ENGINEERING RESEARCH INSTITUTE
THE UNIVERSITY OF MICHIGAN
ANN ARBOR

Final Report

A DESIGN STUDY OF SUPERSONIC NOZZLES FOR THE OXYGEN CONVERSION PROCESS

D. R. Glass
P. O. Hays

Project 2638

McLOUTH STEEL CORPORATION
TRENTON, MICHIGAN

June 1957

ABSTRACT

Four nozzles (McLouth Lance tips 1, 1A, 3, and 3A), which were designed for approximately 3500 cfm, have been tested at 5200 cfm. Velocity head measurements were made of the jet at a position 60 in. downstream of the nozzle exit.

A nozzle was designed and tested which required 86 psig to produce a flow rate of 5200 cfm. The effect of changing the nozzle's divergence angle on the velocity pattern was also tested.

OBJECTIVE

The primary objective of this project was to establish the optimum design for a 5200-cfm oxygen nozzle for use in the oxygen conversion (of steel) process. Related problems in oxygen flow systems were also to be considered.

INTRODUCTION

The oxygen conversion process, as operated by the McLouth Steel Corporation, requires a jet of high velocity oxygen directed onto the surface of molten iron. The performance of this process is dependent not only on the constituents and conditions of the molten iron, but also on the character of the gaseous jet impinging on the liquid surface. The character of this jet will depend mainly on the position of the oxygen nozzle relative to the metal surface, the driving pressure of the oxygen, and the nozzle configuration. This report is concerned chiefly with those variables which determine the jet characteristics.

APPARATUS AND EQUIPMENT

The compressed air for these tests was supplied by four 80-cu-ft tanks capable of storing air at pressures up to 2500 psi. An air compressor, driven by a 250-hp electric motor, was used to charge the tanks. A full charge could be obtained in less than four hours. Suitable shut-off valves and regulators were used to control the air flow conditions.

The driving pressure was indicated by a 12-in., laboratory-calibrated pressure gauge which was visible to the control-valve operator.

A recording oscillograph was used to record the test data. The total head tube was connected directly to a pressure-sensitive device, which by a suitable electrical system enabled the oscillograph to indicate and record the pressure. The response characteristics of this system will be discussed later.

Driving pressure and temperature were also recorded by the oscillograph. The temperature was not evaluated carefully since for any one series of tests it was nearly constant. The driving-pressure record served only as a check on the operator to make sure the driving pressure used was correct and steady.

The total head tube was mounted on a traverse system which traveled roughly one inch per second back and forth across the jet in a horizontal plane at right angles to the jet. The direction of travel of the total head tube was controlled remotely.

Two inches above and below the main total head tube were two auxiliary total head tubes. These two auxiliary tubes were connected (one to each side) to a U-tube, mercury-filled manometer. In this way the correct vertical position of the main total head tube could be established with reasonable accuracy.

TEST PROCEDURES

The traversing total head assembly was first set in a position which appeared proper according to visual inspection. The air was turned on and brought up to correct driving pressure, the recording equipment turned on, and the traversing mechanism started. During the traversing period, the U-tube manometer was observed and the maximum displacement of the mercury column recorded. If one leg of the tube indicated a pressure consistently higher than the other leg, then the probe assembly was not in the proper vertical position. After suitable adjustment, this whole procedure was repeated until the U-tube-manometer readings indicated that the probe assembly, and hence the main total head tube, was essentially in the correct vertical position.

The only test data used were those obtained from those runs wherein the total head tube was considered to be within approximately 1/8 in. of the correct position. The "correct position" is considered to have been reached when the total head tube traversed the jet along a local diameter of the jet. The effective jet diameter at the 60-in. position where all data were taken, varied from about 13 to 16 in. Obviously, a chord cutting across the air stream only 1/8 in. from the true center would have essentially the same length as the diameter for this size circle. It is apparent, however, that the velocity distribution indicated near the jet center will be more sensitive to positioning, but with the fluctuations involved an accuracy of ± 1/8 in. appears relatively good.

After the correct vertical position was established for the nozzle being tested, the total head was recorded with the probe traversing the jet first one way and then the other At least two (in most cases four) complete traverses were made for each nozzle configuration.

RESULTS AND DISCUSSION

1. APPLICABILITY OF RESULTS OBTAINED USING AIR TO THE DESIGN OF NOZZLES FOR USE WITH OXYGEN

A previous report for the McLouth Steel Corporation (The University of Michigan Engineering Research Institute Report 2409-1-F) has already dealt with this subject. The flow equation for both air and oxygen are also derived in the report. Briefly:

A. Ratio of Specific Heats

In a supersonic nozzle with a given ratio of exit area to throat area, the exit pressure and exit Mach number are fixed by the ratio of specific heats of the gas. (This assumes the approximately correct driving pressure for the particular nozzle being tested, and does not allow for friction losses within the nozzle.)

The ratio of specific heat (C_p/C_v) for both air and oxygen is almost exactly 1.4 at temperatures near standard.

This means that a supersonic nozzle designed for a particular oxygen driving pressure will have the same exit pressure and exit Mach number when air is supplied to the nozzle (at the design pressure) as it would have with oxygen supplied at the design pressure. Also, any shock formation at the nozzle exit should be very similar for the two gases.

B. Molecular Weights

The mass-flow-rate equations (derived in The University of Michigan Engineering Research Institute Report 2409-1-F) for air and oxygen are:

$$W_{air} = 0.5325\, P_d\, A^*/(T_d)^{1/2} \tag{1}$$

$$W_{O_2} = 0.5595\, P_d\, A^*/(T_d)^{1/2} \tag{2}$$

where

W = flow rate, lb/sec
P_d = driving pressure, psia
A^* = area of nozzle throat, sq in.
T_d = temperature of gas supplied, °Rankine.

The difference in these two constants is due to the difference in the molecular weights for air and oxygen, 29 and 32, respectively.

The above equations show that for air and oxygen supplied to a supersonic nozzle at the same pressure and temperature, the air flow rate will be roughly 6 percent less than the oxygen flow rate. This difference would reduce the total momentum of the jet, but should have very little effect on the relative velocity distribution patterns.

C. Density of the Gas Within the Air and Oxygen Jets

The density of the gas within the air jet existing during the tests reported herein is very near to the density within the oxygen jet created in the conversion process. However, the parameter, which is of more interest, is the ratio of the density of the gas within the jet to the density of the ambient or surrounding fluid. In the case of these tests, this ratio was reasonably close to unity. In the oxygen conversion process, the ratio of ambient temperature to jet-stream temperature probably exceeds 2:1. The density ratio will then be in the order of 1:2.

Under these extreme conditions of large temperature and density differences between the jet stream and its surroundings, the mixing and entrainment process along the jet boundaries could conceivably be quite different from those encountered in these tests.

Reference 2 reports studies and tests made regarding hot gas streams mixing with the relatively cold atmospheric air surrounding the jet. The conclusion reached in that report was that a high temperature jet (and therefore low density jet, since pressure was essentially constant) spreads more rapidly than does a jet which is at approximately the same density as its surroundings. The conditions tested in that study were not identical with those we are considering here, but it seems reasonable to extrapolate their conclusion to our problem. Thus, a cold (more dense) jet exhausting into a hot (less dense) medium should spread less rapidly than if the densities of the jet and surroundings were the same.

Conclusion.—The results of this study should be applicable to the oxygen jets in the converter as regards the relative shape of velocity distribution curves. The absolute values for oxygen-jet diameters should be somewhat less than the air-jet diameters measured under tests conditions. (This difference is probably only a few percent.)

2. NOZZLE DIMENSIONS AND JET MOMENTUM

The oxygen flow rate through a lance tip nozzle, as indicated by Eq. (2), is determined by the nozzle throat area, the nozzle driving pressure (P_d), and the nozzle driving temperature (T_d). P_d and T_d are defined as conditions at the nozzle inlet.

Figure 1 is based on Eq. (2) and an assumed oxygen flow rate of 1000 cfm. The correct throat and exit area are plotted as well as the jet momentum. These plots can be corrected to a lance tip capable of handling 5200 cfm merely by multiplying the vertical scales by 5.2.

A driving pressure of 175 psig is assumed to be the maximum available. Thus, one other curve is presented in Fig. 1 which shows the jet-stream momentum as a percent of the jet stream momentum possible at 175 psig. This curve shows that a drop in driving pressure from 175 to 85 psig results in total momentum decrease of only 10 percent. Another 10-percent drop in momentum occurs if the driving pressure is dropped from 85 to 45 psig. Since minimum driving pressure is desirable from the standpoint of oxygen compressor equipment, it seems reasonable as a compromise, to try for a driving pressure in the range of 85 to 100 psig.

The total jet momentum, however, is only about half the story in regard to the penetration capabilities of a jet stream. The effective jet diameter must also be considered. The penetration appears to be determined by the ratio, total momentum over effective jet area (as discussed in Ref. 3). The remainder of this report will be concerned with nozzle-design considerations leading to maximum penetration capabilities for a given position of the nozzle and at minimum driving pressure.

3. POSITION OF LANCE-TIP NOZZLE RELATIVE TO METAL SURFACE

Reference 1 includes graphs which show typical jet diameters as a function of distance from the nozzle. The same pattern of jet spreading was indicated for all nozzles thus far tested. Therefore, it was considered redundant and unncessarily expensive to evaluate the performance of different nozzles by measuring the velocity head distribution at more than one plane. The plane chosen for all tests reported here was 60 in. downstream of the nozzle exit.

It is obvious, again from Ref. 1, that one method of increasing penetration is to move the lance-tip nozzle closer to the metal surface. The problems and consideration relative to the positioning of the nozzle, however, are considered outside the scope of this study. The operation of the conversion unit with any given nozzle will determine the best position.

Two points have arisen which may be of interest regarding lance-tip-nozzle position:

a. Very intense velocity fluctuations are present in the jet. (Data regarding this are presented later in this report.) One advantage in keeping the nozzle a considerable distance from the metal could result from the damping effect of time and distance on these fluctuations.

b. The entrainment of gases surrounding the oxygen stream will certainly increase with distance. Thus, the average oxygen concentration in the jet at the metal is reduced with distance. This tends to make the chemical reaction at the gas-metal interface less violent. Also, the recirculation of some of the gases above the metal surface probably increases the efficiency of the systems as regards oxygen usage.

4. RESULTS OF INITIAL SERIES OF TESTS OF NOZZLES 1, 1A, 3, AND 3A

These four nozzles had dimensions which made them appear practical for use at an oxygen flow rate of 5200 cfm. Nozzles 1 and 1A require a driving pressure of 129 psig to flow 5200 cfm of oxygen, assuming the oxygen to be stored at 60°F. Nozzles 3 and 3A require a driving pressure of 154 psig.

After conducting these initial tests, it was discovered that the location of the pressure tap produced an error of about 5 lb for 3 and 3A, and an error of about 6 lb for 1 and 1A. The driving pressure used for 3 and 3A was therefore actually 159 psig (± 2 lb—the indicating gauge was accurate within less than 1 lb). The driving pressure used for 1 and 1A was actually 135 psig.

Since these errors are relatively small percentagewise, the resultant data seem to have meaning for our purposes. Figure 2 is a plot of oscillograph trace deflection vs jet radius for nozzle 1. (Note: trace deflection is directly proportional to velocity head. See individual graphs for multiplying factor.) The data points taken from the oscillograph records are included to show the type of data scatter involved. This graph is typical of curves plotted for other nozzles. Figure 3 is a composite plot of nozzles 1, 1A, 3, and 3A at the above listed conditions. The conclusion which would normally be drawn from Fig. 3 is that these four nozzles perform so nearly the same as to leave little basis for choosing one over the other, as regards penetration. From the standpoint of driving pressure, nozzles 1 and 1A would be preferable since they require about 129-psig driving pressure versus 154 for 3 and 3A. Subsequent data, however, leave some doubt about this conclusion.

5. RESULTS OF THE SECOND SET OF TESTS FOR NOZZLES 1, 1A, AND 3A

A plot of oscillograph deflection (again directly proportional to velocity head) versus jet radius is shown in Fig. 4 for these nozzles. The driving pressure for nozzles 1 and 1A was indicated to be 128 psig (± 1 lb); the driving pressure for 3A was 154 psig (± 1 lb). The penetration of nozzle 1A is shown to be considerably below that of nozzles 1 and 3A. This development was <u>not</u> expected. No explanation for this situation is readily available. The first thought is that some error was made in test-procedure-data development. A careful check of the recorded data did not indicate any error. Each of the curves presented is the average of at least two or three separate (though successive) tests. If test procedures were at fault, it seems strange that it would occur only on the runs with 1A and not with the other two nozzles.

As possible explanation is that the shock formation at the exit of 1A is such that, for a driving pressure near 128 psig, a change of a few pounds could result in fairly extensive changes in jet penetration. Presently, however, this does not appear a wholly adequate explanation.

Most experience with nozzles of this type has shown that a decrease in maximum velocity head (i.e., the velocity head at the jet center) is accompanied by an increase in jet diameter. This is true for nozzle 1A as shown by Fig. 4. The jet diameter of 1A is over 14 in.; the jet diameters of 1 and 3A are less than 13 in.

<u>Conclusions</u>.—Either 1) the driving pressure used in obtaining the test data for 1A as shown in Fig. 4 is less than recording equipment indicated, or 2) the penetration of 1A is appreciably less than that of No. 1 at driving pressures of 128 psig.

Time has not permitted retesting these nozzles at this point. Extensive tests near this range of driving pressures appear to be the only way to clarify the situation.

6. RESULTS OF A SERIES OF TESTS OF A NOZZLE DESIGNED FOR 86-PSIG DRIVING PRESSURE

Because of the interest in limiting driving pressure, a nozzle was designed under the following assumptions:

a. The pressure feeding the entire lance system, i.e., after regulators, etc., would be essentially the same as is now used for nozzle 3A at 3500 cfm.

b. The pipe sizes leading to the lance tips would not be changed.

The line loss for 3A at 3500 cfm was estimated to be about 8 psig (from Ref. 1). At 5200 cfm, the same line system should produce a pressure drop of 17 psig. This assumes the same density oxygen and the line loss proportional to the velocity squared.

The pressure on the lance assembly for nozzle 3A at 3500 cfm is approximately 106 psig since the driving pressure at the nozzle should be 98 psig and the friction loss in the system is 8 lb. Now if this same pressure is applied to the same plumbing system flowing 5200 cfm, the losses in the lines will be approximately 17 lb. Using a conservative pressure drop of 20 psi, the driving pressure available at the nozzle is only 86 psig. It should be noted that the pressure loss through the flexible hose connecting the lance to the oxygen supply system was <u>not</u> included in this study.

The lance nozzles previously used by the McLouth Steel Corporation have shown considerable variance in divergence angle. Consequently, the 86-psig nozzle was planned so that the effect of divergence angle could be evaluated. This was accomplished by machining the nozzle initially so that the divergence half-angle (i.e., the angle between the straight wall of the divergent section of the nozzle and the nozzle centerline) was 7-1/2°. The throat diameter was 1.937 in. and the exit diameter was 2.452 in. (calculated from Fig. 1, using 86-psig driving pressure). After testing at 7-1/2°, the divergence half-angle was increased in stages to 15, 22-1/2, 30, and 90°, At all divergence angles, except 90°, the exit diameter was the same, i.e., 2.452 in. At 90° the nozzle was simply convergent only; the exit and throat area were identical. The resulting velocity head profiles are plotted in Fig. 5.

It is fairly clear from these curves that at 86-psig driving pressure:

a. Divergence half-angles in excess of 22-1/2° are undesirable.

b. Some divergence is desirable if reasonable angles are employed.

c. The divergence half-angle should be in excess of 7-1/2°; 15° is better than 7-1/2°. This should not, however, be interpreted as saying that 15° is the best angle, since the next angle setting (i.e., 22-1/2°) showed such a severe drop in penetration. The optimum angle apparently lies between 7-1/2° and 22-1/2°. It would appear, from previous experience with these nozzles, that a conservative half-angle would be between 7-1/2° and 15°.

d. Higher driving pressures should be expected to alter these results somewhat; quantitatively, not qualitatively.

One other test was conducted with this nozzle while it has a divergence half-angle of 15°. The end of the nozzle was machined off to give an exit diameter of 2.298 in. Thus, the exit area was equal to 88 percent of the "correct" exit area. The data from this test were not plotted since they coincided almost exactly with the curve shown for the 15° nozzle having the "correct" exit area. Thus, at these conditions, a reduction in exit area of <u>12 percent</u> below the theoretically calculated correct exit had no detrimental effect upon the penetration capabilities of the jet.

7. FLUCTUATIONS IN LOCAL JET VELOCITY

The velocity distribution across the jet has been measured in previous tests by U-tube manometers. The manometers were connected by long tubes to the total head probes mounted in the air stream. The effect of the long connecting tubes and the inertia of the liquid in the manometers (usually mercury) was to damp out any pressure pulses existing at the probe.

The velocity head measurements made in these tests were measured by a pressure transducer (pickup), which is basically a diaphragm supported in such a way that two strain gauges undergo elongation as the pressure increases, while two other strain gauges contract. This diaphragm support system has a natural frequency of 5000 cycles per second. This particular pickup should be reasonably reliable up to 2000 or 3000 cps.

The resultant output of this pickup is fed into a galvanometer in the recording oscillograph. All the routine data for these tests were recorded by means of a galvanometer having a natural frequency of 50. By use of proper damping resistors in the circuit, this galvanometer can be used with good dependability up to 30 cps. Thus, the system is good for only 30 cps. Above the frequency, the response falls off so that at, say, 80 cps, the galvanometer response is not nearly proportional to the input signal. Other galvanometers capable of higher frequency were also used to evaluate the extent of variations in total head at any local point within the jet. The conclusions reached after studying the resultant records are only approximate, but are listed below since they do seem to give additional information regarding the character of the air or oxygen jet. All conclusions refer to the position 60 in. downstream from the nozzle and in particular for nozzle 3A. Other nozzles would almost certainly produce somewhat similar conditions.

a. At the jet centerline, deviations from average pressure of over 30 percent occurred about 30 times per second and over 25 percent about 70 times per second.

b. Two inches off the jet centerline, 3 to 5 times per second the velocity head deviated from the average velocity head by over 30 percent. Between roughly 10 and 20 times per second, the velocity head deviated from the average by 25 percent. Smaller deviations occur at increasingly higher frequencies.

All this presents a rather indefinite and confusing picture regarding fluctuations within the jet, but a tremendous amount of testing would be required to define accurately the magnitude of the local velocity fluctuations. It seems that any considerations of the oxygen jet produced for the conversion process should be made with the knowledge that velocity head fluctuations of over ± 30 percent occur several times per second. In other words, the impact pressure near the jet centerline, 60 in. from the nozzle exit, can change by ± 8 in. of mercury several times a second. This constitutes a velocity change of roughly 600 ft per second.

It seems probable that these velocity fluctuations play a tremendously important role in increasing the reaction surface, thereby increasing the reaction rate.

SUMMARY AND CONCLUSIONS

Lance tips 1, 1A, 3, and 3A have been tested with air at driving pressures approximately equal to the oxygen driving pressure required to produce 5200 cfm. Some discrepancy was present between different sets of data. With this reservation, the following conclusions have been reached.

1. Lance tips 3 and 3A produce apparently good penetration. A driving pressure of 154 psig is required to produce 5200 cfm of oxygen with these tips.

2. Lance tip 1 produces essentially the same penetration as 3 and 3A. A driving pressure of 128 psig is required to produce 5200 cfm with this tip.

3. Lance tip 1A should produce the same penetration as No. 1, again at 128 psig. Because of the above reservation, this conclusion should be held in abeyance pending repeated tests.

4. As a result of testing a special nozzle designed for 86-psig driving pressure, the following conclusions have been reached (5200 cfm of oxygen would flow through this nozzle at 86-psig driving pressure).

a. The penetration of the jet produced by this nozzle is considerably less than that obtained with nozzles 1, 1A, 3, and 3A, when these nozzles are flowing 5200 cfm.

b. A divergence half-angle of 15° produced better penetration than either 7-1/2° or 22-1/2°. A considered guess is that the divergence half-angle should be less than 15°. An angle of 10° should be a good compromise pending further tests.

c. The nozzle exit area for this driving pressure can be less than theoretical calculations would predict by at least 12 percent with no ill effects. This same general conclusion was reached in Ref. 1 for other nozzles at higher driving pressures.

d. This nozzle with a divergence half-angle of 22-1/2° (5200 cfm and 86 psig) produces a velocity head distribution pattern very similar to that which would be obtained with nozzle 3A at 3500 cfm (approximately 100-psig driving pressure).

Thus, in terms of penetration capabilities, this special nozzle (again 5200 cfm and 86 psig), with a reasonably good divergence angle, is superior to 3A at 3500 cfm.

REFERENCES

1. Glass, D. R., and Howard, E. T., "A Study of Supersonic Nozzle Design as Applied to the Oxygen Conversion Process," The University of Michigan Engineering Research Institute Report 2409-1-F, November, 1955.

2. Consin, S., and Uberoi, M. S., "Further Experiments on the Flow and Heat Transfer in a Heated Turbulent Air Jet," National Advisory Committee for Aeronautics Report No. 998, 1950.

3. Glass, D. R., and Hays, P. O., "An Evaluation of the Average Impact Pressure Produced by a Supersonic Nozzle Operating at Conditions Specified for the Oxygen Conversion Process," The University of Michigan Engineering Research Institute Report 2625-1-F, February, 1957.

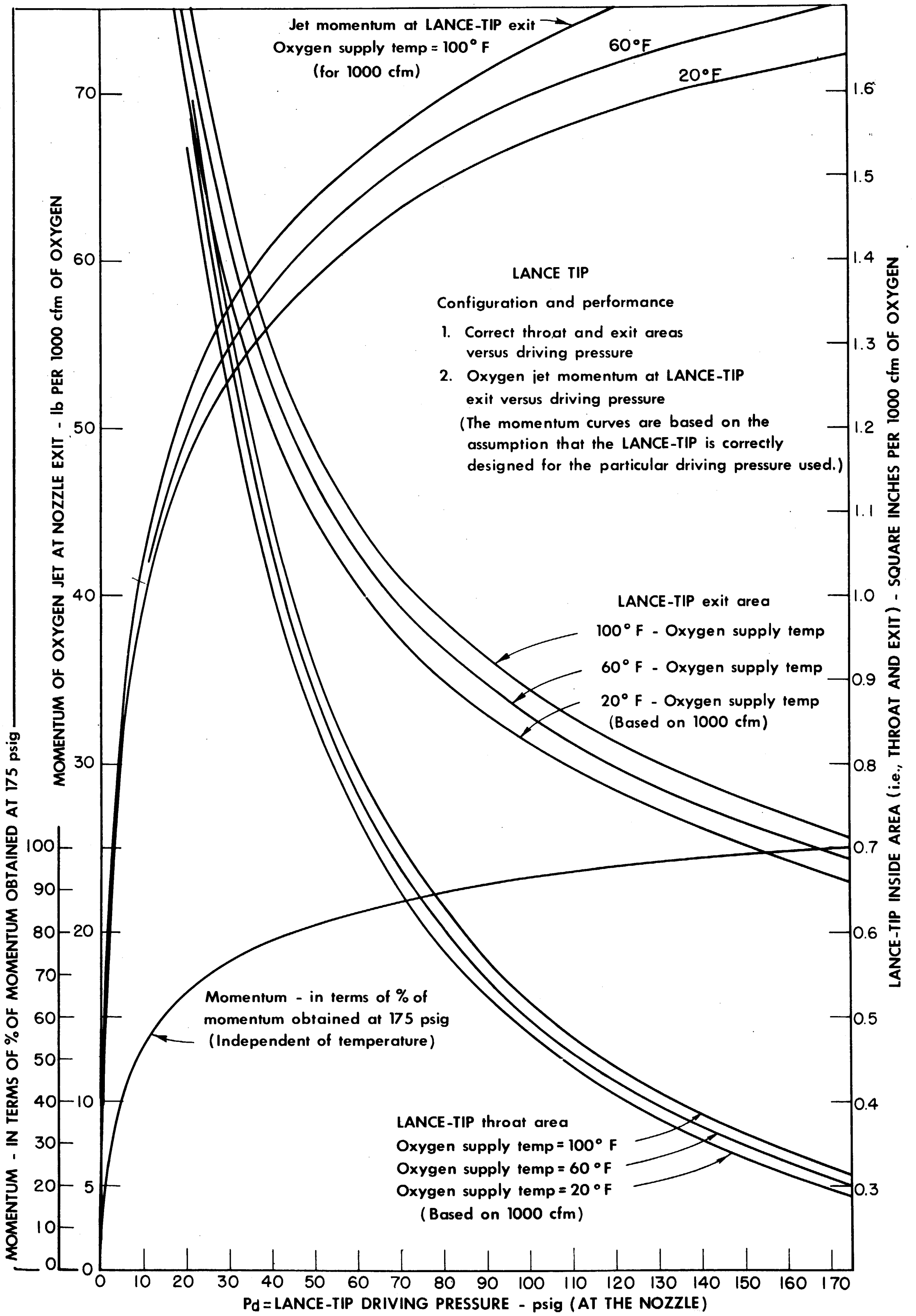
Jet momentum at LANCE-TIP exit
Oxygen supply temp = 100° F
(for 1000 cfm)
60°F
20°F
LANCE TIP
Configuration and performance
1. Correct throat and exit areas versus driving pressure
2. Oxygen jet momentum at LANCE-TIP exit versus driving pressure
(The momentum curves are based on the assumption that the LANCE-TIP is correctly designed for the particular driving pressure used.)
LANCE-TIP exit area
100° F - Oxygen supply temp
60° F - Oxygen supply temp
20° F - Oxygen supply temp
(Based on 1000 cfm)
Momentum - in terms of % of momentum obtained at 175 psig
(Independent of temperature)
LANCE-TIP throat area
Oxygen supply temp = 100° F
Oxygen supply temp = 60 °F
Oxygen supply temp = 20 °F
(Based on 1000 cfm)
MOMENTUM OF OXYGEN JET AT NOZZLE EXIT - lb PER 1000 cfm OF OXYGEN
0
5
10
20
30
40
50
60
70
MOMENTUM - IN TERMS OF % OF MOMENTUM OBTAINED AT 175 psig
0
10
20
30
40
50
60
70
80
90
100
LANCE-TIP INSIDE AREA (i.e., THROAT AND EXIT) - SQUARE INCHES PER 1000 cfm OF OXYGEN
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
Pd = LANCE-TIP DRIVING PRESSURE - psig (AT THE NOZZLE)

Fig. 1

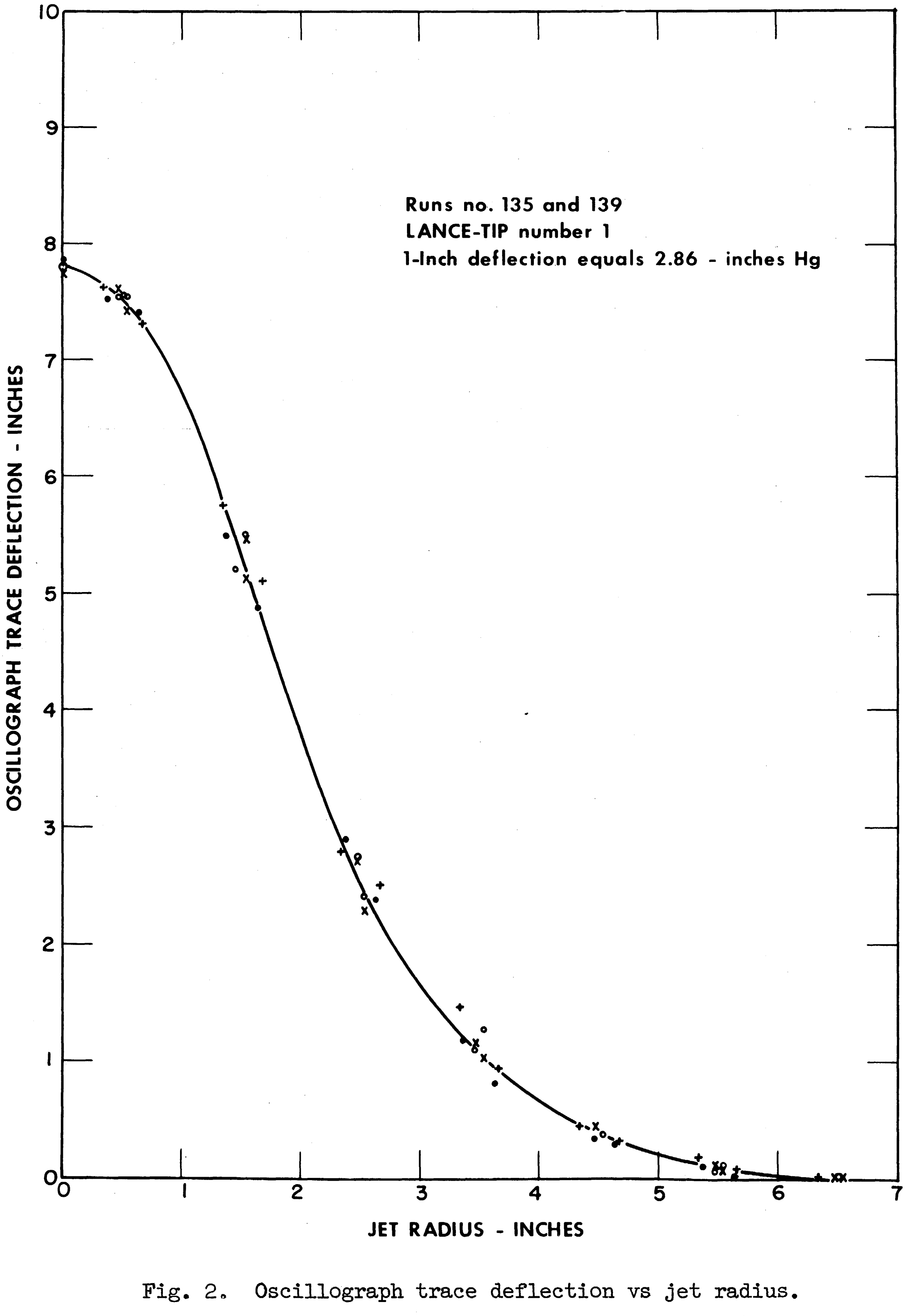

Fig. 2. Oscillograph trace deflection vs jet radius.
(Velocity profiles at flow rate of 5200 cfm)

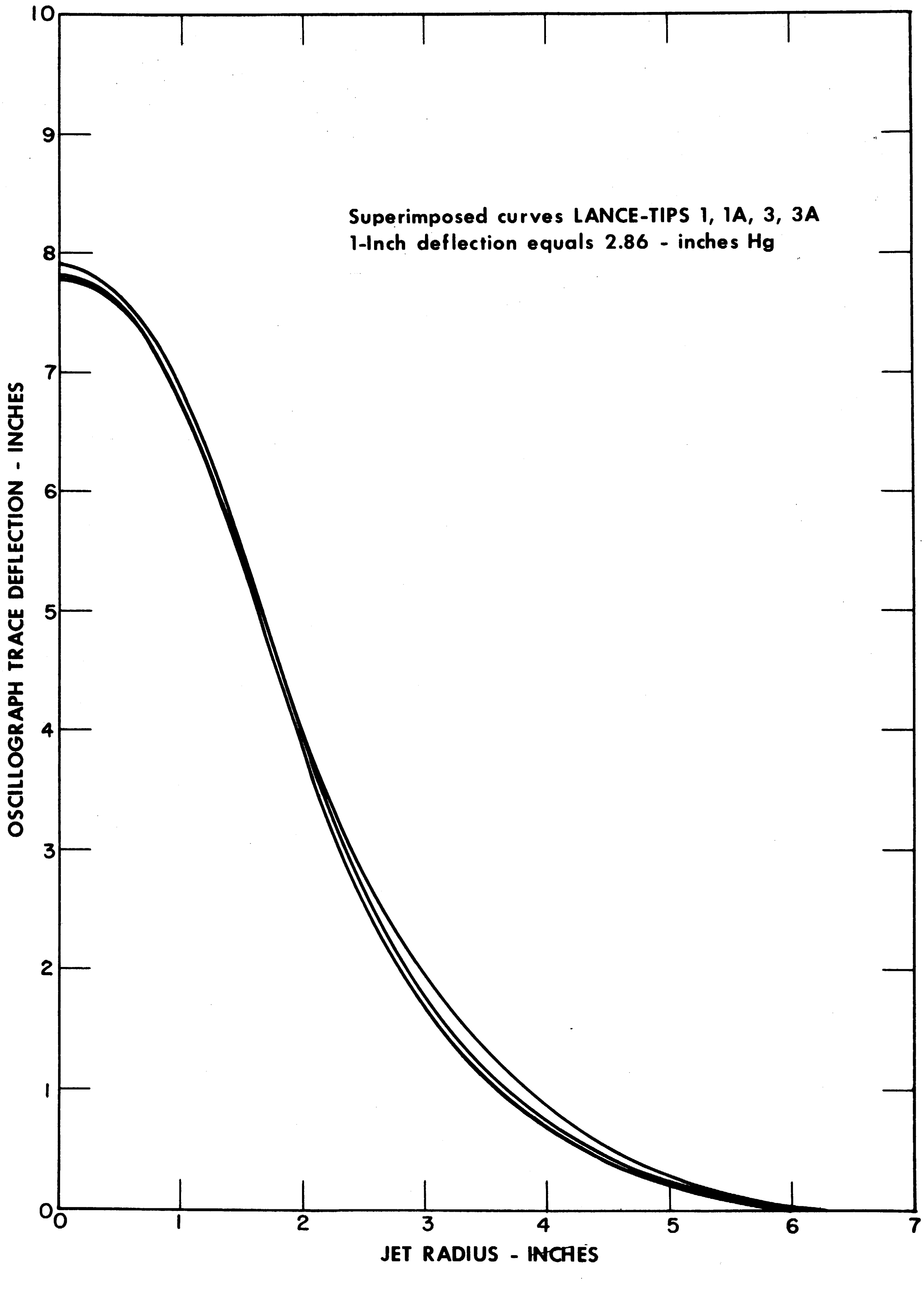

Fig. 3. Oscillograph trace deflection vs jet radius.

(Velocity profiles at flow rate of 5200 cfm)

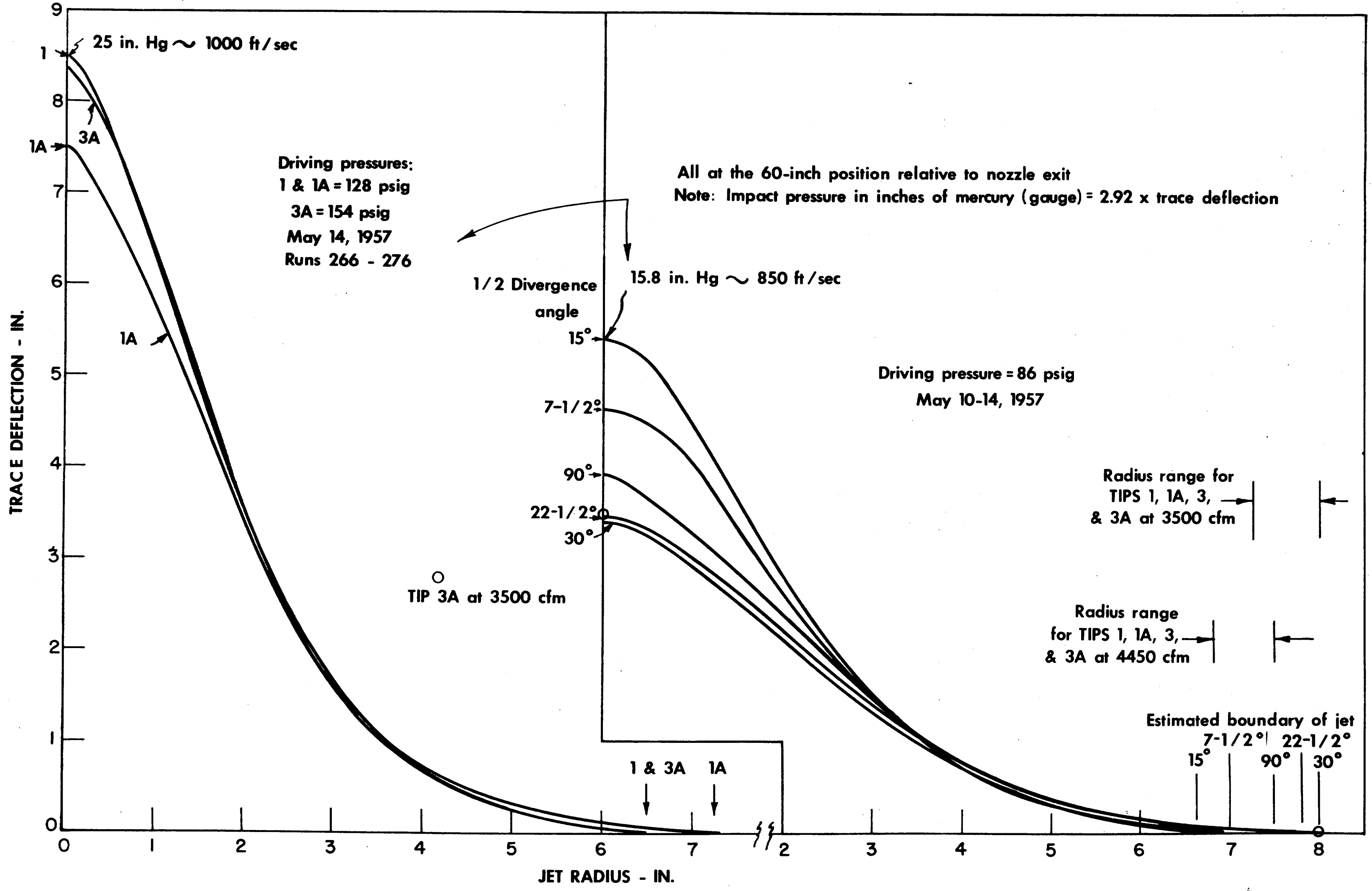

Fig. 4. Oscillograph trace deflection vs jet radius. (Velocity profiles at flow rate of 5200 cfm)

Fig. 5. Oscillograph tract deflection vs jet radius. (Velocity profiles at flow rate of 5200 cfm)