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FINAL REPORT

A STUDY OF SUPERSONIC NOZZLE DESIGN AS APPLIED TO THE OXYGEN CONVERSION PROCESS

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OBJECTIVE

The purpose of this study was to establish the relationship between nozzle (i.e. lance tip) design and the velocity distribution across the issuing gas stream at one or more positions downstream of the nozzle. The jet boundaries and characteristics were to be further established by optical techniques.

It was anticipated that recommendations, based upon this work, would be made regarding optimum lance tip design for various operating conditions.

SUMMARY

Seven lance tips, provided by the McLouth Steel Corporation, were tested at various air flow rates. The velocity head distribution, at one or more positions downstream of the lance tip, was recorded. Shadowgraph pictures were taken of the air jet just downstream of the lance tip. Several conclusions have been reached regarding the optimum operating range of lance tips if maximum jet penetration is desired.

The pressure loss through the entire lance assembly was measured and found to be of minor importance.

Variations between specified and actual lance tip dimensions were checked and found to be well within allowable limits as regards lance tip performance.

INTRODUCTION

Supersonic nozzles are used by the McLouth Steel Corporation in their oxygen conversion process to direct a stream of oxygen onto the surface of molten iron. The design of these nozzles, or lance tips, has considerable effect upon the pattern of oxygen penetration and, hence, upon the overall operation of the converter. For this reason, it was desireable that an understanding of the effect of lance tip design upon velocity distribution within the jet be obtained.

This investigation was carried out for the McLouth Steel Corporation by personnel of the Engineering Research Institute of the University of Michigan, attached to the University's Aircraft Propulsion Laboratory.

APPARATUS AND EQUIPMENT

The compressed air for these tests was supplied by two, 80 cu. ft. tanks capable of storing air at pressures up to 2500 psi. Two engine driven compressors were used which could charge the tanks in about four hours.

Suitable shut off valves and pressure regulators were used to control the air flow to the lance undergoing tests. Pressure and temperature gauges were installed just upstream of the lance tip.

A fixed position velocity head rake was used for the first series of runs, lance tips 1 through 5, located 72 inches downstream of the tip exit. This rake was replaced by an improved and more flexible assembly when it became necessary to measure velocity heads at various distances from the lance tip. Figure 1 is a photograph of the improved rake assembly. Figure 2 is a photograph of the rake assembly showing its position relative to a lance tip in test position. The individual total head tubes (1/8 in. O. D.) are mounted on 2 inch centers except near the jet axis where they are mounted on 1 inch centers. The vertical rake was needed to determine the corrections necessary in the case of slight error in the vertical positioning of the horizontal rake.

In both rake assemblies each total head tube was connected to a "U" tube manometer. All manometers were located on a panel of translucent plexiglass, lighted from behind. In this way the entire bank of manometers could be photographed simultaneously once the correct conditions were established in the lance tips.

A General Electric Photoglash unit was used to provide essentially parallel rays of light for the shadowgraph pictures. The duration of each light flash was less than 5 microseconds. The light source was located approximately fifty feet to one side of the jet while an eight by ten film holder was supported about six inches from the jet on the opposite side. With this technique major density discontinuities, and hence pressure and temperature discontinuities, within the jet were indicated on the film as adjacent dark and light lines.

TEST PROCEDURES

1. Measurement of Total Head Distribution

The mass flow rate of gas (in this case air) through any supersonic nozzle, such as a lance tip, is dependent upon the throat or minimum area, the driving pressure, and the air temperature. Thus, for any particular lance tip and desired flow rate the driving pressure varies only with the temperature of the air supply--actually the square root of the temperature. (See appendix equation 5).

Since a temperature difference of 20°F would result in only a 1 1/2% change in driving pressure required for a given flow rate, it was not practical to alter the driving pressure for slight temperature changes. A preliminary run before each series of tests was sufficient to indicate approximately the air temperature to be expected during the series. The driving pressure could then be calculated for each flow rate and lance tip combination to be tested at that time. Throughout the entire program the indicated air temperature ranged between 40 and 70°F.

Before each series of tests with any lance tip, the total head rake was adjusted, if necessary, so that the rake center was as close as possible to the jet centerline. The rake was located so that the upstream ends of the total head tube were at some specified distance from the lance tip - such as 60 or 72 inches.

Velocity head data at each desired flow rate was obtained by turning on the air and adjusting the pressure regulator until the lance tip driving pressure had reached the value reguired to produce that flow rate. After allowing sufficient time at constant driving pressure for the manometer readings to stabilize, a photograph was taken of the manometer board. These photographs were enlarged, the manometer readings were transcribed, and then plotted against the relative positions of the total head taken within the jet.

THE ONLY EFFECT OF SMALL ERRORS IN THE HORIZONTAL POSITIONING IS TO SHIFT THE PEAK VELOCITY TO ONE SIDE OR THE OTHER OF THE RAKE CENTERLINE WITHOUT CHANGING THE SHAPE OR VALUE OF THE VELOCITY PROFILE. HOWEVER, A SMALL ERROR IN VERTICAL POSITIONING CAUSES THE VELOCITY HEAD MEASUREMENTS TO BE TAKEN ALONG A CHORD OF THE AIR STREAM WHICH IS NOT A DIAMETER. THE TOTAL PRESSURE READINGS OBTAINED FROM THE VERTICAL RAKE SERVE TO DETECT THIS ERROR AND INDICATE THE NECESSARY CORRECTION FOR THE VELOCITY PROFILE CURVES. FIGURE 3 IS A TYPICAL PLOT OF VELOCITY HEAD DATA OBTAINED WITH BOTH HORIZONTAL AND VERTICAL RAKES. THIS FIGURE INDICATES THAT AT 3900 CFM, THE PEAK VELOCITY HEAD SHOULD BE INCREASED FROM 5.5 TO 6.6 AND THE ENTIRE CURVE INCREASED PROPORTIONALLY.

2. SHADOWGRAPH PICTURES

THESE PICTURES WERE TAKEN AT NIGHT SINCE IT WAS NOT FEASIBLE TO ELIMINATE EXTRANEOUS LIGHT BY BUILDING A LIGHT TIGHT SYSTEM. THE FILM WAS MOUNTED IN POSITION AND EXPOSED FOR SEVERAL SECONDS WHILE THE AIRFLOW WAS BROUGHT UP TO THE DESIRED VALUE AND THE PHOTOGLASH LIGHT WAS TRIGGERED.

IN ONE TEST A FILM WAS LEFT IN PLACE WHILE TWO LIGHT FLASHES WERE TRIGGERED APPROXIMATELY THREE SECONDS APART. THE AIRFLOW WAS HELD CONSTANT. THIS PICTURE WAS ESSENTIALLY IDENTICAL WITH ANOTHER PICTURE OBTAINED AT THE SAME FLOW CONDITIONS BUT WITH ONLY ONE LIGHT FLASH. THE SHOCK WAVES APPEARED AS SLIGHTLY THICKENED LINES AND THE TURBULENCE WAS LESS DISTINCT ON THE DOUBLE EXPOSURE, BUT THE BASIC SHOCK FORMATIONS WERE CERTAINLY SHOWN TO BE STABLE WITH TIME.

3. PRESSURE LOSS THROUGH THE ENTIRE LANCE

THE ENTIRE LANCE ASSEMBLY WAS INSTALLED WITH TWO TOTAL HEAD TUBES, ONE MOUNTED JUST UPSTREAM OF THE LANCE TIP AND THE OTHER MOUNTED UPSTREAM OF THE ENTIRE ASSEMBLY. THE AIRFLOW WAS REGULATED UNTIL THE PRESSURE OF THE LANCE TIP ATTAINED THE DESIRED VALUE; AT THIS TIME THE PRESSURE UP-STREAM OF THE LANCE ASSEMBLY WAS RECORDED. THE DIFFERENCE BETWEEN THE TWO PRESSURE READINGS IS, BY DEFINITION, THE PRESSURE LOSS THROUGH THE LANCE.

THE TWO PRESSURE GAUGES USED FOR THESE TESTS HAD BEEN CALIBRATED AGAINST A LABORATORY TEST GAUGE. ALL PRESSURE READINGS LISTED HEREIN ARE THE VALUES FOR PRESSURE OBTAINED AFTER NECESSARY GAUGE CORRECTIONS WERE MADE.

RESULTS AND DISCUSSIONS

1. Tolerence in Lance Tip Machining

The critical lance tip measurements are listed below for the several lance tips tested.

Lance Tip No.	Throat Diameter-inches Specified	Throat Diameter-inches Measured	Exit Diameter-inches Specified	Exit Diameter-inches Measured
1	1.625	1.624	1.875	1.873
1A	1.625	1.624	2.112	2.090
2	1.875	1.869	2.8125	2.759
3	1.500	1.495	2.170	2.170
3A	1.500	1.503	2.042	2.035
4	1.375	1.336	1.625	1.628
5	1.625	1.618	2.813	2.737

All values listed are the average of several measurements. Exit diameters are somewhat questionable because of the rounded lips at the tip exit. Because of the uncertainity as to the effective exit area it is improbable that a lance tip of this type can be designed <u>precisely</u> for any particular driving pressure.

The greatest difference between specified and measured exit diameters in the above indicates an exit area difference of about six per cent. If the difference is comparable areas of two supposedly identical lance tips does not exceed six per cent the performance of the two tips should not be significantly different in most practical cases.

None of the measurements or tests conducted thus far have led to any conclusions regarding forces which might produce lance tip oscillations. Additional studies aimed primarily at the problem of instabilities in the gas jet should shed some light on the problems of a swinging lance tip.

2. Pressure Loss Through the Lance Tube

A complete lance assembly was tested to determine pressure losses in the tube. The results of these tests are listed below:

Equiv. O_2 Flow rate-CFM	Measured Upstream Pressure-PSIG	Measured Lance Tip Pressure-PSIG	Measured Pressure Loss-PSIG
2900	76.9	69.5	7.4
3400	91.5	83.7	7.8
3900	105.8	98.0	7.8
4350	121.0	111.5	9.5

Lance tip throat diameter = 1.622 in.
Lance tip exit diameter = 2.150 in.

Although these pressure losses are not entirely negligible they do not appear sufficient to alter any of the basic results and conclusions.

It should be noted that the drop in static pressure through the lance tip is, in the main, not a pressure loss since increased gas velocity is realized by this pressure drop. The pressure drop along the length of the lance, however, is a loss since no useful work, such as the acceleration of the air, is realized. More than 90% of the driving pressure is available for accelerating the gas at all the above flow rates.

3. Shadowgraph Pictures of the Jet

If a supersonic nozzle is properly designed, aerodynamically, the static pressure at the nozzle exit will be essentially equal to the ambient pressure, in this case atmospheric pressure.

If the pressure at the nozzle exit (i.e. lance tip in these studies) is appreciably above atmospheric pressure the jet diameter will increase immediately downstream of the nozzle. Conversely, if the exit static pressure is below atmospheric pressure the diameter of the jet will decrease immediately downstream of the nozzle.

The total head losses through the shock formations downstream of the lance tip would be expected to increase

AS THE DIFFERENCE BETWEEN EXIT STATIC PRESSURE AND ATMOSPHERIC PRESSURE INCREASES.

SHADOWGRAPH PICTURES (FIGURES 4 THROUGH 10) ARE PRESENTED OF THE FLOW ISSUING FROM LANCE TIPS 1, 1A, 2, 3, 3A, 4, AND 5. ALL OF THESE PICTURES WERE TAKEN AT AN AIR MASS FLOW RATE EQUIVALENT TO AN OXYGEN FLOW RATE OF 3900 CFM.

INSPECTION OF ANY SINGLE SHADOWGRAPH DOES NOT YIELD INFORMATION REGARDING THE PENETRATION OF THE JET IN QUESTION. COMPARISON OF THE SHADOWGRAPHS OF TWO OR MORE JETS WHICH HAVE RESULTED FROM THE SAME DRIVING PRESSURE AND MASS FLOW SHOULD INDICATE RELATIVE PENETRATION. THE SHADOWGRAPH PICTURES OF THE FLOW FROM LANCE TIPS 1, 1A, AND 5 (FIGURES 4, 5, AND 10) ARE A GOOD EXAMPLE OF THIS SINCE ALL THREE WERE TAKEN AT ESSENTIALLY THE SAME DRIVING PRESSURE AND MASS FLOW. OF THESE THREE, THE GREATEST LOSS IN PEAK VELOCITY HEAD WOULD BE EXPECTED WITH LANCE TIP NO. 5, SINCE THE FLOW FROM LANCE TIPS 1 AND 1A CONTAIN LESS SEVERE SHOCK WAVES. THE JET FROM LANCE TIP 1A APPEARS SLIGHTLY LESS DISTURBED THAN THAT OF 1, PRIMARILY AS REGARDS THE SECONDARY SHOCK FORMATION.

THE SHADOWGRAPH PICTURES OF THE FLOW FROM LANCE TIPS 3 AND 3A (FIGURES 7 AND 8) INDICATE VERY LITTLE DIFFERENCE ALTHOUGH THE SECONDARY SHOCK FORMATIONS IN THE JETS APPEAR SLIGHTLY LESS SIGNIFICANT FOR LANCE TIP 3A THAN FOR 3. DRIVING PRESSURES AND MASS FLOW RATES ARE THE SAME FOR BOTH PICTURES.

CONSIDERING ALL SEVEN SHADOWGRAPH PICTURES AS A GROUP, THE JETS FROM LANCE TIPS 2 AND 5 STAND OUT AS ONES UNDERGOING THE MOST SEVERE DISTURBANCES. THE FLOW FROM LANCE TIP NO. 4 IS NEXT IN ORDER AS REGARDS SEVERITY OF SHOCK FORMATIONS, AND HENCE MIGHT BE EXPECTED TO RESULT IN POOR PENETRATION. THE HIGHER DRIVING PRESSURE REQUIRED BY LANCE TIP 4 COULD FEASIBLY MORE THAN OFF SET THE SHOCK LOSSES. THE JETS FROM LANCE TIPS 1A AND 3A WHICH ARE OPERATING ESSENTIALLY AT THEIR DESIGN POINTS, ARE THE LEAST DISTURBED.

4. VELOCITY HEAD MEASUREMENTS

LANCE TIPS 1 THROUGH 5 WERE TESTED AT THREE FLOW RATES EACH, WITH THE TOTAL HEAD RAKE MOUNTED 72 INCHES DOWNSTREAM OF THE TIP EXIT. THE RESULTS OF THESE TESTS ARE PLOTTED IN FIGURE 11.

IT IS QUITE OBVIOUS FROM FIGURE 11 THAT THE PENETRATION OF LANCE TIPS 1, 3, AND 4 IS CONSIDERABLY GREATER THAN THAT OF TIPS 2 AND 5. IT CAN ALSO BE NOTED THAT THE EFFECTIVE JET DIAMETERS 72 INCHES FROM THE TIPS IS GREATER FOR TIPS 2 AND 5 THAN IT IS FOR 1, 3, AND 4. THE MORE INTENSE SHOCK WAVES IN THE AIR STREAMS OF TIPS 2 AND 5 (SEE

SHADOWGRAPH PICTURES) WOULD PRESUMABLY BE AN EXPLANATION FOR BOTH THE WIDER JETS AND THE REDUCED PENETRATION OF TIPS 2 AND 5.

SINCE LANCE TIPS 1 AND 3 PRODUCED RELATIVELY GOOD PENETRATION AND HAD BEEN FOUND TO WORK VERY WELL IN OPERATION, AN ATTEMPT WAS MADE TO OPTIMIZE THEIR PERFORMANCE AT 3900 CFM OF OXYGEN. THE REVISED TIPS, DESIGNATED 1A AND 3A RESPECTIVELY, WERE TESTED AND COMPARED TO THEIR COUNTERPARTS. THE VELOCITY HEAD WAS EVALUATED AT SEVERAL POSITIONS AND AT VARIOUS FLOW RATES THROUGH THE LANCE TIPS. FIGURES 13 AND 14 INCLUDE THE VELOCITY DISTRIBUTIONS OBTAINED FROM THIS ENTIRE SERIES OF TESTS. THE ORIGINAL VELOCITY HEAD CURVES FROM WHICH FIGURES 13 AND 14 WERE OBTAINED, ARE NOT PRESENTED SINCE ALL THE INFORMATION IS AVAILABLE FROM THE MORE COMPACT CURVES OF THESE 2 FIGURES.

THE JET OUTLINES INDICATED IN FIGURES 13 AND 14 ARE ONLY AN ESTIMATE SINCE IT IS IMPRACTICAL, WITH THE NUMBER OF TOTAL HEAD TUBES EMPLOYED IN THESE TESTS TO STATE PRECISELY WHERE THE VELOCITY PROFILE CURVE REACHES ZERO. THE JET OUTLINES SHOWN, HOWEVER, CERTAINLY GIVE AN INDICATION OF THE OVERALL FLOW PATTERNS. THESE VELOCITY HEAD MEASUREMENTS INDICATE THAT ALTHOUGH THE PEAK PENETRATION OF 1A AND 3A MAY BE ON THE AVERAGE SLIGHTLY BETTER AT 3900 CFM THAN THAT OF 1 AND 3 RESPECTIVELY, THE DIFFERENCE IS VERY SLIGHT. THE ONLY REAL SIGNIFICANT DIFFERENCE IN THIS SERIES OF TESTS IS BETWEEN TIPS 1 AND 1A AT 2900 CFM. AT THIS FLOW RATE 1A RESULTS IN CONSIDERABLY POORER PENETRATION THAN 1. THE ENTIRE SITUATION IS MADE MORE APPARENT BY THE USE OF TABLE 1.

IN TABLE 1 THE MARK "X" INDICATES THE POINTS WHERE THE JET PENETRATION IS INFERIOR (SEE FIGURES 11 AND 13) BECAUSE THE LANCE TIP IS BEING OPERATED SO FAR OFF ITS DESIGN POINT. IT WILL BE NOTED THAT ANY TIME ONE OF THESE TIPS IS OPERATED WITH A DRIVING PRESSURE LESS THAN 50% OF THE THEORETICALLY CORRECT DRIVING PRESSURE THE PENETRATION IS CONSIDERABLY REDUCED. IN THE CASE OF LANCE TIP 1A THE DRIVING PRESSURE IS UP TO 75% OF THEORETICAL BUT THE PENETRATION OR PEAK VELOCITY HAS FALLEN OFF RELATIVE TO THAT FOR LANCE TIP 1 AT THE SAME FLOW. HOWEVER, TIP NO. 3 AT 2900 CFM IS OPERATING AT 60% OF THEORETICAL DRIVING PRESSURE WITHOUT ANY NOTICEABLE REDUCTION IN PENETRATION AS COMPARED TO TIP NO. 3 AT 3900 CFM. THIS LEAVES SOME UNCERTAINITY AS TO JUST HOW MUCH A LANCE TIP CAN BE UNDER-DRIVEN. THE DESIGN OF THE LANCE TIP IN QUESTION PROBABLY HAS SOME EFFECT ON THE LIMITS OF DRIVING PRESSURE THAT ARE PRACTICAL.

IT APPEARS SAFE TO CONCLUDE THAT ANY LANCE TIP OPERATING WITH A DRIVING PRESSURE LESS THAN 50% OF THE THEORETICAL DRIVING PRESSURE WILL PRODUCE RELATIVELY POOR PENETRATION. FURTHERMORE, REDUCED PENETRATION MAY OCCUR IF THE DRIVING PRESSURE IS REDUCED TO 75% OF THEORETICAL.

TABLE 1

Lance Tip Number	Exit Mach Number	Theoretical Driving Press. PSIA*	Equiv. O_2 Flow Rate CFM	Required Driving Pressure: PSIA	Required Driving Pressure: % of Theoretical Driving Pressure	Lance Tip Exit Press. PSIA
1	1.70	70.6	2900	83.8	119.0	16.97
			3400	97.8	139.0	19.80
			3900	112.3	159.0	22.70
			4350	125.8	178.0	25.50
1A	2.00	112.0	2900	83.8	x 75.0	10.72
			3400	97.8	87.0	12.50
			3900	112.3	100.0	14.35
			4350	125.8	112.0	16.10
2	2.30	179.0	2900	63.3	x 35.4	5.06
			3400	74.3	x 41.5	5.94
			3900	85.3	x 47.7	6.82
3	2.25	165.0	2900	98.8	60.0	8.54
			3400	116.3	70.5	10.06
			3900	132.8	80.5	11.50
			4450	151.8	92.0	13.13
3A	2.11	133.0	2900	97.8	73.6	10.53
			3400	115.3	86.7	12.40
			3900	132.8	100.0	14.30
			4450	148.8	112.0	16.00
4	1.84	87.4	2900	123.3	141.0	20.20
			3400	144.3	165.0	23.60
			3900	166.3	190.4	27.20
5	2.59	285.0	2900	84.3	x 29.6	4.29
			3400	98.8	x 34.7	5.02
			3900	112.3	x 39.4	5.71

* Theoretical Driving Pressure is defined here as that driving pressure which produces a static pressure at the lance tip exit equal to the atmospheric pressure.
x–Indicates inferior penetration because the lance tip is operated too far off its design.

THROUGHOUT THIS STUDY NO VELOCITY HEAD DATA WAS TAKEN WHICH INDICATED AN APPRECIABLE REDUCTION IN RELATIVE PENETRATION BECAUSE OF TOO HIGH A DRIVING PRESSURE. AT 3900 CFM LANCE TIP NO. 4 REQUIRED A DRIVING PRESSURE 90% GREATER THAN THE THEORETICALLY CORRECT PRESSURE. IT APPEARS VERY LIKELY (NOTE SHADOWGRAPH OF TIP NO. 4) THAT THERE IS SOME LOSS IN PENETRATION BECAUSE OF OFF-DESIGN OPERATION OF THIS TIP.

IT SHOULD BE NOTED THAT AT 3900 CFM, LANCE TIP NO. 1 REQUIRES A DRIVING PRESSURE 59% GREATER THAN ITS THEORETICAL DRIVING PRESSURE, AND THE PENETRATION IS ESSENTIALLY THE SAME AS THAT OF LANCE TIP 1A OPERATING AT ITS THEORETICALLY CORRECT PRESSURE. APPARENTLY THIS AMOUNT OF OVER DRIVING HAS NO APPRECIABLE EFFECT ON PENETRATION.

LANCE TIP NO. 3 OPERATES AT 80% OF THEORETICAL WHEN FLOWING 3900 CFM AND SEEMINGLY THE PENETRATION IS ESSENTIALLY AS GOOD AS THAT OF TIP 3A OPERATING AT 100% THEORETICAL PRESSURE.

THUS IT IS EVIDENT THAT LANCE TIPS 1 AND 3 ARE BOTH OPERATING SUFFICIENTLY NEAR TO THEIR DESIGN POINT (3900 CFM) AS TO MAKE ANY CHANGES IN THEIR EXIT AREA UNPROFITABLE AS REGARDS JET PENETRATION.

FIGURE 12 IS A PLOT OF VELOCITY VERSUS VELOCITY HEAD FOR AIR AT APPROXIMATELY THE CONDITIONS WHICH EXISTED THROUGHOUT THIS SERIES OF TESTS.

IT IS OF INTEREST TO NOTE THAT SINCE THE DENSITY OF THE MATERIAL IN THE CONVERTER IS ROUGHLY ONE-HALF THAT OF MERCURY, DOUBLING THE VERTICAL SCALE OF FIGURE 11 WOULD CONVERT THE VALUES OF VELOCITY HEAD IN INCHES OF MERCURY TO VELOCITY HEAD IN INCHES OF IRON AND MIGHT INDICATE APPROXIMATELY THE SHAPE OF THE IMPRESSIONS MADE IN THE METAL BY THE OXYGEN JET.

CONCLUSIONS

1. PENETRATION AT ANY GIVEN FLOW RATE AND DRIVING PRESSURE CAN BE MAXIMIZED BY DESIGNING THE DIVERGENT SECTION OF THE LANCE TIP SO THAT ITS THEORETICAL DRIVING PRESSURE[1] IS APPROXIMATELY EQUAL TO THE DRIVING PRESSURE ACTUALLY USED.

2. INCREASING THE DRIVING PRESSURE, AND HENCE FLOW RATE, OF A GIVEN LANCE TIP RESULTS GENERALLY IN GREATER PENETRATION. WITHIN THE RANGE OF DRIVING PRESSURES CONSIDERED THUS FAR, INCREASING THE DRIVING PRESSURE REQUIRED FOR A GIVEN FLOW RATE (I.E. REDUCING LANCE TIP THROAT AREA) RESULTS IN GREATER PENETRATION, PROVIDED THE DIVERGENT SECTION OF THE LANCE TIP IS DESIGNED FOR THE PRESSURE USED.

3. THE OPTIMUM OPERATING RANGE OF ANY GIVEN LANCE TIP CAN BE DEFINED IN TERMS OF THE RATIO OF DRIVING PRESSURE EMPLOYED TO THE LANCE TIP'S THEORETICAL DRIVING PRESSURE.[1] THIS RATIO CAN APPARENTLY RANGE BETWEEN 0.8 AND 1.75 WITHOUT THE PENETRATION BEING REDUCED APPRECIABLY BELOW THAT OBTAINED WHEN THE RATIO IS UNITY.[2]

IN SOME CASES THIS RANGE MAY BE SOMEWHAT GREATER, BUT IT IS APPARENT THAT OPERATING A LANCE TIP TOO FAR OUTSIDE THIS RANGE APPRECIABLY REDUCES PENETRATION BELOW THAT OBTAINABLE WHEN THIS RATIO IS 1.0.

4. TIPS 1A AND 3A, WHICH WERE DESIGNED FOR 3900 CFM, PRODUCED ONLY SLIGHTLY BETTER PENETRATION AT THIS FLOW RATE THAN DID 1 AND 3 RESPECTIVELY, WHICH WERE OPERATING WELL WITHIN THE ABOVE RECOMMENDED LIMITS FOR THE RATIO OF ACTUAL TO THEORETICAL DRIVING PRESSURE.

5. AS FLOW RATES ARE INCREASED ABOVE 3900 CFM THE PENETRATION OBTAINED WITH LANCE TIP 3 SHOULD BECOME INCREASINGLY GREATER THAN THAT OBTAINED WITH LANCE TIP 1. THIS IS DUE TO THE FACT THAT TIP 3 IS MOVING CLOSER TO IT'S DESIGN POINT AS DRIVING PRESSURE INCREASES, WHILE TIP 1 IS MOVING FURTHER AWAY FROM ITS DESIGN POINT AS PRESSURE INCREASES.

6. THE SHADOWGRAPH PICTURES INDICATED QUALITATIVELY THE SAME GENERAL TENDENCIES THAT WERE OBSERVED QUANTATIVELY BY THE TOTAL HEAD MEASUREMENTS. ESSENTIALLY ALL SHOCKS THAT OCCURRED IN THE JETS WERE WITHIN THE FIRST FOOT DOWNSTREAM OF THE LANCE TIP.

7. NO DIFFICULTIES WERE NOTED WHICH COULD BE ATTRIBUTED TO TOLERENCES ALLOWED IN THE MACHINING OF THE LANCE TIPS. A SHORTER THROAT SECTION WITHIN THE TIP SHOULD PROVIDE THE SAME FLOW PATTERN AND MIGHT REDUCE MACHINING COSTS.

8. THE RESULTS OF THIS STUDY SHOULD BE SUFFICIENT TO ENABLE A LANCE TIP TO BE DESIGNED WHICH WOULD BE CAPABLE OF PRODUCING GOOD PENETRATION OVER ANY SPECIFIED RANGE OF FLOW RATES WITHIN REASONABLE LIMITS.

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1 - A LANCE TIP'S THEORETICAL DRIVING PRESSURE IS DEFINED FOR THESE DISCUSSIONS AS THAT DRIVING PRESSURE WHICH WILL PRODUCE A STATIC PRESSURE AT THE LANCE TIP EXIT EQUAL TO THE ATMOSPHERIC PRESSURE. THIS THEORETICAL PRESSURE IS A FUNCTION OF ONLY THE LANCE TIP'S EXPANSION RATIO (EXIT AREA/THROAT AREA), ASSUMING ATMOSPHERIC PRESSURE ESSENTIALLY CONSTANT.

2 - THIS STATEMENT ASSUMES THE SAME FLOW RATE AND DRIVING PRESSURE IN ALL CASES. THE VALUE OF THE RATIO OF DRIVING PRESSURE TO THEORETICAL PRESSURE IS ASSUMED TO VARY OVER A RANGE BY CHANGES IN THEORETICAL PRESSURE DUE TO CHANGES IN NOZZLE DESIGN.

APPENDIX

DEFINITION OF TERMS AND DERIVATIONS OF EQUATIONS USED IN THIS REPORT.

TOTAL HEAD OR TOTAL PRESSURE: THAT PRESSURE WHICH WOULD EXIST IN THE GAS IF IT WERE DECELERATED ISENTROPICALLY TO ZERO VELOCITY. FOR PRESENT PURPOSES THE TOTAL HEAD CAN BE DEFINED AS BEING ESSENTIALLY EQUAL TO THE PRESSURE EXERTED WITHIN A PRESSURE PICK UP TUBE, OPEN ONLY ON THE UPSTREAM END. THIS SIMPLIFICATION CAN BE APPLIED ONLY IN SUBSONIC VELOCITIES.

STATIC PRESSURE: THE PRESSURE EXISTING WITHIN A GAS, ACTING EQUALLY IN ALL DIRECTIONS. THE STATIC PRESSURE AND TOTAL PRESSURE ARE IDENTICAL WHEN THE GAS VELOCITY IS ZERO.

VELOCITY HEAD: THE DIFFERENCE BETWEEN TOTAL PRESSURE AND STATIC PRESSURE. AIR VELOCITY IS DETERMINED BY THE VELOCITY HEAD AT CONSTANT TEMPERATURE AND STATIC PRESSURE (SEE FIGURE 12).

OXYGEN FLOW RATE - CONVERSION FROM FT^3/MIN TO LB/SEC

IT WAS NECESSARY TO CONVERT THE OXYGEN FLOW RATE IN CUBIC FEET PER MINUTE TO POUNDS PER SECOND. THE OXYGEN DENSITY, ρ_{O_2}, AT STANDARD TEMPERATURE AND PRESSURE IS:

$$\rho_{O_2} = P/RT \qquad \text{STATE EQUATION} \qquad (1)$$

$$\rho_{O_2} = 14.7 \times 144/48.3 \times 520 = .0844 \text{ LB/FT}^3$$

P = STATIC PRESSURE - PSIA

R = GAS CONSTANT FOR OXYGEN - FT LB/LB-^{0}F

T = ABSOLUTE TEMPERATURE - DEGREES FAHRENHEIT ABSOLUTE

$$\text{LBS/SEC} = (C.F.M.)(\rho_{O_2})/60 = (C.F.M.)(0.001406) \qquad (2)$$

THUS 3900 CFM = 3900 x 0.001406 = 5.484 LB/SEC

ANY LANCE TIP TESTS MADE AT AN AIR FLOW RATE OF 5.484 LB/SEC IS DEFINED AS HAVING BEEN CONDUCTED AT AN EQUIVALENT OXYGEN FLOW RATE OF 3900 CFM.

THE MASS FLOW THROUGH A NOZZLE (LANCE TIP) IS CALCULATED BY.

$$W = \rho^* V^* A^* \qquad (3)$$

W = AIR FLOW RATE - LB/SEC

V = AIR VELOCITY - FT/SEC

A = CROSS SECTIONAL AREA - FT^2

$*$ = INDICATES CONDITIONS AT THE THROAT OF THE LANCE TIP

NOTING THAT $M = V/a$ WHERE;

a = SPEED OF SOUND - FT/SEC

M = MACH NUMBER

BUT AT THE LANCE TIP THROAT $M = 1$, THAT IS $V = a$

USING THIS SUBSTITUTION AND EQUATION (1) IN EQUATION (3)

$$W = P^*/RT^* \times a^* A^*$$

HOWEVER, SINCE $a = \sqrt{\gamma g RT}$ WHERE γ = RATIO OF SPECIFIC HEATS = APPROXIMATELY 1.4 FOR BOTH AIR AND OXYGEN, AND g = GRAVITY CONSTANT = 32.2 FT/SEC^2

THE FLOW EQUATION BECOMES:

$$\begin{aligned} W &= P^*/RT^*(\gamma g)^{\frac{1}{2}} (RT^*)^{\frac{1}{2}} A^* \\ &= P^*(\gamma g)^{\frac{1}{2}} A^*/(RT^*)^{\frac{1}{2}} \qquad (4) \end{aligned}$$

THERE IS A FIXED RELATION BETWEEN THE TOTAL DRIVING PRESSURE AND TEMPERATURE AND THE PRESSURE AND TEMPERATURE AT THE THROAT. REFER TO TABLE 1 OF NACA REPORT 1135, "EQUATIONS, TABLES, AND CHARTS FOR COMPRESSIBLE FLOW."

P^* = 0.5283 X DRIVING PRESSURE

T^* = 0.8333 X DRIVING TEMPERATURE

EQUATION (4) THEN BECOMES:

$$\begin{aligned} W &= 0.5325\, P_d (1.4 \times 32.2)^{\frac{1}{2}} A^*/(53.3)^{\frac{1}{2}}(0.8333 T_d)^{\frac{1}{2}} \\ &= 0.5325\, P_d\, A^*/(T_d)^{\frac{1}{2}} \text{ LB/SEC.} \qquad (5) \end{aligned}$$

P_d AND T_d ARE DRIVING PRESSURE AND TEMPERATURE RESPECTIVELY.

THE SAME DERIVATION FOR OXYGEN FLOW RATE RESULTS IN:

$$W = 0.5595\, P_d\, A^*/(T_d)^{\frac{1}{2}} \text{ LB/SEC} \qquad (6)$$

NOTE: A^* IN EQUATION (4) AND (5) SHOULD BE IN IN.^{2} RATHER THAN FT^2 AS LONG AS P_d IS IN LB/IN.^{2}.

SINCE A^* IS A FIXED VALUE FOR ANY GIVEN LANCE TIP, THE MASS FLOW RATE IS DEPENDENT ONLY ON DRIVING PRESSURE AND TEMPERATURE.

IT IS INTERESTING TO NOTE THAT, GIVEN AN OXYGEN DRIVING TEMPERATURE OF 100°F (560°F ABSOLUTE) AND AN AIR DRIVING TEMPERATURE OF 56°F (516°F ABSOLUTE) A GIVEN DRIVING PRESSURE FOR BOTH AIR AND OXYGEN WILL RESULT IN THE SAME MASS FLOW FOR BOTH GASES.

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3. Anderson, Arthur R., and Johns, Frank R., "Mondimensional Characteristics of Free and Deflected Supersonic Jets Exhausting into Quiescent Air", NADC-ED-5401 (25 March 1954).

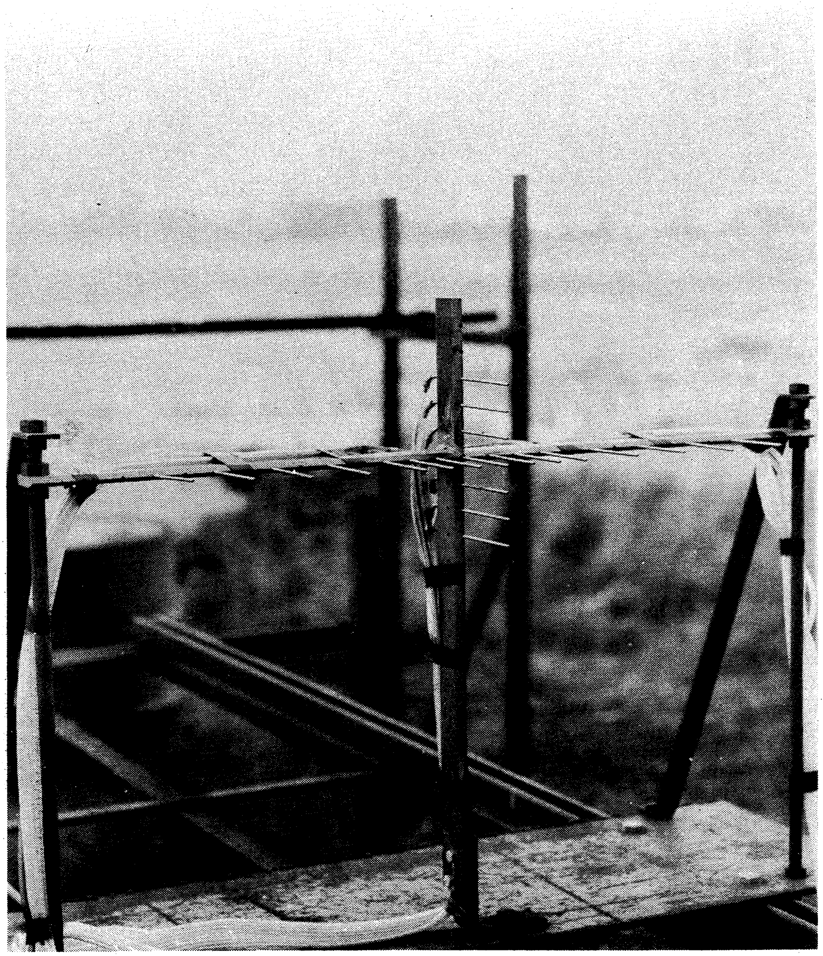

Figure 1

Total Head Rake Assembly

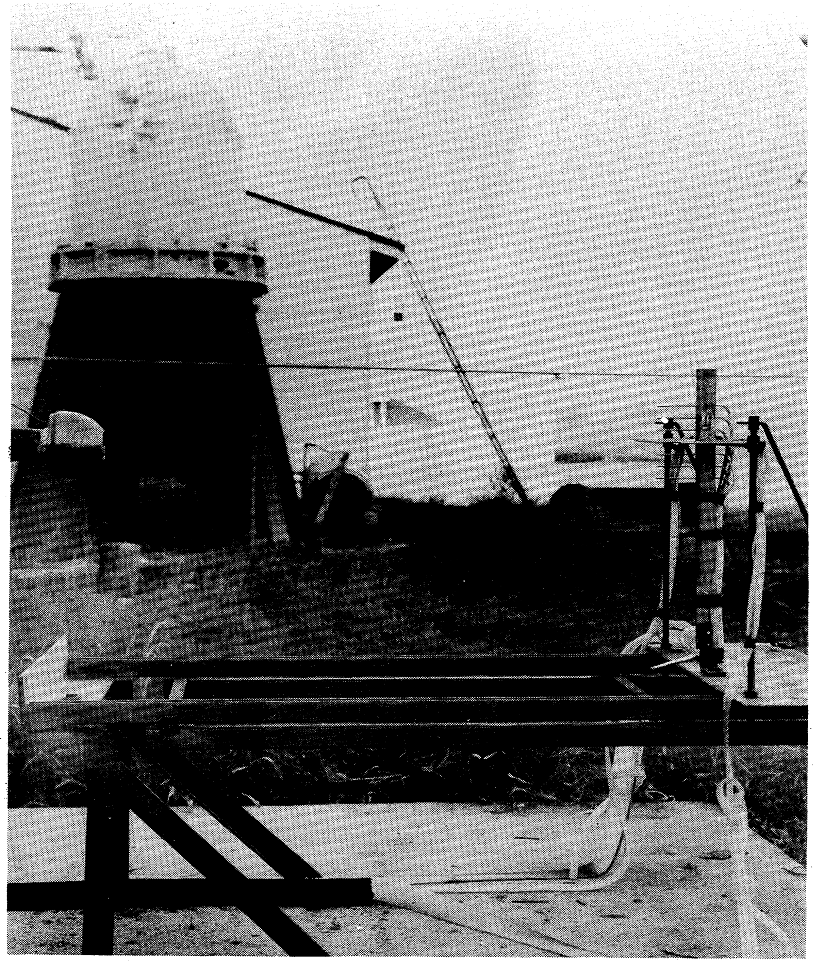

Figure 2

Total Head Rake Assembly and Lance Tip. (High Pressure Air Storage Tanks in Background)

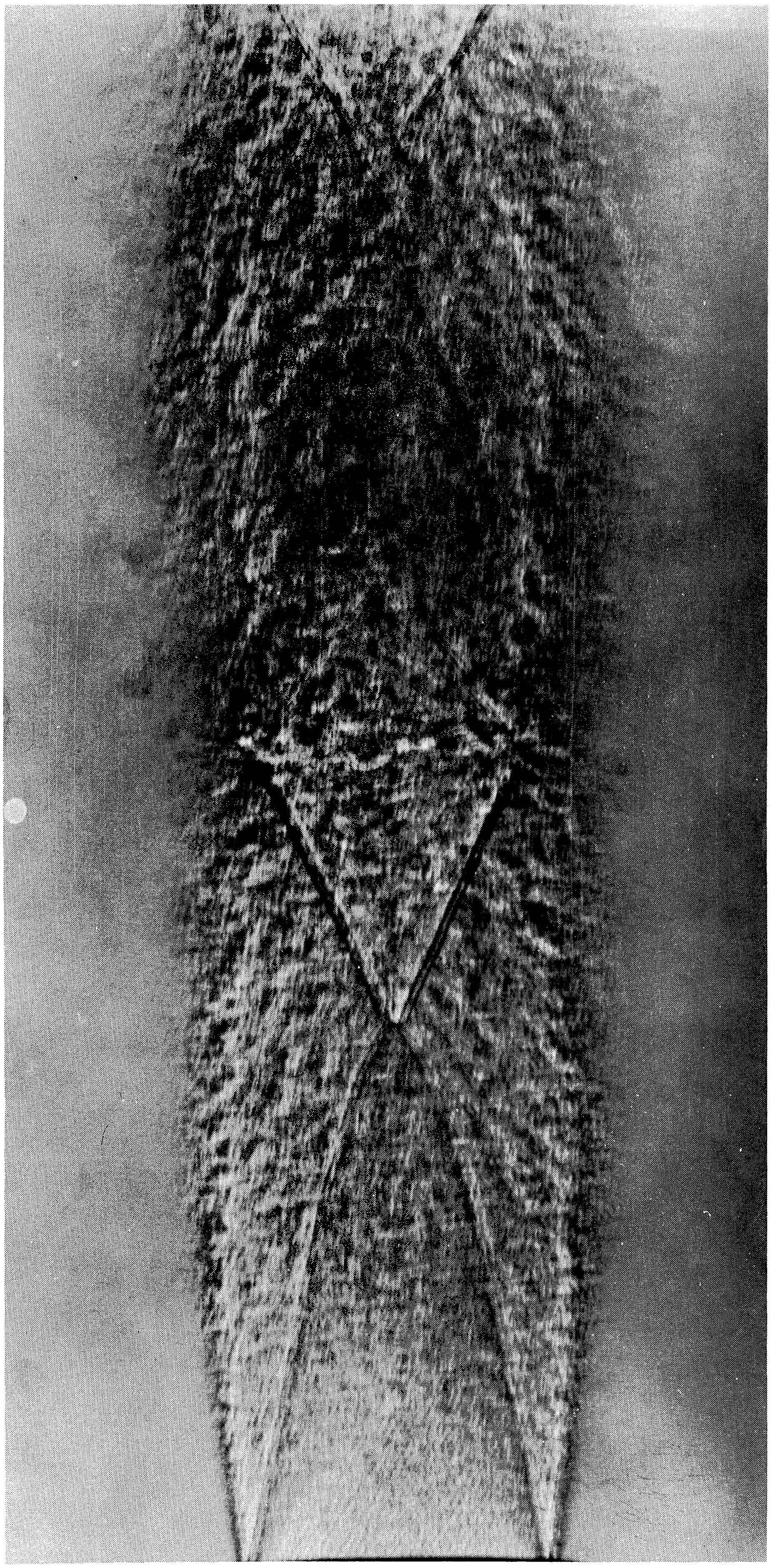

Figure 4 Shadowgraph Picture

McLouth Steel Corp. Nozzle No. 1
Air Driving Pressure: 98 PSIG
Throat Area: 2.072 Sq. In.
Exit Area: 2.76 Sq. In.
Theoretical Exit Mach No.: 1.69
Ambient Air: 29.3 In. Hg.

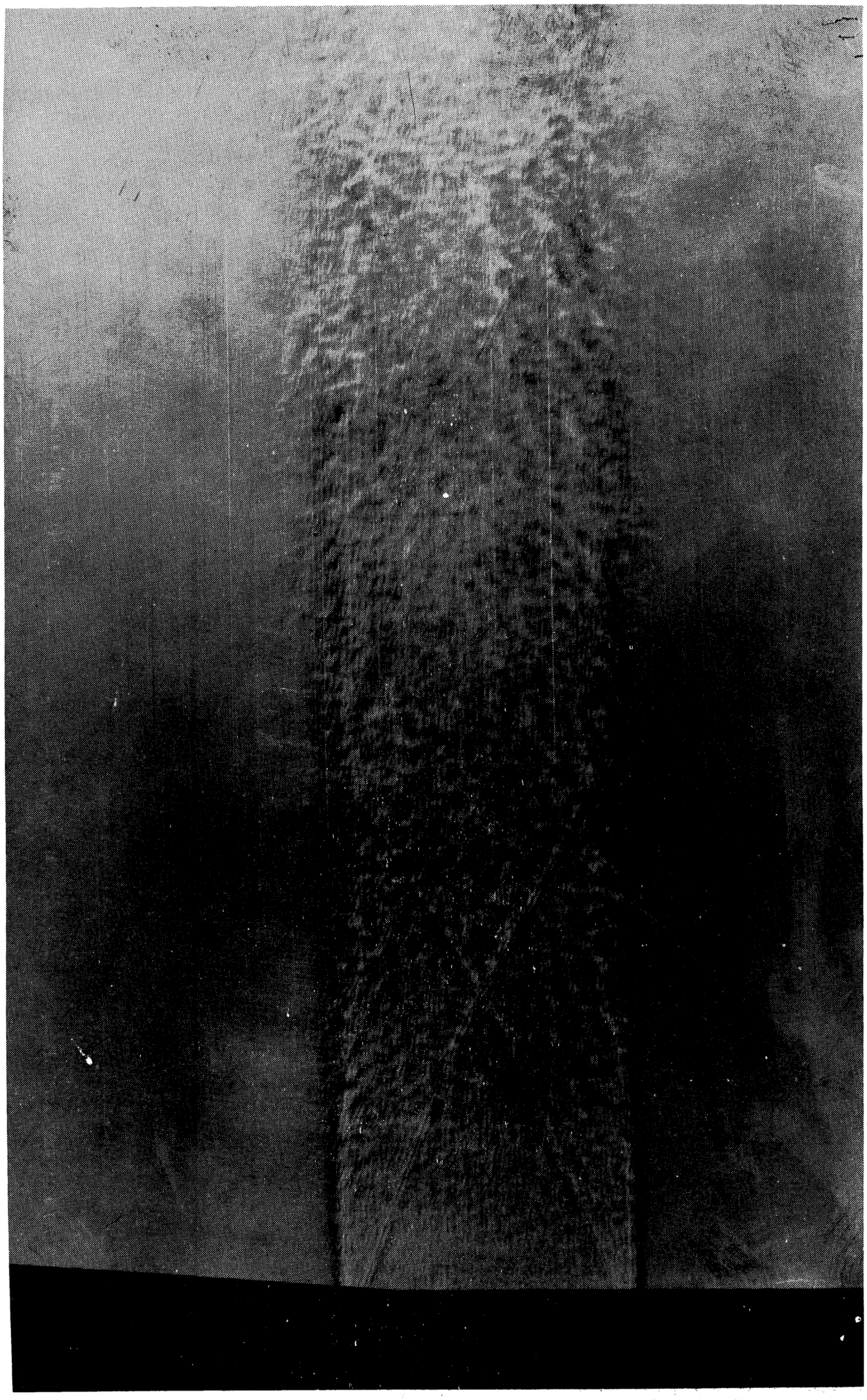

Figure 5 Shadowgraph Picture

McLouth Steel Corp. Nozzle No. 1A
Air Driving Pressure: 98 PSIG
Throat Area: 2.072 Sq. In.
Exit Area: 3.5 Sq. In.
Theoretical Exit Mach No.: 2.00
Ambient Air: 29.2 In. Hg.

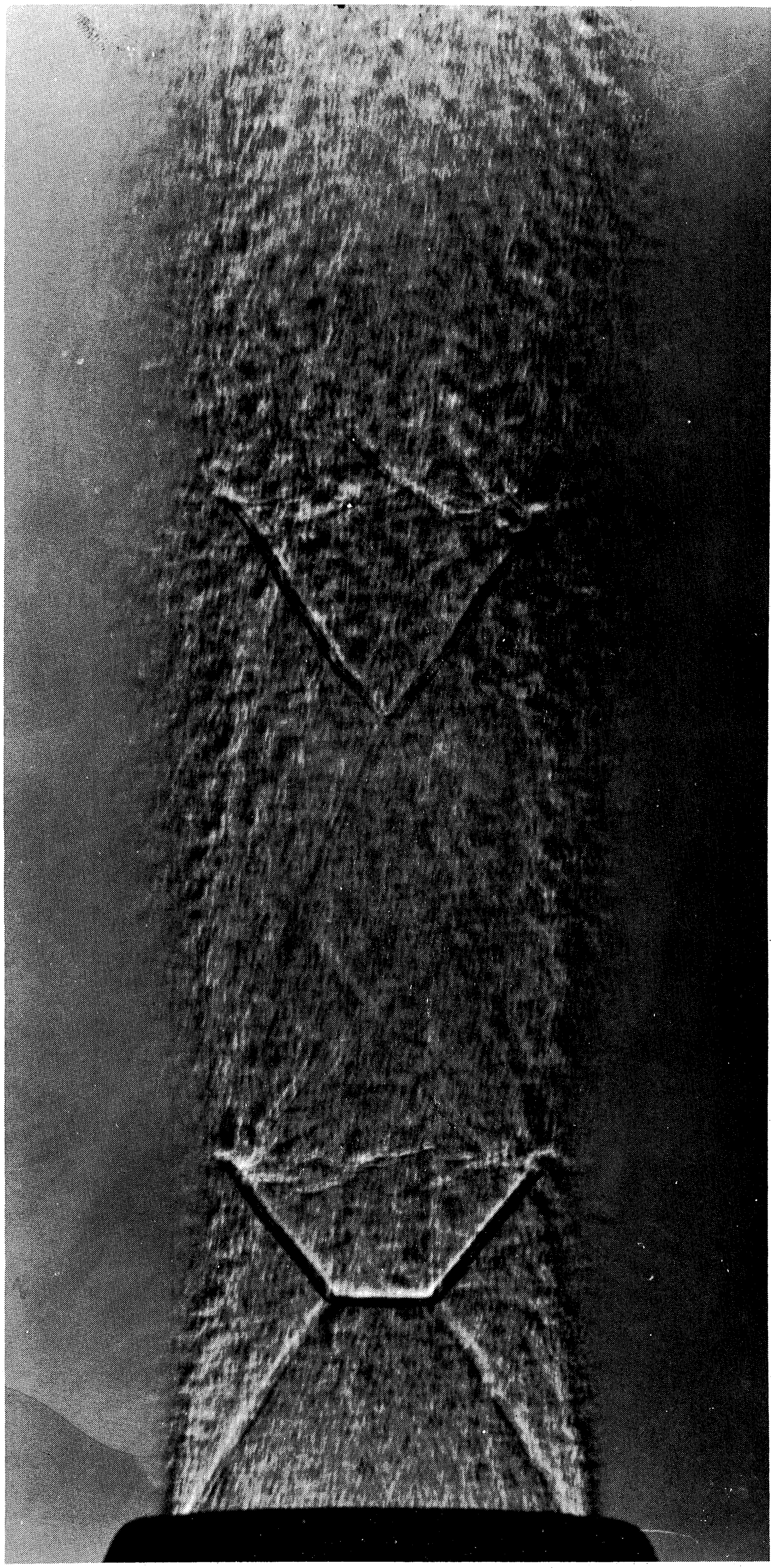

Figure 6 Shadowgraph Picture

McLouth Steel Corp. Nozzle No. 2
Air Driving Pressure: 71 PSIG
Throat Area: 2.74 Sq. In.
Exit Area: 5.98 Sq. In.
Theoretical Exit Mach No.: 2.3
Ambient Air: 29.3 In. Hg.

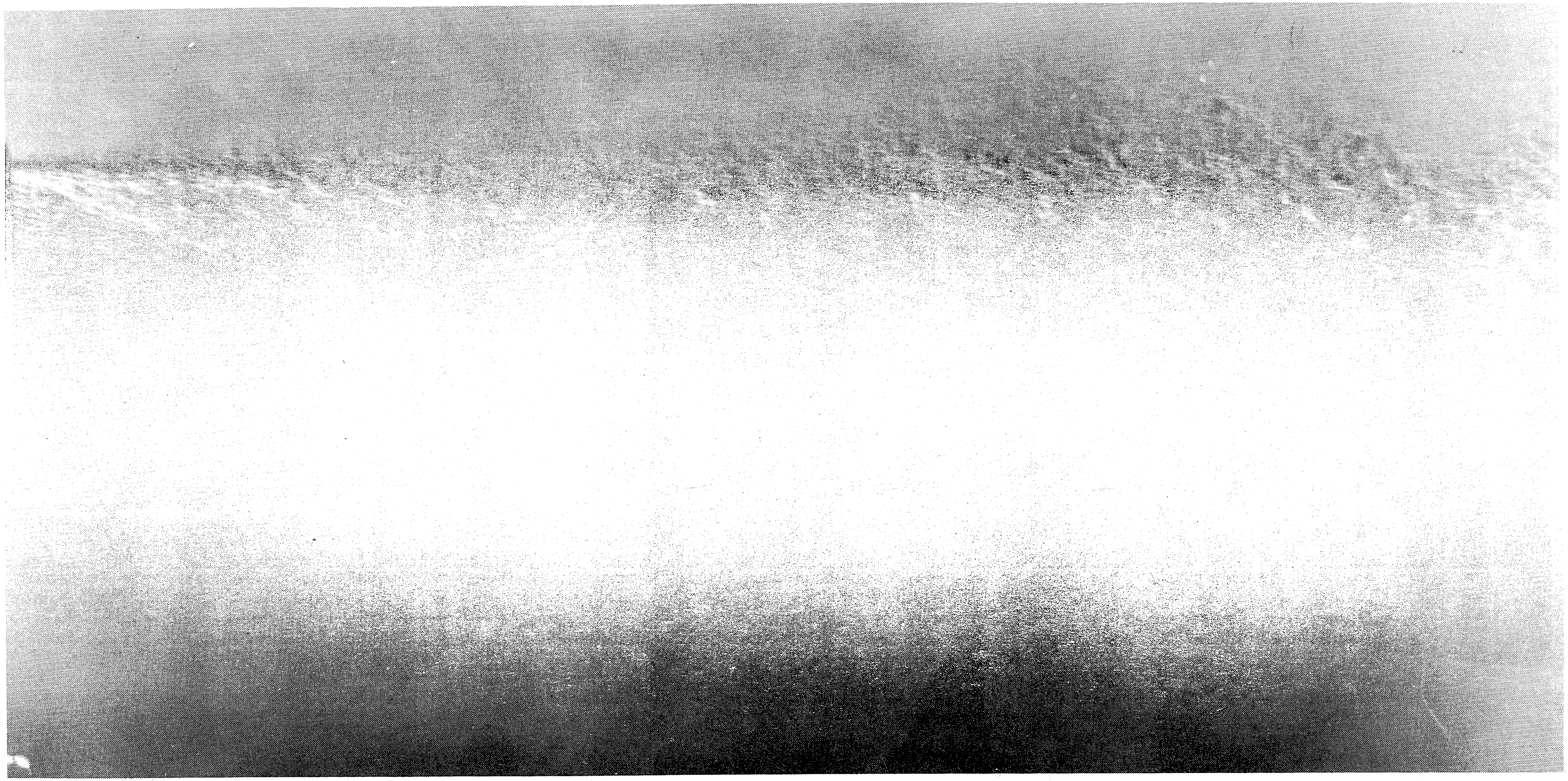

Figure 7 Shadowgraph Picture

McLouth Steel Corp. Nozzle No. 3
Air Driving Pressure: 118.5 PSIG
Throat Area: 1.758 Sq. In.
Exit Area: 3.695 Sq. In.
Theoretical Exit Mach No.: 2.25
Ambient Air: 29.3 In. Hg.

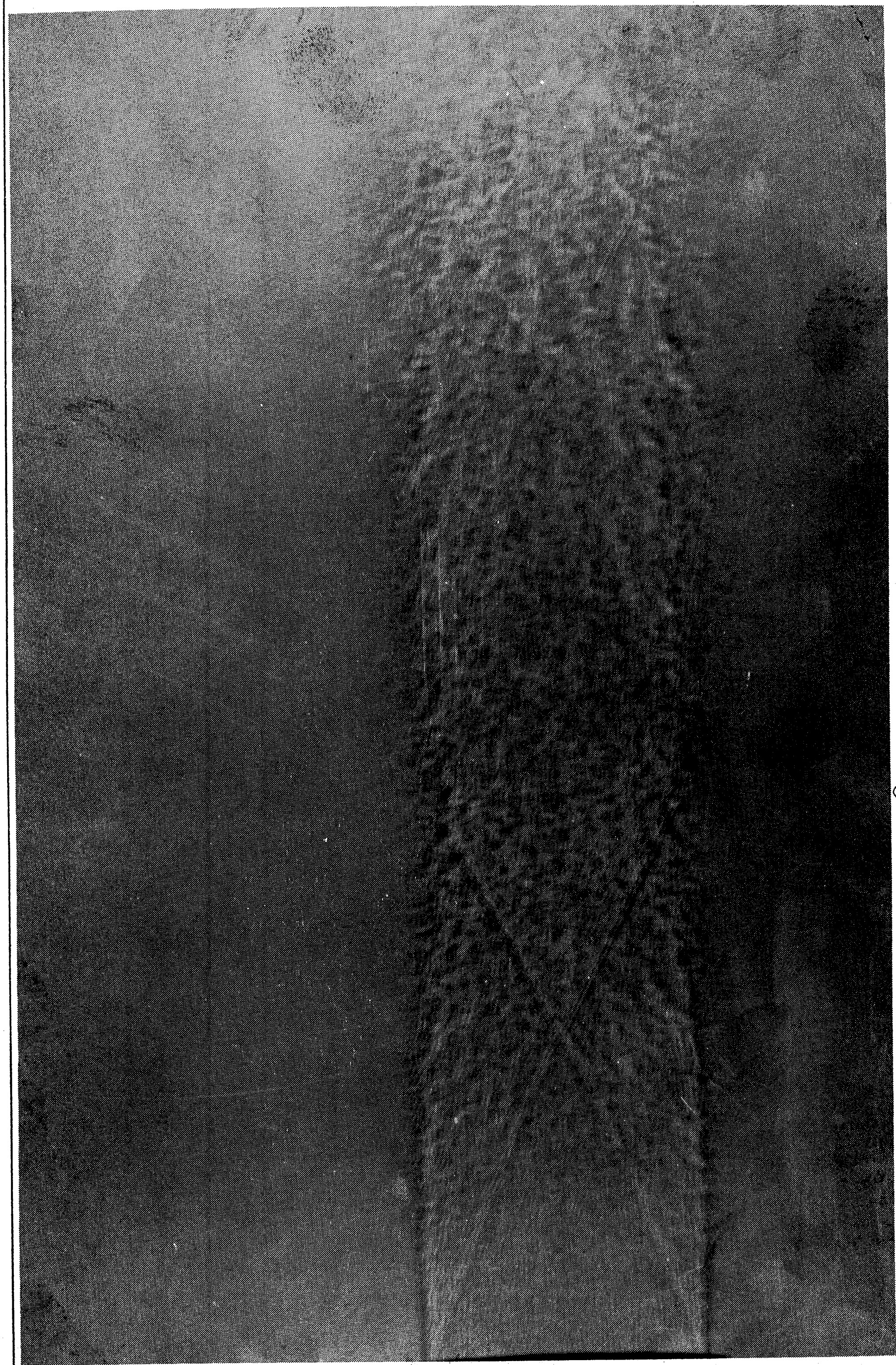

FIGURE 8 SHADOWGRAPH PICTURE

McLOUTH STEEL CORP. NOZZLE NO. 3A
AIR DRIVING PRESSURE: 118.5 PSIG
THROAT AREA: 1.769 SQ. IN.
EXIT AREA: 3.265 SQ. IN.
THEORETICAL EXIT MACH NO.: 2.11
AMBIENT AIR: 29.2 IN. HG.

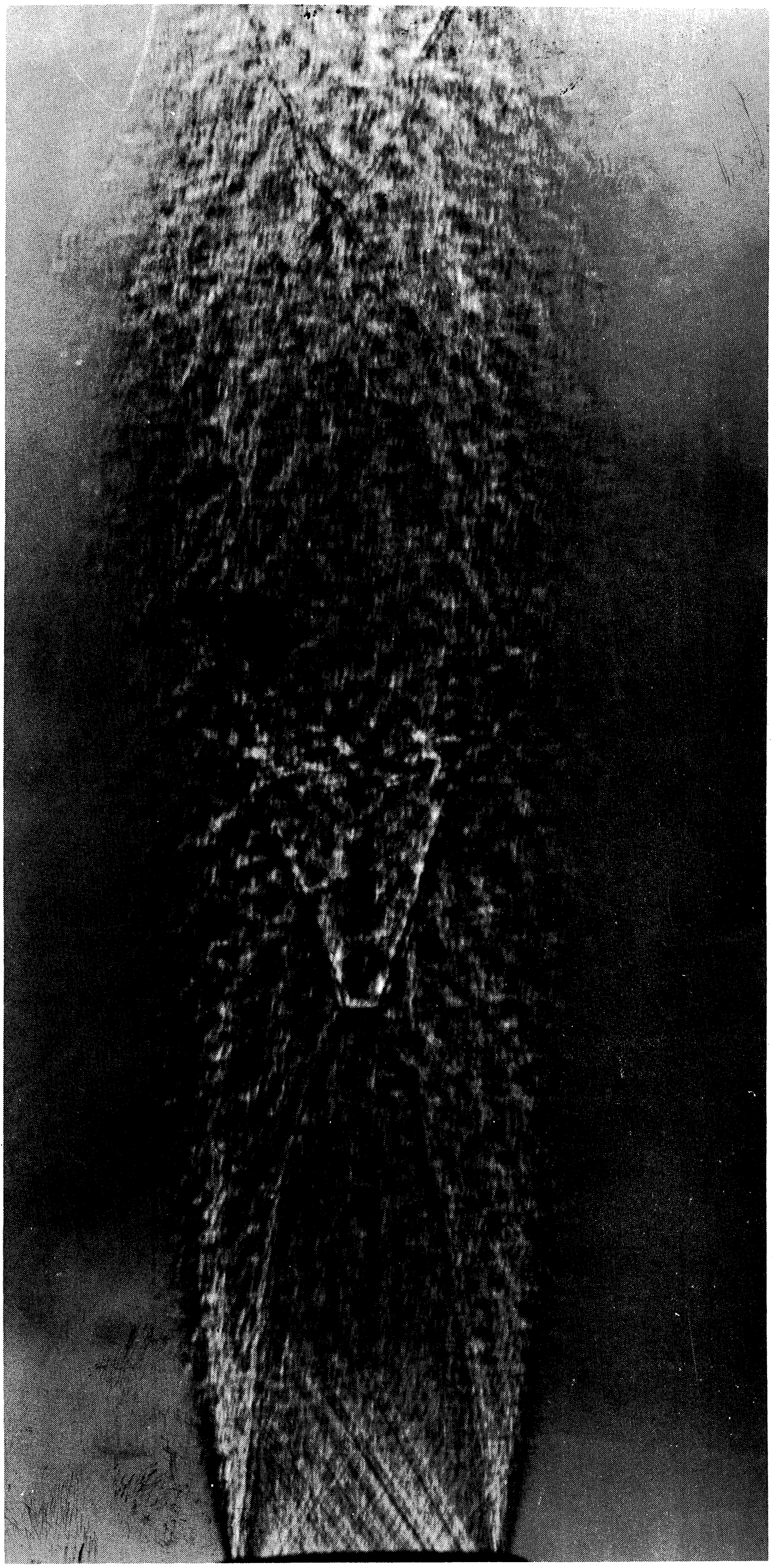

Figure 9 Shadowgraph Picture

McLouth Steel Corp. Nozzle No. 4
Air Driving Pressure: 152 PSIG
Throat Area: 1.403 Sq. In.
Exit Area: 2.083 Sq. In.
Theoretical Exit Mach No.: 1.84
Ambient Air: 29.3 In. Hg.

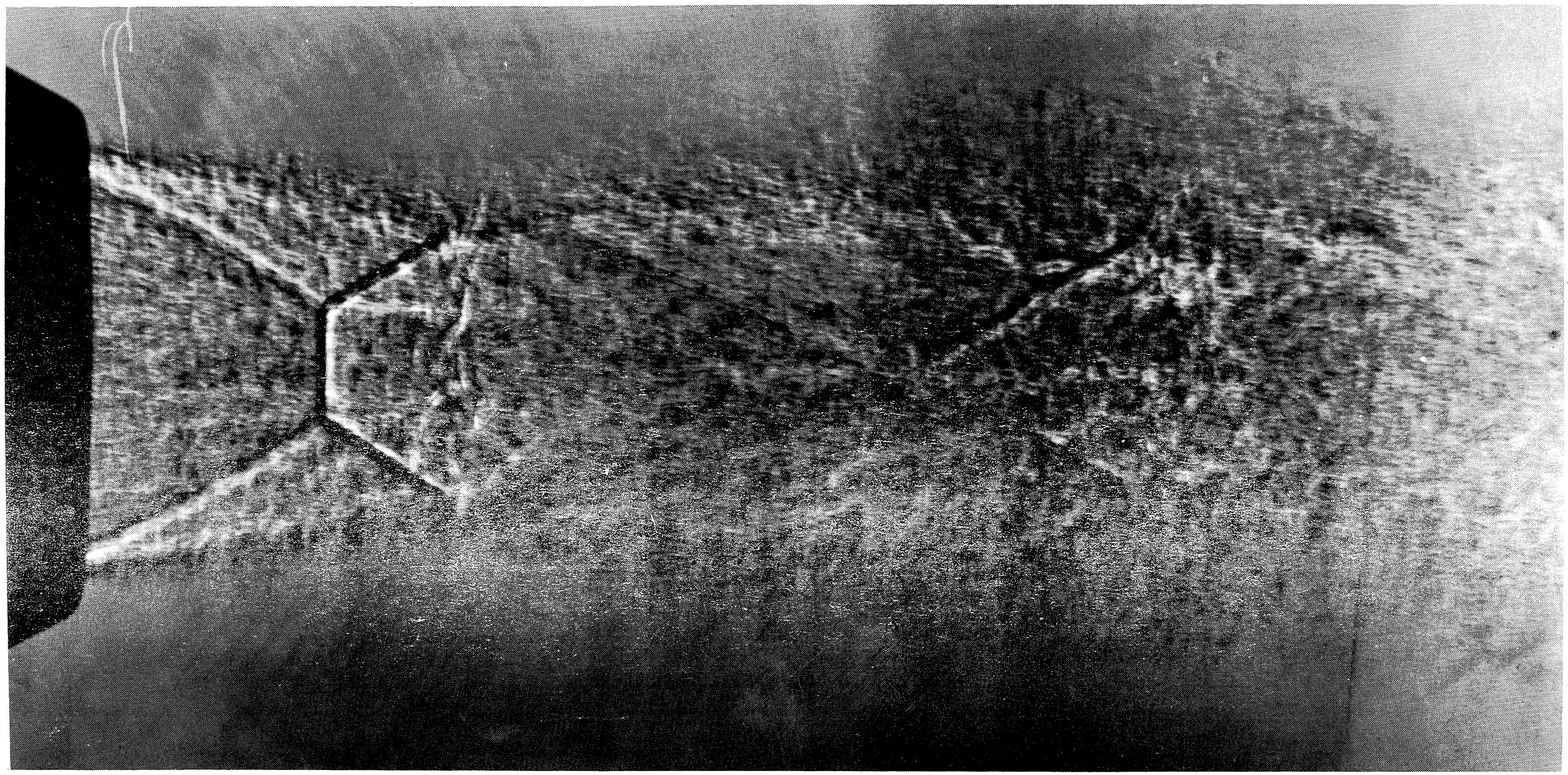

Figure 10 Shadowgraph Picture

McLouth Steel Corp. Nozzle No. 5
Air Driving Pressure: 99 PSIG
Throat Area: 2.06 Sq. In.
Exit Area: 5.88 Sq. In.
Theoretical Exit Mach No.: 2.59
Ambient Air: 29.3 In. Hg.