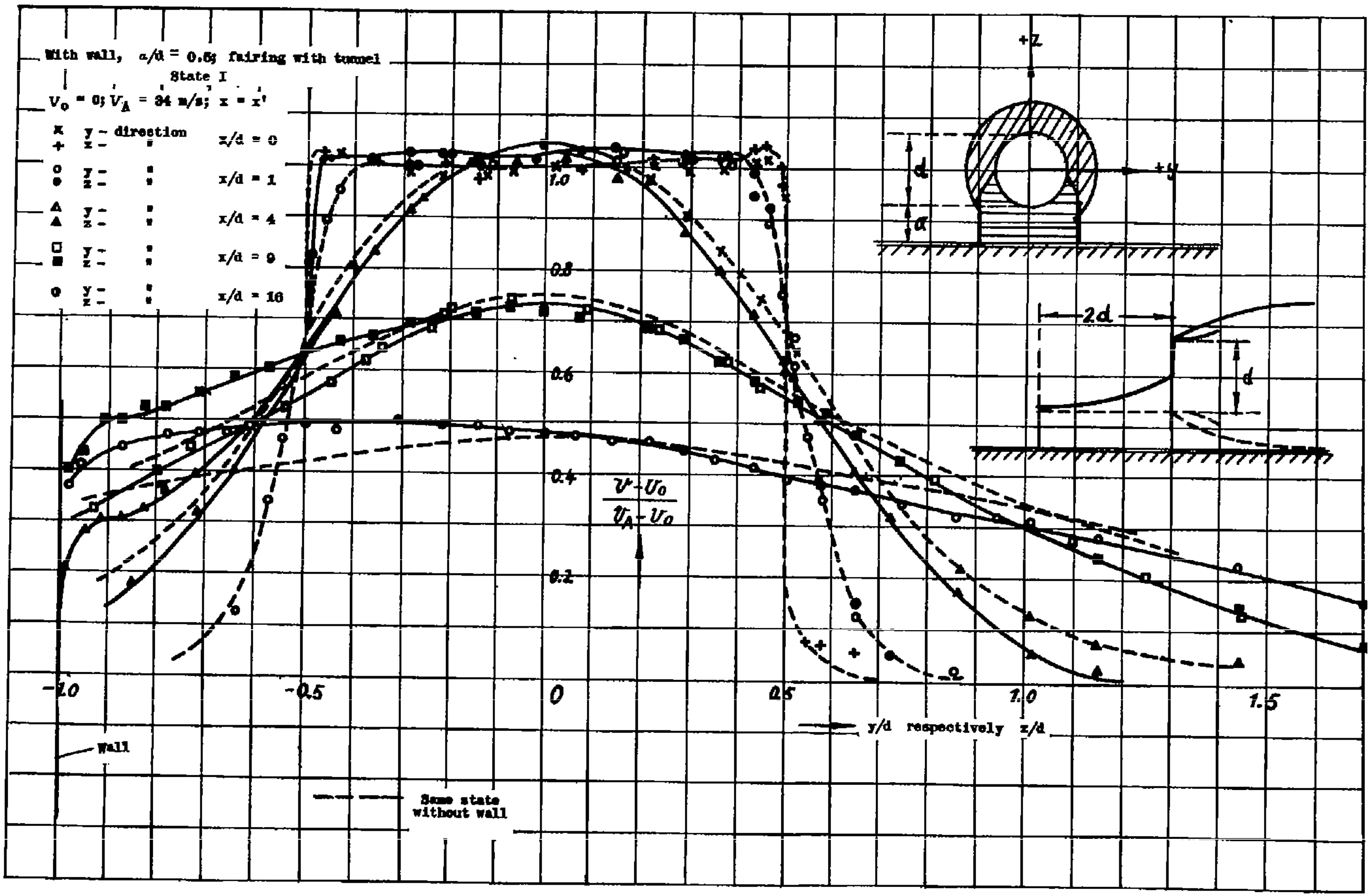

With wall, a/d = 0.5; fairing with tunnel
State I
V0 = 0; VA = 34 m/s; x = x'
y - direction x/d = 0
z - "
y - " x/d = 1
z - "
y - " x/d = 4
z - "
y - " x/d = 9
z - "
y - " x/d = 16
z - "
1.0
0.8
0.6
0.4
0.2
V - U0
VA - U0
-1.0
-0.5
0
0.5
1.0
1.5
y/d respectively z/d
Wall
Same state without wall
+z
+y
d
a
2d
d

Figure 14.

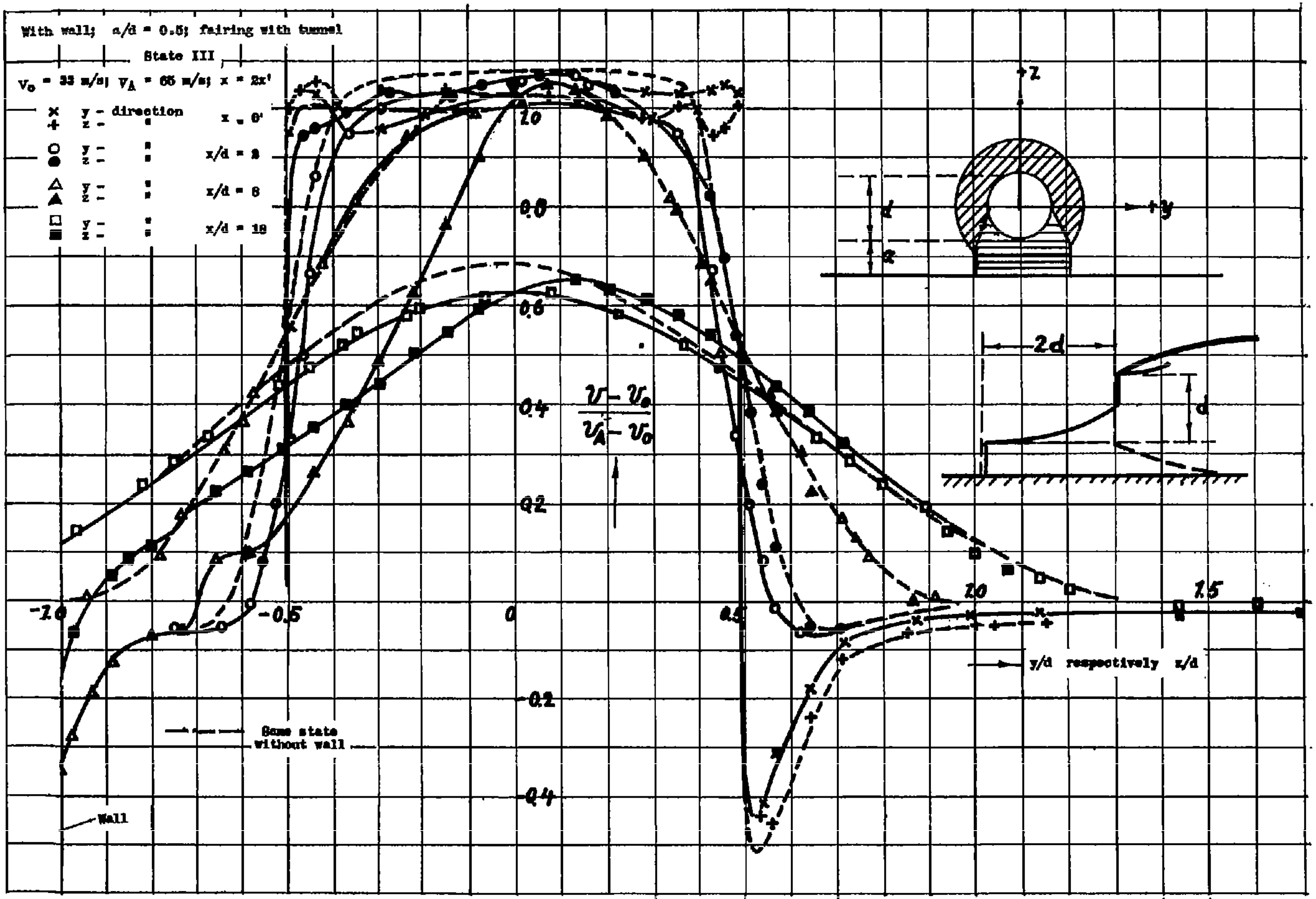

With wall; a/d = 0.5; fairing with tunnel
State III
V_o = 33 m/s; V_A = 65 m/s; x = 2x'
y - direction
z -
x = 0'
x/d = 2
x/d = 6
x/d = 18
$\frac{V - V_o}{V_A - V_o}$
1.0
0.8
0.6
0.4
0.2
-0.2
-0.4
-1.0
-0.5
0
0.5
1.0
1.5
y/d respectively x/d
Same state without wall
Wall
+z
+y
d
a
2d
d

Figure 15.