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Final Report

DESIGN STUDIES OF OXYGEN NOZZLES

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OBJECTIVE

The nozzle design studies described in this report were carried out in an effort to evaluate the performance of "three-hole" nozzles of the type intended for use in the Basic Oxygen Furnace of the Ford Motor Company.

The particular objective of this current phase of the work was the determination of the effects due to the interaction of the three individual jets produced by the "three hole" nozzle, and the extent of this interaction at distances from the nozzle exit which would be of interest in Oxygen Steelmaking.

It was required that the "three hole" nozzles tested be capable of delivering 22, 000 cubic feet of oxygen per minute at a nozzle inlet pressure of 108 psig.

It was also desired that the penetration capability of the "three hole" nozzles be considered, relative to the penetration capability of an equivalent sized single hole nozzle.

SUMMARY

Three laboratory models of "three hole" nozzles have been built and tested at flow rates of from 14,000 to 22,000 cubic feet of air per minute. In all cases the individual nozzle units had a throat diameter of 2.105 inches and an exit diameter of 2.492 inches.

The essential difference between these nozzles was the nozzle spread angle, i.e., the angle between the axis of each individual nozzle and the axis of the entire lance assembly. The nozzles tested had nozzle spread angles of 7^{o}, 10^{o}, and 13^{o}. The majority of test data has been taken with the 10^{o} nozzle.

Data are presented showing the characteristics of the overall jet resulting from the use of these "three hole" nozzles, in particular the impact pressure distribution within the jet and the effective boundaries of the jet.

Two appendices are attached, one which presents the results of water model tests made with small nozzles, and one which includes shadow photographs of the flow from full size "three hole" nozzles.

NOZZLE EQUATIONS AND DESIGN

The oxygen pressure upstream of the nozzles considered in this report can be computed with reasonable accuracy[1] by the equation:

$$Q = 17.15\, P_d A^* \qquad (1)$$

where Q = oxygen flow rate in standard cubic feet per minute (SCFM)

P_d = static pressure (absolute) upstream of the nozzle throat section - psia

A^* = the cross sectional area of the throat (total area in case of multiple nozzles) - square inches

A basic requirement[2] for the multiple nozzle considered in this report is that it should be able to pass 22,000 SCFM at a pressure at the nozzle inlet of not over 108 psig (122.7 psia). The total throat area required can be computed by Equation 1 and is found to be 10.44 square inches[1]. Since the multiple nozzle under consideration is to have three individual throats (therefore referred to as a "three hole" or triple nozzle), the area of each individual throat should be 3.48 square inches or about 2.105 inches in diameter.

The ratio of nozzle exit area to nozzle throat area (A_e/A^*) is discussed in Reference 1. In this reference it was concluded for a single hole nozzle that the ratio A_e/A^* should be established by the lowest driving pressure at which the nozzle is to be used. This result should be applicable to each individual nozzle of the "three hole" nozzle. Thus the ratio A_e/A^* for each individual nozzle should be the same as the A_e/A^* ratio of the nozzle recommended in

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[1] See Reference 1.

[2] Established by the Ford Motor Company.

Reference 1, i. e.,

$$\frac{A_e}{A^*} = \left(\frac{4.317}{3.644}\right)^2 = 1.401$$

Then for the individual nozzle of the "three hole" nozzle assembly:

$$\left(\frac{D_e}{D^*}\right)^2 = \left(\frac{D_e}{2.105}\right)^2 = 1.401$$

or

$$D_e = 2.492 \text{ in.}$$

The current phase of this nozzle work was initially established to test a three hole nozzle having a nozzle spread angle, α, of 10^o, where α = angle between the axis of each individual nozzle and the axis of the entire lance assembly. The test model of the "three hole" nozzle was fabricated in sections in order to facilitate machine work.

Additional tests were desired for a "three hole" nozzle having a nozzle spread angle of 6^o. This would have required a considerable amount of additional machining. However, it was possible with a minimum amount of machining to fabricate a three hole nozzle having a spread angle of about 7^o. Therefore a nozzle having a spread angle of 7^o was made and tested.

A few tests were also made with a 13^o "three hole" nozzle, since the "three hole" nozzle assembly which had a spread angle of 7^o could be easily converted to a nozzle having a spread angle of 13^o.

The essential dimensions of the "three hole" nozzles tested are listed in Figure 1.

Figure 2 is a plot of oxygen flow rate versus nozzle driving pressure (i. e., the pressure in the lance just upstream of the nozzle), computed by Equation 1.

Figure 3 is a plot of the computed distance between the axes of the individual nozzle subunits and the axis of the lance for the triple nozzles having nozzle spread angles of 7, 10 and 13^{o}.

TEST PROCEDURE

The nozzles were tested with air, as were the single throat nozzles tested in an earlier phase of this work (Reference 1). The same air supply and equipment were used as for the previous nozzle tests, with the exception that a special total head rake (Figure 17) was constructed for use with the "three hole" nozzles. This rake consisted of three arms spaced 120^{o} apart, intersecting at the center line of the lance, and supporting 43 total head tubes. The tubes were connected to two multibank mercury manometers. As in the earlier work with single nozzles of similar flow capacity, each run provided data for flow rates from 22,000 to 14,000 SCFM. Photographs were taken of the manometer at intervals during the run, and a continuous record made of nozzle driving pressure, temperature in the header, and impact pressure at one point in the jet, using the Foxboro type 40 RP recorder.

Each arm of the rake traversed one radius of the jet in a manner geometrically similar to the other two arms, as the pattern of the jet was repeated every 120^{o}. Thus it was possible to compare corresponding portions of the jet. In order to obtain data for various other positions in the jet, the nozzle assembly was rotated in the header so that the pressure rake intersected different sections of the jet.

The testing procedure used for these three hole nozzles required that more data be taken with the mercury manometers than was necessary in the case of tests with a one hole nozzle. The impact data in this report has therefore been plotted in inches of mercury. This data can be converted to inches of iron by multiplying by two, since the specific gravity of mercury is just about twice that of molten iron.

RESULTS

1. Nozzle Spread Angle of 10^{o}

Since the "three hole" nozzle having a nozzle spread angle of 10^{o} is the one of primary interest to the Ford Motor Company, it has been tested more extensively than have the other two nozzles listed on Figure 1. For this reason most of the graphs presented in this report are for the 10^{o} nozzle.

The triple nozzles made for laboratory work consisted of the main body onto which three individual but identical nozzle subunits could be assembled. It was therefore possible to test one of the nozzle subunits alone as well as the entire "three hole" nozzle assembly. Figures 4, 5, and 6 were obtained by testing one of these single nozzle subunits alone. This single nozzle had a divergent half angle (i. e., $\theta/2$; see Figure 1) of 3.7^{o} as did all the individual nozzles of the 10^{o} triple nozzle.

Figure 4 is a plot of centerline impact pressure versus nozzle driving pressure for a single nozzle unit, similar to one third of the triple nozzle. While the increase in impact pressure with driving pressure (and hence with flow rate) is reasonably smooth over most of the range of interest there is an appreciable dip in impact pressure at about the middle of this range.

Figure 5 is a cross plot of Figure 4. Figure 6 shows the profile of the impact pressure for two different driving pressures, all for a single nozzle unit at a blowing distance of 69 inches. Figures 4 through 6 are presented for comparison with the results of tests of the entire triple nozzle unit.

Figures 7 through 13 present results of tests with the 10^{o} triple nozzle assembly. A comparison of Figures 7 and 8 with Figures 4 and 5 respectively shows that:

1. The irregularities in the maximum impact pressure curves of Figure 4 for the single nozzle is fairly well smoothed out in the impact pressure curves of Figure 7, obtained for the triple nozzle.
2. The single nozzle by itself generally produces a greater maximum impact pressure at any given downstream distance than does the triple nozzle assembly. This is especially true of the middle to lower flow rates combined with the greater distances from the nozzle.

Figures 9, 10, and 11 show the impact pressure profiles within one of the three "separate jets" from the "three hole" nozzle for various conditions. These figures are of significance when compared with Figure 6 which was obtained by testing one nozzle subunit alone. The radial position of the axis of the nozzle subunit measured from the axis of the nozzle assembly (i. e., the lance axis) can be obtained from Figure 3. The radial position at which the maximum impact pressure is found can be determined from Figures 9, 10, and 11. It can be seen that the maximum impact pressure within the individual jet from a triple nozzle usually does not fall on the nozzle axis (i. e., the axis of the individual nozzle subunit) as it does for the jet from a single nozzle.

Considered together, Figures 9, 10, and 11 show that only at low flow rates and long blowing distances is the position of the point of maximum impact pressure significantly closer to the lance axis than is the axis of the individual nozzle subunit.

A comparison of Figure 11 with Figure 6 shows that the jet from one nozzle of a triple nozzle unit spreads more rapidly than does the jet from one of these same nozzle units when operated alone.

The distortion of the individual jets from a triple nozzle is shown in more detail and in another way by the polar plots of Figures 12 and 13. In each of these figure lines of constant pressure within one jet (i. e., within one of the three individual but similar jets produced by the triple nozzle) have been drawn. The top and bottom half of each figure are for different flow rates and for a fixed distance from the nozzle. In all cases it can be seen that the individual jet is closer to the lance axis at low pressures (i. e., low flow rates) than it is at the higher flow rates.

2. Triple Nozzle With $\alpha = 7^{\circ}$

The triple nozzle having a nozzle spread angle of 7° was not tested as exhaustively as was the 10° triple nozzle. Most of the results of tests with the 7° triple nozzle assembly are shown by Figure 14.

As a result of compromises made in the machining of the three nozzle subunits for the 7° triple nozzle*, these nozzles had a divergent half angle (i. e., $\theta/2$) of 3.1°. The dotted lines of Figure 14 are plots of maximum impact pressure versus nozzle driving pressure for a single nozzle subunit at two blowing distances. There are no indications of any dips in this curve.

The solid lines of Figure 14 are plots of maximum impact pressure versus nozzle pressure, at three different blowing distances. These three curves show a very pronounced "slump" in maximum impact pressure throughout the middle portion of the operating range. Obviously this drop in maximum impact pressure is not due to the individual performance of the individual nozzle subunit since the dotted lines show no such slump. Thus, the interaction of the three individual jets must be the cause of this drop in maximum impact pressure.

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*It was desired that a triple nozzle having a nozzle spread angle of 6° be built and tested. This would have required the machining of a completely new nozzle assembly. However, by accepting a triple nozzle with a nozzle spread angle of something approaching 6° a gross reduction in machining costs was possible.

The exact causes of the peculiar behavior of the solid curves of Figure 14 are not known. The data points for Figure 14 were obtained from a limited number of tests; much more extensive testing would perhaps be required before a complete explanation could be obtained for the behavior of the jet.

A comparison of Figure 14 with Figure 7 shows that with both the 7^{o} nozzle and the 10^{o} nozzle the maximum impact pressure within the jet is lower in the midrange than would be expected from tests with the corresponding single nozzles; the 7^{o} nozzle is much worse in this respect. Without other data to the contrary, it seems reasonable to expect that a three hole nozzle having a nozzle spread of 6^{o} would be a worse offender in this respect than the 7^{o} nozzle.

3. Nozzle Spread Angle of 13^{o}

The three hole nozzle assembly having a nozzle spread angle of 7^{o} could be converted to a three hole nozzle having a spread angle of 13^{o} by simply rotating each of the three nozzle subassemblies through 180^{o}. Since this conversion was so simple it was felt that a few tests with a 13^{o} nozzle would be worth the effort.

The data obtained during a few tests with the 13^{o} three hole showed that modification of the test facility would be required in order to obtain satisfactory data. Since there is apparently no real interest in three hole nozzles with nozzle spread angles of 13^{o}, tests with the 13^{o} nozzle were discontinued. No useful results have been obtained with this nozzle.

CONCLUSION

1. The maximum impact pressure (and therefore the maximum velocity) within each of the jets from a three hole nozzle is generally somewhat less than it is in a jet from one of the three nozzle subunits operating alone; all for some fixed distance downstream and some fixed flow rate.

2. The maximum impact pressure in the jet from a three hole nozzle (7^{o} or 10^{o}) is extremely reduced from that of an equivalent single hole nozzle (as reported on in Reference 1), again for a fixed flow rate and downstream position.

3. The implication of conclusion number 2 above is that a three hole nozzle, at any given flow rate, would have to be much closer to the bath than an equivalent single hole nozzle to do a comparable job of agitating the bath and throwing particles of molten iron up into the space above the bath. The Water Model tests (Appendix A), however, show that this is not true. From these tests it is concluded that the penetrating capability of a multi-jet cannot be directly determined, even in a relative sense, from measurements of the impact pressure within a jet blowing in room air; the individual jets from a three-hole nozzle may combine when being blown into a liquid in such a way as to produce a deeper cavity in the bath than such room air tests would indicate.

4. When the angle of nozzle spread was 15^{o} or more, separate indents were produced in the bath during the water model tests. A nozzle spread of 10^{o} or less did not produce separate indents. Unfortunately these numbers cannot be directly applied to a basic oxygen furnace. Larger and higher velocity jets operating in the atmosphere of an oxygen converter can be expected to spread less rapidly than these small jets. Therefore, although it is felt that a 10^{o} three hole nozzle probably produces a single

hole (with nodules) in the molten iron, this is not a proven fact. Nozzles having spread angles of 7^{o} or less will surely create a single cavity in the molten iron, for normal operating ranges.

5. Three hole nozzles grossly distort the "nice" symmetrical flow pattern usually obtained with single jets. These complexities presumably arise mainly from the subsonic mixing and entrainment which occur in the downstream portions of the jet; shadowgraph pictures show that no interference between the individual jets occurs immediately downstream of the nozzle.

6. The depth of penetration produced by the use of the 10^{o} three hole nozzle will surely be less than the penetration resulting from the use of an equivalent single hole nozzle, all at fixed flow rates and blowing heights. This difference appears to be about 20-25%.

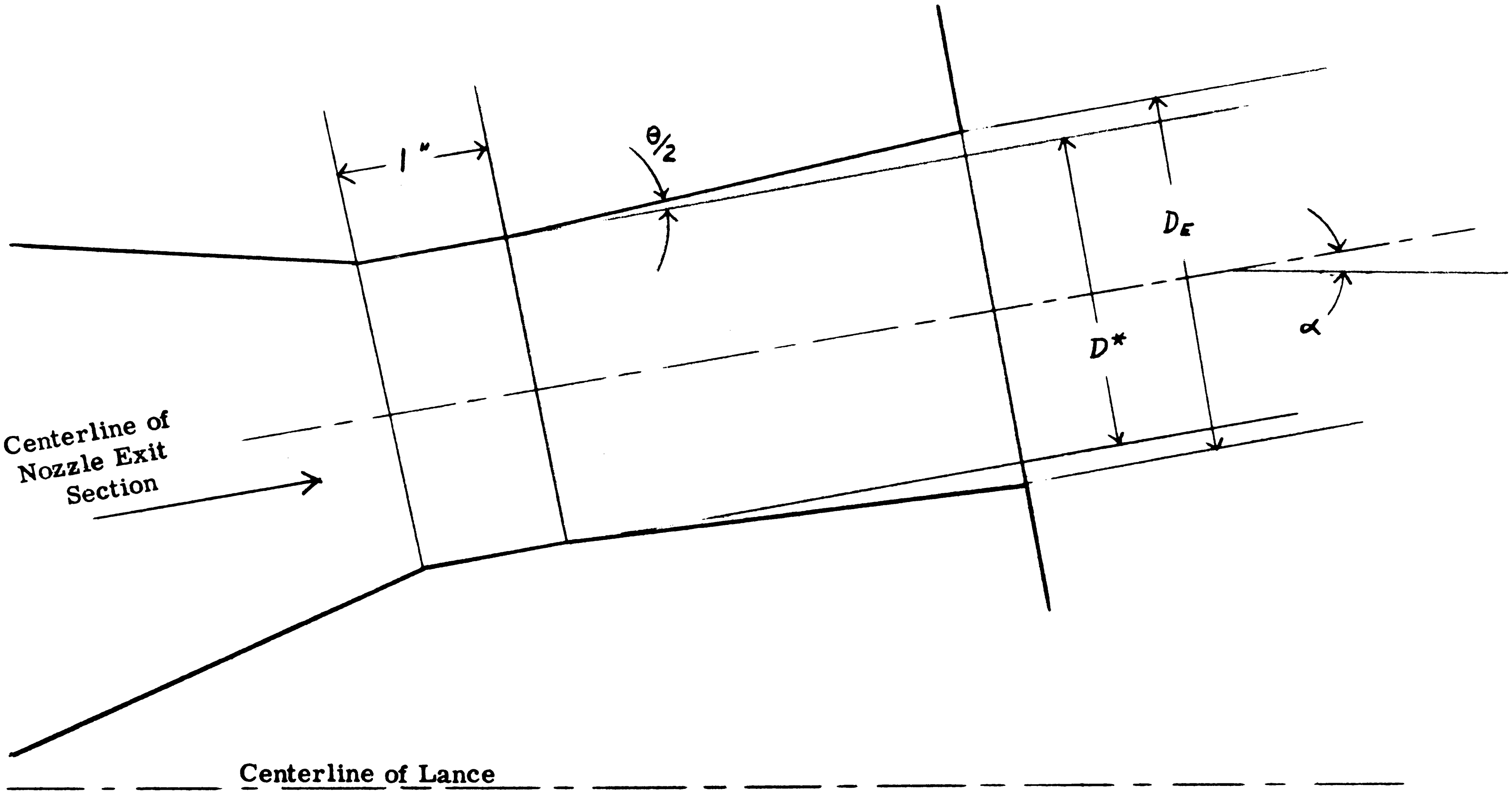
7. The depth of penetration for a 7^{o} (or 6^{o}) three hole nozzle would probably differ (from the depth of a single hole nozzle) by less than 20%.

8. Due to the reduced penetration with a three hole lance, a three hole lance will need to be operated at closer blowing distances than will a single hole lance. At these closer blowing distances, the effects of the lance height above the surface of the bath are more sensitive to changes in lance height, as compared with the operation of a single hole lance.

REFERENCE

1. Kurath, E., Hays, P. O., and Glass, D. R., "Design Studies of Oxygen Nozzles," Univ. of Mich., ORA Report 05983-1-P, December 1963.

Figure 1. Triple Nozzle Configurations Tested



D^*	D_E	$\theta/2$	α
2.105"	2.492"	3.7^o	10^o
2.105"	2.492"	3.1^o	7^o
2.105"	2.492"	3.1^o	13^o

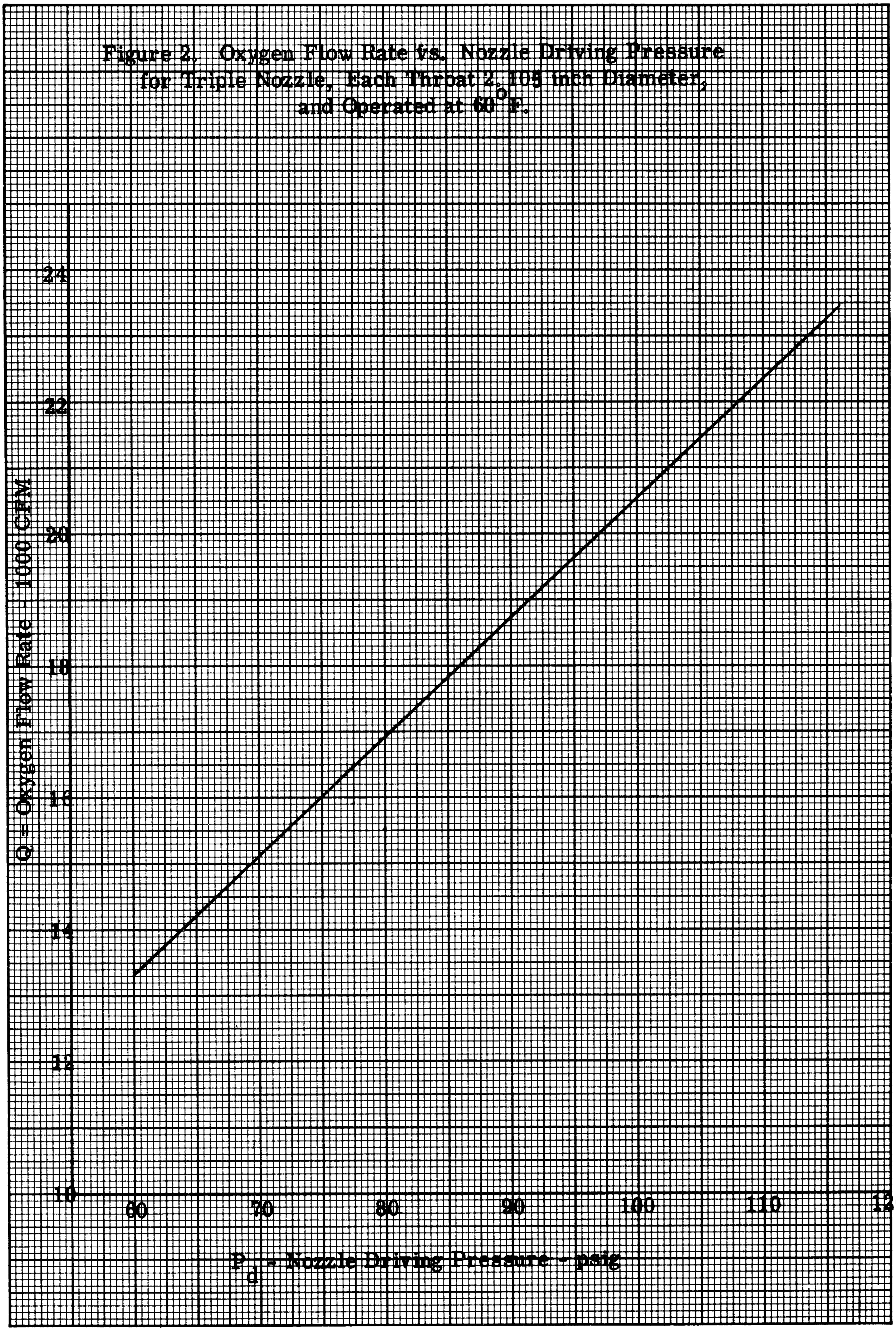


Figure 2. Oxygen Flow Rate vs. Nozzle Driving Pressure for Triple Nozzle, Each Throat 2.105 inch Diameter, and Operated at 60°F.

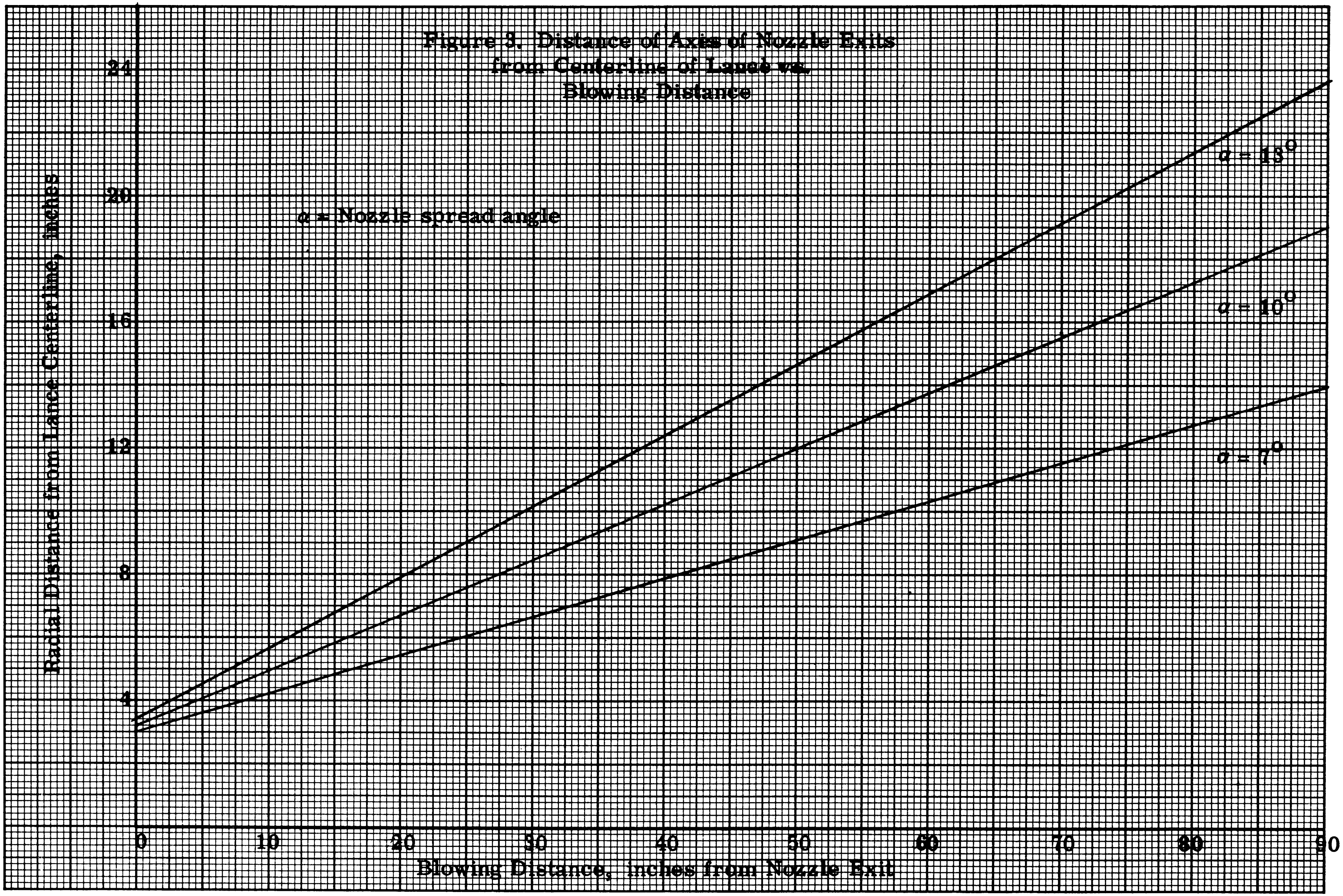
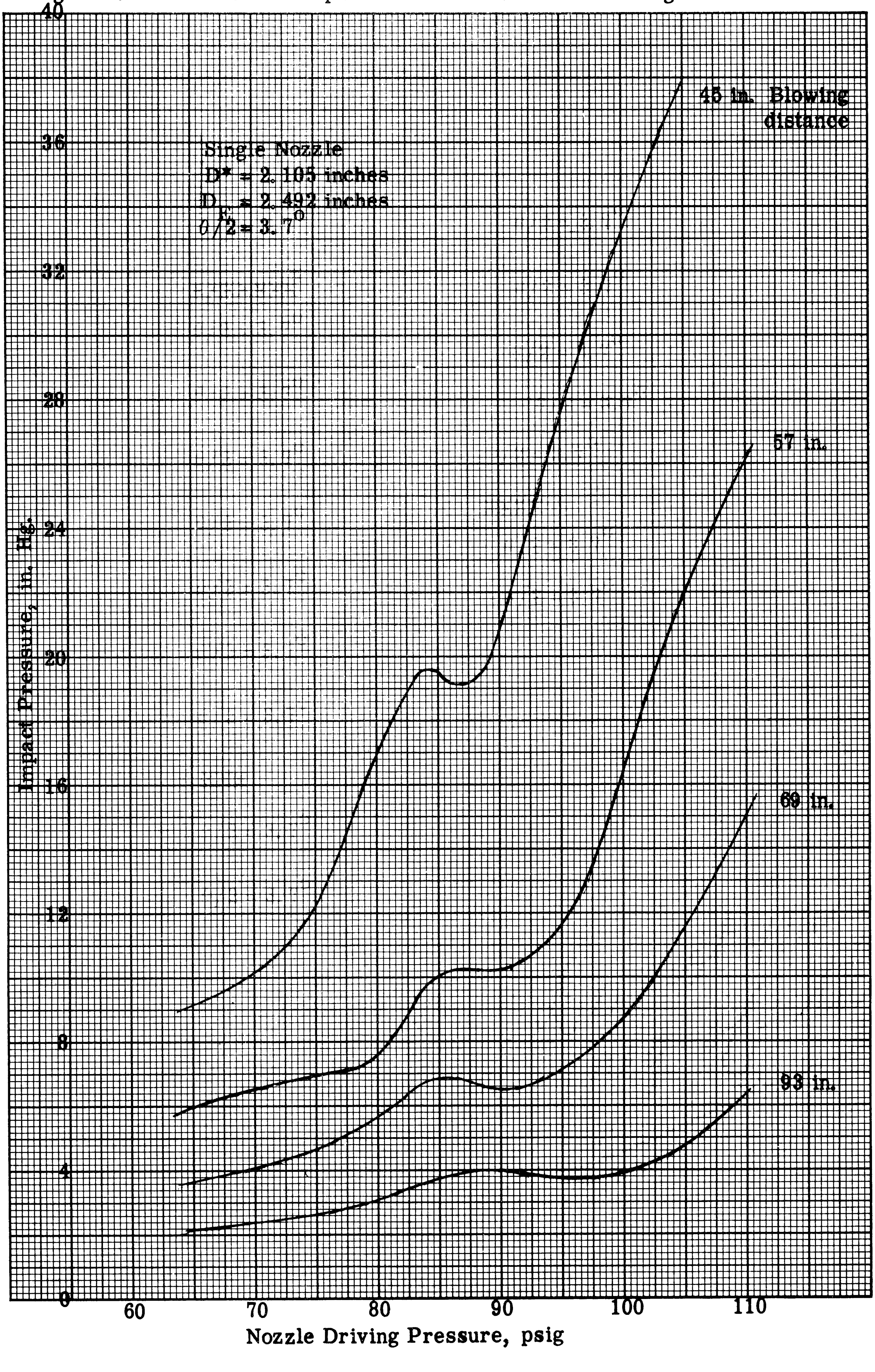


Figure 3. Distance of Axis of Nozzle Exits from Centerline of Lance vs. Blowing Distance

Figure 4. Jet Centerline Impact Pressure vs. Nozzle Driving Pressure



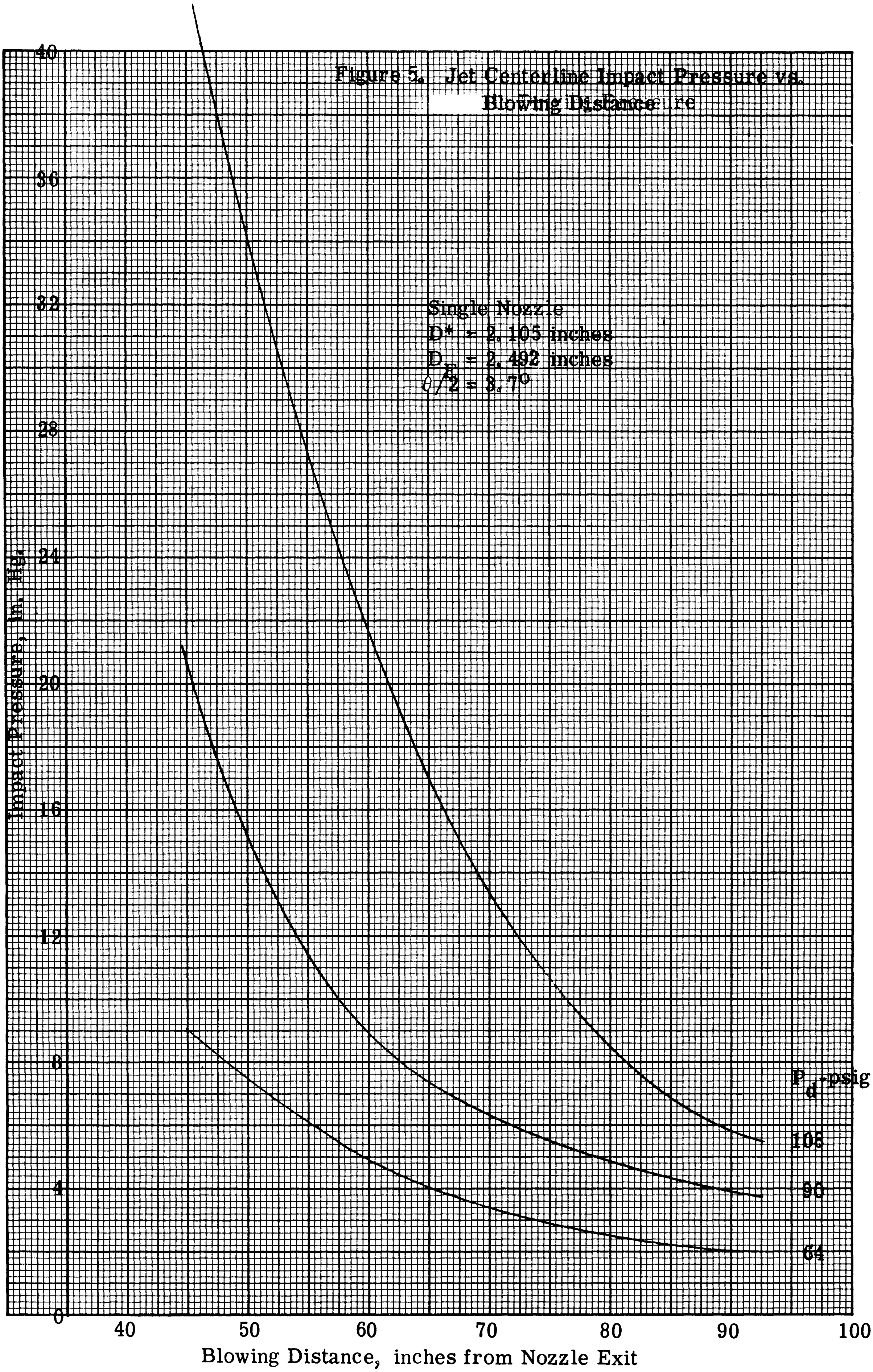


Figure 5. Jet Centerline Impact Pressure vs. Blowing Distance

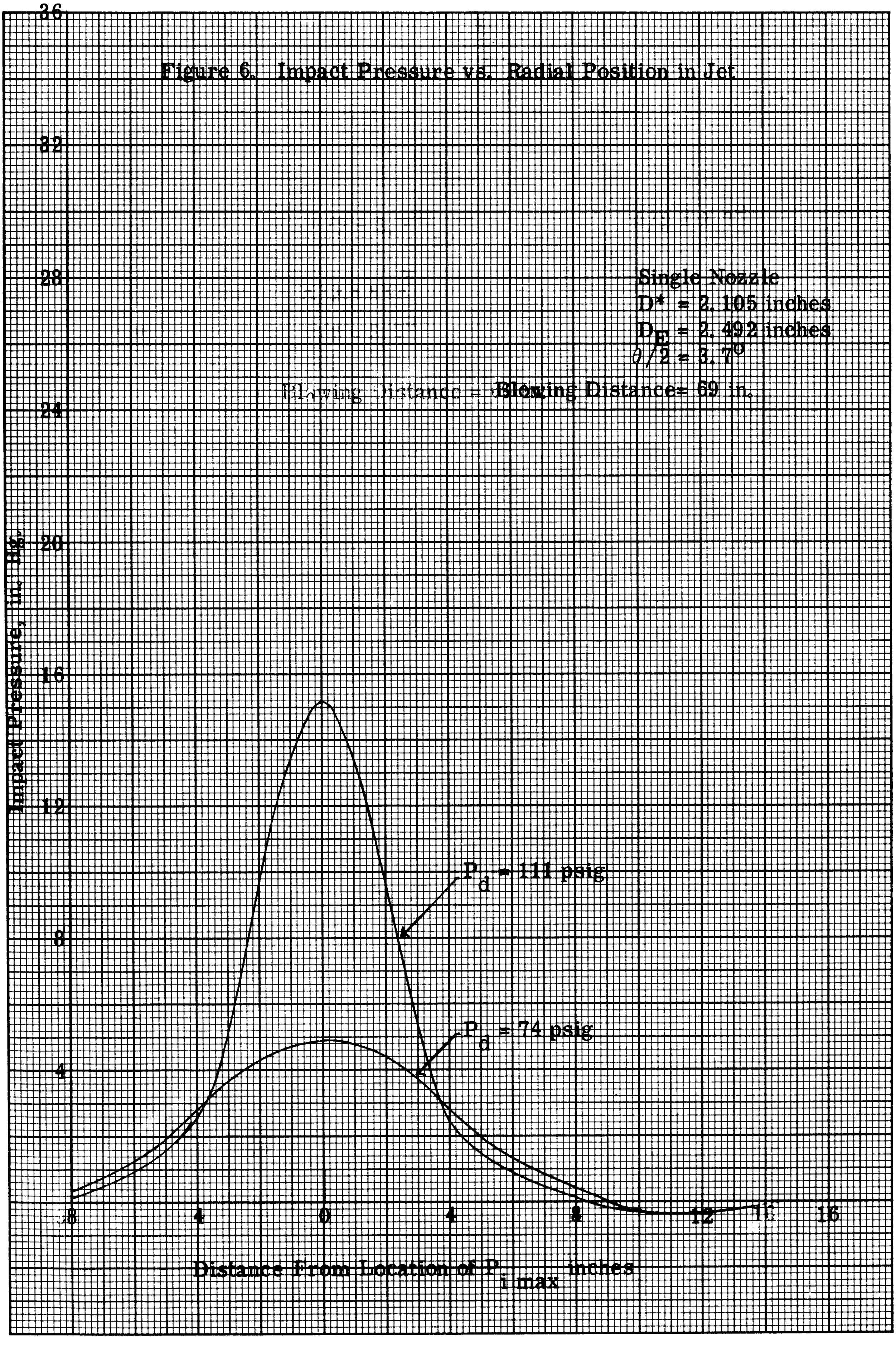


Figure 6. Impact Pressure vs. Radial Position in Jet
Single Nozzle
D* = 2.105 inches
D_E = 2.492 inches
$\theta/2$ = 3.7°
Blowing Distance= 69 in.
P_d = 111 psig
P_d = 74 psig
Impact Pressure, in. Hg.
36
32
28
24
20
16
12
8
4
8
4
0
4
8
12
16
Distance From Location of $P_{i\,max}$ inches

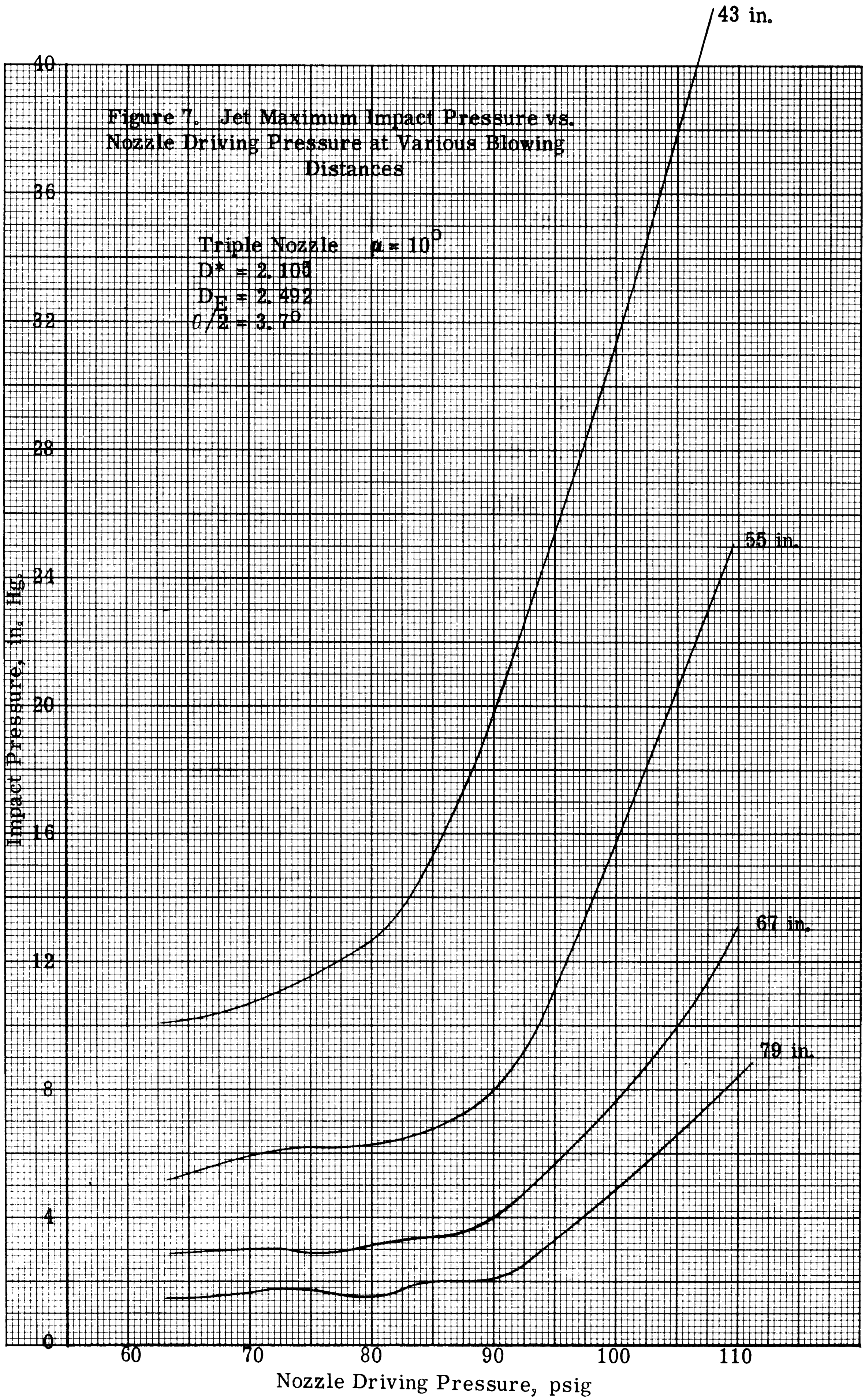


Figure 7. Jet Maximum Impact Pressure vs. Nozzle Driving Pressure at Various Blowing Distances
Triple Nozzle α = 10°
D* = 2.108
D_E = 2.492
θ/2 = 3.7°
43 in.
55 in.
67 in.
79 in.
40
36
32
28
24
20
16
12
8
4
0
60
70
80
90
100
110
Impact Pressure, in. Hg.
Nozzle Driving Pressure, psig

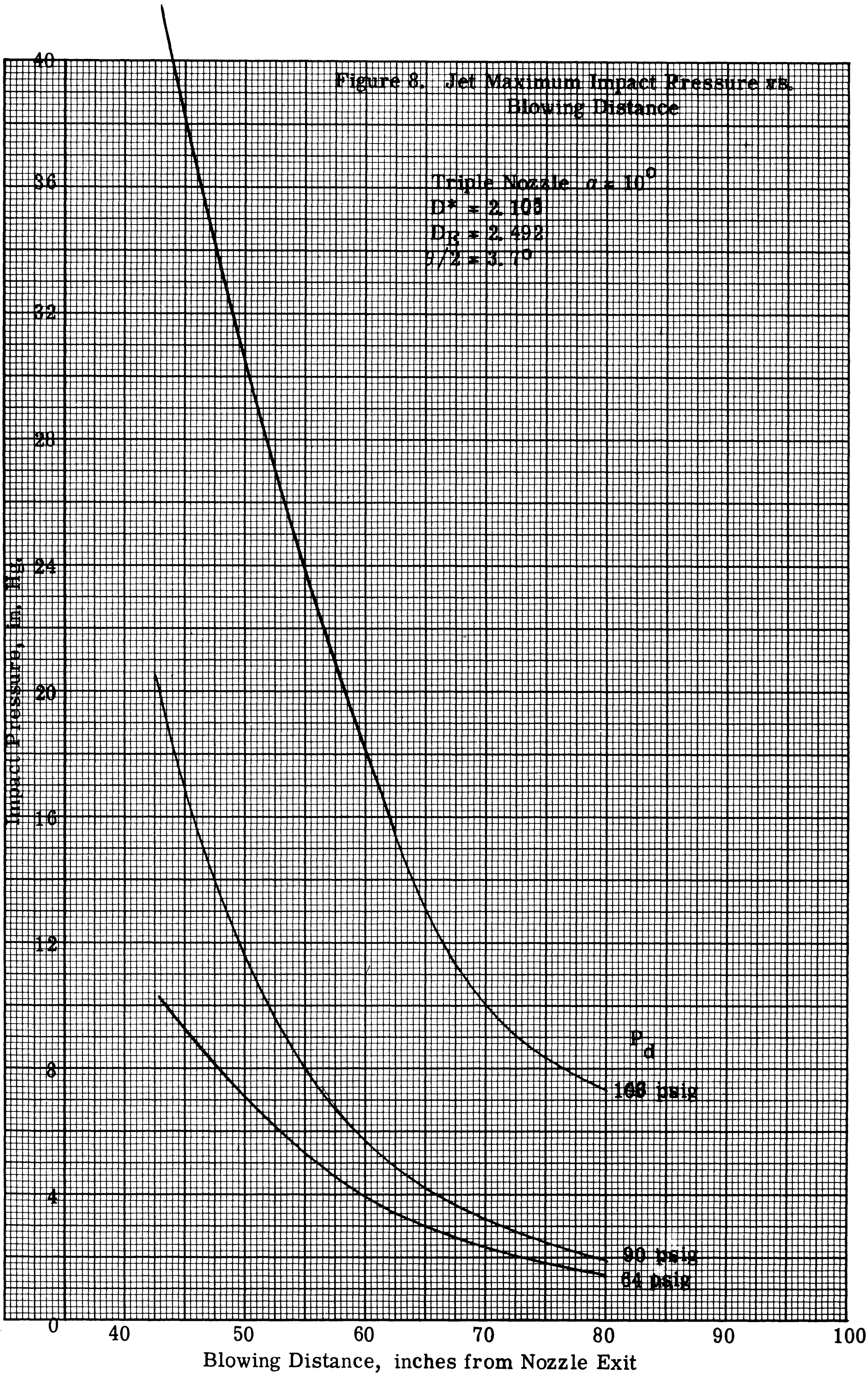


Figure 8. Jet Maximum Impact Pressure vs. Blowing Distance
Triple Nozzle α = 10°
D* = 2.105
D_E = 2.492
θ/2 = 3.7°
P_d
108 psig
90 psig
64 psig
Impact Pressure, in. Hg.
0
4
8
12
16
20
24
28
32
36
40
50
60
70
80
90
100
Blowing Distance, inches from Nozzle Exit

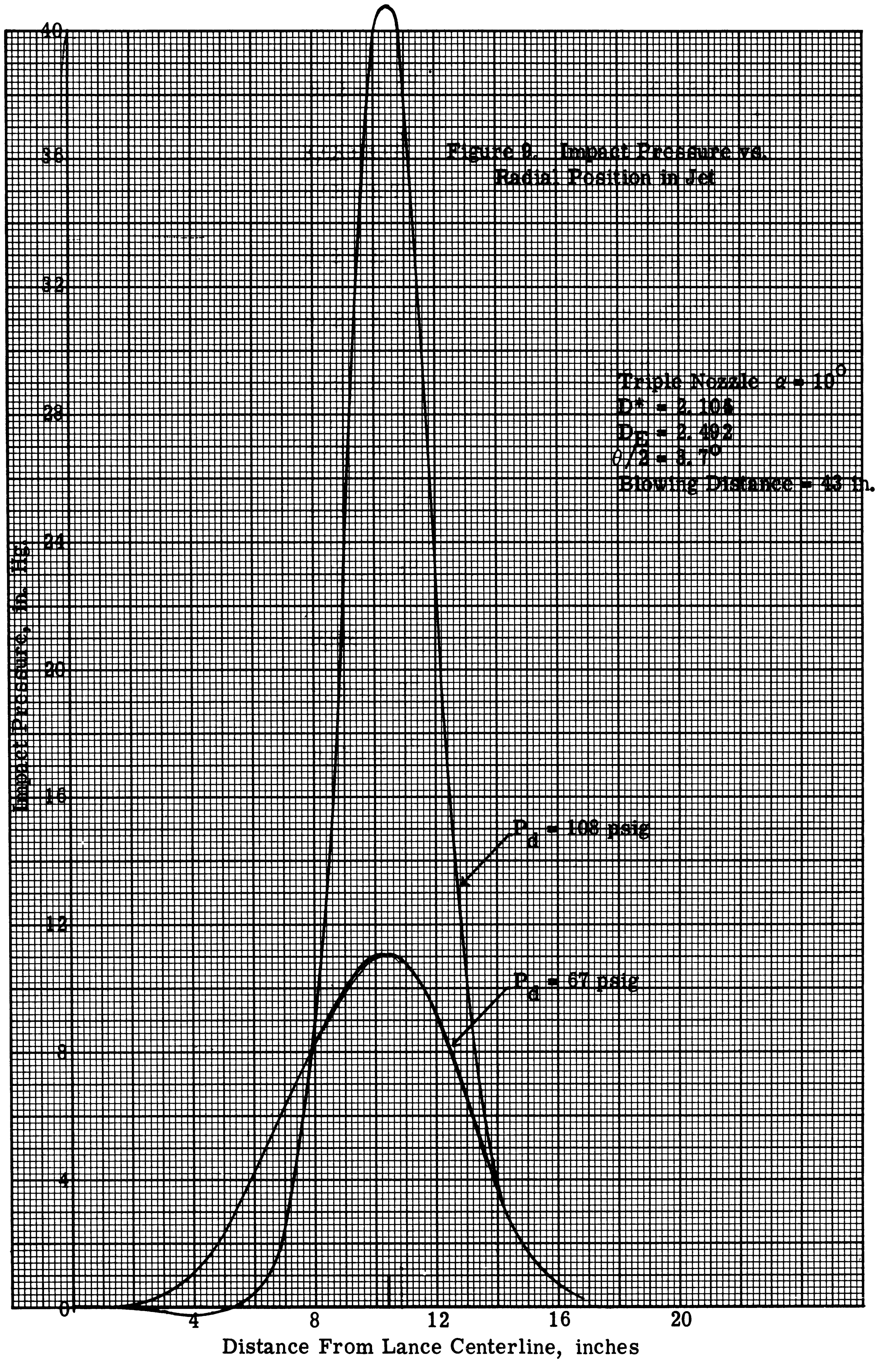


Figure 9. Impact Pressure vs. Radial Position in Jet
Triple Nozzle α = 10°
D* = 2.104
D_E = 2.492
θ/2 = 3.7°
Blowing Distance = 43 in.
P_d = 108 psig
P_d = 67 psig
Impact Pressure, in. Hg.
0
4
8
12
16
20
24
28
32
36
40
4
8
12
16
20
Distance From Lance Centerline, inches

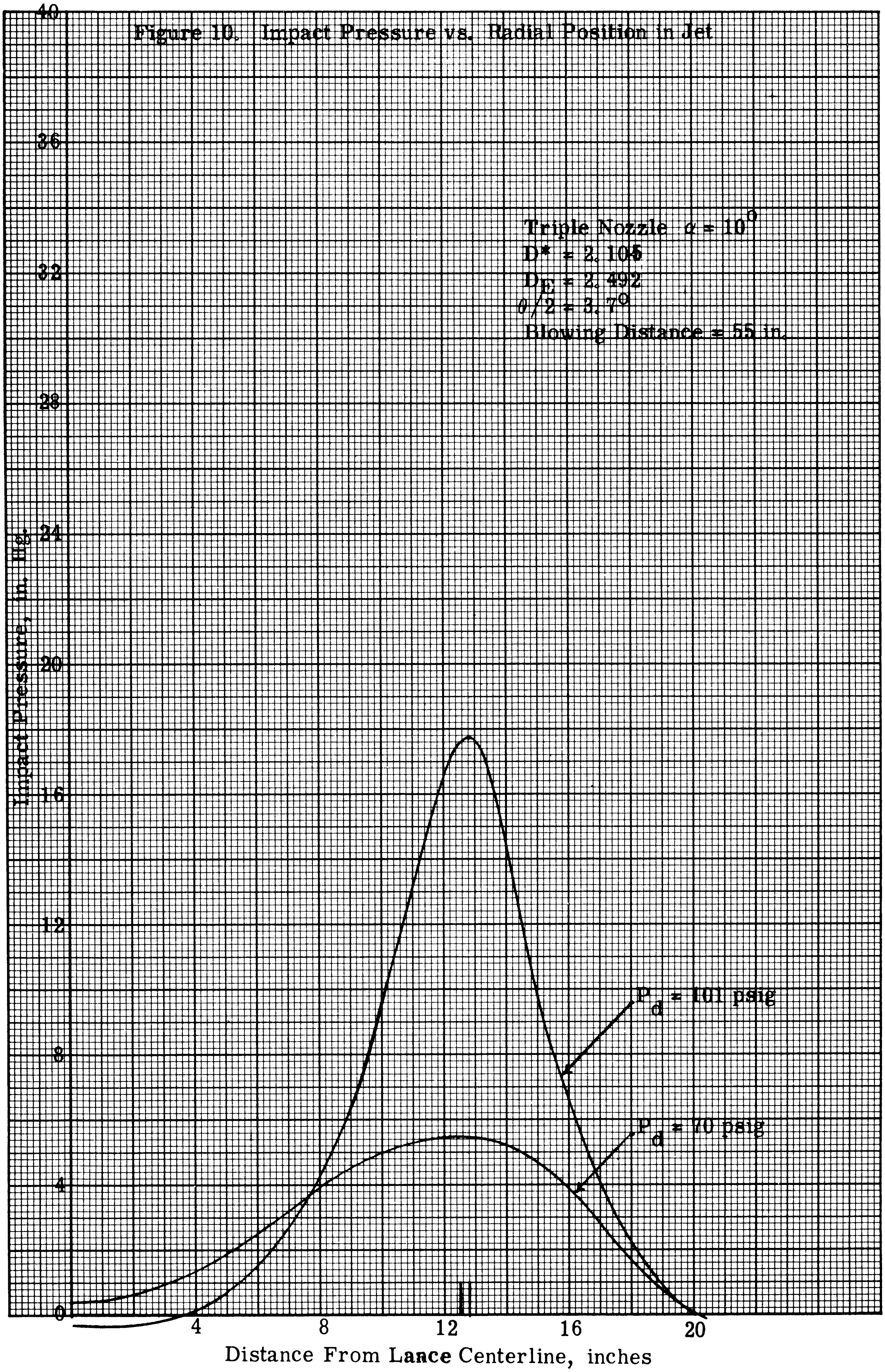


Figure 10. Impact Pressure vs. Radial Position in Jet
Triple Nozzle α = 10°
D* = 2.105
D_E = 2.492
θ/2 = 3.7°
Blowing Distance = 55 in.
P_d = 101 psig
P_d = 70 psig
Impact Pressure, in. Hg.
0
4
8
12
16
20
24
28
32
36
40
4
8
12
16
20
Distance From Lance Centerline, inches

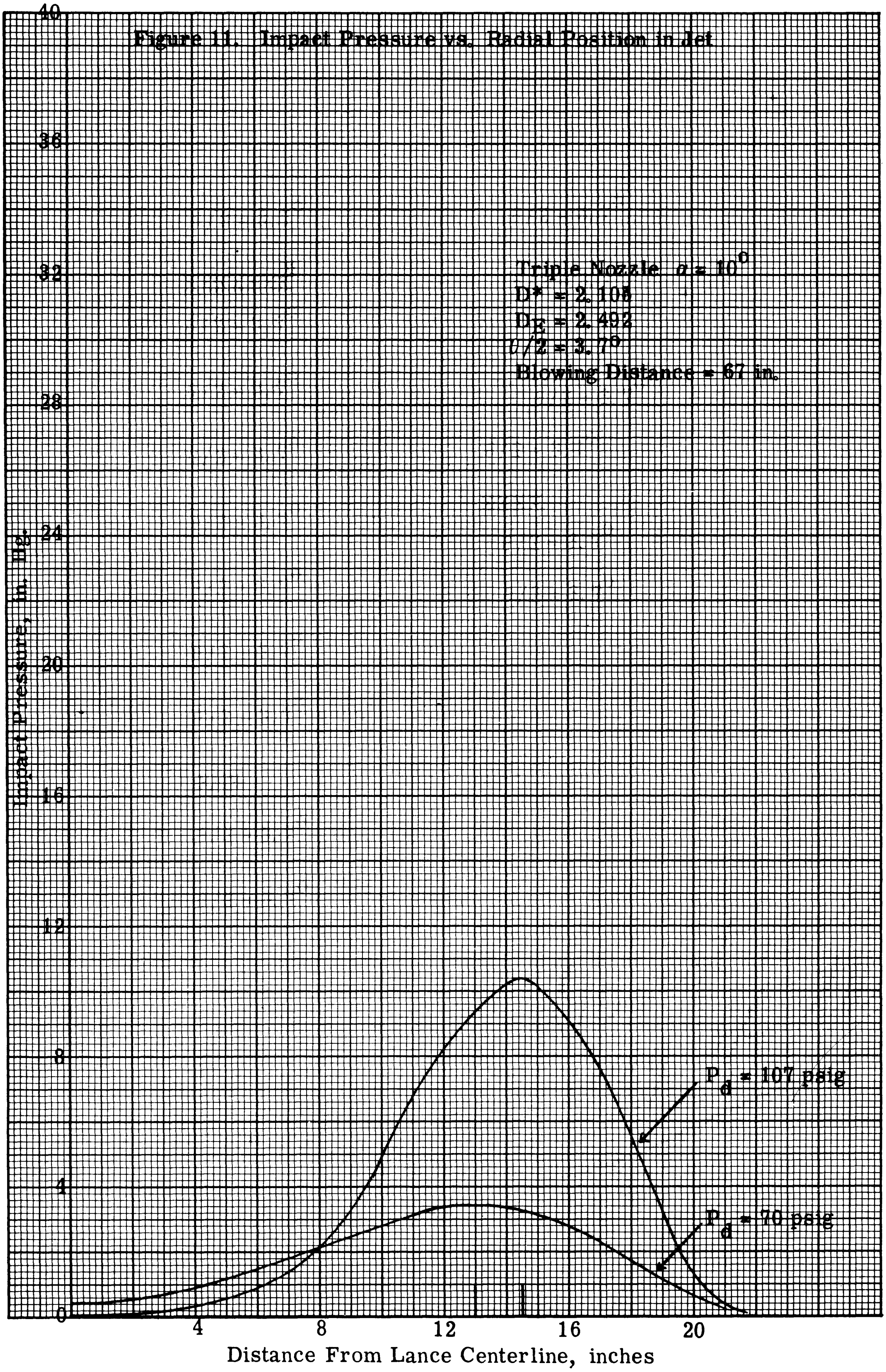


Figure 11. Impact Pressure vs. Radial Position in Jet

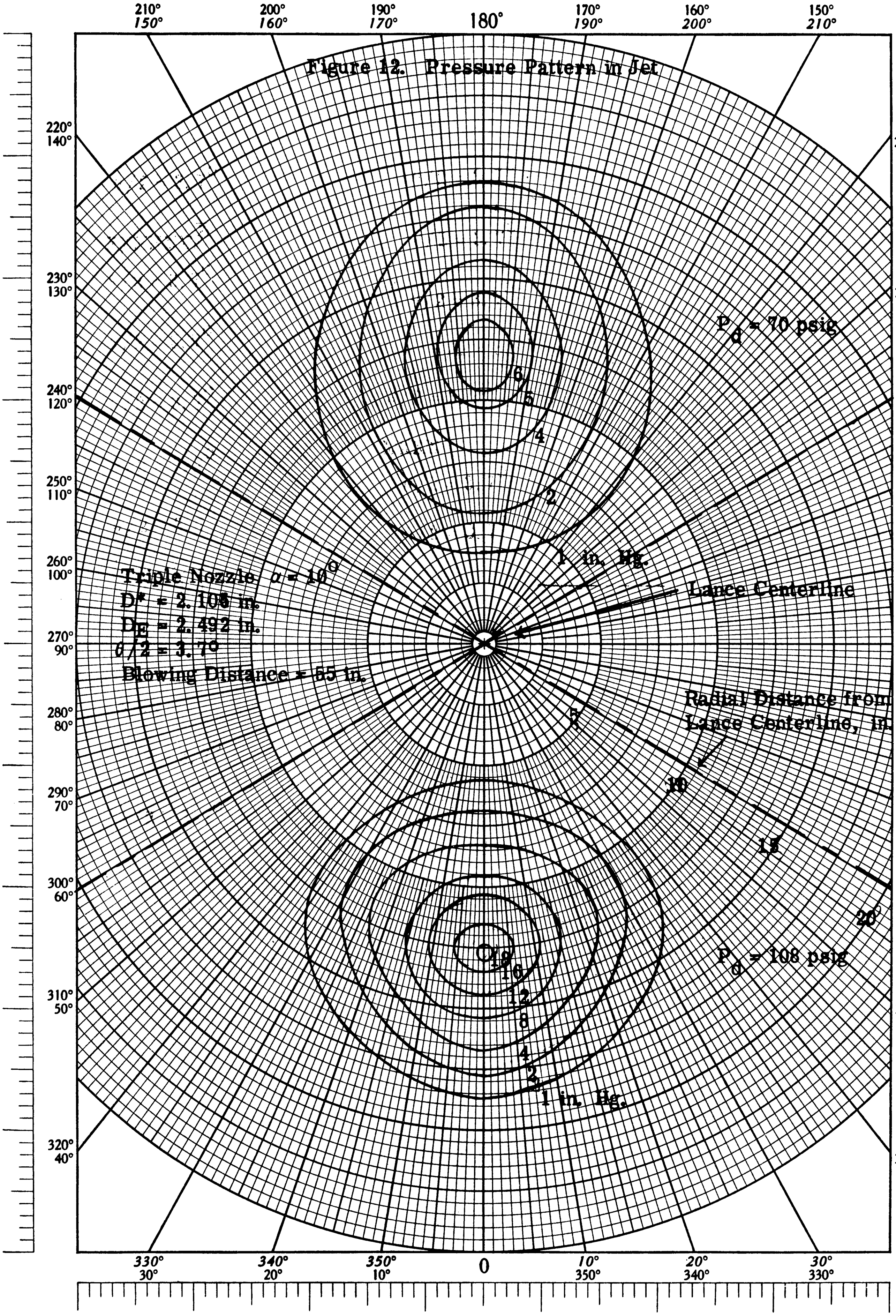


Figure 12. Pressure Pattern in Jet

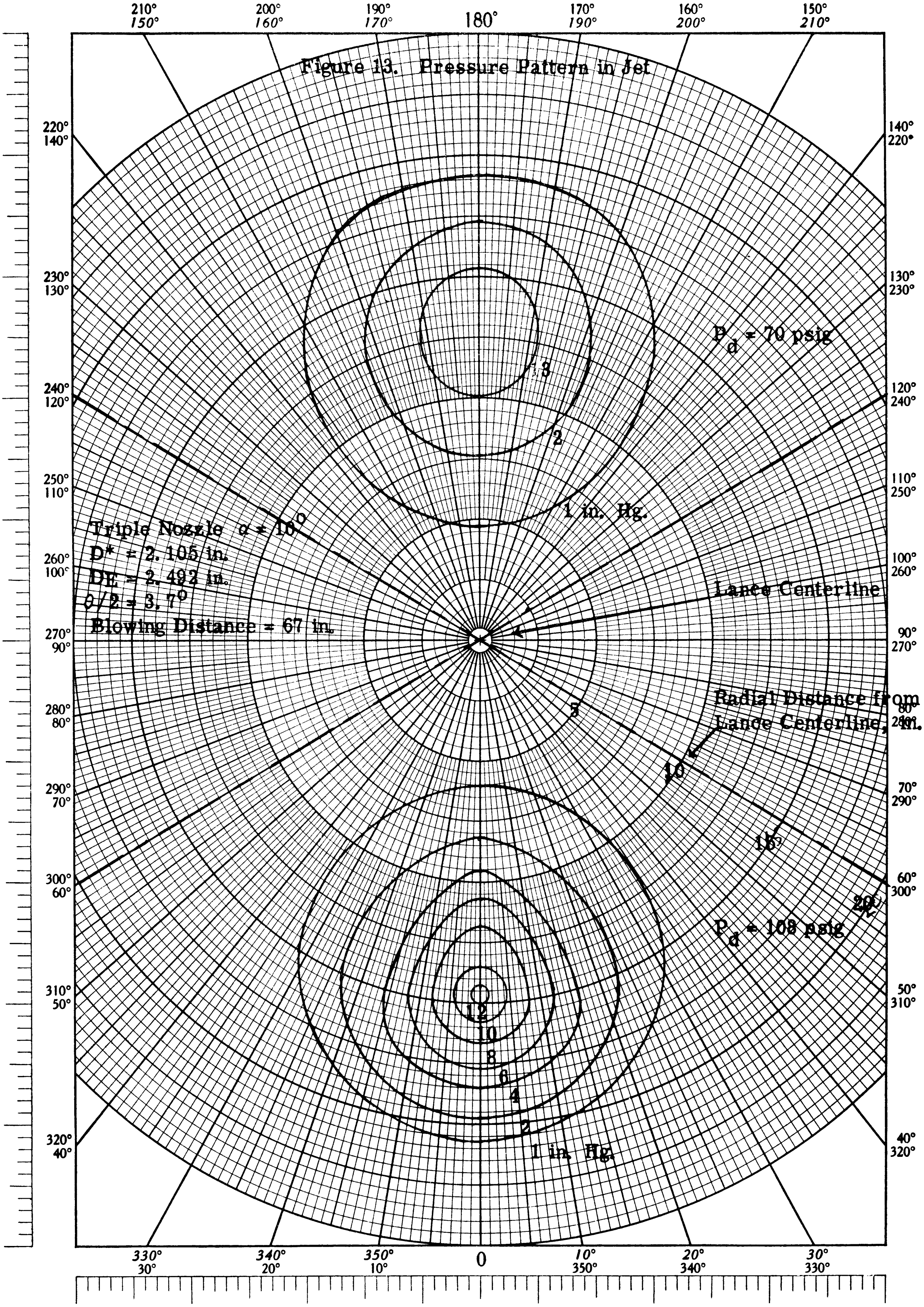


Figure 13. Pressure Pattern in Jet

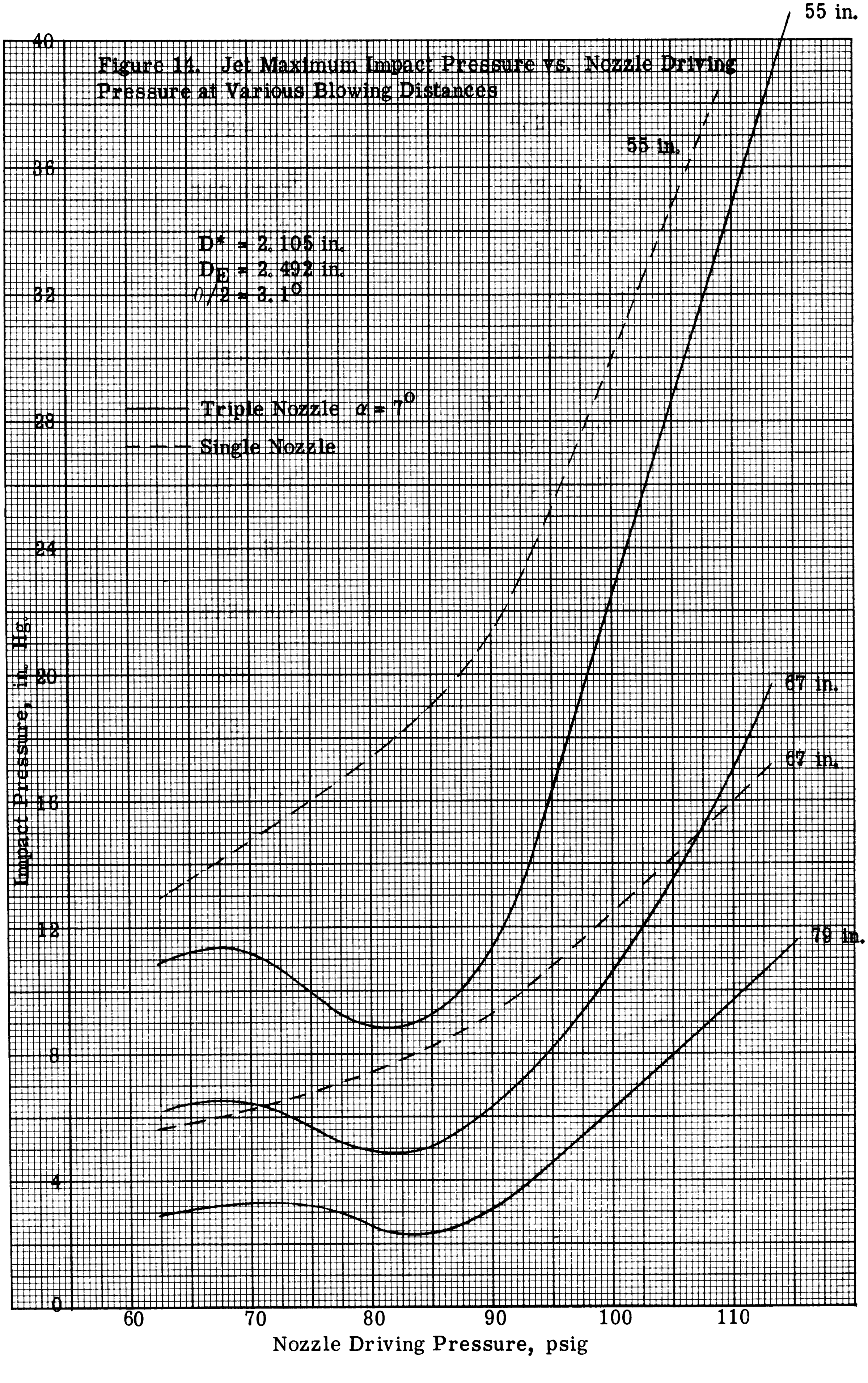


Figure 14. Jet Maximum Impact Pressure vs. Nozzle Driving Pressure at Various Blowing Distances
D* = 2.105 in.
D_E = 2.492 in.
$\theta/2$ = 3.1°
Triple Nozzle α = 7°
Single Nozzle
55 in.
55 in.
67 in.
67 in.
79 in.
Impact Pressure, in. Hg.
0
4
8
12
16
20
24
28
32
36
40
60
70
80
90
100
110
Nozzle Driving Pressure, psig

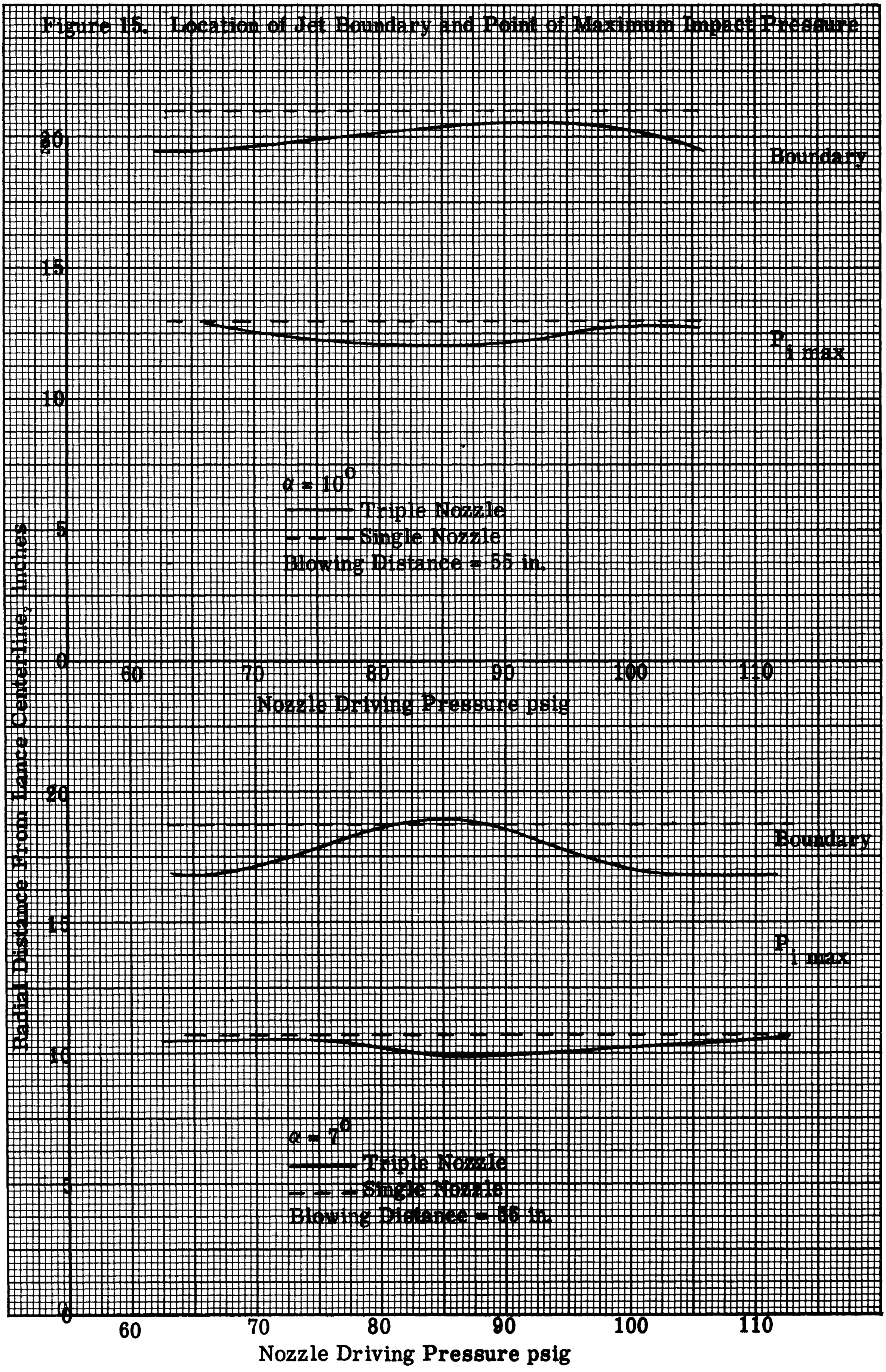


Figure 15. Location of Jet Boundary and Point of Maximum Impact Pressure

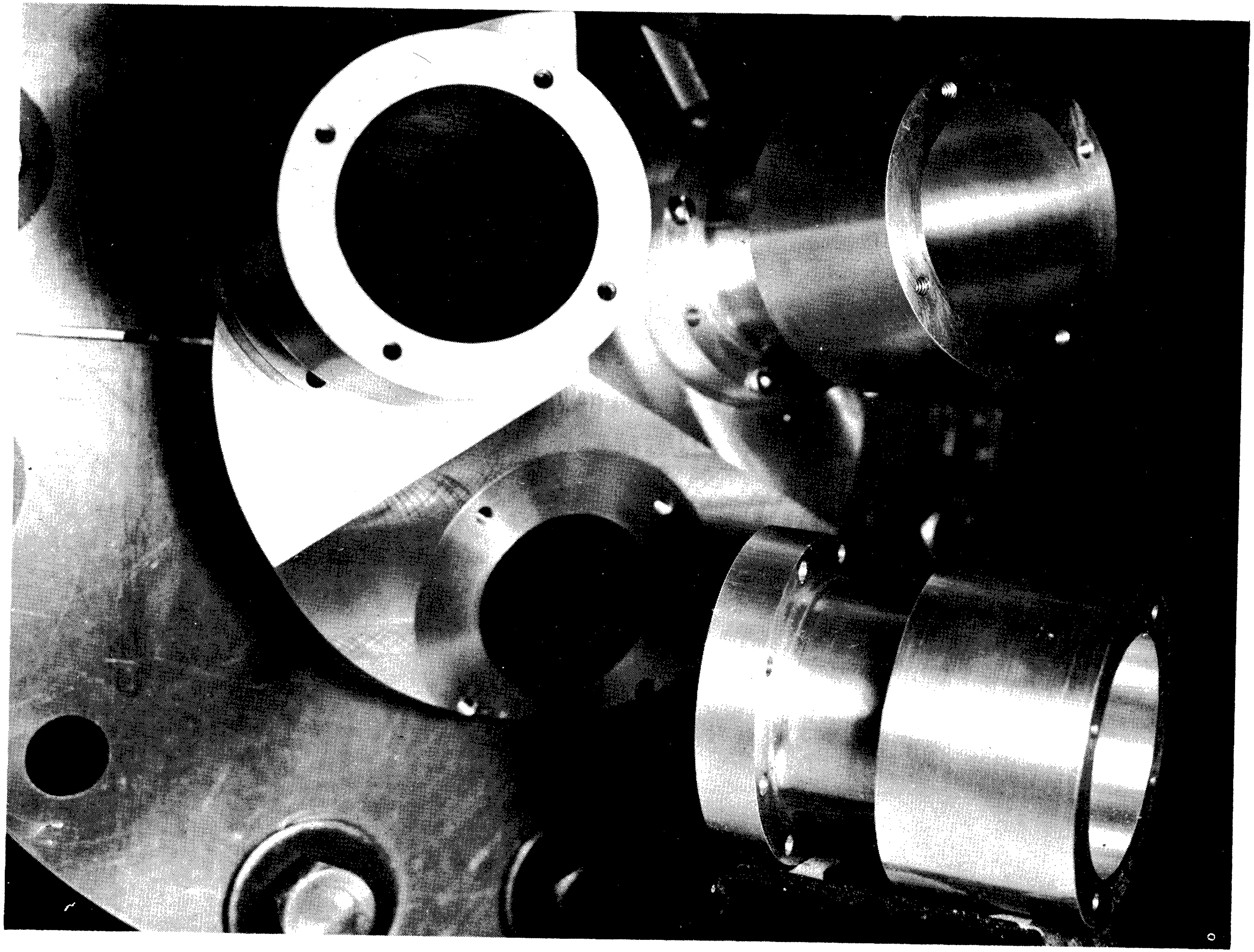


Figure 16. The "Three Hole" Nozzle Assembly.

Figure 17. The "Three Arm" Total Head Rake.

Appendix A

WATER MODEL TESTS

A series of small "three hole" nozzles were fabricated and used in water model tests. The diameter of each throat of the nozzles was 0.093 inches, and the centerline of each exit was located 1/8 inch from the lance axis. The nozzles differed only in spread angle.

In addition, one nozzle was made with a single throat of 0.162 inch diameter, the area of this single throat nozzle being equal to the total throat area of each of the "three hole" nozzles.

Figure A-1 is a series of photographs which show the patterns of indent and splash created by these nozzles blowing in a 6 inch water bath. The vessel was 12 inches in diameter by 24 inches in height. In each test the nozzle was placed 4 inches above the bath surface and air was blown at a pressure of 20 psig. The exposure time for each photograph was 1/4 of a second.

To reduce optical distortion the bottom of the cylindrical test vessel was surrounded by a square Plexiglas vessel and the space between the two vessels was also filled with water to the same level as the water in the test vessel. The cylindrical vessel alone magnifies horizontal distances in the water bath so that the width of the indent would appear greater than it is in fact.

Separation of Indents

Three distinct indents were produced by the $\alpha = 15^{\circ}$ and $\alpha = 20^{\circ}$ nozzles. These produced separate indents at all reasonable driving pressures and blowing heights. At 20 psig driving pressure the $\alpha = 10^{\circ}$, 5°, and 0° nozzles produced a single indent. The indent for $\alpha = 10^{\circ}$ was somewhat three sided but had no cusp at the center.

At very low driving pressures the $\alpha = 10^{\circ}$ nozzle produced three separate, very shallow, indents in the water. The flow at the nozzle exit was subsonic under those conditions. At any driving pressure above a few psig, the indent was definitely a single depression. For these particular model tests the transition from single to triple depression generally occurs between $\alpha = 10^{\circ}$ and α $\alpha = 15^{\circ}$ and depends to some extent on driving pressure.

Depth of Indent(s)

The depth of penetration (see Figure A-1) of the gas jet into the liquid is practically the same for the single 0.162 inch nozzle, the three hole nozzle having a spread angle of 0°, and the three hole nozzle having a jet spread angle of 5°. Any apparent difference in penetration shown by the photographs taken during the tests with these three nozzles is within the experimental variation to be expected between two identical tests. In all three cases the average depth of penetration is a little over 5 inches. The black marks on the front of the vessel are 1 inch apart.

The average depth of indent obtained with the three hole nozzle having a 10° spread angle is about 4 1/2 inches, or almost 20% less penetration than with the single hole nozzle.

The average depth of the three indents obtained with the 15° nozzle is about 3 inches, or about 40% less than with the single hole nozzle.

The average depth of the three indents obtained with the 20° nozzle is somewhat less than 3 inches.

From these tests it can be concluded that:

a. The depth of indent is not significantly reduced, relative to the indent of an equivalent single hole nozzle, until the individual jets have sufficient divergence to appreciably spread the jet and thus widen the cavity, and

b. the depth of indent is further reduced when the cavity has become essentially three separate indents.

Splash Pattern

The pattern of the splash above the bath, obtained with the single throat nozzle, the 0° or the 5° three hole nozzles is not significantly different. The splash pattern resulting from the use of the 10° nozzle seems to be slightly broader and perhaps not quite as high. The splash pattern obtained with the 15° and the 20° nozzles is further broadened and decreased in height. All comparisons are relative to the splash obtained with the single hole nozzle.

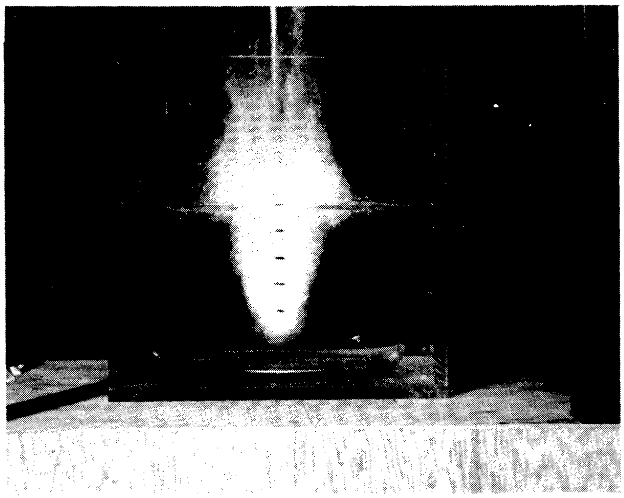
Conclusions Based on Model Tests

These model tests are extremely limited in terms of the number of conditions which have been varied and number of tests performed. In spite of this, some qualitative conclusions can be stated:

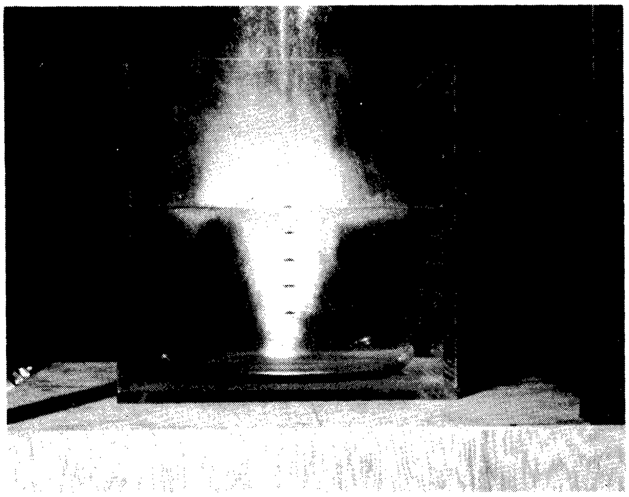
1. The depth and shape of the cavity in the bath and the splash pattern above the bath are not significantly altered in going from a single hole nozzle to equivalent three hole nozzles, until the spread angle of the three hole nozzle is appreciably greater than 0.
2. Increasing the spread angle of a three hole nozzle tends to decrease the depth of penetration, increase the "diameter" of the cavity (i. e., increase the total cross-sectional area of the indent, or indents if there are three separate indents), decrease the height of the major portion of the liquid splash and increase the diameter of the splash pattern.
3. The use of three hole nozzles having spread angles of 15° or 20° produces a greater breakup of the liquid than does an equivalent single hole nozzle. The single hole nozzle may pick up out of the

bath almost as much liquid as does a three hole nozzle, but the individual "chunks" of liquid picked up by the single hole nozzle appear to be much larger on the average than the particles picked up by a three hole nozzle. The extent of liquid breakup may be very significant in the operation of Basic Oxygen Furnaces.

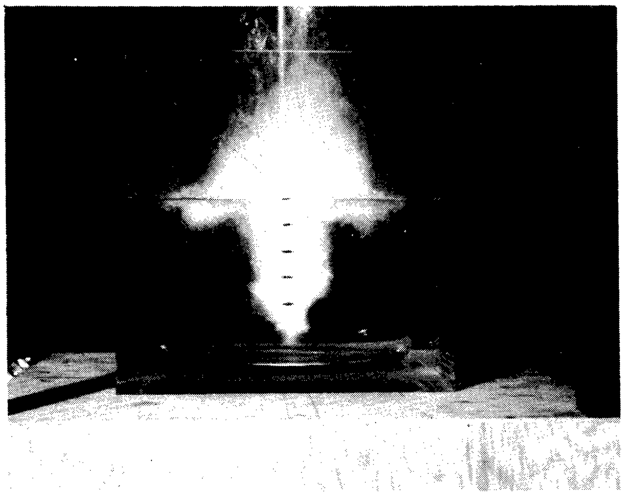
4. It seems unlikely that a significant portion of the splash thrown up by the jet(s) is actually thrown upward toward the nozzle <u>between</u> the three jets when the triple nozzle has a nozzle spread angle of 10° or less. In the model tests it appeared that even with a nozzle having a nozzle spread angle of 20° the liquid thrown upward from the mound between the three separate indents was not very great.



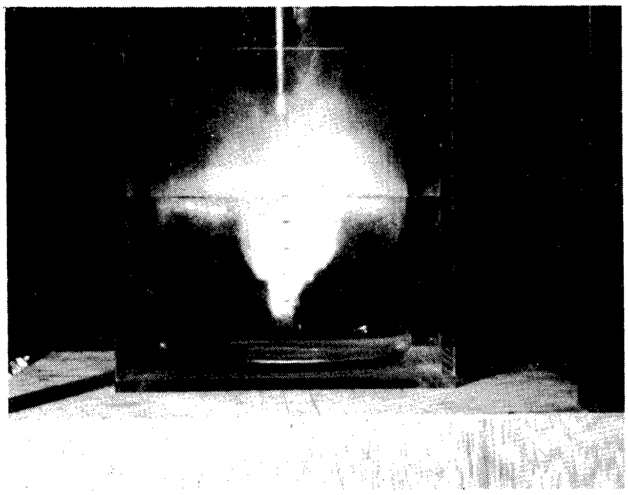
Single hole



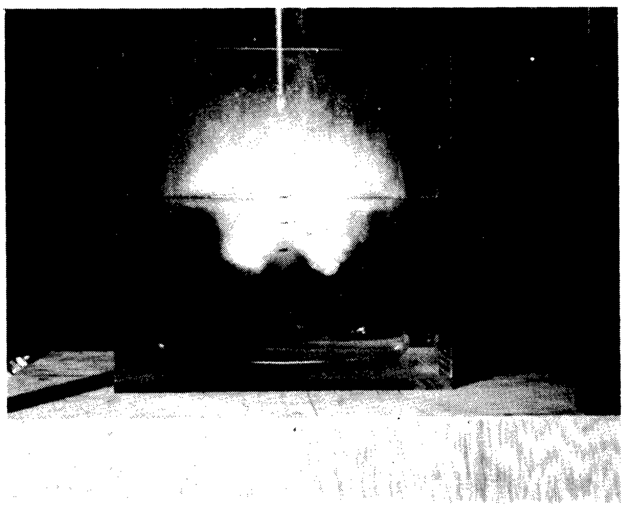
Three hole ; $\alpha = 0°$



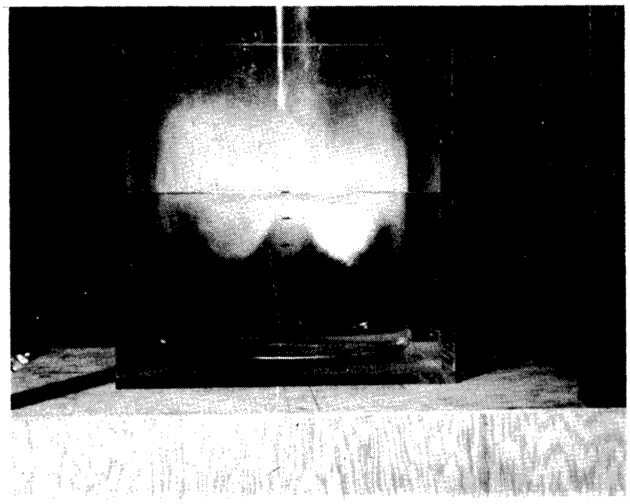
Three hole ; $\alpha = 5°$



Three hole ; $\alpha = 10°$



Three hole ; $\alpha = 15°$



Three hole ; $\alpha = 20°$

Bath depth = 6"
Nozzle height = 4"
Nozzle pressure = 20 psig

Total throat area of all nozzles typical = (0.02 in.^{2})
α = Angle between Nozzle center line and Lance axis

FIGURE A-1. WATER MODEL TESTS .

Appendix B

SHADOWGRAPH PICTURES OF THE JET(S) FROM A THREE HOLE NOZZLE

The jet outline and shock waves within a jet can be observed by various optical techniques. The "shadowgraph" technique is about the simplest of these optical techniques in terms of time and equipment, but it is not the most sensitive. It is, however, sensitive enough to show the flow in the jet, near the nozzle, under conditions of interest in this report.

Several shadowgraph pictures (sometimes called "Shadow-photographs") have been taken of the jets produced by the three hole nozzle having a nozzle spread angle of 7° (i. e., the second nozzle listed on Figure 1). Two of these photographs are included in this report; Figures B-1 and B-2.

Figure B-1 was taken when the nozzle pressure was 78 psig, which corresponds to an oxygen flow rate of about 16,500 CFM. The light, from a point source several feet away, passes through the jet (or jets) at essentially right angles to the axis of the entire nozzle assembly (i. e., the same as the lance axis) and falls on a large photographic negative positioned in a plane parallel to the lance axis and perpendicular to the light bath. Since the axis of each of the three jets was at an angle of 7° to the lance axis, none of the jets were parallel to the negative. In spite of this slight problem Figure B-1 clearly shows the three jets as being completely separated for about the first foot from the nozzle. Dimensions in these shadowgraphs may be approximated by making use of the fact that the jet diameter right of the nozzle exit is about 2 1/2 inches.

Shadowgraph pictures are able to show details in the flow by virtue of sharp changes in the density of the gas. Shock waves (which are by definition those "lines" or "surfaces", within the supersonic flow along which sudden pressure, temperature, velocity, and density changes occur simultaneously in order that "adjustments" be made as required by all the combined conditions imposed on the flow), show up clearly on the shadowgraph pictures. As mixing occurs along the jet boundary, there is no longer a sudden change in density near the jet boundary. Thus the jet boundary well downstream of the nozzle is no longer discernible in the shadowgraph picture. More sensitive optical systems are capable of "seeing" the jet for a greater distance.

The shock waves which appear within about the first 5 inches of the jet are relatively "weak" waves. Such weak waves are typical of a supersonic jet produced by a nozzle operating near its design pressure. It is practically impossible to entirely eliminate all such waves with conical nozzles. Strong shock waves in a jet would appear as darker and heavier lines in the shadowgraph pictures. Such strong shock waves are produced when a nozzle is operated far from its design pressure, and are indicative of greater losses (in terms of momentum concentration in a jet).

Figure B-2 was taken when the nozzle driving pressure was 108 psig (instead of the design pressure of 64 psig) and the shock waves are therefore somewhat stronger, though still not really severe in terms of their effect on the distribution of jet momentum.

One of the three separate nozzles was removed and the opening closed before the picture in Figure B-2 was taken. This was done to preclude the possibility that the three jets might overlap in the shadowgraph picture. It turned out this was not a necessary precaution since, even at 108 psig nozzle pressure, the diameter of each individual jet just downstream of the nozzle was not great enough to produce any overlapping on the shadowgraph picture.

Conclusions

1. The shadowgraph pictures show that the individual nozzles perform well at 78 and 108 psig. It is fully expected that shadowgraphs taken at any pressure between 64 and 108 psig (the anticipated operating range) would lead to similar conclusions.
2. The shadowgraphs show that; whatever problems or questions arise in regard to the operation of a three hole nozzle of the geometry used in these tests, the difficulty is not due to interaction of the three jets within the first foot or so of the nozzle. This conclusion can surely be extended to a similar nozzle having a nozzle spread angle of 6^o instead of 7^o.
3. The shadowgraphs do not explain the "sag" in the curves for the triple nozzle such as Figure 14. Figure B-1 was taken at a pressure of 78 psig at which nozzle pressure the impact pressure for the triple nozzle is relatively low. No difficulty is apparent in this shadowgraph of the jet. Thus, the difficulties which lead to the peculiar performance of the 7^o nozzle, as shown by Figure 14, must lie in the interaction of the three jets at downstream distances greater than one foot.

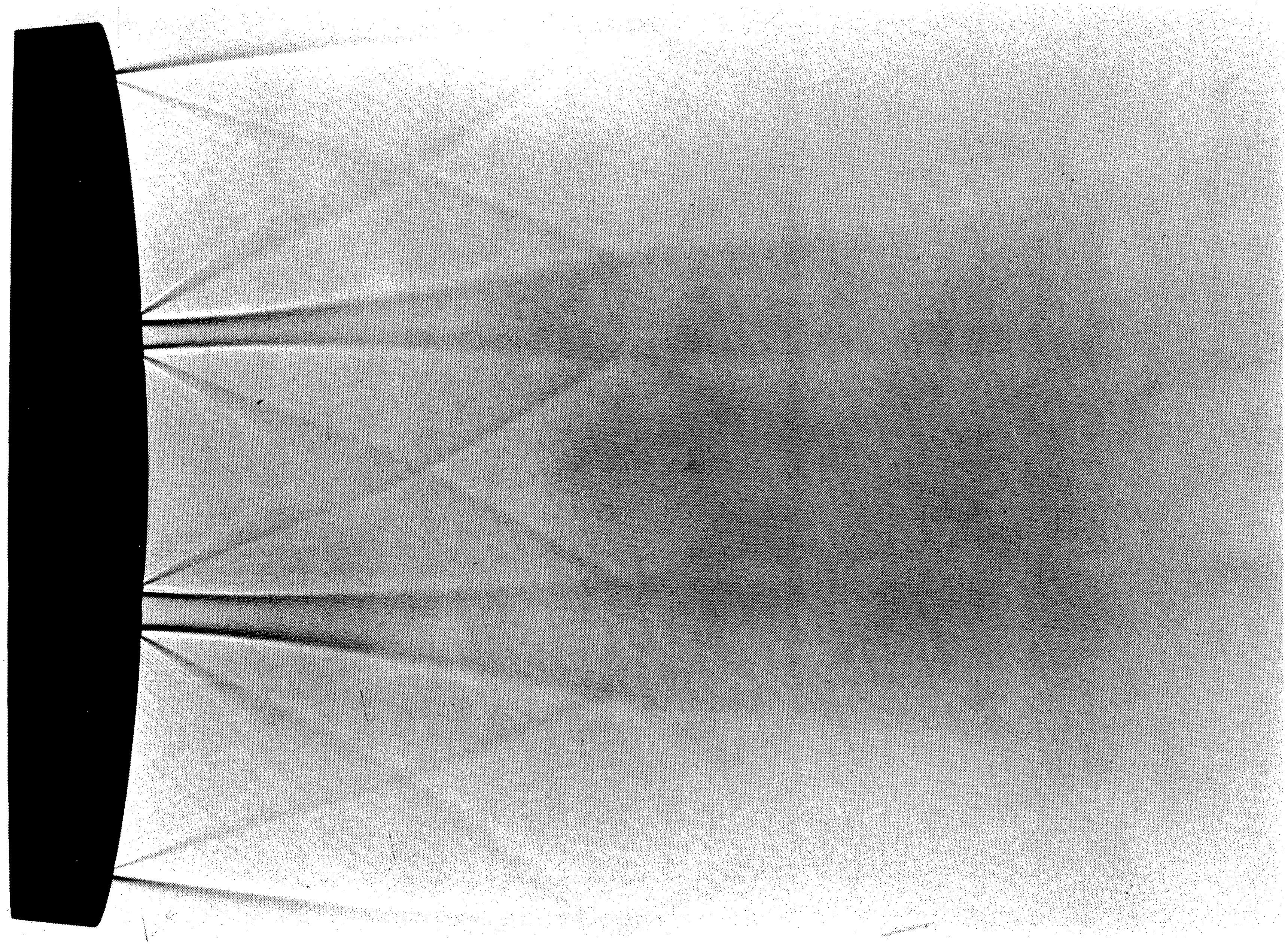


Figure B-1. Shadowgraph of the Flow from a 7° "Three Hole" Nozzle at a Flow Rate of 16, 500 CFM.

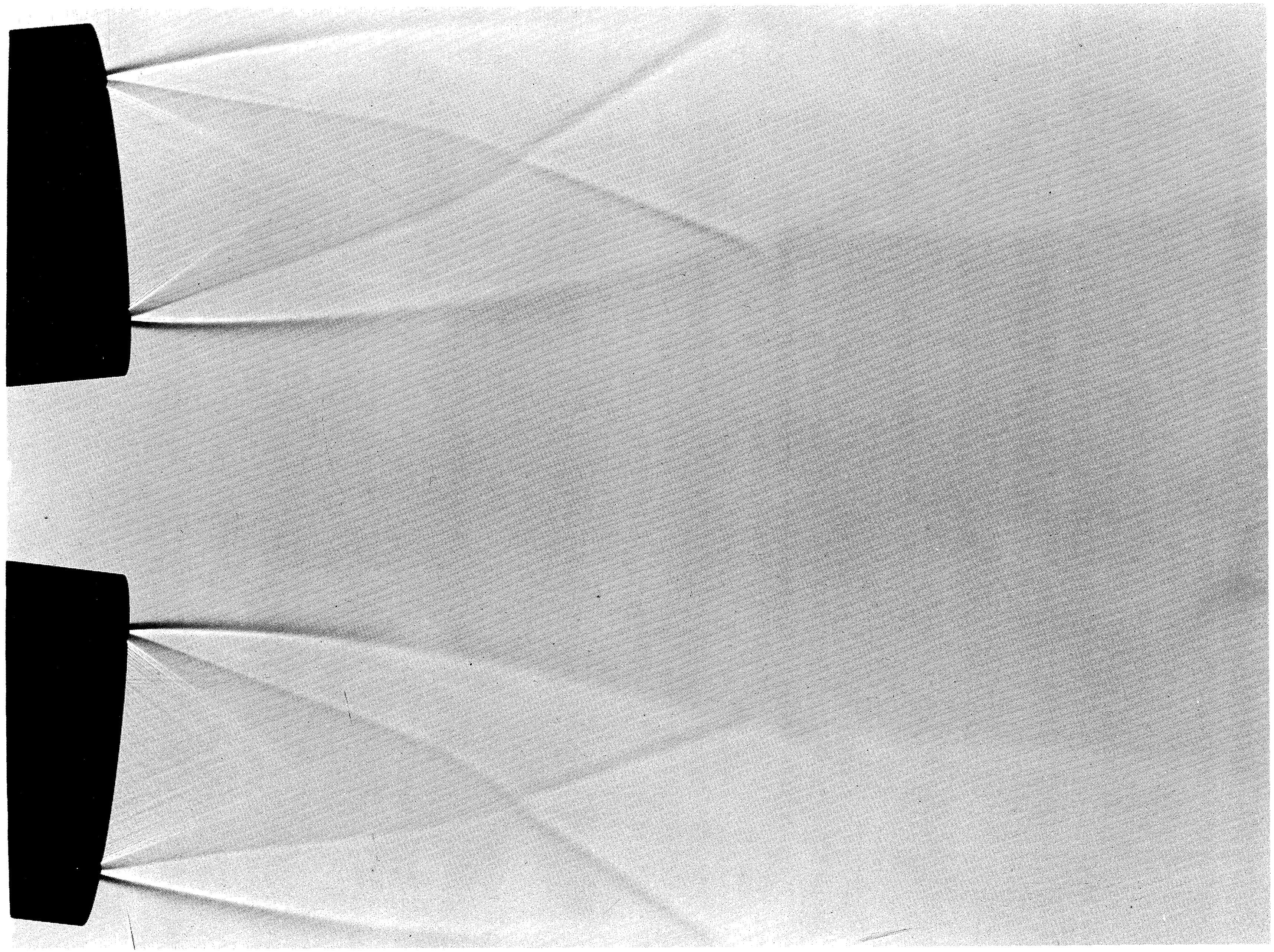


Figure B-2. Shadowgraph of the Flow from Two Openings of a 7^{o} "Three Hole" Nozzle at 108 psig Nozzle Pressure.