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HIGH PRESSURE WATER JET BARRIER

- DESIGN OPTIMIZATION -

EE-88

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by

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EE-88

April 1987

ABSTRACT

A design optimization study is documented for a high pressure water jet barrier. The influence on air flow velocity of variations in pressure, nozzle height, depression angle and nozzle spacing is analyzed. Corresponding induced surface current velocities were also measured. An optimal nozzle type is identified and a method recommended for selection of nozzles.

RÉSUMÉ

Optimisation de la puissance requise pour contenir une nappe d'huile sur l'eau en utilisant des jets d'eau sous pression.

Considérant que la performance des jets d'eau lors de retenue d'hydrocarbures sur l'eau est directement reliée au courant d'air qu'ils génèrent, un anémomètre de type "laser Doppler" est utilisé pour mesurer la vitesse de ce courant à différents points en surface d'une nappe d'eau devant un jet. Les conditions optimales d'opération (pression, angle d'inclinaison, hauteur au-dessus de l'eau) sont déterminées pour différents volumes et étalements de jet. L'espacement des jet ainsi que la puissance requise par mètre d'estacade sont ensuite estimés pour une distance de retenue choisie.

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1. INTRODUCTION

The application of high pressure water jets for oil spill containment was initiated by the Environmental Emergencies Technology Division of Environment Canada in 1979. Following the introduction of the original concept, tests were performed in 1980 at OHMSETT (Oil and Hazardous Materials Simulated Environmental Test Tank) [1], which explored the effects of water jet flare angle, height, pressure, flow rate, current and waves on an oil slick. It was suggested that the flow of entrained air rather than induced water current was the dominant mechanism for the water jet barrier.

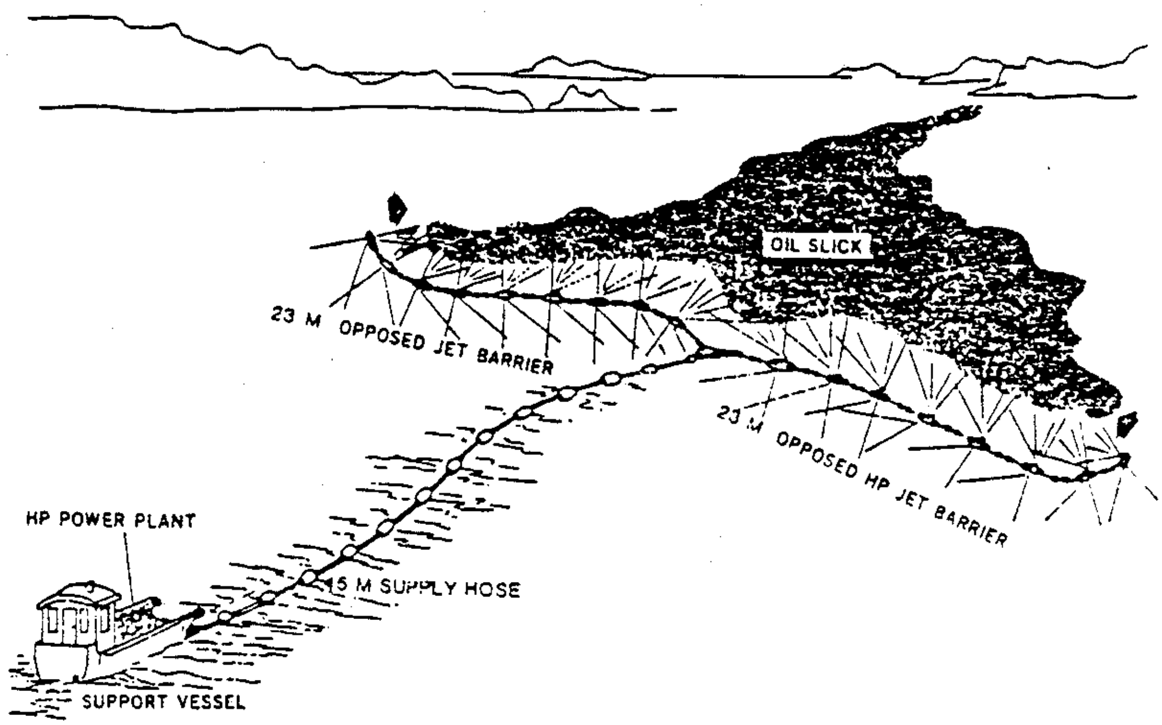
According to Meikle [2], the introduction of high pressure, low flow rate, horizontally mounted fan type nozzles, resulted in a significant improvement in performance. Figure 1.1 illustrates the configuration of the EPS barrier with opposing pairs of jets mounted on floats and spaced at intervals to provide continuous oil slick containment. The opposing jets were controlled separately to either maintain static equilibrium of wind, and current loads and jet momenta or to actually propel the system.

The objective of the present study was to optimize the design of the existing barrier. This was achieved by performing systematic experiments to determine the influence of the various parameters involved. The optimum performance of the water jet was believed to be directly related to the maximum associated air flow. Hence, it was necessary to devise some means of measuring the air velocity at selected points near the water surface. For this purpose, a laser doppler anemometer (LDA) was selected. Other techniques such as pitot tubes, pressure transducers, and hot wire and hot film anemometers were also considered but judged inadequate for this application.

This report describes the experimental program, test results, conclusions and recommendations.

FIGURE 1.1

WATER JET BARRIER DESIGN CONFIGURATION



2. TEST PLAN

2.1 Test Parameters

An experimental test program was devised to investigate the influence of system parameters on the performance of the water jet barrier. Independent variables which were deemed relevant as based on an assessment of the physical problem are listed in Table 2.1 and include:

- nozzle spread angle
- nozzle aperture
- height above surface
- depression angle
- flow rate
- distance downstream
- spacing

Principal dependent variables were air flow velocity, water surface velocity and nozzle flow rate. Two series of tests were planned to achieve the objectives of the study:

(1) Individual Nozzle Performance Tests; measuring air flow velocity and water current velocity for selected parameter variations in commercial fan type nozzles.

(2) Multiple Nozzle Performance Tests; measuring air flow velocity for varied equi-spaced combinations of identical jets.

2.2 Experimental Set-Up

A. Single Nozzle Tests: Figure 2.1 illustrates the test set-up for measurement of air flow induced by operation of individual water jet nozzles. The system consisted of:

- adjustable position carriage
- lateral motion support assembly,
- high pressure pumping system, manifold and water jet nozzles
- water filled basin
- Laser Doppler Anemometer (LDA) system, optical bench, support structure
- current meter (fixed position).

The LDA system was positioned along the basin wall. It measured the axial velocity component of the two phase flow occurring within a small control volume at

TABLE 2.1

LIST OF VARIABLES

INDEPENDENT VARIABLES:

- Nozzle Pressure, P
- Spread Angle, α
- Orifice Diameter, d
- Height above Water Surface, h
- Depression Angle, β
- Water Jet Spacing, s
- Axial Distance from Nozzle, χ

CONSTANT VARIABLES:

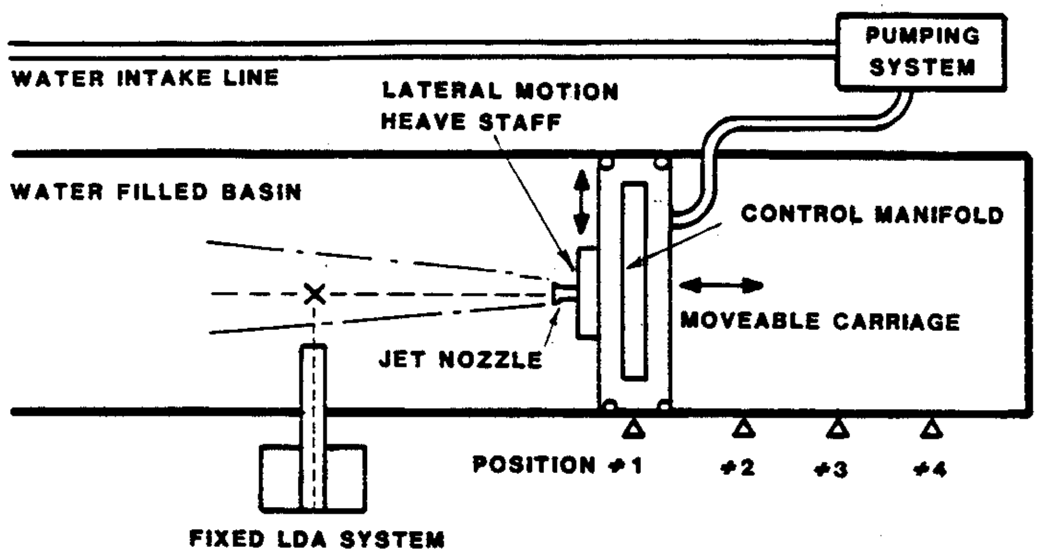
- Gravitational Constant, g
- Water Density, ρ_W
- Air Density, ρ_A
- Kinematic Viscosity (Water), ν_W
- Kinematic Viscosity (Air), ν_A

DEPENDENT VARIABLES:

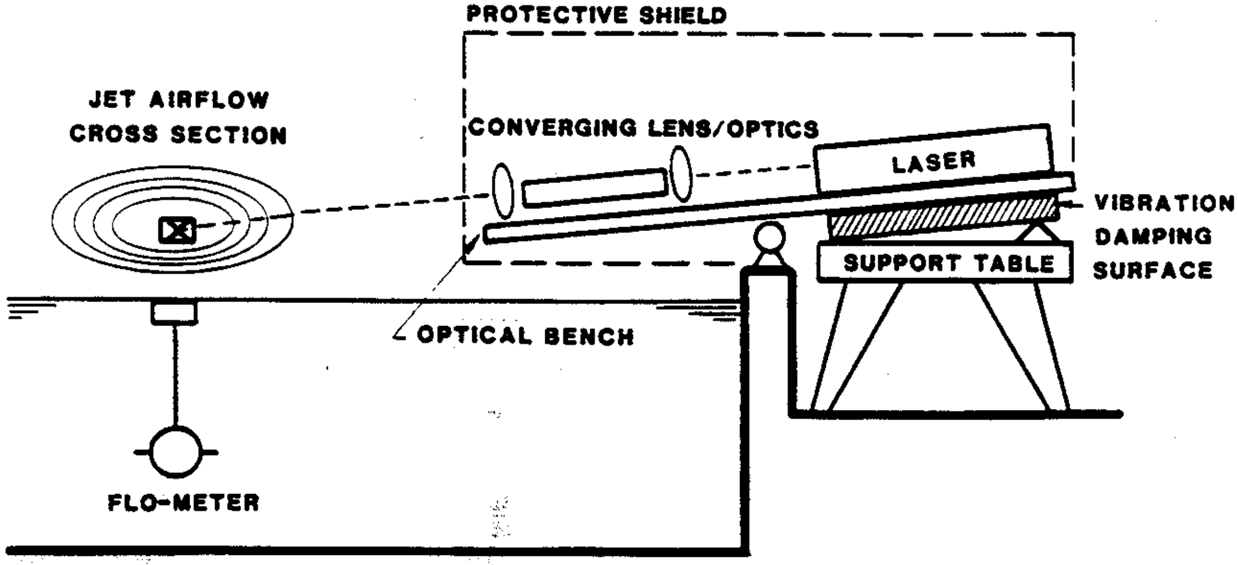
- Axial Velocity of Air Flow, V_A
- Velocity of Surface Current, V_W
- Water Flow Rate, q

Figure 2 . 1

EXPERIMENTAL SET-UP: SINGLE NOZZLE AIRFLOW TESTS



DETAIL of LDA SYSTEM



the point of focus. The calculated mean velocity of air/water/dust droplets within the mixed flow was considered as the airflow velocity. The axial measurement location with respect to the nozzle was adjusted by moving the carriage to new positions. Lateral adjustment was provided by movement of the carriage heave staff assembly. The high pressure manifold was carried on the basin carriage. Flexible hosing connected it to the pumping system and to a single water jet mounted on the heave staff at a fixed distance above the basin water surface. Figure 2.2 presents photographs of several elements of the test system and its operation. It should be noted that all the jets used in multiple nozzle tests, Figure 2.2(d) were identical and apparent differences are due to reflections.

The LDA optical bench was aligned at an angle to the water surface. This allowed measurement of the axial velocity at a fixed height of five centimeters above the surface. The converging lens and optics were situated at a distance from the jet centerline which corresponded to the focal length. This necessitated a protective shield for the short focal length lens as signal-to-noise ratio problems limited the range of focal lengths applicable. Additional details of the lateral motion assembly are shown in Figure 2.3 and LDA photographs in Figure 2.4.

B. Multiple Water Jet Tests: Figure 2.3 illustrates the experimental arrangement for investigating the influence of spatial variation on oil barrier effectiveness. Three equi-distant water jets were affixed to an extended lateral support assembly. Current flow velocities were recorded. The system included:

- fixed basin carriage
- fixed support assembly
- high pressure pumping system
- water filled basin
- video system and/or alternate recording method
- current flow-meter

Figure 2.5 shows the arrangement for multiple nozzle testing.

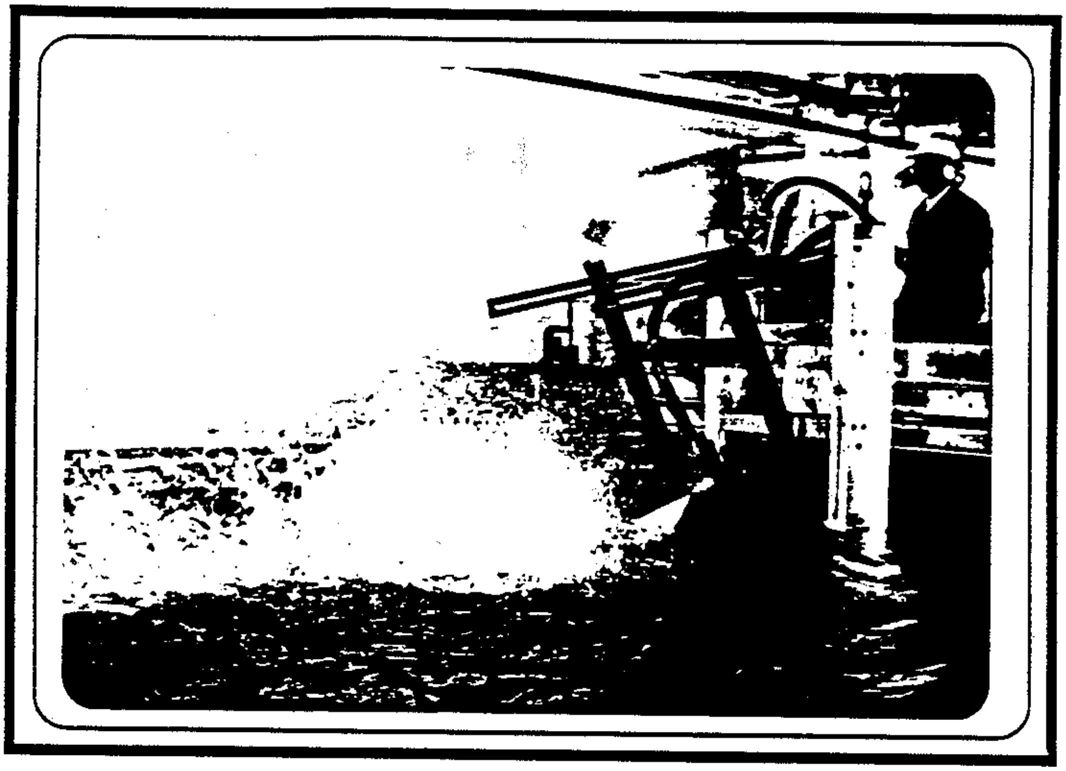
During preparation for the experiment, it was determined that the existing high pressure hosing between the triplex pump and manifold and water jets was not of a sufficient rating to permit the complete range of pressure testing. Therefore, the hosing and associated components were replaced with those having higher working and burst strength. Hosing between the manifold and the water jet nozzles was reduced from 3.81 cm to 2.54 cm (1 1/2 to 1 inch) inside diameter. The manifold was pressure tested for safety and three pressure gauges were replaced.

Figure 2.2
ELEMENTS of TEST APPARATUS

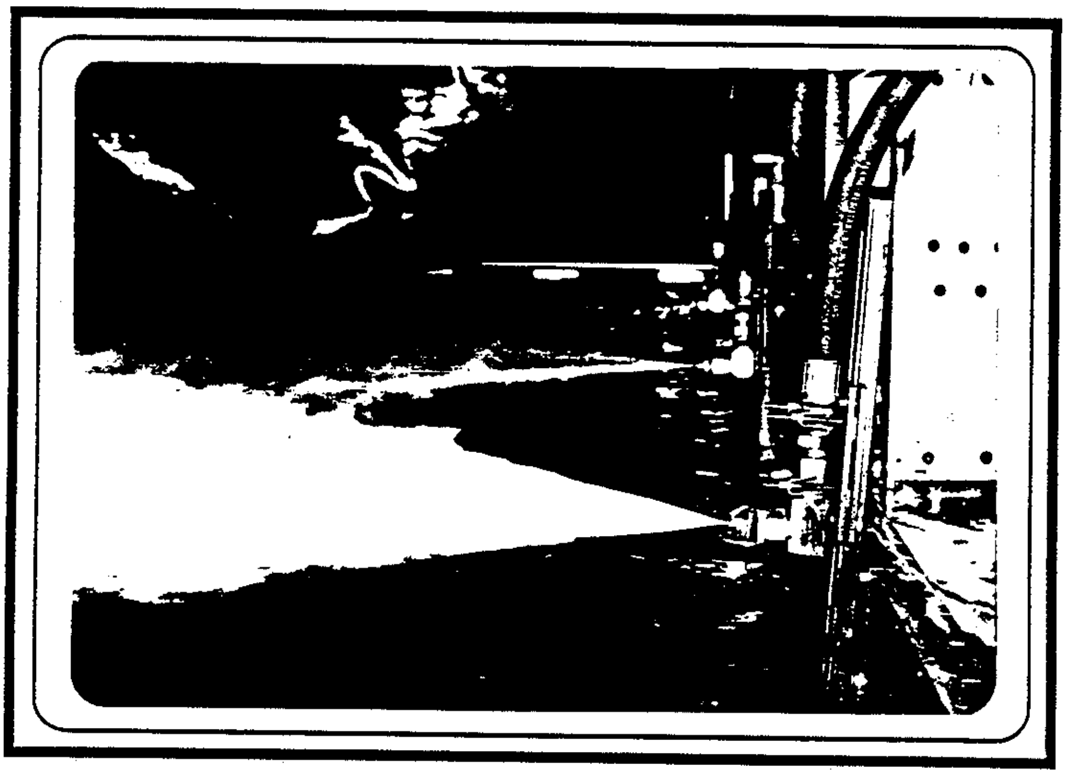
(A) High Pressure Triplex Pump System.

(B) Manifold Set-up For One Water Jet.

Figure 2.2 (cont.)
ELEMENTS of TEST APPARATUS



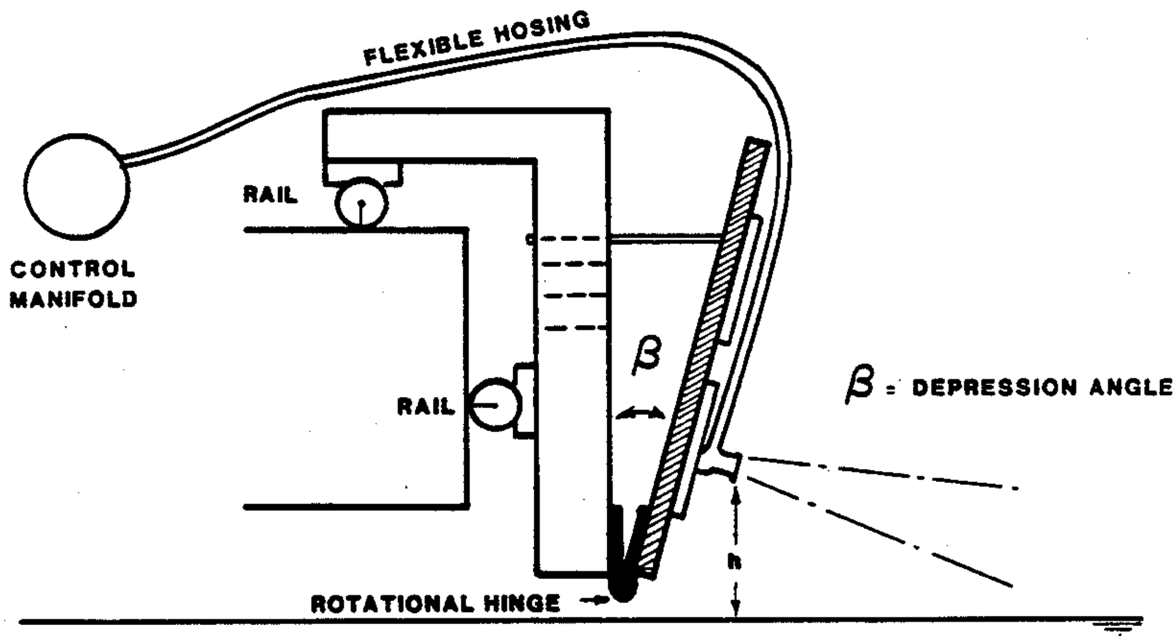
(C) Depression Angle 30° Test



(D) Multiple Nozzle Test

Figure 2.3

DETAIL of MULTIPLE WATER JET NOZZLE SUPPORT ASSEMBLY



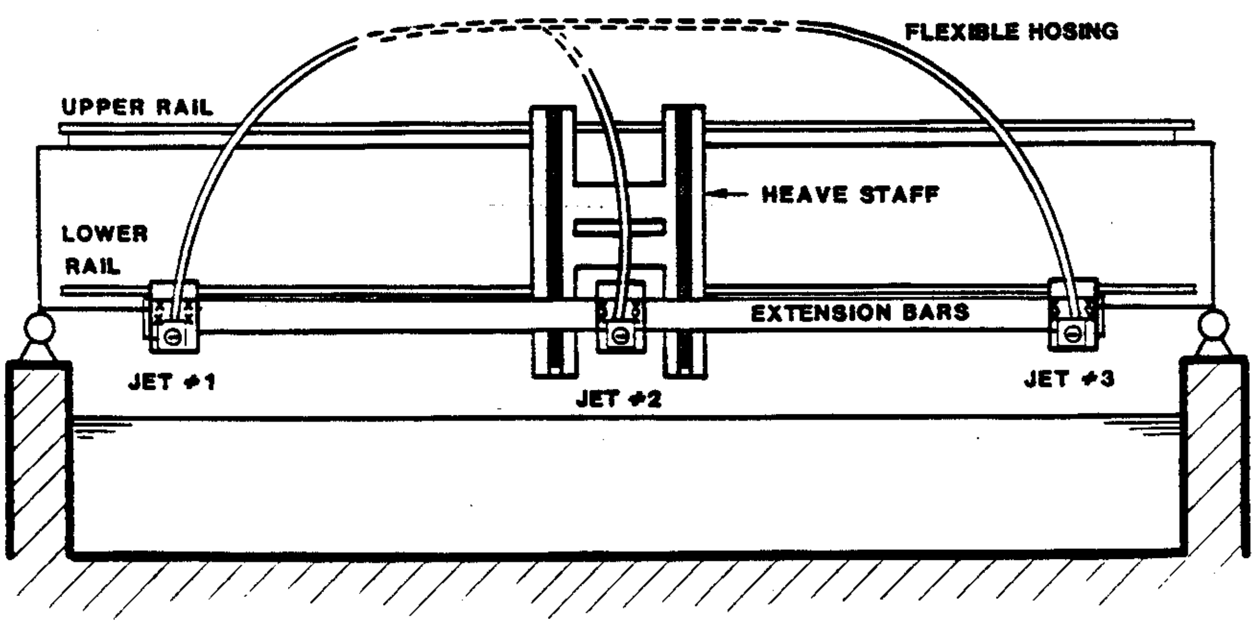
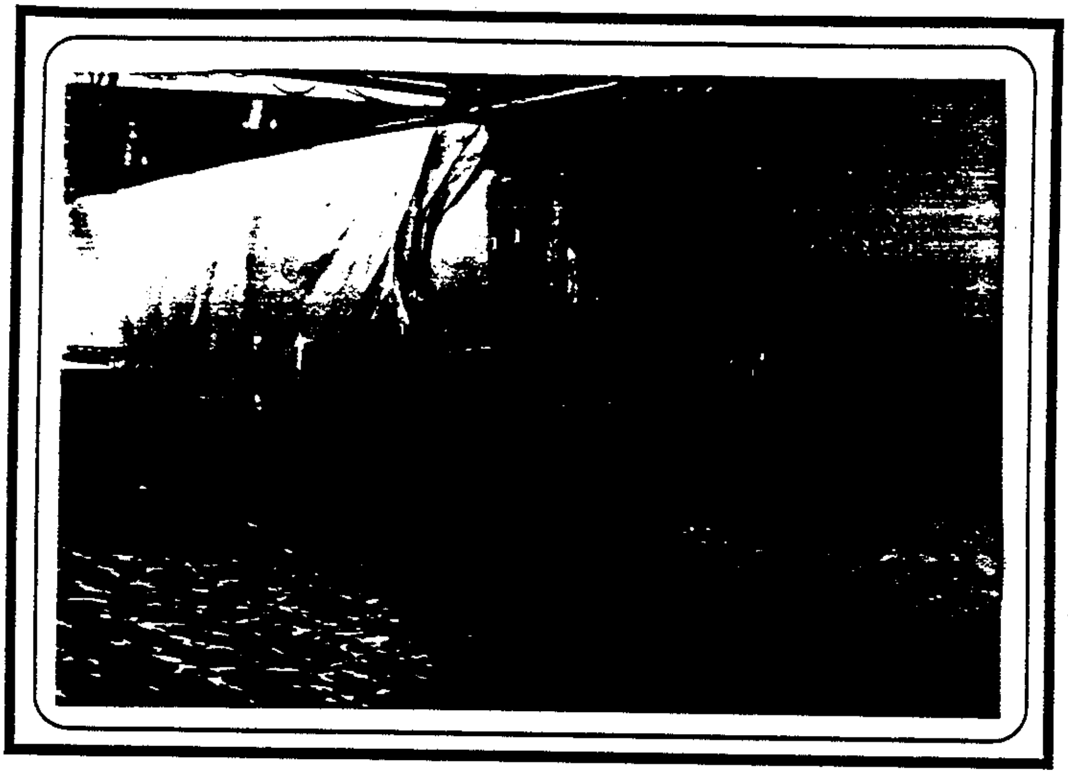


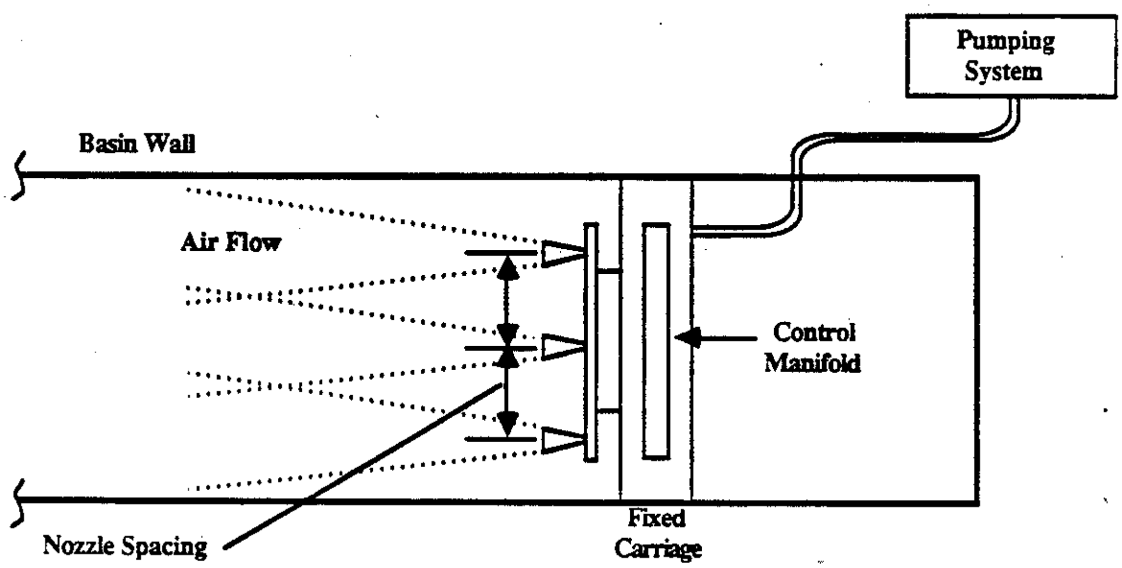
Figure 2.4
MEASUREMENTS of AIR FLOW and CURRENT FLOW



(A) Downstream View of Water Jet Air Flow with Stream Flow Probe.

(B) Laser Doppler Anemometer Measuring Water Jet Air Flow Velocity.

Figure 2.5
EXPERIMENTAL SET-UP: MULTIPLE WATER JETS



The laser doppler anemometer (LDA) system was situated at a fixed position along the side of the basin. Its components were mounted on a rigid light table which projected a few meters into the basin. This in turn was affixed to a one-half tonne slab of steel which served to reduce vibrations. The laser was approximately 1.5 meters in length. Its light beam was split into two parallel beams by a collimator and focussed through a 600 mm focal length lens which was mounted near the projecting end of the light table. This focusing gave rise to a known fringe interference pattern. The fringe pattern acted as a measuring grid for particles moving through it. A photo-multiplier on the lens constantly monitored light reflected back and counted the progressive passage of particles through the fringes as a function of time.

The LDA was calibrated at the beginning of the tests using a rotating disc of accurate known speed. With the progress of the experiments the laser enclosure was subjected to jet and induced wind slamming and mist. During Test No. 13 of Nozzle 4040 when the height of the nozzle was lowered to 0.075 m (3-in) the LDA was soaked and the light beam disappeared. The LDA was taken apart and lenses were cleaned, dried and reassembled. An alignment check was done in-situ and recalibration was performed, using the rotating disc, from the auxiliary carriage. The calibration value was close to the original calibration. However, some change in readings was observed and it was attributed to minor misalignment or dirt on the lenses. The effect of this was a reduction of signal to noise ratio and additional filtering was required. The effect of different filter settings was examined and was found to produce little or no effect on the measured velocities in most cases, and it was estimated that the difference would be of the order of 5 - 10% on the average. This was acceptable as an experimental error and it was reasonable to proceed with the test program to meet scheduling requirements.

The Dixon stream flow probe was calibrated prior to testing and checked midway through the test program. Misalignment of the probe during one series of tests was observed and these erroneous current flow results were subsequently corrected. The probe was a propeller-like device approximately one centimeter in diameter. It was set at one centimeter below the water surface in most tests in order to measure the surface flow. However, wave interference was observed at this depth and more consistent results were obtained when the probe depth was increased to three centimeters. (The water current velocity data are tabulated in Appendix A, but will not be further analyzed in this report).

A photographic record of individual elements of the apparatus and operational aspects of the testing has been accumulated. A limited video recording is also available, although mist formation tends to obscure vision.

Pressure measurements were recorded manually from gauges mounted on the water jet cut-off valve at the manifold. Values of flow rate are those given by the nozzle manufacturer and shown in Table 1 of Appendix A.

2.3 Test Matrix

Thirty-four single nozzle parametric tests were carried out during the first phase. Table 2.2(a) provides a breakdown of the single nozzle air flow test program into five categories:

- nozzle geometric configurations testing
- variable height testing
- pressure variation testing
- depression angle testing
- spatial variation testing

A series of eleven flat or fan-type nozzles were examined under fixed conditions. Spread angles varied between 25° and 65°. Aperture diameter varied between 0.191 and 0.465 cm (0.075 and 0.183 inches). Pressure was varied between 6,900 and 20,680 kPa (1000 and 3000 psi) with a reference value of 13,790 kPa (2000 psi). A standard 15.2 cm (6 inch) distance of the nozzle above the water level was selected. Vertical heights ranged from 7.6 to 30.5 cm (3 to 12 inches). Depression angles varied between level and 30°.

Four additional series of tests explored the variation in current velocity with depth below the water surface. The effect on the depth profile due to pressure and depression angle were further studied at particular locations in the jet stream. As stated earlier, induced water current measurements are reported in Appendix A but will not be analyzed in this report.

Following completion of single nozzle testing the experimental basin arrangement was modified to allow operation of three identical water jet nozzles. Table 2.2(b) lists multiple nozzle tests. Three sets of tests were carried out in order to investigate the influence of air velocity distributions for the case of multiple nozzles.

TABLE 2.2
TEST MATRIX

A. <u>SINGLE NOZZLE AIR FLOW TEST PROGRAM</u>

1. NOZZLE TYPE TESTS

NOZZLE TYPE DESIGNATION: AABB where:
AA = angular spread (degrees
BB = Aperture Diameter
10 = .191 cm (.075 in.), 20 = .269 cm (.106 in.),
30 = .330 cm (.130 in.), 40 = .381 cm (.150 in.),
60 = .465 cm (.183 in.)

→ increasing aperture; ↓ increasing flare angle

2510	2520	**2530	2540	
4010	4020	4030	4040	4060
**6510	6520	6530	--	

Pressure = 13790 kPa (2000 psi)
Jet Position; level, h = 15.2 cm (6 inches)
**Not Tested

2. VARIABLE HEIGHT TESTS

NOZZLE	HEIGHTS			
4030	15.2 cm (6") STD	7.6 cm (3")	22.9 cm (9")	30.5 cm (12")

Pressure = 13790 kPa (2000 psi)

3. PRESSURE VARIATION TESTS

NOZZLE	PRESSURES kPa (PSI)				
2520	6900 (1000)	10340 (1500)	13790 (2000)	17240 (2500)	20680 (3000)
4030					
6520					

Jet Position; level, h = 15.2 cm (6 inches)

4. DEPRESSION ANGLE TESTS

NOZZLE	DEPRESSION ANGLE			
6520	0° STD	7.5°	15°	30°
4030				

Pressure = 13790 kPa, (2000 psi)
Jet Position, h = 15.2 cm (6 inches)

5. CURRENT DEPTH PROFILE TESTS

NOZZLE	DEPTH				
4030	1cm	3cm	5cm	7cm	9cm

NOZZLE ANGLE			
0° STD	7.5°	15°	30°

Pressure = 6900 kPa, 13790 kPa
(1000 psi), (2000 psi)

B. MULTIPLE NOZZLE TEST PROGRAM

1. SPATIAL VARIATION TESTS

NOZZLE	NOZZLE SPACING		
4020	1.37 m (4.5′)	1.98 m (6.5′)	2.74 m (9.0′)

Jet Position, h = 15.2 cm (6 inches), level
Pressure = 13790 kPa (2000 psi)

2.4 Test Procedure

A consistent test procedure was adopted and followed during testing. In general a complete nozzle test consists of approximately 15 individual trials, measuring data at two cross sections and at six points along the centerline.

During each individual trial the triplex pumping system was engaged and the diesel engine revolution rate increased to an adequate level. The control valve on the manifold for the discharge line was progressively closed until the required pressure reading in the nozzle line was attained. At this juncture readings of stream flow probe and laser doppler anemometer system were started. Successive sampling over a one minute time interval allowed determination of a mean velocity corresponding to steady state. A longer period was not employed to avoid distortions arising from wave reflections from the end of the basin and formation of a dense mist. Each trial was followed by a four minute interval for the basin to return to a settled condition.

3. TEST RESULTS

3.1 Data Representation

A complete set of acquired high pressure water jet test data was reduced and presented in Table 2 of Appendix A. Each record of this table contains a series of individual data points accumulated at a particular test condition. A total of 38 records are tabulated.

A typical record is illustrated in Figure 3.1 and Figure 3.2 for nozzle type 40-10 which was investigated under the standard test conditions: 13790 kPa (2000 psi) pressure, 15.2 cm (6 inch) height and 0° depression angle. Air flow velocity was measured 5 cm above the water surface. Longitudinal velocity profile along the water jet centre-line is illustrated in Figure 3.1. Data points span a range between 3.05 meters (10 feet) and 12.2 meters (40 feet) in distance from the nozzle. An exponential decay curve was found to provide a good fit to the data. However, extrapolation of air flow and current velocity curves to regions close to the nozzle or beyond 15 meters (50 feet) should be viewed cautiously.

Cross-section air flow velocity profiles, Figure 3.2 are given at 3.05 meters (10 feet) and 6.1 meters (20 feet) from the nozzle. In both cases data measurements were obtained between negative .305 meter (1 foot) and 1.83 meters (6 feet) distance offset from the water jet centreline. The cross-section of the air velocity profile was found to be best represented by a normal or bell shaped curve. Since data was obtained primarily on one side of the centreline, it was impossible to entirely rule out asymmetries in the water jet or errors in nozzle alignment. Within this limitation the normal shaped curve provided a good representation of the measured velocity cross-section and allowed an approximation of the trailing off velocities beyond the range of measurement. There was a problem in fitting curves to the data only where cross-sections showed a relatively unchanged velocity over the offset range and considerable scatter. This occurrence was observed for current flows in certain tests with nozzles having a 65° spread angle.

Longitudinal profiles and cross-sections of air flow showing measured data points are compiled in Appendix B. All comparative nozzle tests at standard conditions are included. In later sections of the report, a few families of curves are presented which summarize trends of variation in air flow with particular parameters such as pressure, height of nozzle and depression angle.

FIGURE 3.1

AIR FLOW DATA

TEST NO. 3 ALONG CENTERLINE

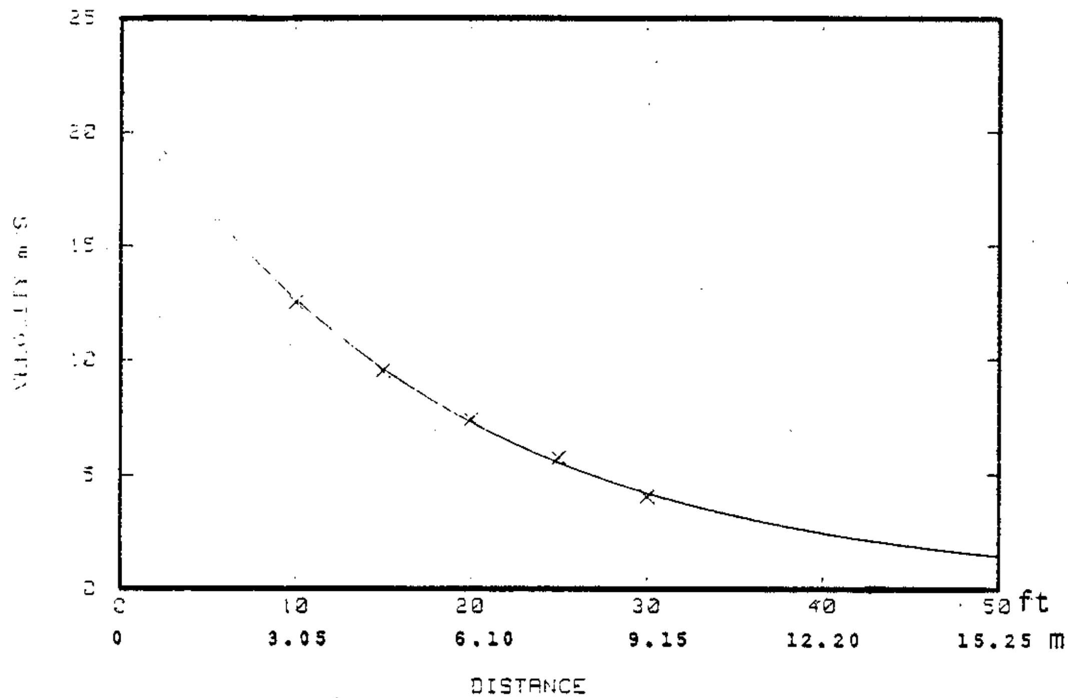
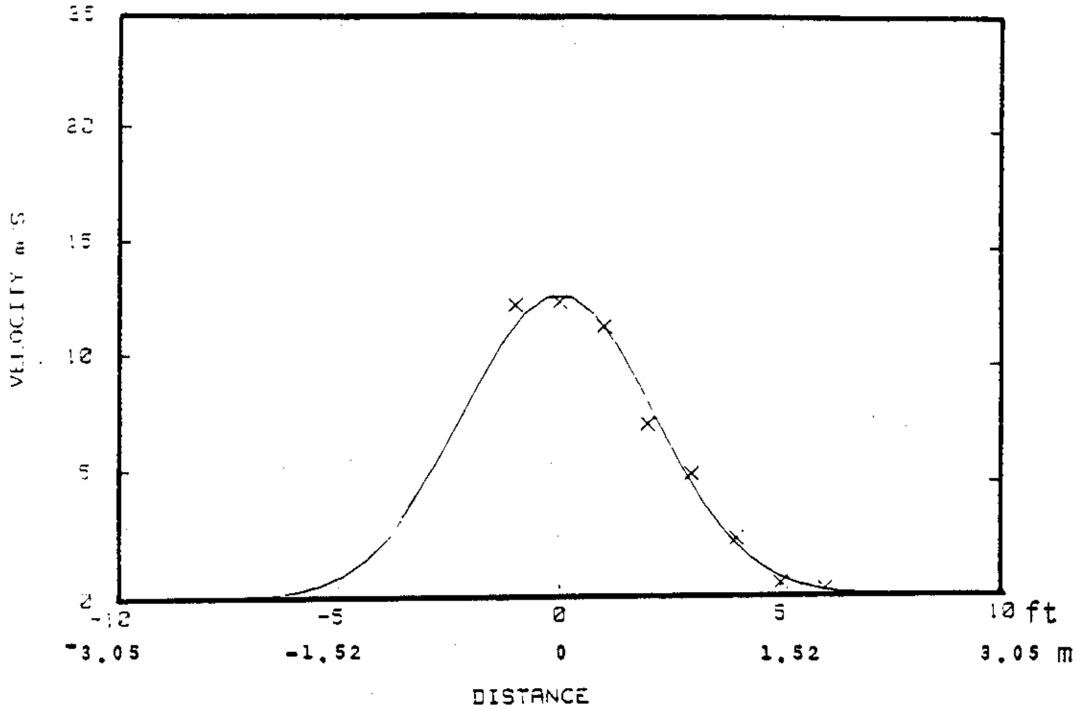


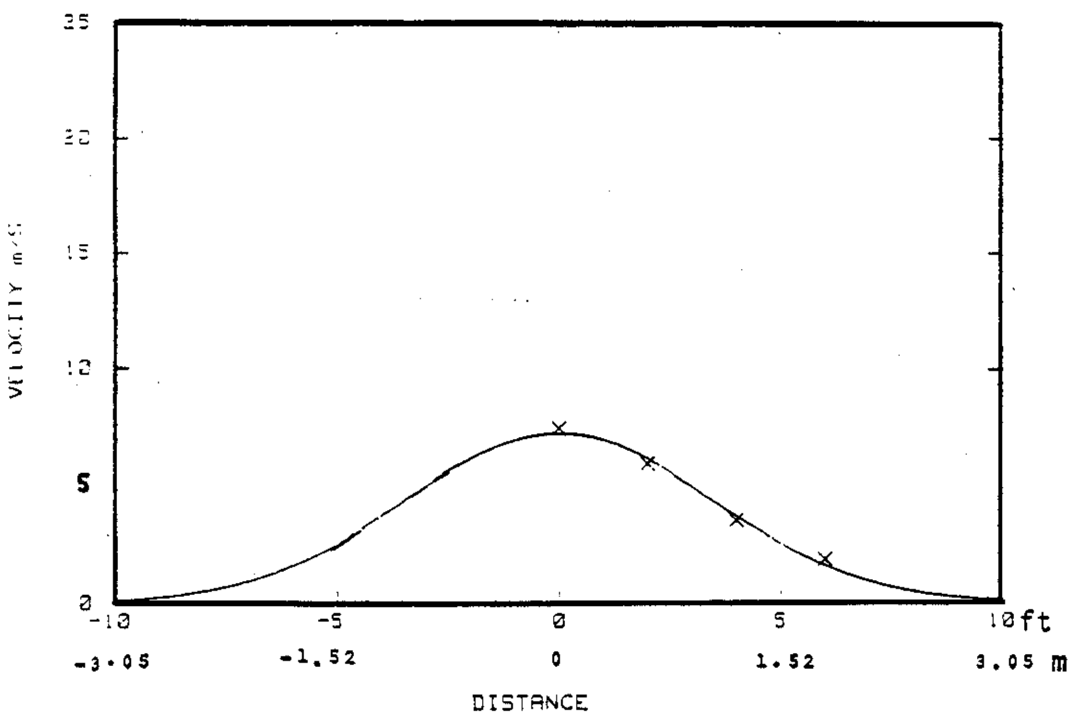
FIGURE 3.2

AIR FLOW DATA

TEST NO. 3 AT 3.05 m (10 ft)



TEST NO. 3 AT 6.1 m (20 ft)



3.2 Summary of Results

Appendix A contains tables of data and results. Table 1 of Appendix A describes the physical characteristics of all the fan-type nozzles investigated and it tabulates the variation of maximum flow rate with change in pressure. The flow rate depends linearly on the nozzle aperture.

Table 2 of Appendix A contains the air flow velocity and current flow data obtained during the testing program. Records 1 through 10 and record 19 provide comparative information on air flow and current flow for the series of nozzles. Pressure was 13790 kPa (2000 psi), depression angle 0 degrees and nozzle height 15.2 cm (6 inches) during these tests. Nozzle spread angles of 25 degrees, 40 degrees and 65 degrees were investigated. Nozzle aperture varied between 1.9 mm (0.075 inches) and 4.65 mm (0.183 inches). Records 11 through record 28 describe water jet performance for variations in pressure, nozzle height and depression angle. Multiple nozzle data are presented in records 29, 30 and 31. Measurement of the current velocity at different stream flow probe depths was explored in the later records as a function of the experimental parameters.

Table 3 of Appendix A provides a summary of the centreline air flow and current flow velocities as a function of distance from the water jet. The exponential curve fit for each sampled set of velocity data is expressed in terms of amplitude at zero distance and an exponential decay constant. The velocity at any point downstream from the nozzle is given by:

$$\text{VELOCITY} = \text{CONSTANT} * e^{(\text{EXPONENT} \times \text{DISTANCE})}$$

However, caution should be employed in extrapolating beyond the measurement range.

The effectiveness of the water jet nozzles under particular operating conditions may be expressed in terms of air flow flux. Flux values are calculated and tabulated for the different parametric tests. Flux is calculated by numerical integration using the normal flux density function with the mean equal to 0. The air flow flux is given by:

$$\text{AIR FLOW FLUX} = \int_{-\infty}^{\infty} \frac{A}{\text{Sigma}\sqrt{2\pi}} e^{-1/2(Y/\text{sigma})^2} dy$$

where A and SIGMA are determined by the curve fitting to experimental data. The standard deviation SIGMA is a measure of the broadness of the velocity cross-section. Values of the flux coefficient, A and broadness, SIGMA, have been calculated for all cross sections and are listed in Table 4, Appendix A.

3.3 Parametric Variation Results

A. Nozzle Spread Angle (Flare Angle)

Figure 3.3 illustrates the trend in air flow velocities along the water jet centreline as the nozzle spread angle increases and the aperture was held constant. The air flow velocity curves exhibited a similar exponential decay with distance and were found to decrease approximately linearly with increased angle. The flux was spread over a proportionately greater area.

B. Aperture

Variation of centreline velocity profiles with nozzle aperture is shown in Figure 3.4. Air flow velocities were approximately double in value for nozzle 4060 with an aperture of 4.65 mm (0.183 inches) than for nozzle 4010 or 4020 with apertures of 1.9 and 2.7 mm (0.075 and 0.106 inches) respectively. The exponential decay was similar for each curve. That the two smallest aperture nozzles were identical is assigned to experimental error.

C. Nozzle Height

The influence of the vertical height at which a water jet was positioned above the water surface is depicted in Figure 3.5. Air flow was observed to decrease slightly as the jet was lowered from 30.5 cm (12 inches) to 15.2 cm (6 inches) in height. It dropped by a further 40 percent when the nozzle position was lowered to 7.6 cm (3 inches). In all cases the exponential decay with distance from the nozzle remained a valid fit to the data.

D. Depression Angle

A small increase in depression angle caused a significant reduction in air flow flux. Figure 3.6 shows centreline velocity curves for depression angles between 0 degrees (level) and 30 degrees. Velocities were halved every 7.5 degrees for the type 4030 nozzle tested. Below 15 degrees the air flow velocities downstream from the nozzle were essentially zero.

FIGURE 3.3

AIR FLOW DATA

NOZZLE APERTURE = .106 mm

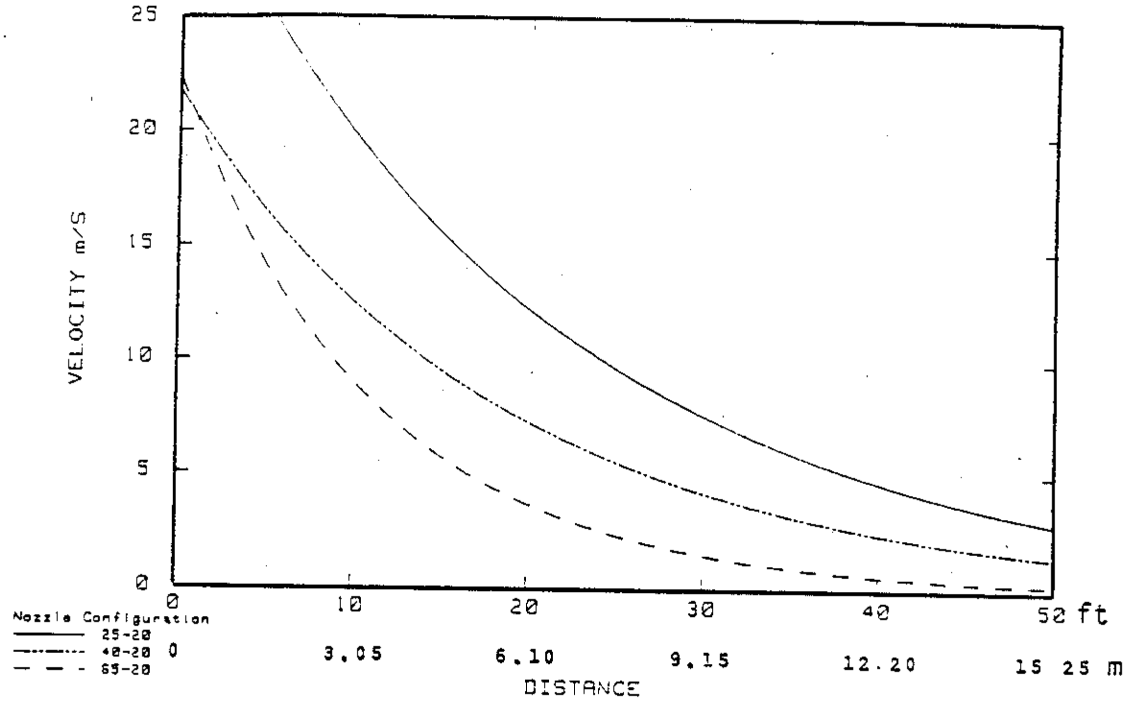


FIGURE 3.4

AIR FLOW DATA

VARIOUS NOZZLE APERTURES

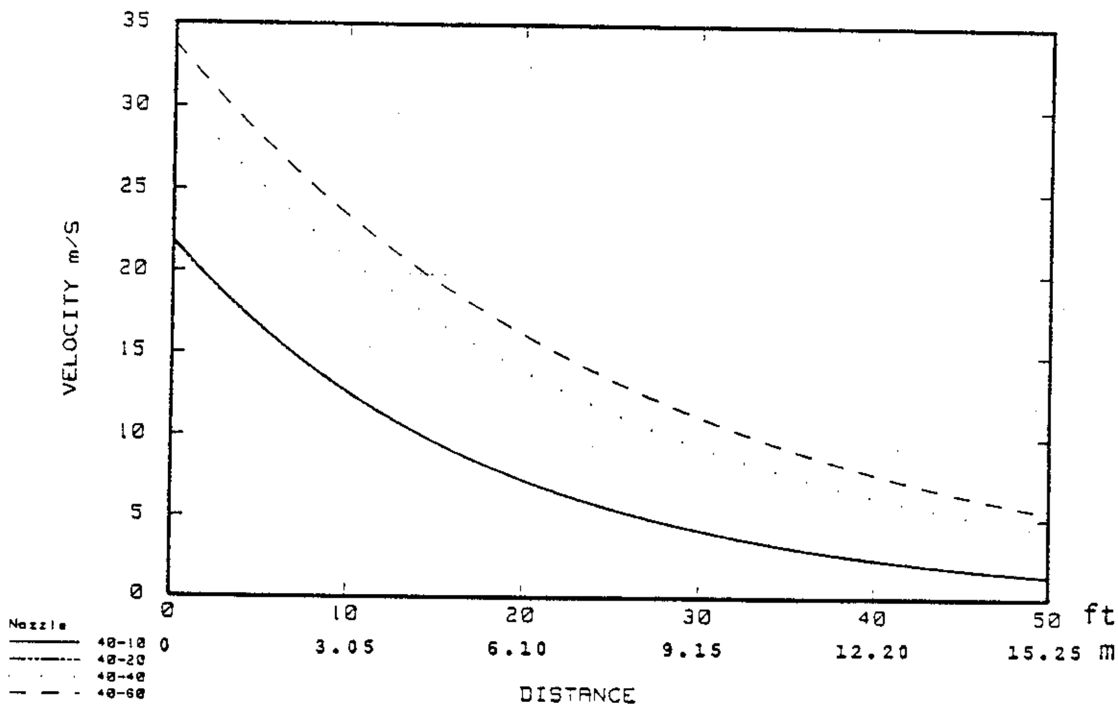


FIGURE 3.5

AIR FLOW DATA
FOR NOZZLE TYPE 4040

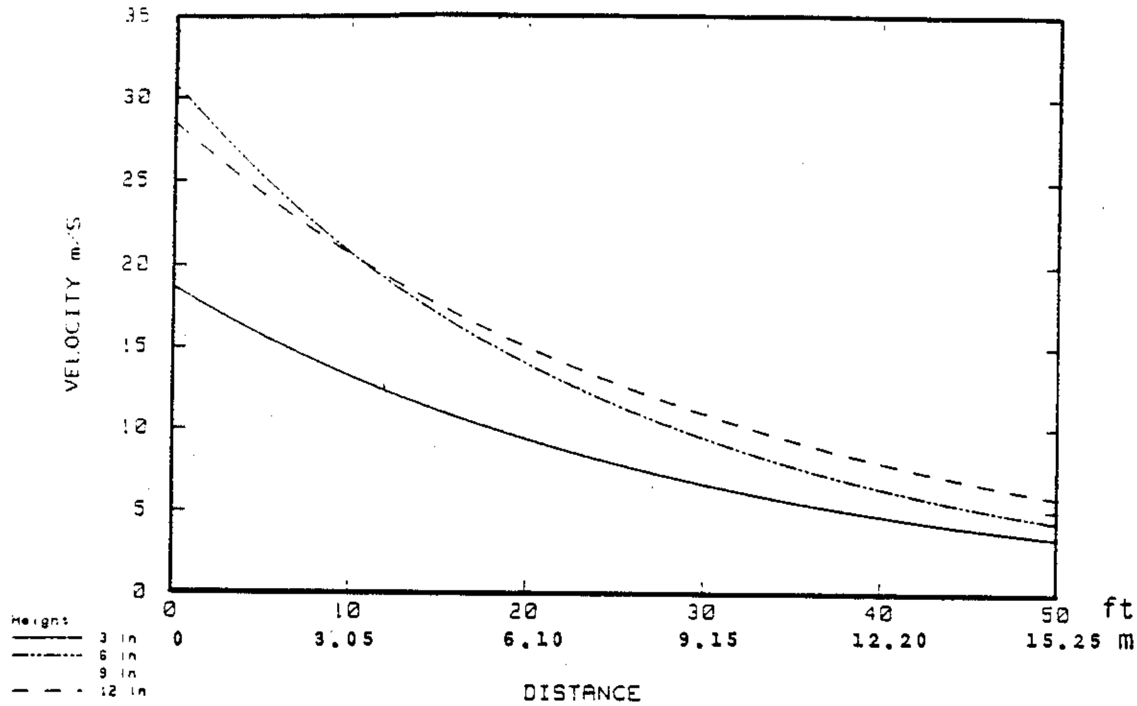
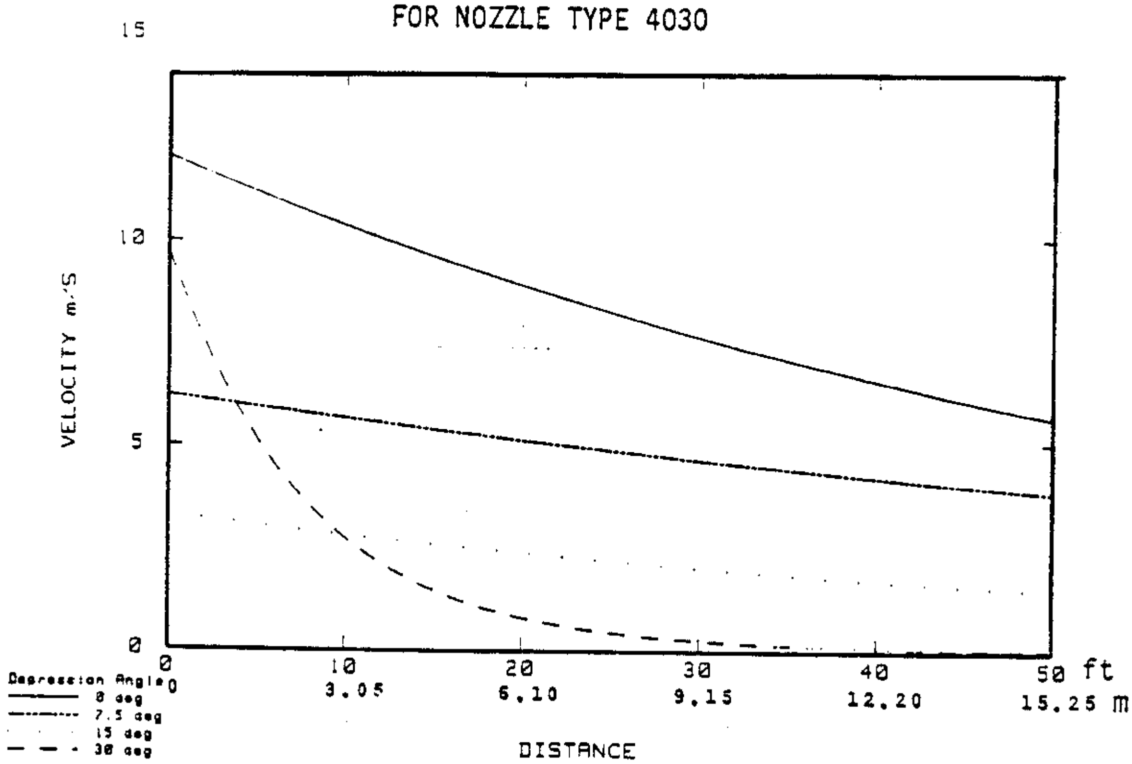


FIGURE 3.6

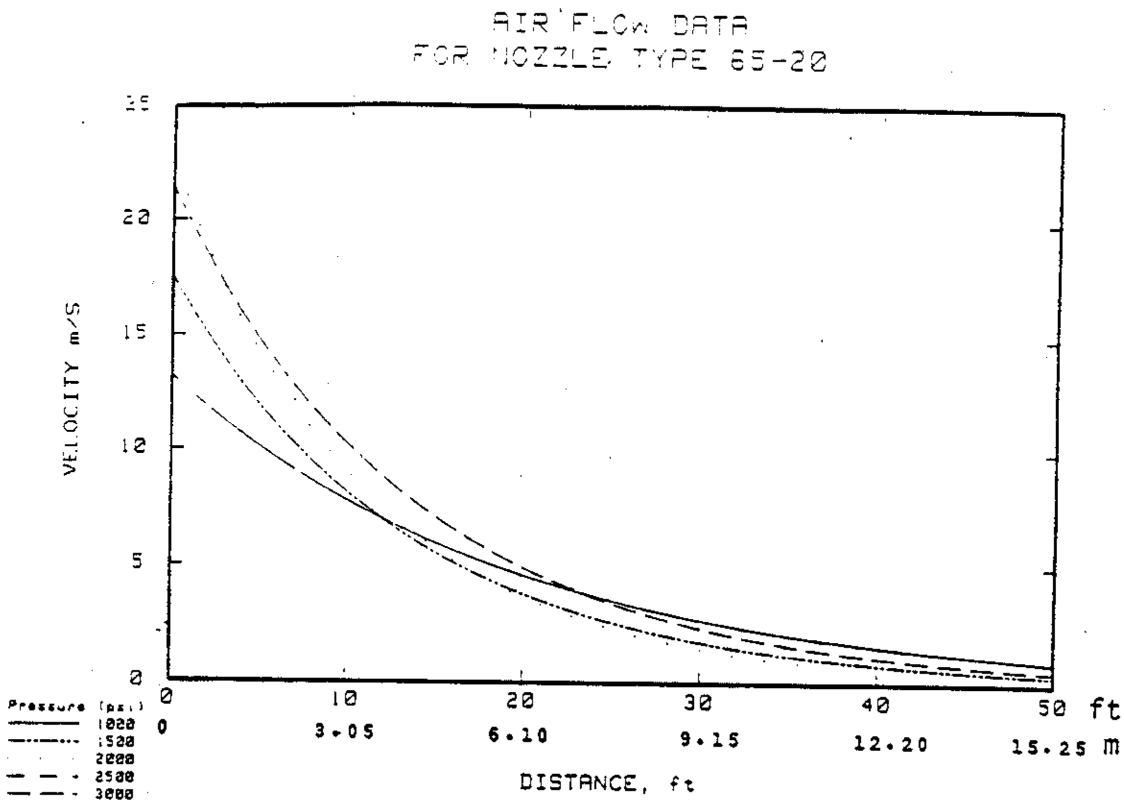
AIR FLOW DATA
FOR NOZZLE TYPE 4030



E. Pressure

A marginal increase in air flow velocity profiles and cross-sections was observed as pressure was varied from 6900 kPa to 20680 kPa (1000 psi to 3000 psi). Pressure variation data was recorded for three nozzle types. Figure 3.7 presents data for nozzle 6520 which has a spread angle of 65 degrees and aperture of 2.7 mm (0.106 inch). The curves representing velocity profiles for different pressures are intertwined both for centreline profiles and cross-sections. The lower values at 13790 kPa (2000 psi) do not compare well with the other curves since they were derived from earlier nozzle configuration tests where different nozzle alignment and operational conditions applied. The bias of velocities towards higher values was a problem common to all later tests and was caused by filtering of LDA signals. Figure 3.8 shows a trend towards higher velocity profiles with increased pressure for nozzle 2520, which had a spread angle of 25 degrees and the same aperture as previously. However the cross-section air flow velocity distribution was a maximum at 10340 kPa (1500 psi) for a distance of 3.05 m (10 feet) from the nozzle. The minimum was at 6900 kPa (1000 psi) and the higher pressures were in between. Figure 3.9 shows a clear trend towards increasing air flow velocity profiles with increased pressure for nozzle 4030. This nozzle has a spread angle of 40 degrees and an aperture of 3.3 mm (0.130 inches).

FIGURE 3.7


AIR FLOW DATA
FOR NOZZLE TYPE 65-20
VELOCITY m/S
25
20
15
10
5
0
0
10
20
30
40
50 ft
0
3.05
6.10
9.15
12.20
15.25 m
DISTANCE, ft
Pressure (psi)
1000
1500
2000
2500
3000

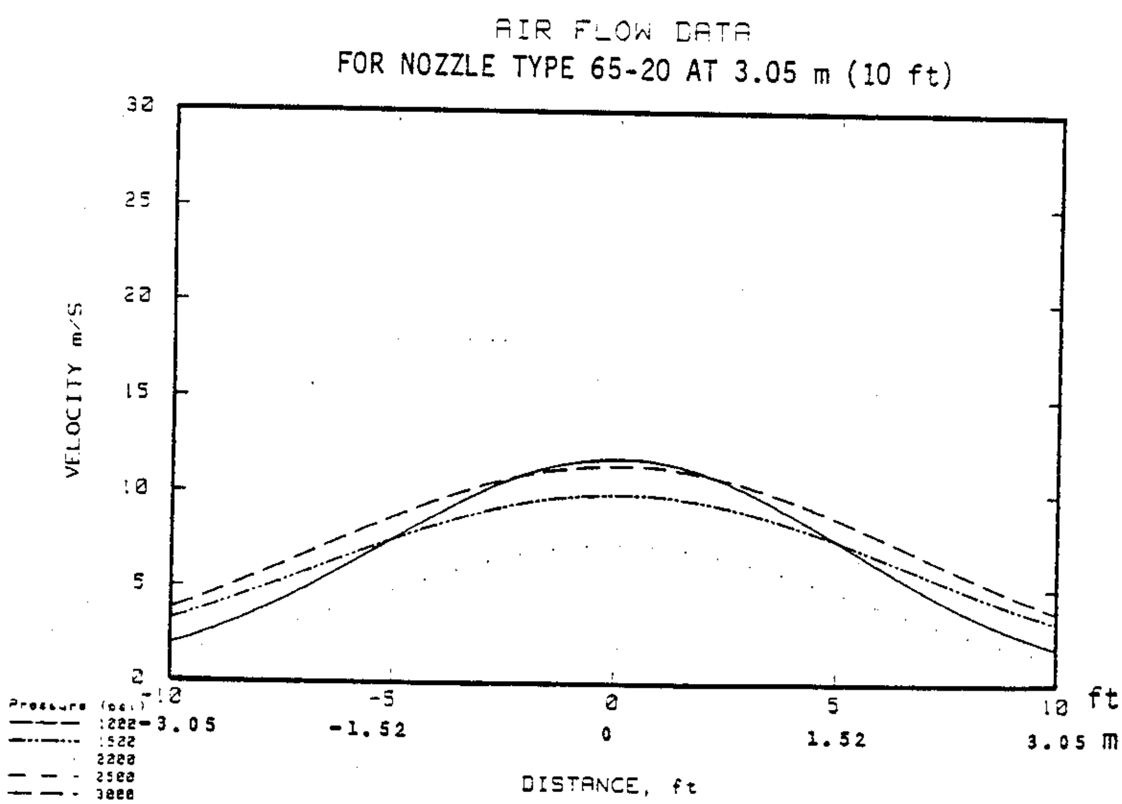
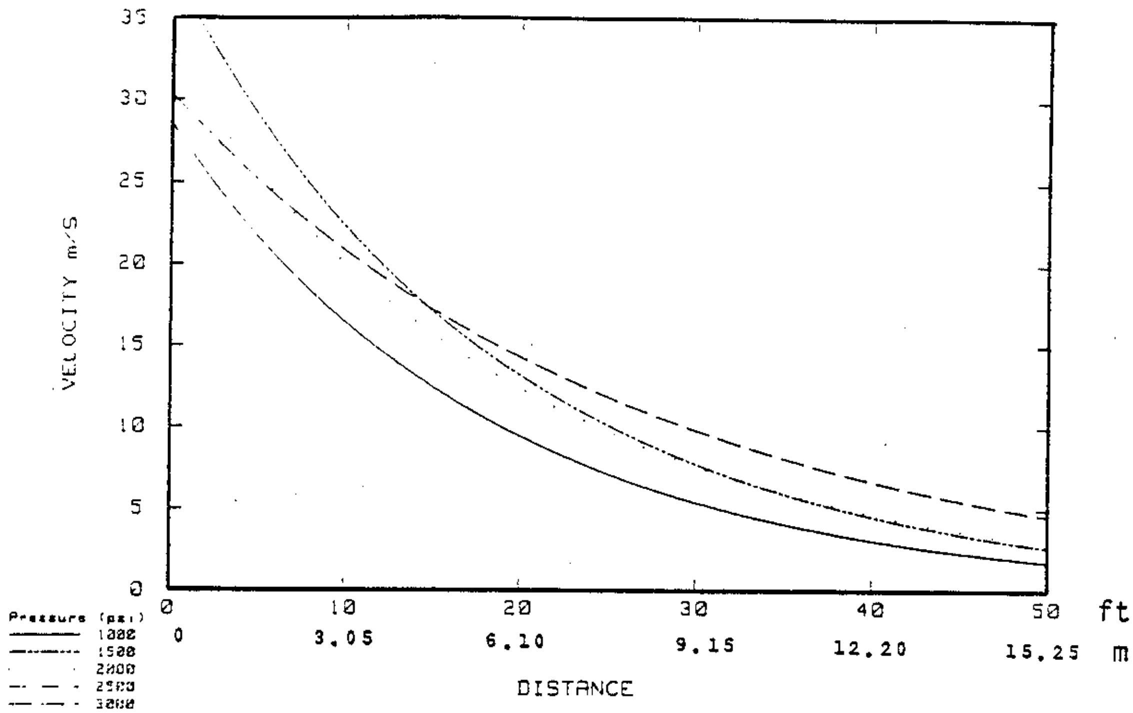

AIR FLOW DATA
FOR NOZZLE TYPE 65-20 AT 3.05 m (10 ft)
VELOCITY m/S
30
25
20
15
10
5
0
-10
-5
0
5
10 ft
-3.05
-1.52
0
1.52
3.05 m
DISTANCE, ft
Pressure (psi)
1000
1500
2000
2500
3000

FIGURE 3.8

AIR FLOW DATA

FOR NOZZLE TYPE 2520



AIR FLOW DATA

FOR NOZZLE TYPE 2520 AT 3.05 m (10 ft)

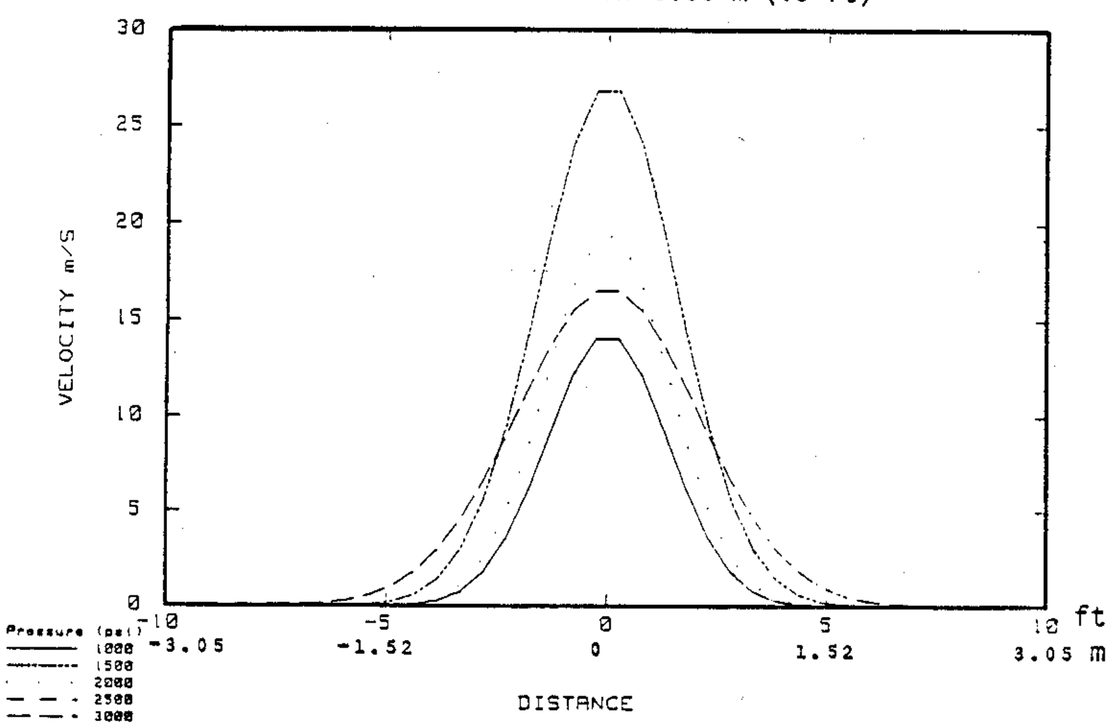
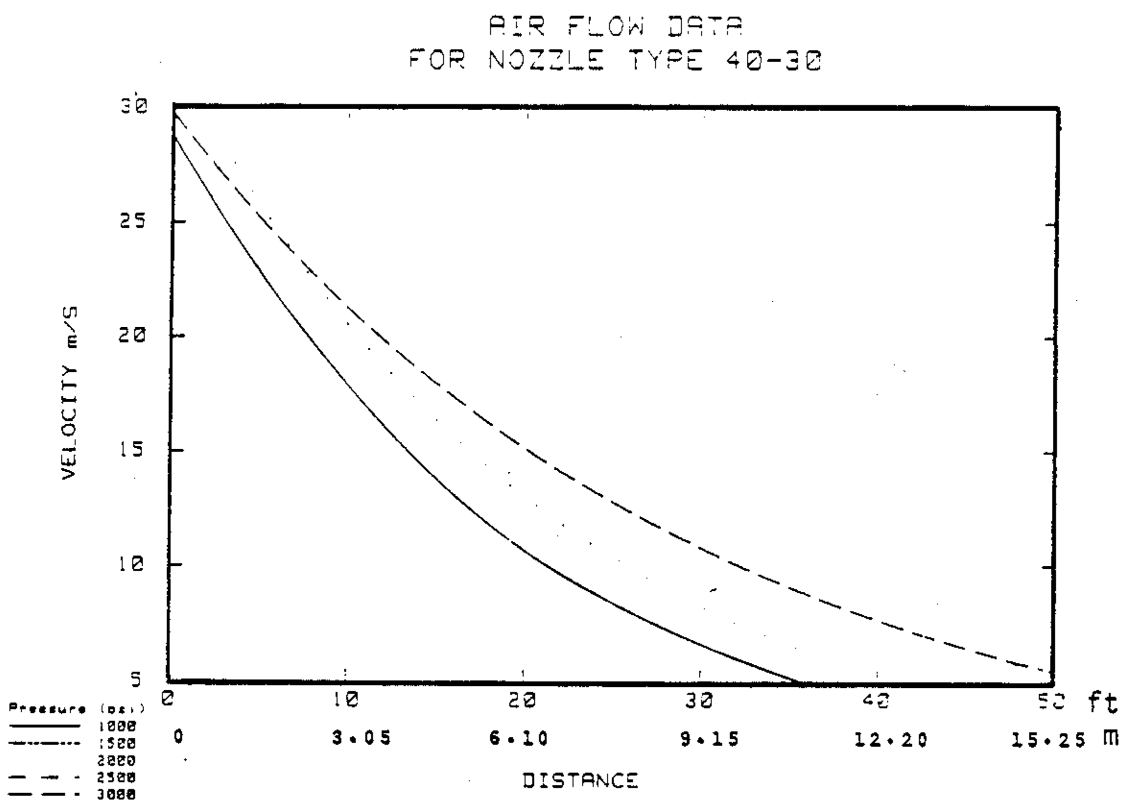


FIGURE 3.9


AIR FLOW DATA
FOR NOZZLE TYPE 40-30
VELOCITY m/S
30
25
20
15
10
5
0
10
20
30
40
50 ft
0
3.05
6.10
9.15
12.20
15.25 m
DISTANCE
Pressure (psi)
1000
1500
2000
2500
3000

3.4 Discussion of Results

The significant parameters influencing the effectiveness of high pressure water jets as an oil spill barrier were investigated through a series of parametric tests.

Figure 3.10 presents a comparison of nozzle efficiency. The first series of curves illustrate the air flow velocity for four nozzles each with 40 degree spread angles, but having increasing apertures. The curves collapse together such that there is only a marginal velocity difference between upper and lower bounds as formed by the two smallest aperture curves. The larger aperture values fall in between. A similar collapsing of air flow data is observed in the second graph, which compares three nozzles with constant aperture and varied spread angle.

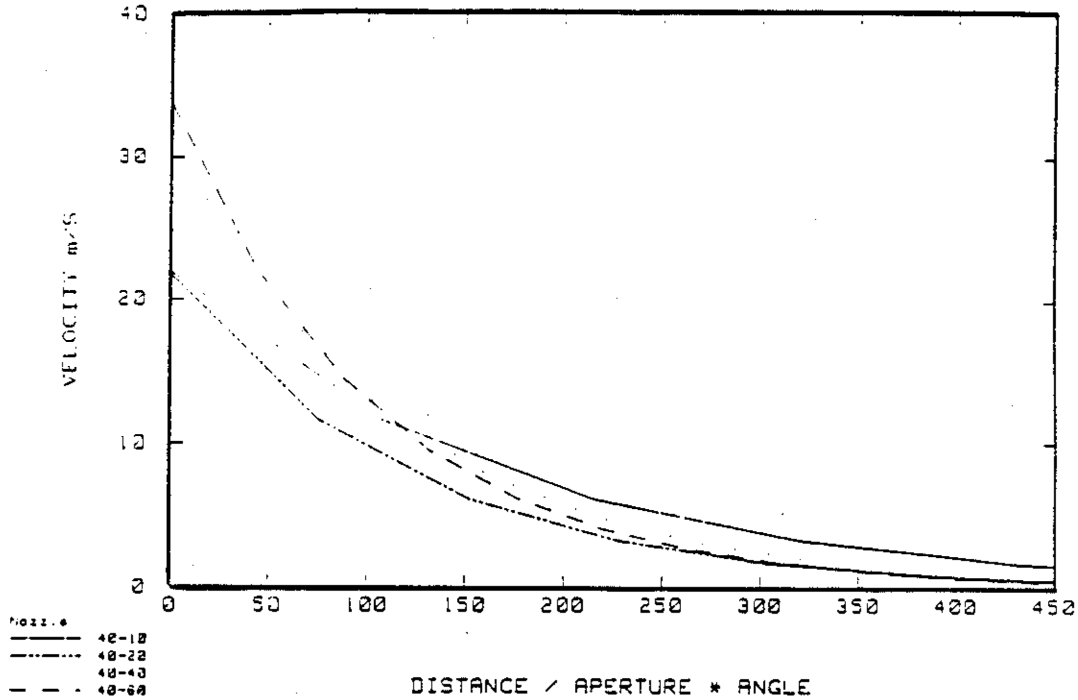
The significance of the comparative ratio is that it establishes comparisons of velocity which take into account the broadness of the velocity cross-sections. A narrow jet should be expected to show higher centreline velocities, but a sharper drop off in velocity outward from the jet centreline. Therefore the correction for nozzle spread angle establishes corresponding distance parameter values at which different nozzles may be compared. The collapsing of the air flow curves indicates a similarity in the effectiveness of all the nozzles examined.

The air flow velocity flux was found to remain essentially constant for water jet nozzles which have varied spread angles and constant aperture. Figure 3.11 shows flux as a function of broadness SIGMA. SIGMA is divided by radian spread angle and distance downstream. Flux is divided by nozzle flow rate. The two points corresponding to the two cross-sections obtained for each nozzle are plotted with straight lines between their end points. The 4010 nozzle shows the largest ratio of flux to flow rate. Large aperture nozzles at the same 40 degree spread angle have progressively smaller ratios. Similarly, the 2510 nozzle has the largest ratio for the 25 degree spread angle nozzles. Only one 65 degree nozzle is represented. However the trend suggests that a 6510 nozzle would provide the overall optimum ratio of air flow flux to flow rate.

FIGURE 3.10

AIR FLOW DATA

APERTURE VARIATION WITH SPREAD ANGLE = 40°



AIR FLOW DATA
NOZZLE APERTURE = .106 mm

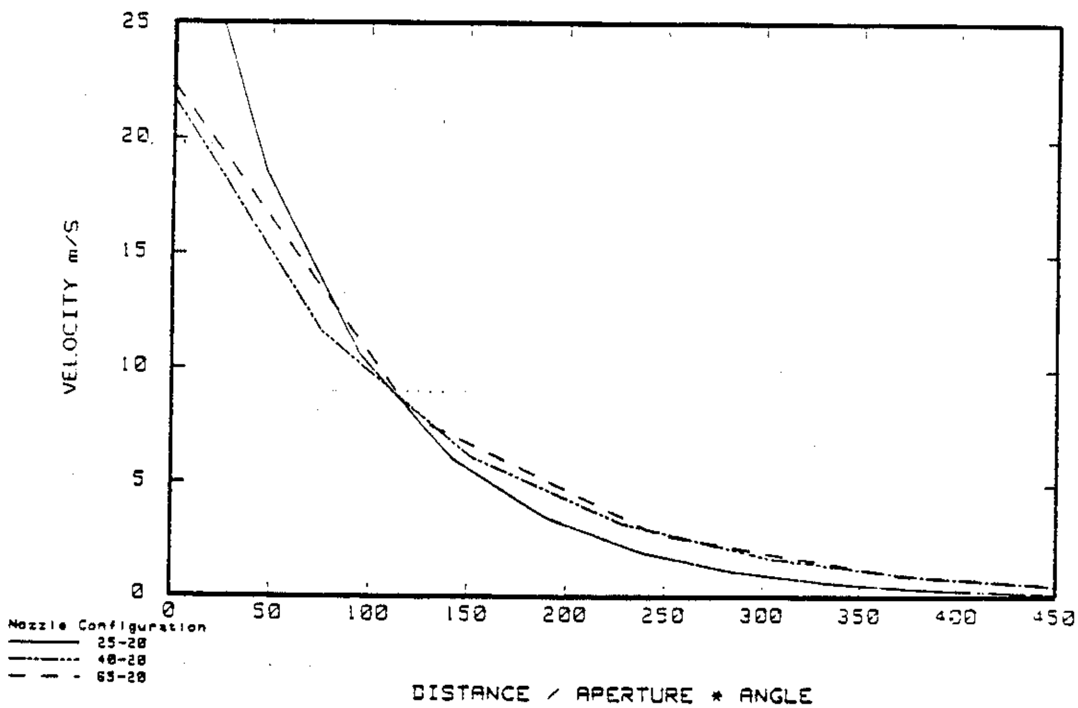


FIGURE 3.11
AIR FLOW DATA
NON-DIMENSIONAL FLUX VARIATION

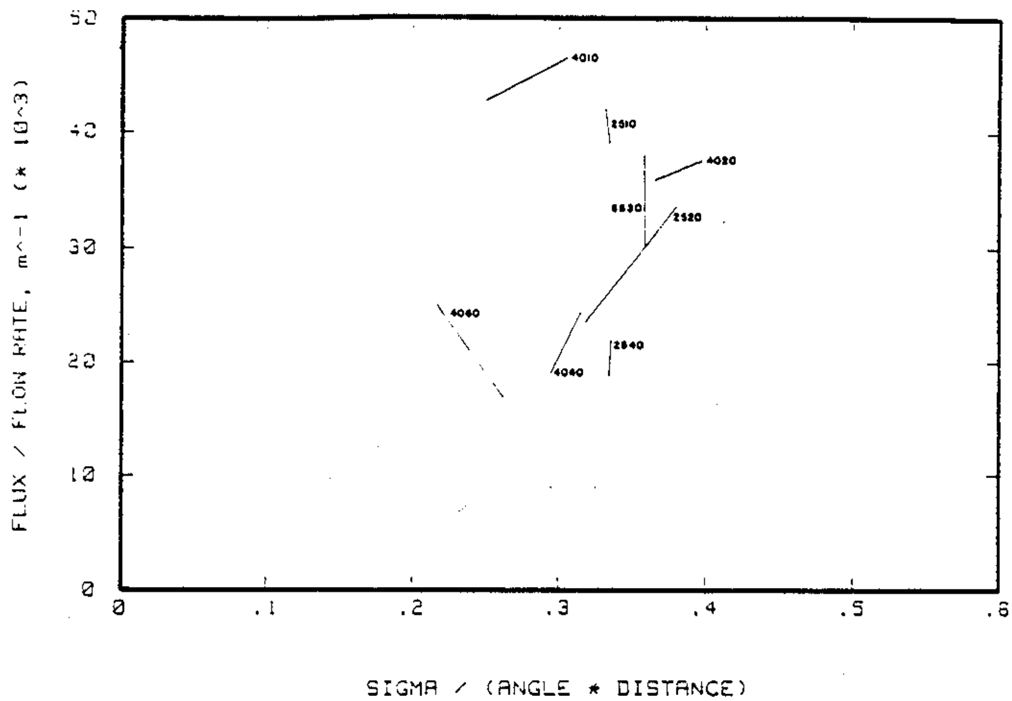
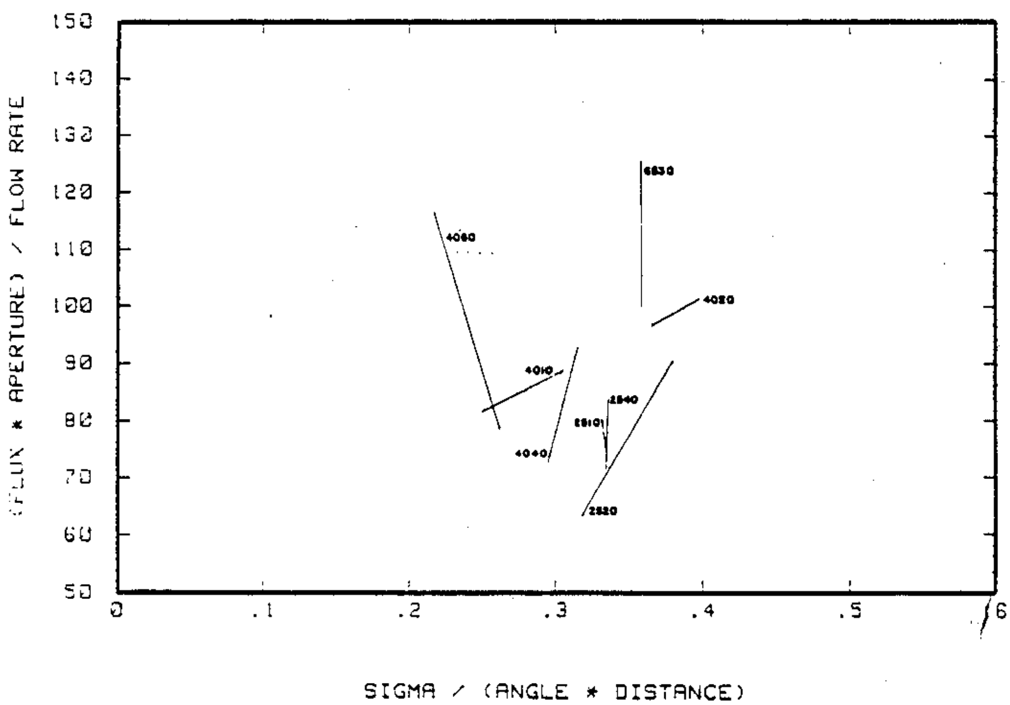


FIGURE 3.12
AIR FLOW DATA
NON-DIMENSIONAL FLUX VARIATION



A replotting of the flux data is presented in Figure 3.12. The flux is divided by aperture and flow rate. Since the ratio of aperture to flow rate is a single constant which is applicable to all nozzle types, the flux is directly plotted (times a constant). Since the broadness parameter is also non-dimensional the nozzle types appear closely grouped. Flux appears to increase with increased nozzle spread angle. However, the normal curve may be less valid as an assumption and less accurate in application as the broadness SIGMA becomes larger than the offset data measurement range. This leads to the conclusion that all nozzles are roughly equivalent, with minimal value ascribed to increasing aperture.

Based on the foregoing discussions it appears that the use of a single nozzle with smaller aperture and greater flare would produce an overall optimum ratio of air flow flux to water flow rate. However, it is important to know how many nozzles would be required for a given barrier length in order to compare the total power requirements. For this reason it was necessary to determine the optimum spacing for each type of nozzle tested and some criteria were established to define this optimum operating condition.

The required nozzle spacing (for a uniformly spaced multiple nozzle barrier) will depend on several parameters:

a) The maximum desirable fluctuation in air velocity: If two nozzles operate at sufficient distance apart, there will be no interference and the air flow velocity will be a maximum at the centreline of each jet and will decay in accordance with the cross section profile for the jet. As the jets are brought closer to one another interference will occur and at some point the two adjacent air flows will combine to form an integral air flow on the water surface. While the mechanism of jet interference is complex, it will be assumed in the following analysis that simple superposition of air velocity profile will give a reasonable approximation to the actual condition. This will permit the evaluation of a maximum nozzle spacing which gives an acceptable fluctuation in velocity. For the purposes of this analysis the permissible fluctuation is set at 10 percent of the maximum air velocity (which occurs at the jet centre line).

b) The distance from the nozzle: As demonstrated earlier the air flow velocity decays in an exponential form as the distance away from the nozzle increases. The selection of this distance is arbitrary, and hence calculations in the following analysis have been made for two stand off distances being 3.05 m (10 ft) and 6.10 m (20 ft).

c) Nozzle characteristics: Particularly, the flare or spread angle of the nozzle. Nozzles with narrow flare are expected to be closely spaced in order to achieve an acceptable air flow uniformity, and vice versa.

Based on the above criteria, the optimum nozzle spacing has been calculated. Details are provided in Appendix C, and a summary of the results is given in Table 3.1.

It should be noted that for the given spacing and distance from the nozzle the flux for each nozzle type may vary. This means that the airflow velocity will be different for each type. This will result in different operating constraints for different types of nozzles. The mean airflow velocity values are also listed in Table 3.1.

It is obvious that the air velocity at the selected range increases with increased aperture, i.e. increased water flow through the nozzle and for the same aperture it decreases with increasing flare. Therefore, the selection of an optimum nozzle has to be done with due consideration of the minimum required air flow velocity under given conditions of operation.

It should be noted that greater spacing is associated with greater nozzle flare or spread. It may also be observed that increasing the aperture, hence flow volume, is not necessarily beneficial. In fact for the same spread the maximum spacing is associated with smaller apertures.

The total hydraulic horsepower may be estimated from:

$$HHP_{max} = \frac{PQ}{1714}$$

where P is the system operating pressure in psi and Q is the volume flow rate of water in gallons per minute. The maximum volume flow rates, as per manufacturer specifications were used, and a pressure of 13,790 kPa (2000 psi) was used as a basis for comparison. The results of power requirements per meter of barrier length are given in Table 3.2 AND FIGURE 3.13. It is clearly shown by examination of the horsepower requirements per unit length of the barrier that in order to minimize the power, nozzles with smaller aperture and larger spread are preferred.

TABLE 3.1

SUMMARY OF MULTIPLE NOZZLE OPTIMUM SPACINGS

NOZZLE TYPE	TEST NO.	PRESSURE (kPa)	OPTIMUM SPACING AT 3.05 m (m)	MEAN AIRFLOW VELOCITY m/s at 3.05 m	OPTIMUM SPACING AT 6.10 m (m)	MEAN AIRFLOW VELOCITY m/s at 6.10 m
2510	5	13790	1.022	17.1	2.027	9.3
4010	3	13790	1.494	14.0	2.448	7.8
2520	2	13790	.973	21.5	2.323	12.8
4020	1	13790	1.942	17.2	3.577	8.9
6520	4	13790	3.868	7.9	-	-
6530	7	13790	2.852	14.0	5.690	8.8
2540	6	13790	1.024	32.3	2.056	18.9
4040	8	13790	1.442	23.3	3.084	13.9
4060	9	13790	1.061	62.6	2.565	17.5

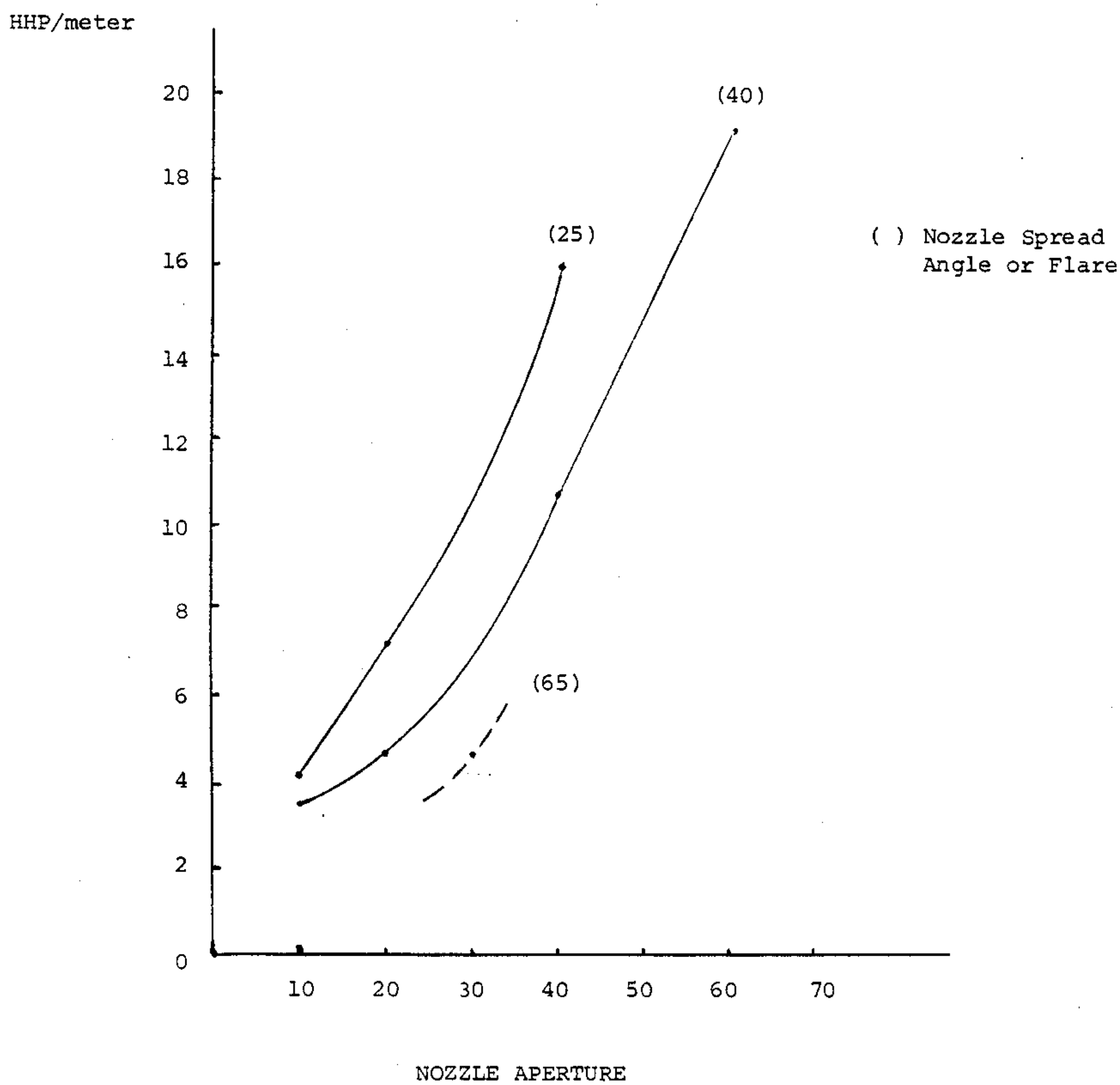
TABLE 3.2

POWER REQUIREMENTS

NOZZLE TYPE	Q_{max} gpm	HHP_{max} per nozzle	SPACING, m (at 6.1 m)	HHP_{max} per meter length
2510	7.1	8.28	2.027	4.08
4010	7.1	8.28	2.448	3.38
6510	7.1	8.28	-	-
2520	14.7	16.45	2.323	7.08
4020	14.7	16.45	3.577	4.60
6520	14.7	16.45	-	-
6530	21.0	24.50	5.690	4.31
2540	28.0	32.67	2.056	15.89
4040	28.0	32.67	3.084	10.59
4060	42.0	49.01	2.565	19.11

FIGURE 3.13

POWER REQUIREMENTS AT 13790 kPa



4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

The problem of optimizing the operation of the high pressure water jet barrier has been examined in this report. An experimental investigation was carried out in which the air flow velocities were measured and their variation with relevant parameters was identified.

The experimental set-up allowed simultaneous measurement of air flow velocity for a series of water jets. An attempt was also made to measure water current velocity. A modification to the apparatus allowed limited testing of multiple nozzle configurations. A laser doppler anemometer system was utilized to extract the air flow velocity of the two phase water jet. This innovative application of laser technology proved very successful. The principal independent variables tested included: nozzle spread angle, aperture, vertical height, depression angle, and pressure. Dependent variables were: air flow velocity at fixed distance above the water surface and current flow velocity. Longitudinal and cross-sectional velocity profiles were derived.

It was found that normal shape curves provided a good fit to the velocity cross-section data. Exponential decay curves described the longitudinal velocity profiles along the water jet centreline. The use of normal curves allowed a convenient representation of the effectiveness of different nozzle types in terms of the velocity flux and its corresponding broadness.

As a result of the experimental study several trends were identified which affected the performance of a nozzle. Increasing pressure from 6900 kPa to 20680 kPa (1000 psi to 3000 psi) translated into higher current velocity, but only marginal variations in air flow flux or broadness. As the depression angle (below the horizontal) was increased to about 15 degrees, the airflow was reduced to zero. No significant reduction in airflow velocity was observed as the water jet nozzle was progressively raised from its minimum height of 7.6 cm to its maximum height of 30.5 cm.

A methodology of establishing optimum spacing of multiple water jets was proposed which utilized the collected broadness data. A minimum reference distance downstream was first selected as the point at which a uniform flux intensity cross-section was realized. Subsequently a spacing corresponding to 2.3 times the broadness at that point was derived.

An estimation of minimum power requirements is provided for each of the nozzles tested. The trends observed in the airflow analysis and power calculation suggest that selection of a small aperture, large flare angle water jet nozzle will result in optimum performance of the barrier.

4.2 Recommendations

One consequence of the present parametric analysis is the identification of several aspects of the optimization problem which may warrant further attention:

1. The selection of an optimum nozzle type which has the smallest aperture of the group tested suggests that nozzle types with yet smaller apertures may be feasible and should be assessed.

2. Extension and verification of the hypothesized mechanism for inducing water surface currents should be carried out to include the influence of air flow on the transport of oil spread on the water surface. Containment distances may be analyzed for a range of parameter variations.

3. Extension of the existing quantitative assessment of barrier performance with pressure should focus on current flux obtained at various depths of the stream flow probe. This would establish a calibration of the influence of pressure on water current velocities. Measurements of containment distances for an oil lamina at varied pressures would give complementary information as to the relative effects of wind shear and particle momentum transfer.

4. Effort should be directed at defining the air flow distributions associated with multiple nozzles and experimentally verifying the method of calculating optimum spacing. The corresponding effect of peaks and troughs in the water current velocity cross-sections of multiple nozzle configurations also require further investigation.

5. For operation of the barrier in a deflection mode, in which nozzles are oriented at an angle from the perpendicular to the barrier line, questions remain as to optimization of the velocity cross-section and its characterization. A wide basin to accommodate varied multi-nozzle configurations is suggested. Two dimensions of current velocity or oil lamina movement should be measured to define the streamlines.

6. Testing of the system under controlled adverse wave, wind and current conditions may be undertaken to calibrate the system performance against environmental factors.

7. Implementation of a system configuration prediction algorithm based on the totality of parametric results would be a valuable tool in operating the barrier in a flexible and efficient manner. Site environmental data would be input and an appropriate barrier configuration would be derived.

5. REFERENCES

[1] The Use of Coherent Water Jets to Control Oil Spills, M.K. Breslin, U.S. Environmental Protection Agency, OHMSETT Report, 1980.

[2] The Use of High-Pressure Water for Spill Containment, K.M. Meikle, (Environmental Protection Service). Proceedings of the 6th Arctic Marine Oil Spill Program Technical Seminar, June 1983.

ACKNOWLEDGEMENT

The authors are grateful to Harry Whittaker and Francine Laperriere of the Environmental Protection Service for their support and active interest in this project.

We would also like to thank Gordon Hadaller and Ed Ritchie of Westinghouse Canada Limited for their cooperation in making available and operating their laser doppler anemometer system.

APPENDIX A - TABLES

TABLE 1.

NOZZLE CHARACTERISTICS

TYPES	NOZZLE SPREAD ANGLE (deg)	NOZZLE APERTURE (inch)	MAXIMUM FLOW RATE (GPM) AT PRESSURE (psi) 1000	1500	2000	2500	3000
2510	25						
4010	40	0.075	5.0	6.1	7.1	7.9	8.7
6510	65						
2520	25						
4020	40	0.106	10.0	12.3	14.1	15.8	19.3
6520	65						
4030	40	0.130	15.0	18.4	21.0	24.0	26.0
6530	65						
2540	25						
4040	40	0.150	20.0	24.0	28.0	32.0	35.0
4060	40	0.183	30.0	37.0	42.0	47.0	52.0

TABLE 2

HIGH PRESSURE WATERJET OIL BARRIER TEST RESULTS

TEST: 1

NOZZLE TYPE	40-20	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	40	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.106	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10	13.60	0	.319	15
10	16.52	1	.281	15
10	13.46	2	.310	15
10	8.57	3	.292	15
10	4.74	4	.217	15
10	3.14	5	.177	15
15	9.18	0	.304	20
20	7.04	0	.223	25
20	8.30	1	.198	25
20	8.40	2	.261	25
20	7.40	3	.222	25
20	5.81	4	.200	25
20	5.00	5	.200	25
20	3.90	6	.131	25
25	5.20	0	.189	30
30	4.05	0	.171	35
30	4.59	2	.114	35
30	4.51	4	.120	35
30	3.45	6	.073	35
35	3.45	0	.079	40

TEST: 2

NOZZLE TYPE	25-20	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	25	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.106	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10	12.73	-1	.626	15
10	21.00	0	.367	15
10	15.90	1	.459	15
10	6.73	2	.425	15
10	3.39	3	.281	15
10	1.03	4	.171	15
10	6.10	5	.111	15
10	3.95	6	.084	15
15	15.10	0	.558	20

HIGH PRESSURE WATERJET OIL BARRIER TEST RESULTS

TEST: 2

NOZZLE TYPE	25-20	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	25	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.106	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
20	11.70	0	.481	25
20	10.01	2	.356	25
20	5.51	4	.256	25
20	2.40	6	.177	25
25	9.73	0	.380	30
30	7.79	0	.314	35

TEST: 4

NOZZLE TYPE	65-20	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	65	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.106	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10	7.80	-1	.275	15
10	9.50	0	.252	15
10	6.40	1	.264	15
10	6.34	2	.292	15
10	4.76	3	.269	15
10	3.49	4	.321	15
10	5.99	5	.287	15
10	5.08	6	.275	15
15	5.57	0	.212	20
20	3.64	0	.108	25
20	4.44	2	.143	25
20	5.19	4	.154	25
20	5.69	6	.160	25
25	2.05	0	.068	30
30	1.62	0	.073	35

HIGH PRESSURE WATERJET OIL BARRIER TEST RESULTS

TEST: 5

NOZZLE TYPE	25-10	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	25	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.075	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10	13.97	-1	.496	15
10	16.34	0	.508	15
10	10.35	1	.364	15
10	5.24	2	.208	15
10	2.88	3	.183	15
10	2.26	4	.141	15
10	.89	5	.105	15
10	.41	6	.090	15
15	12.42	0	.382	20
20	9.39	0	.275	25
20	5.46	2	.175	25
20	3.30	4	.166	25
20	1.89	6	.113	25
25	6.72	0	.216	30
30	5.87	0	.190	35

TEST: 6

NOZZLE TYPE	25-40	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	25	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.150	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10	28.80	0	.215	15
10	25.00	1	.254	15
10	10.77	2	.345	15
10	3.52	3	.354	15
10	1.08	4	.340	15
10	.80	5	.318	15
10	.32	6	.242	15
15	19.16	0	.265	20
20	19.09	0	.420	25
20	11.09	2	.384	25
20	7.15	4	.264	25
20	3.55	6	.181	25
25	14.93	0	.503	30
30	11.32	0	.475	35

HIGH PRESSURE WATERJET OIL BARRIER TEST RESULTS

TEST: 7

NOZZLE TYPE	65-30	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	65	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.130	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10	13.04	-1	.579	15
10	15.12	0	.537	15
10	7.04	1	.433	15
10	12.33	2	.404	15
10	13.16	3	.412	15
10	7.83	4	.429	15
10	4.99	5	.355	15
10	3.72	6	.322	15
15	9.67	0	.482	20
20	8.03	0	.357	25
20	8.11	2	.378	25
20	6.93	4	.265	25
20	6.27	6	.247	25
25	6.98	0	.210	30
30	5.47	0	.192	35

TEST: 8

NOZZLE TYPE	40-40	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	40	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.150	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10	18.21	-1		15
10	21.30	0	.283	15
10	20.66	1	.366	15
10	11.93	2	.460	15
10	7.65	3	.440	15
10	3.48	4	.375	15
10	1.58	5	.320	15
10	1.57	6	.215	15
15	16.77	0	.402	20
20	13.65	0	.420	25
20	10.91	2	.440	25
20	7.47	4	.319	25
20	5.94	6	.225	25
25	11.38	0	.400	30

HIGH PRESSURE WATERJET OIL BARRIER TEST RESULTS

TEST: 8

NOZZLE TYPE	40-40	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	40	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.150	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
30	9.61	0	.415	35

TEST: 9

NOZZLE TYPE	40-60	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	40	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.183	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10	24.20	2	.425	15
10	7.11	3	.431	15
10	2.96	4	.390	15
10	2.41	5	.286	15
10	2.35	6	.215	15
15	19.30	0	.352	20
20	16.22	0	.575	25
20	13.77	2	.442	25
20	8.26	4	.401	25
20	4.71	6	.293	25
25	13.85	0	.503	30
30	11.02	0	.407	35

TEST: 10

NOZZLE TYPE	40-10	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	40	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.075	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10	12.33	-1	.408	15
10	12.49	0	.376	15
10	11.44	1	.322	15

HIGH PRESSURE WATERJET OIL BARRIER TEST RESULTS

TEST: 10

NOZZLE TYPE	40-10	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	40	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.075	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10	7.28	2	.208	15
10	5.16	3	.197	15
10	2.46	4	.160	15
10	.56	5	.139	15
10	.31	6	.098	15
15	9.49	0	.253	20
20	7.40	0	.177	25
20	5.88	2	.174	25
20	3.54	4	.166	25
20	1.92	6	.102	25
25	5.74	0	.194	30
30	4.04	0	.104	35

TEST: 11

NOZZLE TYPE	40-40	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	40	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.150	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	12.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10	19.40	0	.211	15
10	32.10	1	.209	15
10	9.79	2	.191	15
10	4.56	3	.152	15
10	2.21	4	.118	15
10	1.92	5	.081	15
10	1.16	6	.070	15
15	20.44	0	.209	20
20	13.39	0	.160	25
20	13.71	2	.130	25
20	8.23	4	.100	25
20	3.37	6	.081	25
25	13.16	0	.111	30
30	10.86	0	.083	35

HIGH PRESSURE WATERJET OIL BARRIER TEST RESULTS

TEST: 12

NOZZLE TYPE	40-40	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	40	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.150	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	9.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10	12.10	0	.304	15
10	19.74	1	.363	15
10	22.18	2	.393	15
10	6.24	3	.336	15
10	.92	4	.205	15
10		5	.182	15
10	.38	6	.143	15
20	14.60	0	.203	25
20	13.62	2	.169	25
20	8.60	4	.120	25
20	4.70	6	.081	25
25	9.95	0	.164	30
30	11.02	0	.110	35

TEST: 13

NOZZLE TYPE	40-40	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	40	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.150	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	3.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10	12.30	0	.516	15
10	13.85	1	.572	15
10		2	.533	15
10	9.43	3	.632	15
10	4.74	4	.448	15
10	1.74	5	.359	15
10	1.84	6	.255	15
15	12.10	0	.630	20
20	9.18	0	.666	25
20	10.40	2	.614	25
20	7.38	4	.611	25
20	4.13	6	.352	25
25	8.26	0	.573	30
30	6.24	0	.541	35

HIGH PRESSURE WATERJET OIL BARRIER TEST RESULTS

TEST: 14

NOZZLE TYPE	65-20	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	65	PRESSURE (psi)	1500
NOZZLE APERTURE (mm)	.106	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10	8.80	0		15
10	9.49	1		15
10	9.95	2		15
10	10.40	3		15
10	8.19	4		15
10	8.16	5		15
10	5.66	6		15
15	4.93	0		20
20	3.96	0		25
20	3.83	2		25
20	4.13	4		25
20	4.86	6		25
25	2.39	0		30
30	1.85	0		35

TEST: 15

NOZZLE TYPE	65-20	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	65	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.106	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10	8.33	0		15
10	10.25	2		15
10	9.12	4		15
10	5.06	6		15

HIGH PRESSURE WATERJET OIL BARRIER TEST RESULTS

TEST: 16

NOZZLE TYPE	65-20	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	65	PRESSURE (psi)	3000
NOZZLE APERTURE (mm)	.106	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10	10.94	0		15
10	11.26	1		15
10	11.05	2		15
10	11.02	3		15
10	10.10	4		15
10	8.06	5		15
15	6.69	0		20
20	4.60	0		25
20	5.58	2		25
20	5.26	4		25
20	6.80	6		25
25	3.43	0		30
30	2.42	0		35

TEST: 17

NOZZLE TYPE	40-30	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	40	PRESSURE (psi)	1000
NOZZLE APERTURE (mm)	.130	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10	16.96	0	.204	15
15	14.20	0	.186	20
20	10.80	0	.177	25
25	8.23	0	.149	30
30	6.24	0	.121	35

HIGH PRESSURE WATERJET OIL BARRIER TEST RESULTS

TEST: 18

NOZZLE TYPE	40-30	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	40	PRESSURE (psi)	3000
NOZZLE APERTURE (mm)	.130	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10	20.20	0	.220	15
10		2	.251	15
10		4	.204	15
10		6	.110	15
15	18.36	0	.170	20
20	16.83	0	.126	25
25	11.69	0	.106	30
30	10.86	0	.102	35

TEST: 19

NOZZLE TYPE	40-30	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	40	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.130	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10	21.10	0	.231	15
10	10.80	2	.264	15
10	2.72	4	.205	15
10	1.13	6	.120	15
15	15.61	0	.129	20
20	13.30	0	.247	25
25	10.10	0	.222	30
30	8.42	0	.175	35

HIGH PRESSURE WATERJET OIL BARRIER TEST RESULTS

TEST: 20

NOZZLE TYPE	40-30	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	40	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.130	DEPRESSION ANGLE (deg)	15.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10	2.65	0	.609	15
15	2.74	0	.559	20
20	2.37	0	.360	25
25	2.09	0	.255	30
30		0	.203	35

TEST: 21

NOZZLE TYPE	40-30	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	40	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.130	DEPRESSION ANGLE (deg)	7.5
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10	5.54	0	.361	15
15	5.32	0	.409	20
20	5.39	0	.369	25
25	4.67	0	.369	30
30		0	.185	35

TEST: 22

NOZZLE TYPE	40-30	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	40	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.130	DEPRESSION ANGLE (deg)	30.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10	2.40	0	.383	15
15	1.37	0	.323	20
20	1.18	0	.242	25
25	.30	0	.221	30

HIGH PRESSURE WATERJET OIL BARRIER TEST RESULTS

TEST: 23

NOZZLE TYPE	25-20	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	25	PRESSURE (psi)	1000
NOZZLE APERTURE (mm)	.106	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10	6.46	-1		15
10	16.37	0		15
10	12.48	1		15
10	5.16	2		15
10	3.40	3		15
10	1.64	4		15
10	.39	5		15
10	.74	6		15
15	12.85	0		20
20	10.63	0		25
20	5.86	2		25
20	3.76	4		25
20	3.20	6		25
25	5.01	0		30
30	5.01	0		35

TEST: 24

NOZZLE TYPE	25-20	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	25	PRESSURE (psi)	3000
NOZZLE APERTURE (mm)	.106	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10	19.34	0		15
10	11.93	1		15
10	10.47	2		15
10	4.09	3		15
10	5.55	4		15
10	1.07	5		15
10	.99	6		15
15	19.34	0		20
20	13.77	0		25
20	11.57	2		25
20	8.51	4		25
20	6.85	6		25
30	9.61	0		35

HIGH PRESSURE WATERJET OIL BARRIER TEST RESULTS

TEST: 25

NOZZLE TYPE	25-20	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	25	PRESSURE (psi)	1500
NOZZLE APERTURE (mm)	.106	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10	22.18	-1		15
10	23.90	0		15
10	27.70	1		15
10	9.90	2		15
10	3.87	3		15
10	1.93	4		15
10	.88	5		15
10	.50	6		15
15	16.46	0		20
20	11.70	0		25
20	9.67	2		25
20	4.97	4		25
20	2.68	6		25
25	10.63	0		30
30	7.89	0		35

TEST: 26

NOZZLE TYPE	65-20	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	65	PRESSURE (psi)	1000
NOZZLE APERTURE (mm)	.106	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10	9.87	0		15
10	12.45	1		15
10	12.06	2		15
10	10.53	3		15
10	9.26	4		15
10	7.01	5		15
10	5.91	6		15
15	4.74	0		20
20	4.35	0		25
20	4.18	2		25
20	4.36	4		25
20	4.70	6		25
25	2.93	0		30
30	3.32	0		35

HIGH PRESSURE WATERJET OIL BARRIER TEST RESULTS

TEST: 27

NOZZLE TYPE	40-30	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	40	PRESSURE (psi)	1500
NOZZLE APERTURE (mm)	.130	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10		0	.244	15
15		0	.247	20
20		0	.197	25
25		0	.128	30
30		0	.099	35

TEST: 28

NOZZLE TYPE	40-30	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	40	PRESSURE (psi)	2500
NOZZLE APERTURE (mm)	.130	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10		0	.201	15
15		0	.247	20
20		0	.235	25
25		0	.205	30
30		0	.179	35

TEST: 29

NOZZLE TYPE	40-20	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	40	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.106	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	3	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10		0	.352	15
10		0	.274	20
10		1	.388	20
10		2	.580	20
10		3	.606	20

HIGH PRESSURE WATERJET OIL BARRIER TEST RESULTS

TEST: 29

NOZZLE TYPE	40-20	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	40	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.106	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	3	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10		4	.335	20
10		5	.342	20
20		0	.266	25
25		0	.219	30
30		0	.179	35

TEST: 30

NOZZLE TYPE	40-20	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	40	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.106	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	3	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10		0	.348	15
10		0	.295	20
10		1	.268	20
10		2	.330	20
10		3	.366	20
10		4	.524	20
10		5	.309	20
20		0	.178	25
25		0	.104	30
30		0	.095	35

TEST: 31

NOZZLE TYPE	40-20	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	40	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.106	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	3	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10		0	.402	15

HIGH PRESSURE WATERJET OIL BARRIER TEST RESULTS

TEST: 31

NOZZLE TYPE	40-20	DEPTH OF PROBE (cm)	1.0
SPREAD ANGLE (deg)	40	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.106	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	3	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10		0	.303	20
10		1	.301	20
10		2	.284	20
10		3	.275	20
10		4	.302	20
10		5	.235	20
10		6	.197	20
20		0	.226	25
25		0	.108	30
30		0	.096	35

TEST: 32

NOZZLE TYPE	40-30	DEPTH OF PROBE (cm)	3.0
SPREAD ANGLE (deg)	40	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.130	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10		0	.539	15
10		2	.447	15
10		4	.245	15
10		6	.134	15
30		0	.281	35

TEST: 33

NOZZLE TYPE	40-30	DEPTH OF PROBE (cm)	5.0
SPREAD ANGLE (deg)	40	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.130	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10		0	.458	15

HIGH PRESSURE WATERJET OIL BARRIER TEST RESULTS

TEST: 33

NOZZLE TYPE	40-30	DEPTH OF PROBE (cm)	5.0
SPREAD ANGLE (deg)	40	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.130	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10		2	.326	15
10		4	.212	15
10		6	.129	15
30		0	.227	35

TEST: 34

NOZZLE TYPE	40-30	DEPTH OF PROBE (cm)	7.0
SPREAD ANGLE (deg)	40	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.130	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10		0	.352	15
10		2	.226	15
10		4	.191	15
10		6	.125	15
30		0	.206	35

TEST: 35

NOZZLE TYPE	40-30	DEPTH OF PROBE (cm)	9.0
SPREAD ANGLE (deg)	40	PRESSURE (psi)	2000
NOZZLE APERTURE (mm)	.130	DEPRESSION ANGLE (deg)	0.0
NUMBER OF NOZZLES	1	HEIGHT (inches)	6.0

LENGTH (ft)	AIR FLOW VELOCITY (M/S)	DISTANCE OFFSET (ft)	CURRENT FLOW VELOCITY (M/S)	LENGTH (ft)
10		0	.315	15
10		2	.224	15
10		4	.135	15
10		6	.098	15
30		0	.232	35

RECORD 36

NOZZLE TYPE: 40-30
HEIGHT: 6 inches

PRESSURE: 2000 psi
LENGTH: 15 feet

DEPRESSION ANGLE (deg)	DEPTH OF PROBE (cm)	CURRENT FLOW VELOCITY (m/s)
0	1	.231
	3	.539
	5	.458
	7	.352
	9	.315
7.5	1	.361
	3	.543
	5	.451
	7	.358
15	1	.609
	3	.554
	5	.459
	7	.386
30	1	.383
	3	.427
	5	.403
	7	.321

RECORD 37

NOZZLE TYPE: 40-30
HEIGHT: 6 inches

DEPRESSION ANGLE: 0°
LENGTH: 15 feet

PRESSURE (psi)	DEPTH OF PROBE (cm)	CURRENT FLOW VELOCITY (m/s)
1000	1	.204
	3	.367
	5	.348
	7	.285
	9	.190
2000	1	.231
	3	.539
	5	.458
	7	.352
	9	.315
3000	1	.191
	3	.571
	5	.565
	7	.463
	9	.332

RECORD 38

NOZZLE TYPE: 40-30
DEPRESSION ANGLE: 0°

PRESSURE: 2000 psi
LENGTH: 30 feet

HEIGHT (in)	DEPTH OF PROBE (cm)	CURRENT FLOW VELOCITY (m/s)
6	1	.175
	3	.281
	5	.227
	7	.206
	9	.232
9	1	.122
	3	.209
	5	.221
	7	--
	9	.212
12	1	.135
	3	.267
	5	.228
	7	--
	9	.217

TABLE 3

HIGH PRESSURE WATERJET OIL BARRIER TEST RESULTS

CENTERLINE VELOCITY

TEST	AIR FLOW CONSTANT (ft/S)	AIR FLOW EXPONENT (ft^-1)	CURRENT FLOW CONSTANT (ft/S)	CURRENT FLOW EXPONENT (ft^-1)
1	71.40	-.055	2.57	-.051
2	106.31	-.048	1.91	-.014
4	73.33	-.091	2.46	-.072
5	89.84	-.053	3.43	-.051
6	136.06	-.042	.38	.045
7	71.79	-.047	4.55	-.058
8	101.19	-.040	.85	.015
9	110.95	-.037	1.25	.006
10	71.95	-.055	2.74	-.057
11	93.32	-.032	1.66	-.050
12	46.03	-.008	2.17	-.049
13	61.31	-.035	1.91	-0.000
14	57.49	-.077		
16	70.04	-.074		
17	39.48	-.015	1.02	-.025
18	97.82	-.034	1.24	-.040
19	105.91	-.045	.64	-0.000
20	10.84	-.017	5.29	-.060
21	20.39	-.010	2.20	-.029
22	31.86	-.128	2.24	-.039
23	93.85	-.056		
24	99.59	-.038		
25	124.23	-.053		
26	43.30	-.053		
27			1.92	-.049
28			.86	-.008
29			1.81	-.031
30			3.62	-.073
31			4.50	-.078
32			2.89	-.033
33			2.54	-.035
34			1.73	-.027
35			1.30	-.015

TABLE 4

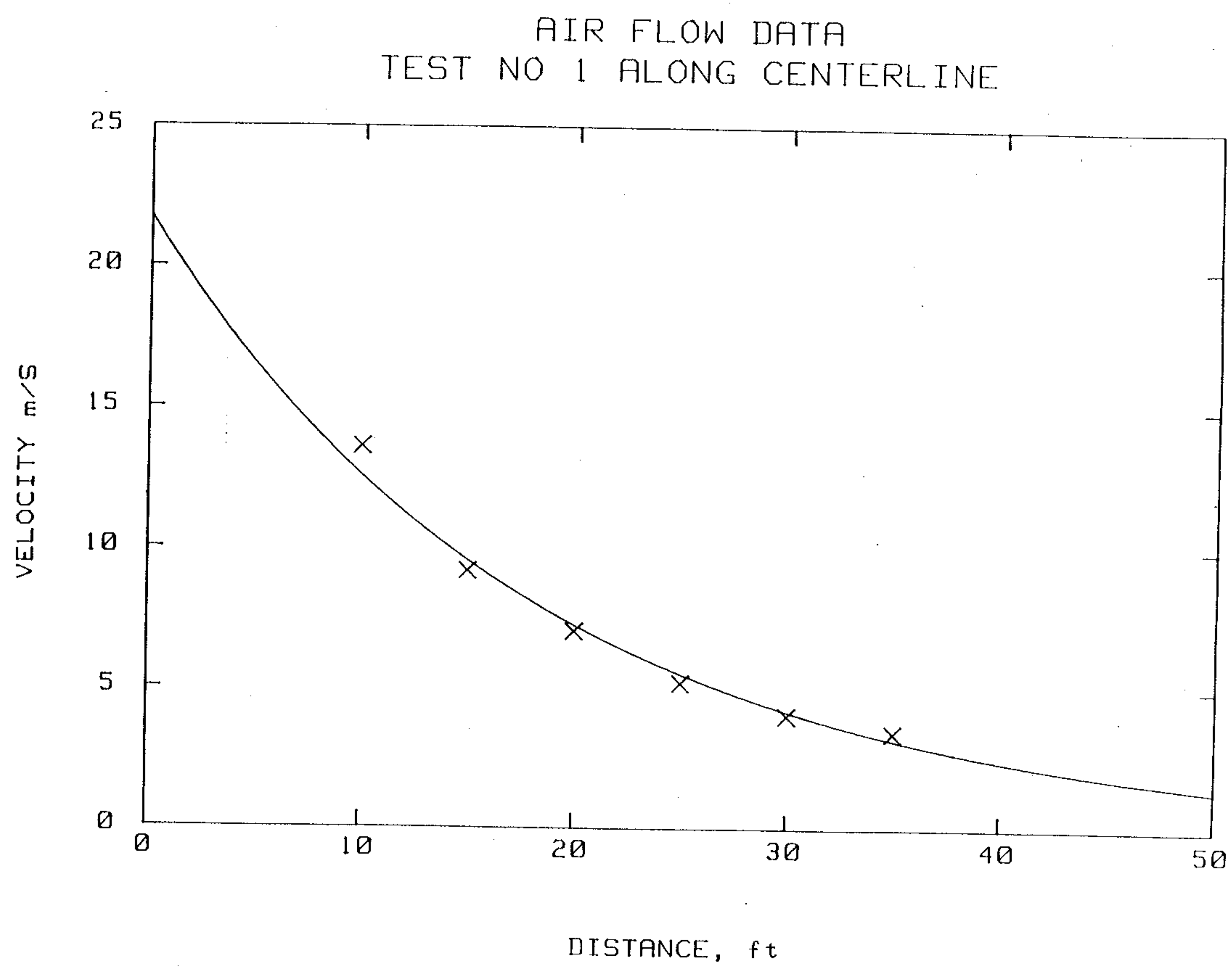
HIGH PRESSURE WATERJET OIL BARRIER TEST RESULTS

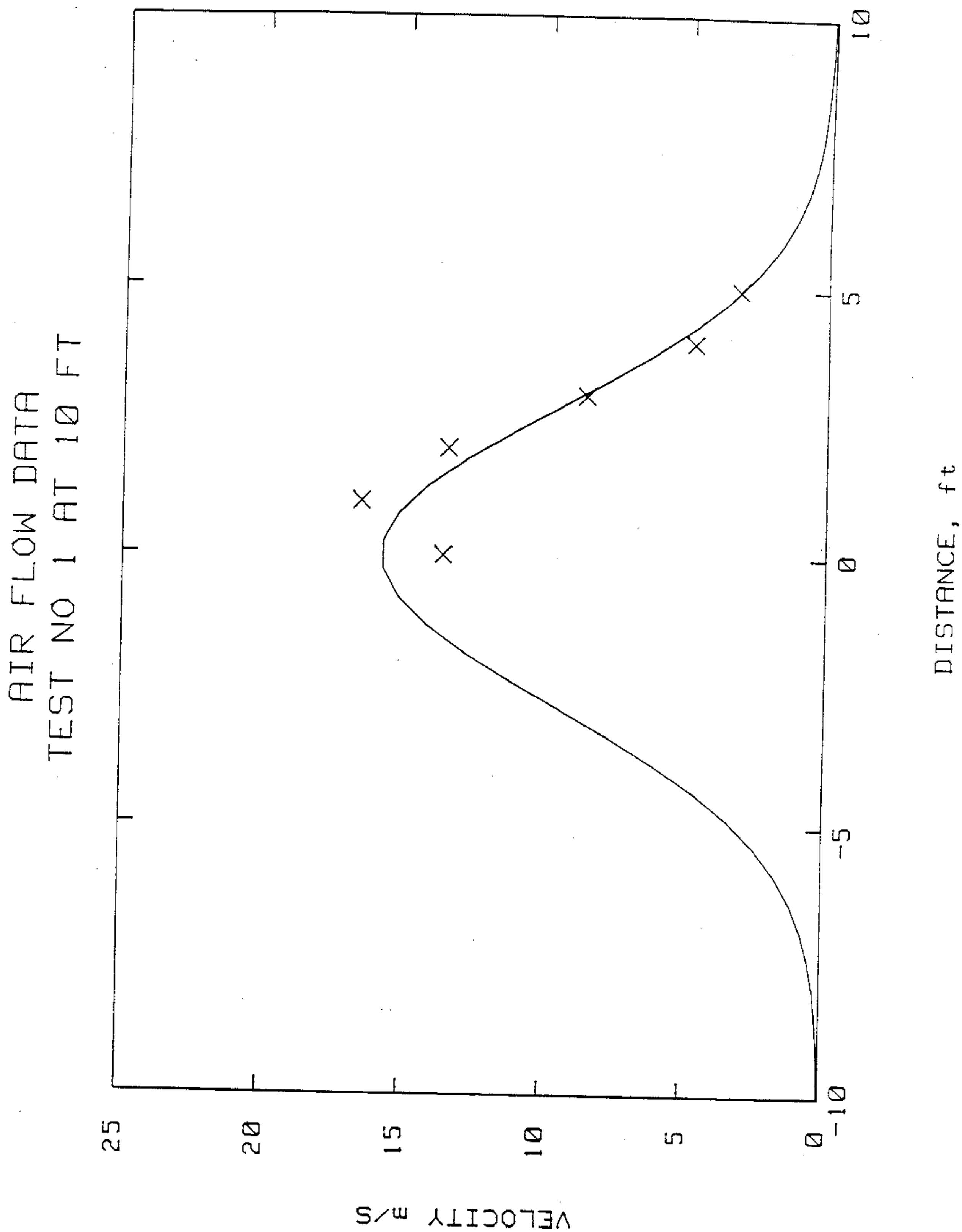
VELOCITY FLUX COEFFICIENTS

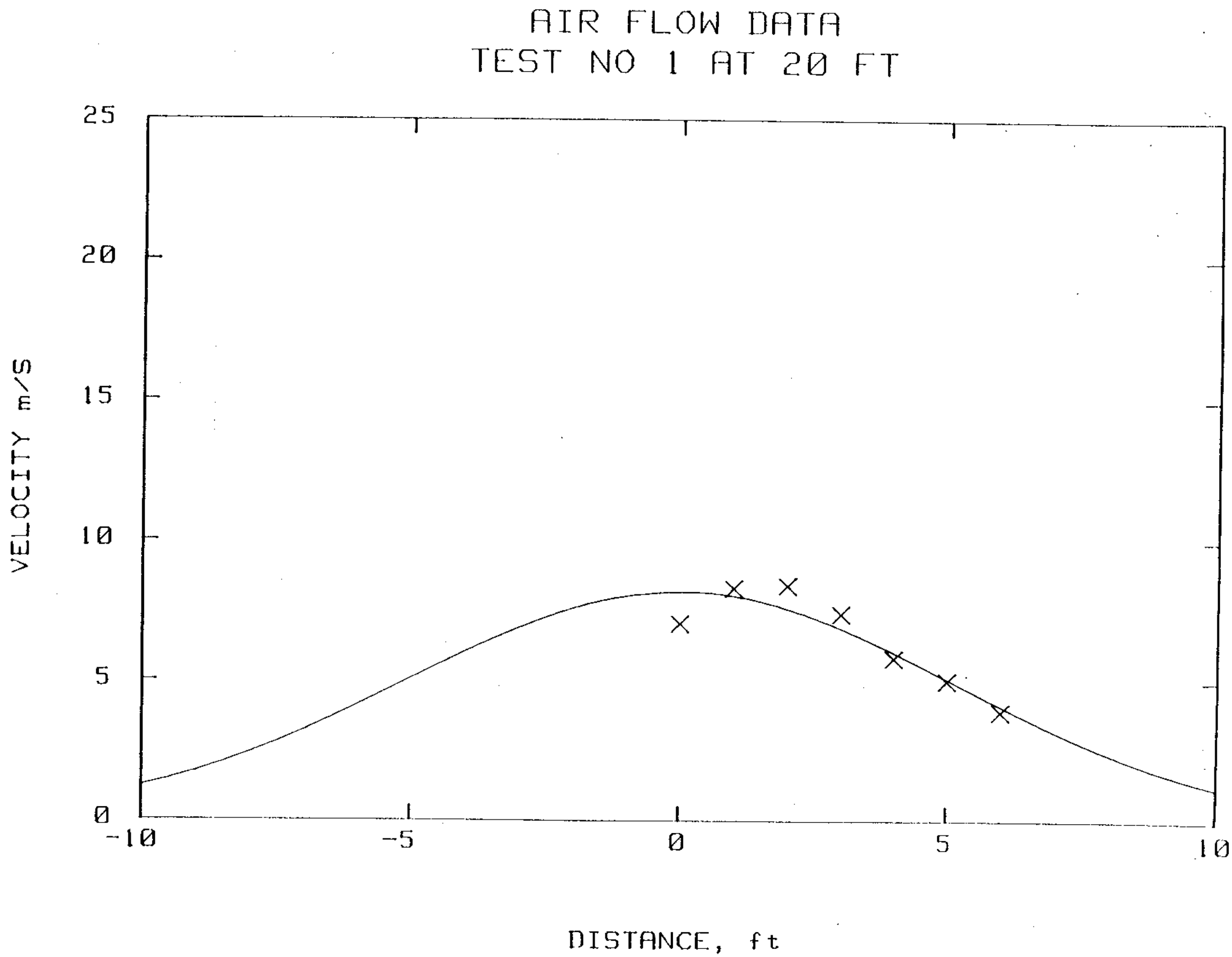
TEST	LENGTH (ft)	AIR FLOW FLUX (ft^2/S)	AIR FLOW SIGMA (ft)	CURRENT FLOW FLUX (ft^2/S)	CURRENT FLOW SIGMA (ft)	LENGTH (ft)
1	10	359.8	2.77	12.711	4.87	15
1	20	343.5	5.10	12.985	6.73	25
1	30	356.2	9.72	6.240	4.97	35
2	10	224.9	1.39	12.128	2.95	15
2	20	321.2	3.31	14.906	4.08	25
4	10	330.8	5.52			15
5	10	188.6	1.46	8.890	2.36	15
5	20	202.6	2.89	9.116	4.61	25
6	10	356.3	1.46			15
6	20	417.3	2.93	15.394	4.48	25
7	10	431.2	4.07	25.383	6.21	15
7	20	541.3	8.12	18.941	6.28	25
8	10	361.6	2.06	23.241	7.13	15
8	20	462.5	4.40	18.784	5.18	25
9	10	714.8	1.51	19.925	4.89	15
9	20	482.1	3.66	23.334	5.35	25
10	10	224.3	2.13	9.421	3.25	15
10	20	206.2	3.49	9.167	6.05	25
11	10	369.5	1.73	6.613	3.77	15
11	20	441.0	3.73	6.203	5.04	25
12	10	373.3	2.44	13.262	4.38	15
12	20	481.2	3.92	6.904	4.30	25
13	10	323.4	2.88	25.183	5.21	15
13	20	396.1	4.74	32.112	5.75	25
14	10	546.4	6.69			15
15	10	486.2	6.06			15
16	10	634.4	6.73			15
18	10			10.585	5.22	15
19	10	312.6	1.82	11.036	5.23	15
23	10	161.9	1.38			15
23	20	246.0	3.25			25
24	10	283.5	2.07			15
24	20	526.5	4.90			25
25	10	353.3	1.58			15
25	20	311.2	3.26			25
26	10	511.2	5.24			15
29	10			10.890	37.16	20
30	10					20
31	10			17.780	7.06	20
32	10			14.782	3.47	15
33	10			12.401	3.54	15
34	10			10.537	4.12	15
35	10			8.484	3.54	15

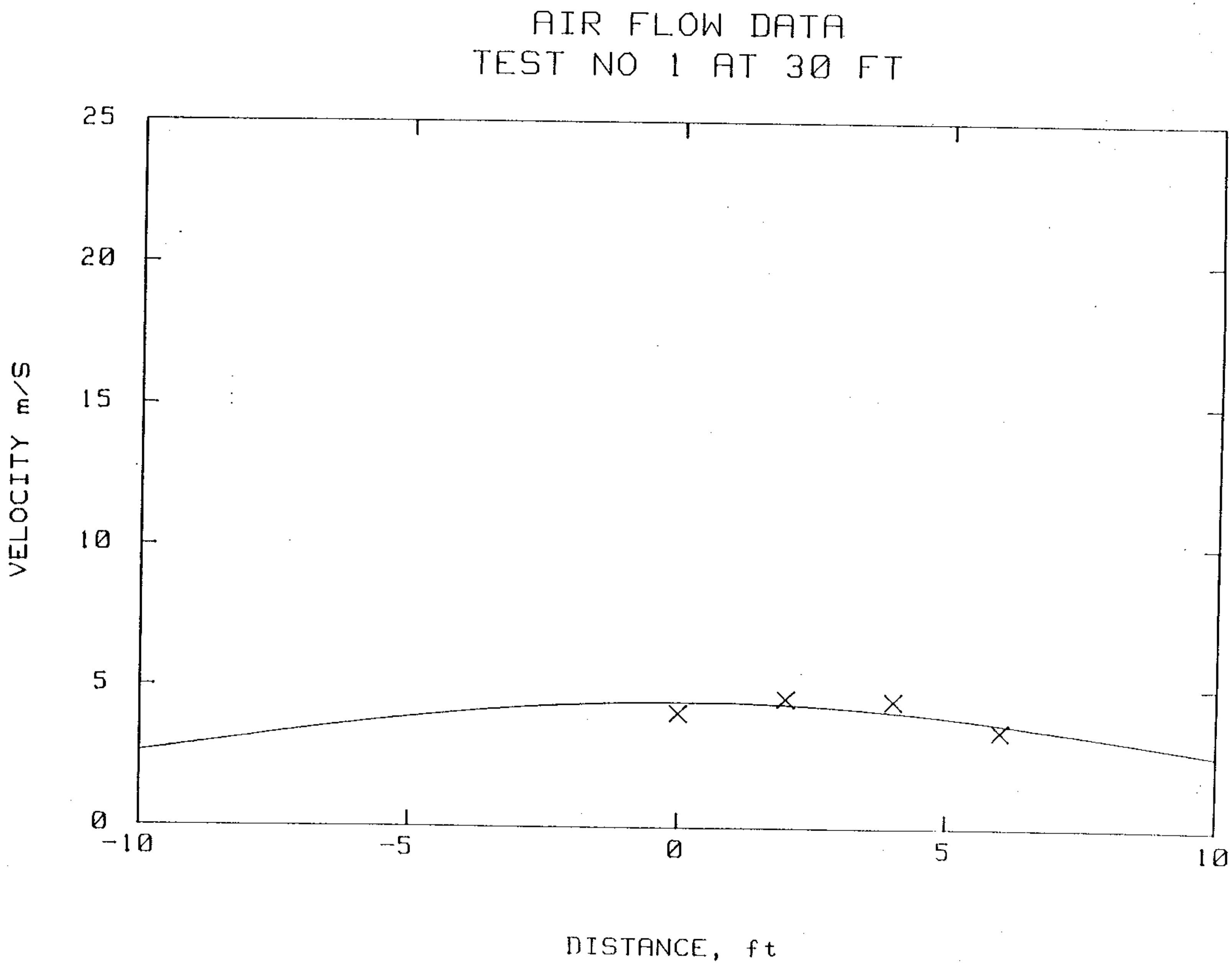
APPENDIX B

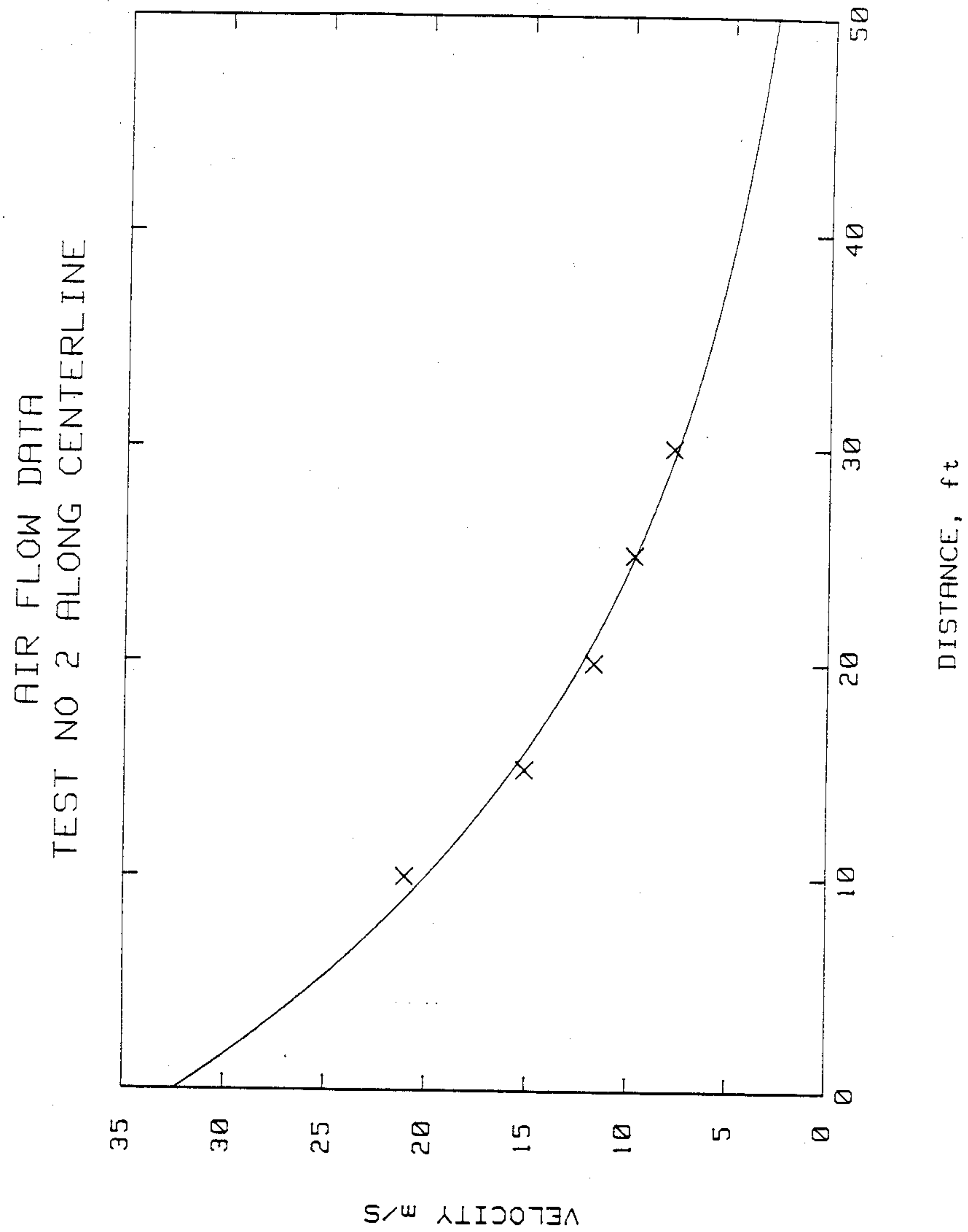
VELOCITY CURVE FITS FOR COMPARATIVE NOZZLE TESTS


AIR FLOW DATA
TEST NO 1 ALONG CENTERLINE
VELOCITY m/S
25
20
15
10
5
0
0
10
20
30
40
50
DISTANCE, ft

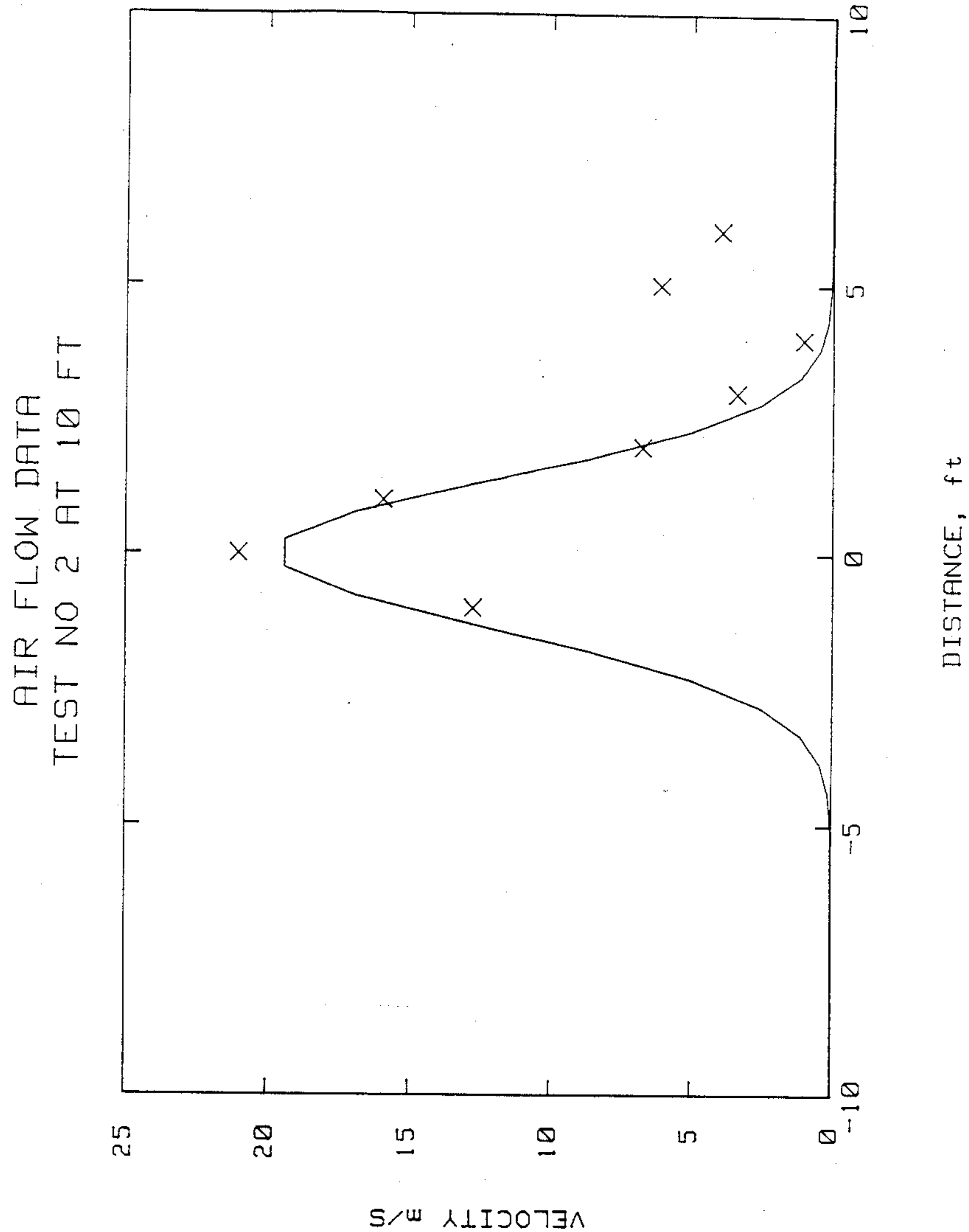

AIR FLOW DATA
TEST NO 1 AT 10 FT
VELOCITY m/s
DISTANCE, ft
0
5
10
15
20
25
−10
−5
0
5
10

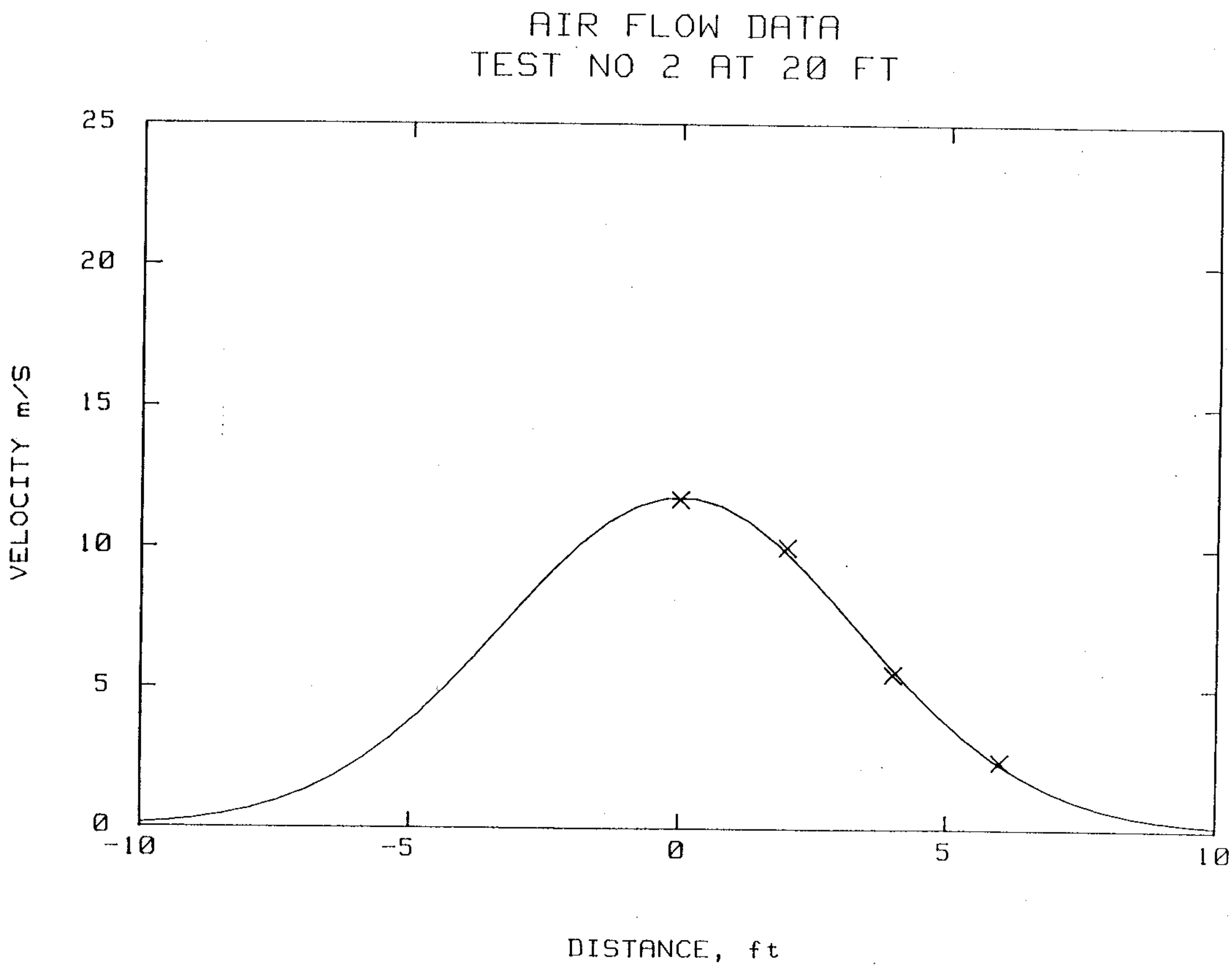

AIR FLOW DATA
TEST NO 1 AT 20 FT
VELOCITY m/S
DISTANCE, ft
25
20
15
10
5
0
-10
-5
0
5
10

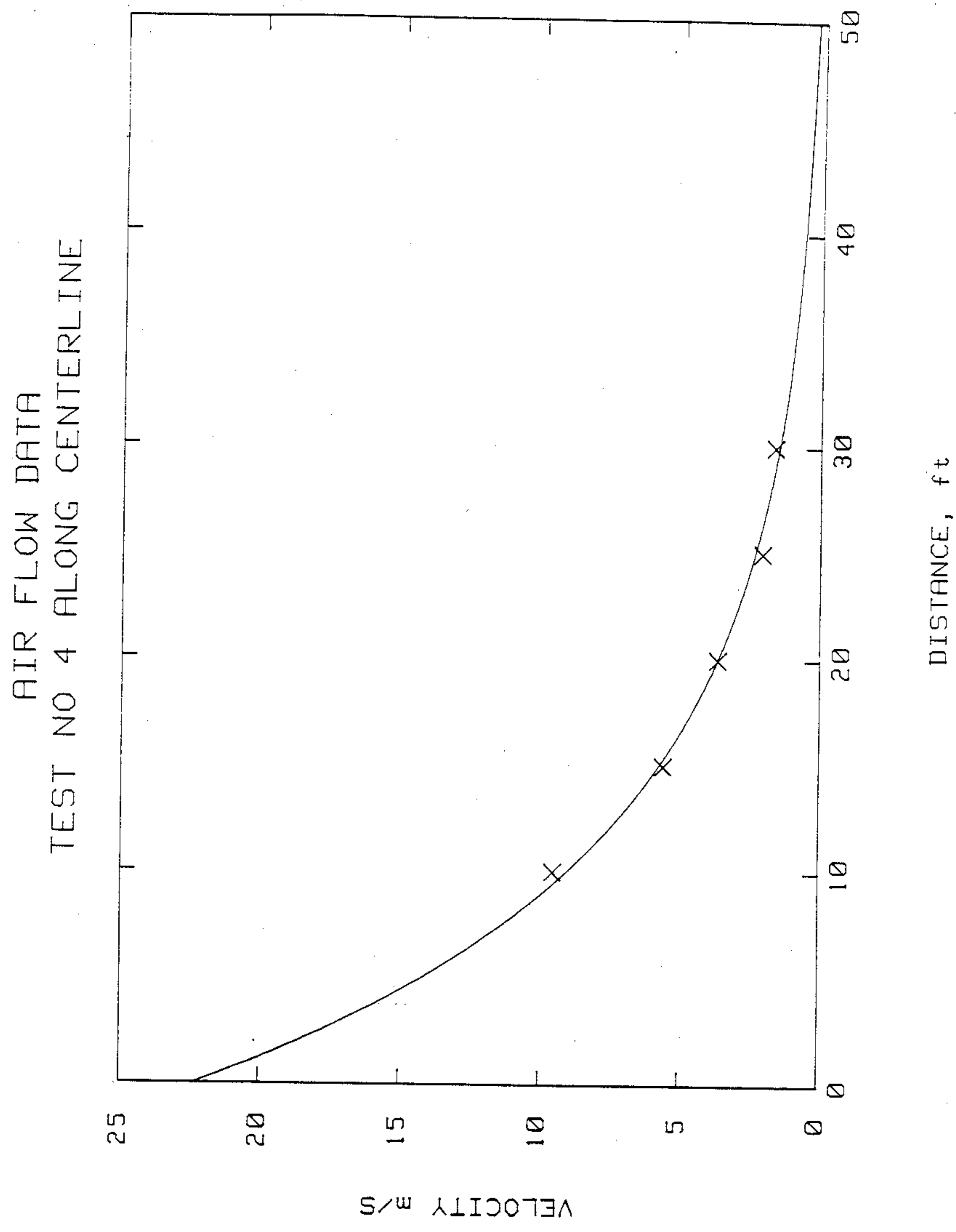

AIR FLOW DATA
TEST NO 1 AT 30 FT
VELOCITY m/S
25
20
15
10
5
0
-10
-5
0
5
10
DISTANCE, ft

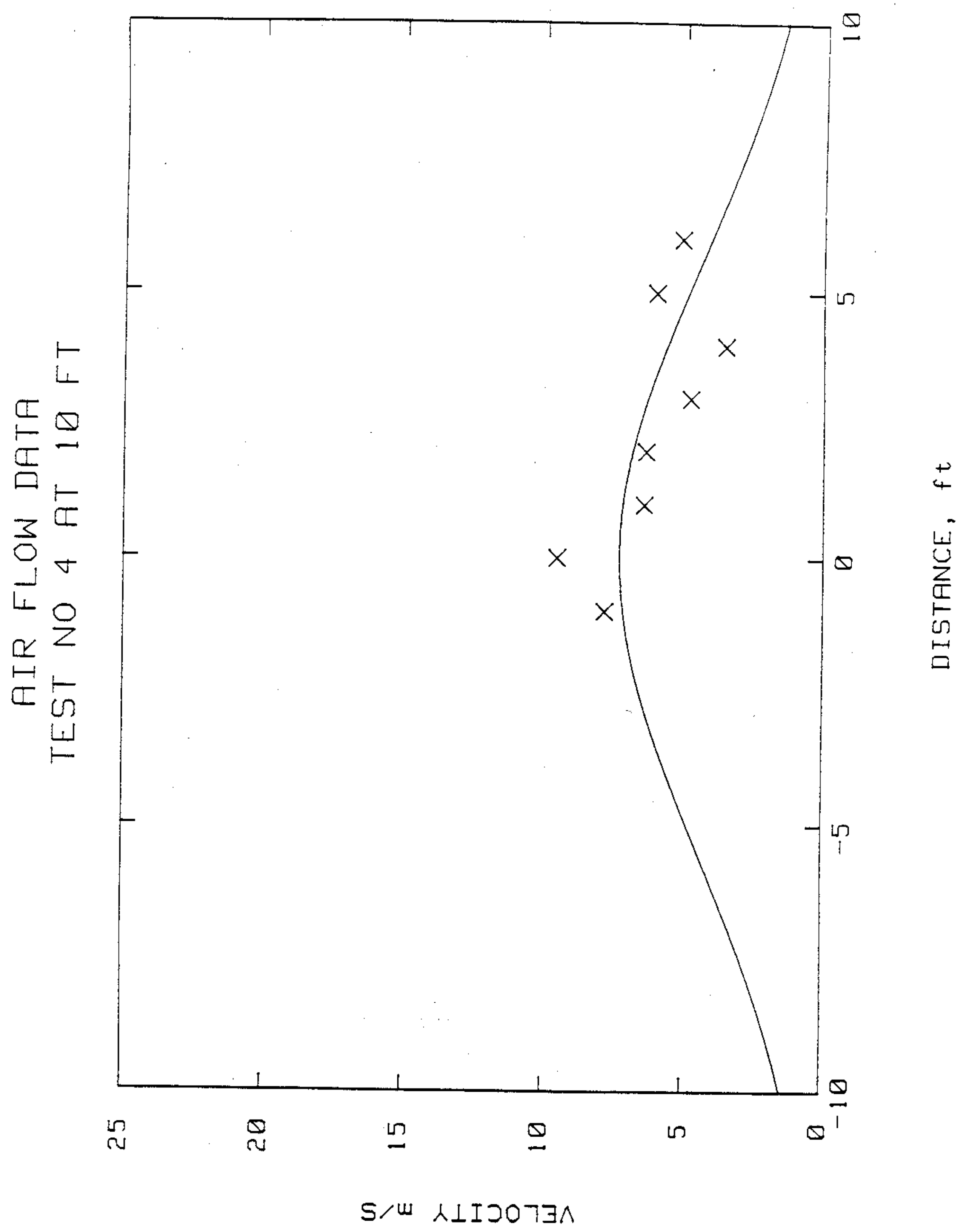


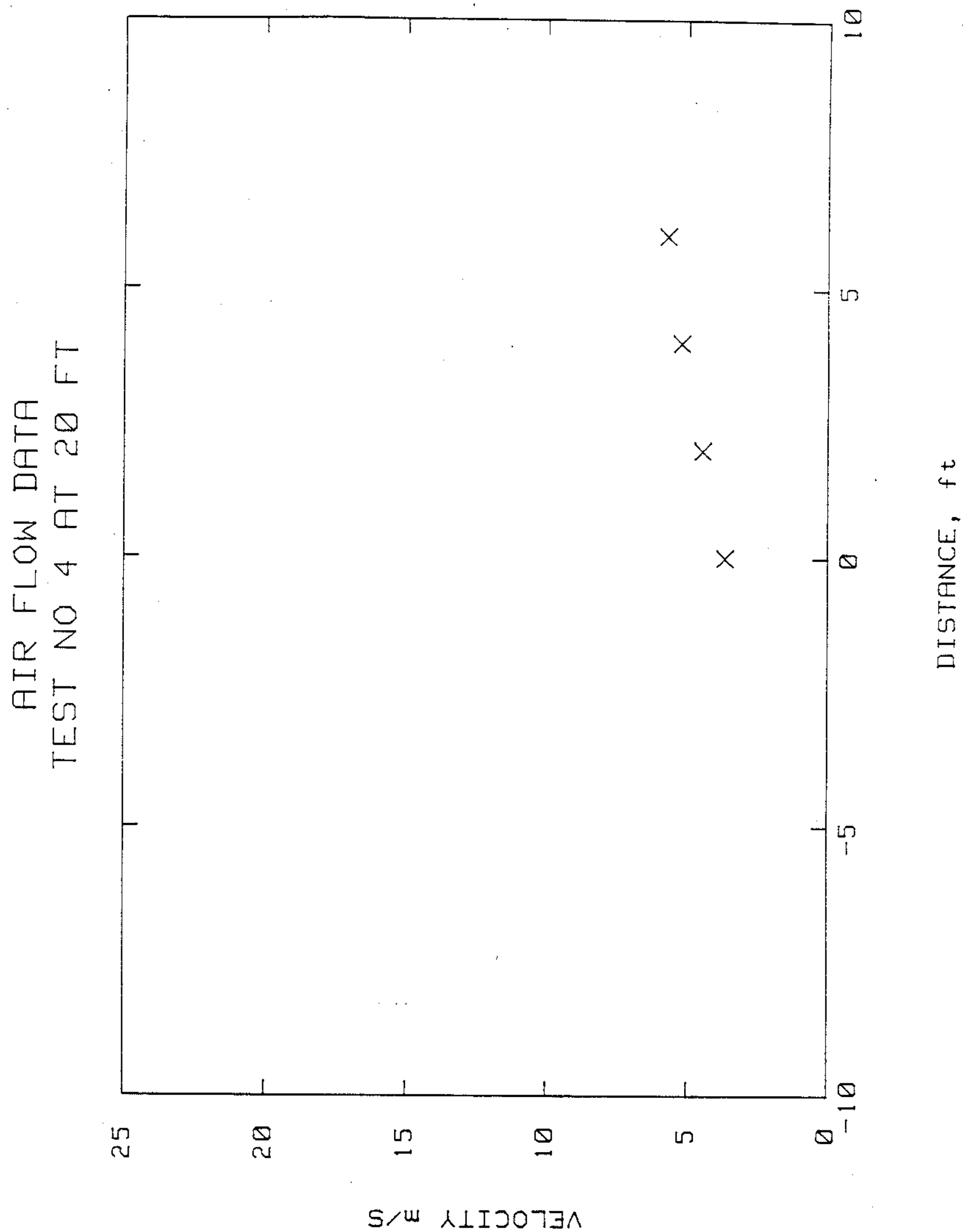
AIR FLOW DATA
TEST NO 2 ALONG CENTERLINE
VELOCITY m/S
DISTANCE, ft
0
5
10
15
20
25
30
35
0
10
20
30
40
50


AIR FLOW DATA
TEST NO 2 AT 10 FT
VELOCITY m/S
DISTANCE, ft
0
5
10
15
20
25
-10
-5
0
5
10

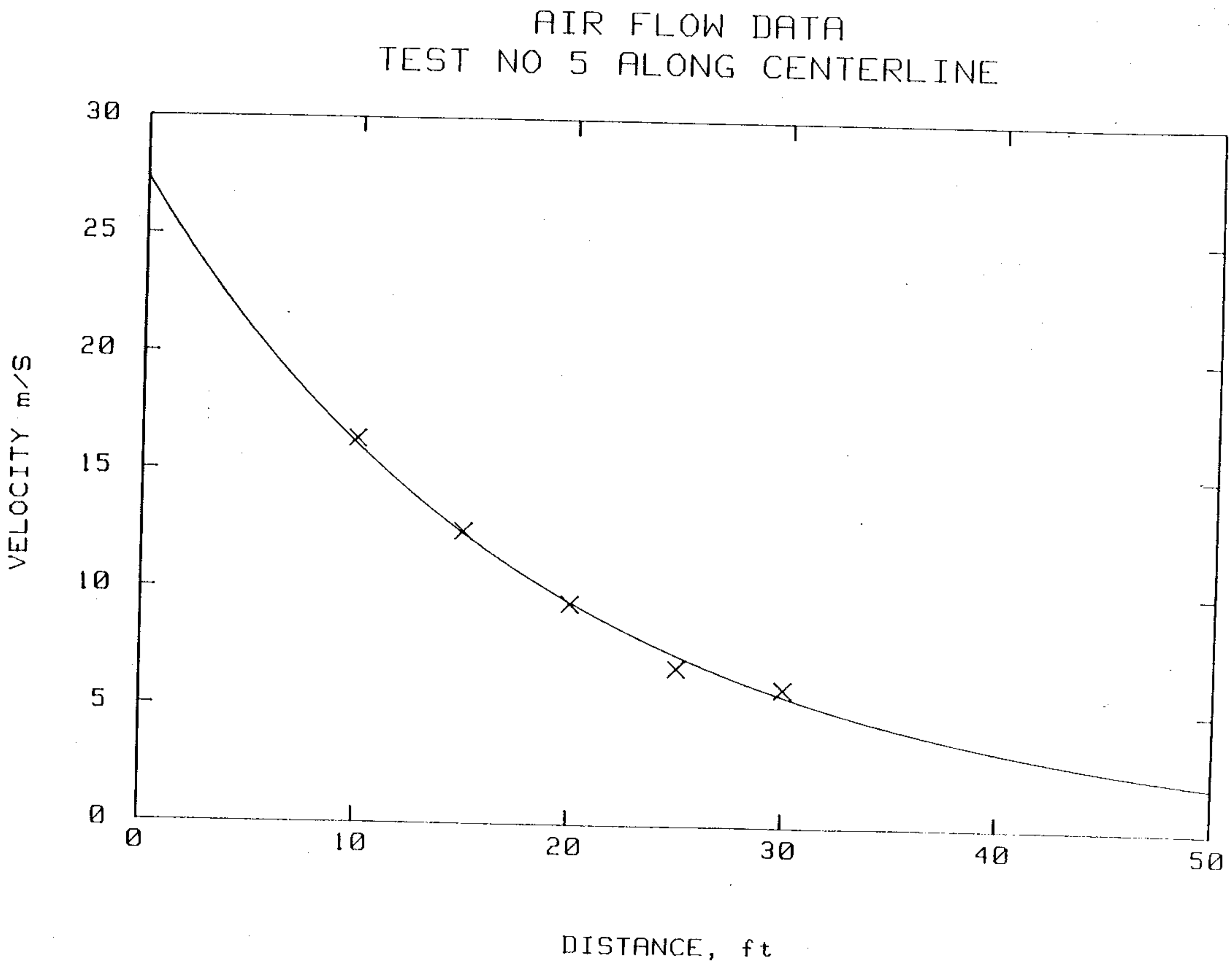

AIR FLOW DATA
TEST NO 2 AT 20 FT
VELOCITY m/S
DISTANCE, ft
25
20
15
10
5
0
-10
-5
0
5
10


AIR FLOW DATA
TEST NO 4 ALONG CENTERLINE
VELOCITY m/S
DISTANCE, ft
0
5
10
15
20
25
0
10
20
30
40
50

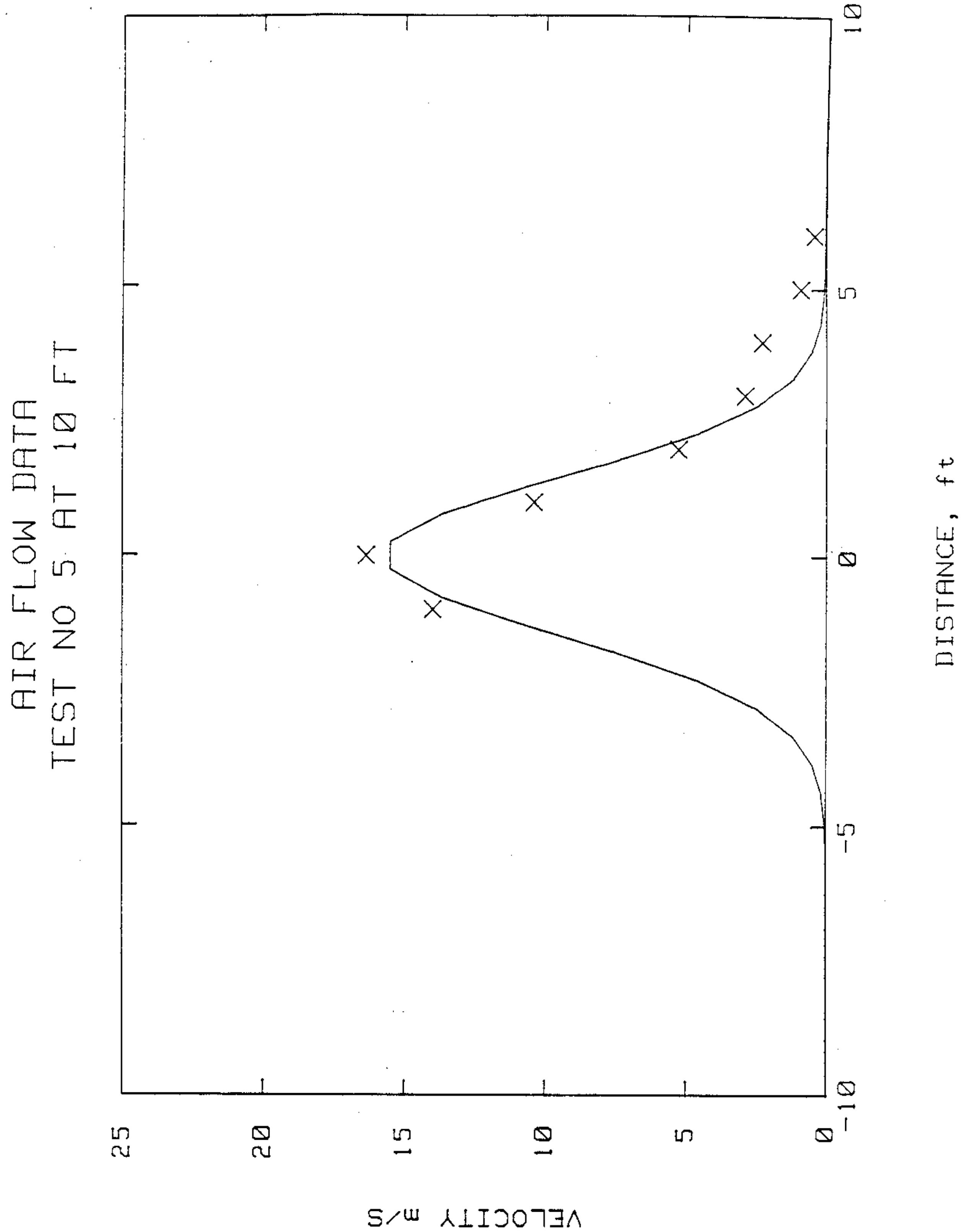

AIR FLOW DATA
TEST NO 4 AT 10 FT
VELOCITY m/s
DISTANCE, ft
0
5
10
15
20
25
-10
-5
0
5
10

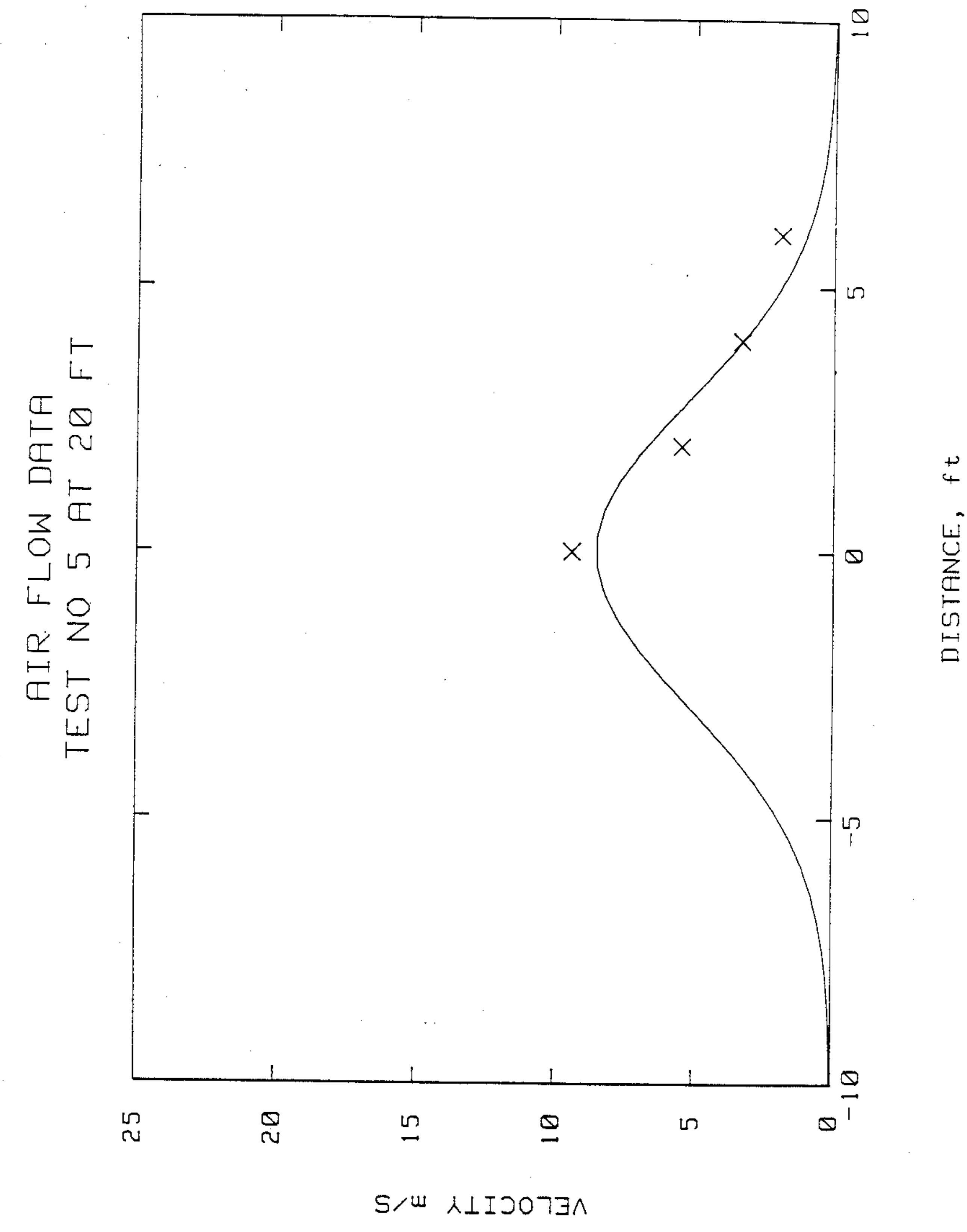


AIR FLOW DATA
TEST NO 4 AT 20 FT
VELOCITY m/S
25
20
15
10
5
0
-10
-5
0
5
10
DISTANCE, ft

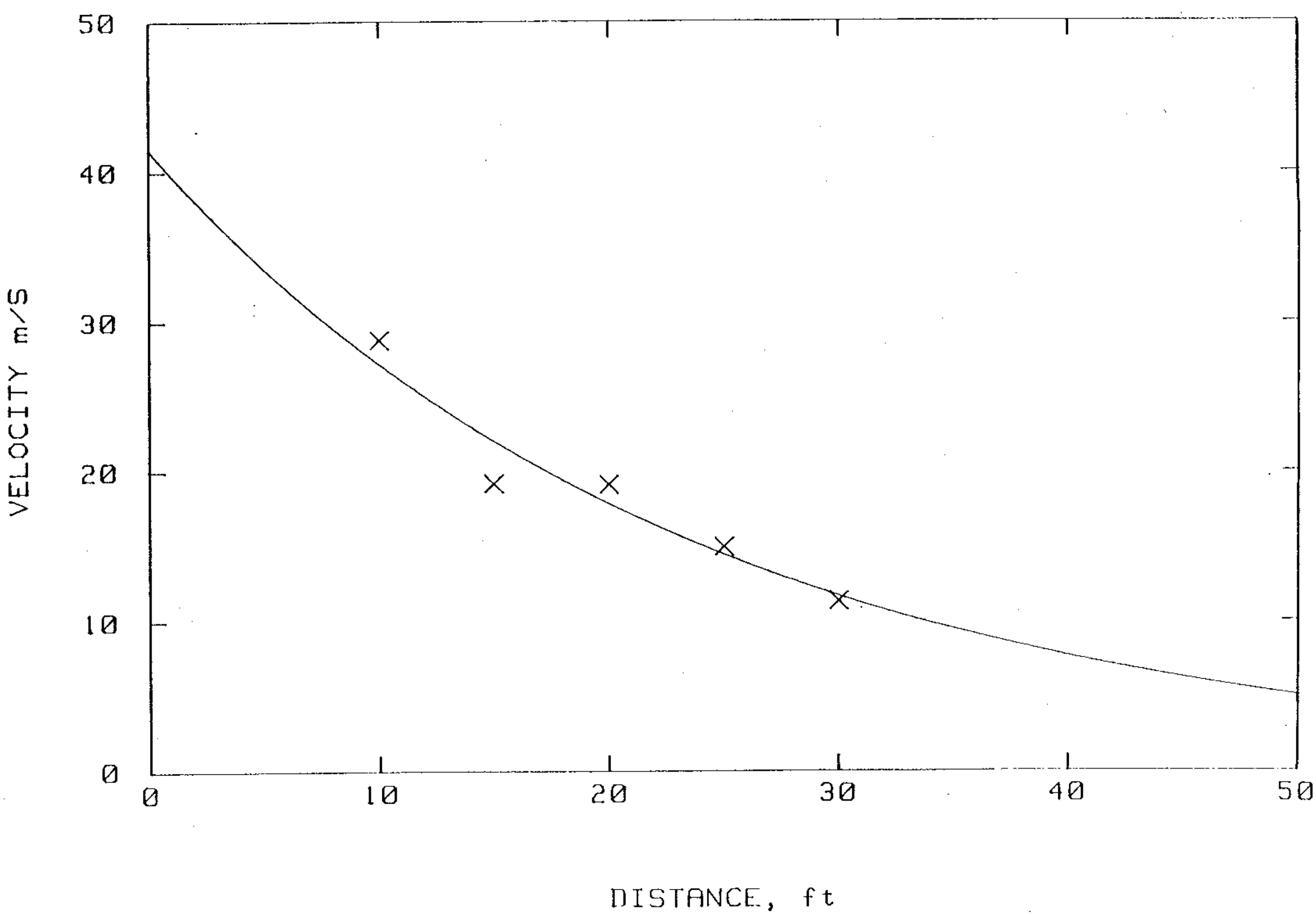


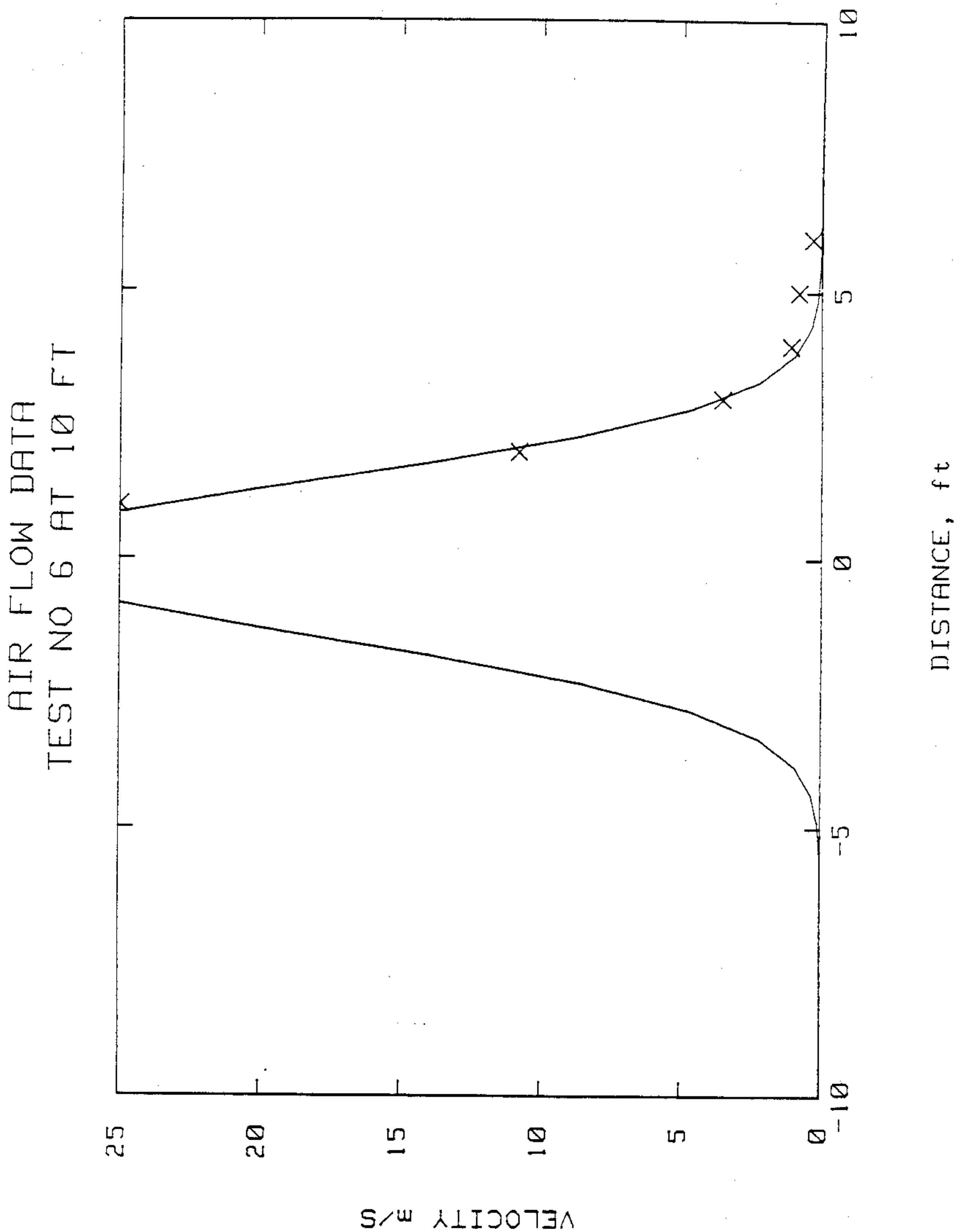
AIR FLOW DATA
TEST NO 5 ALONG CENTERLINE
VELOCITY m/S
DISTANCE, ft
0
5
10
15
20
25
30
0
10
20
30
40
50

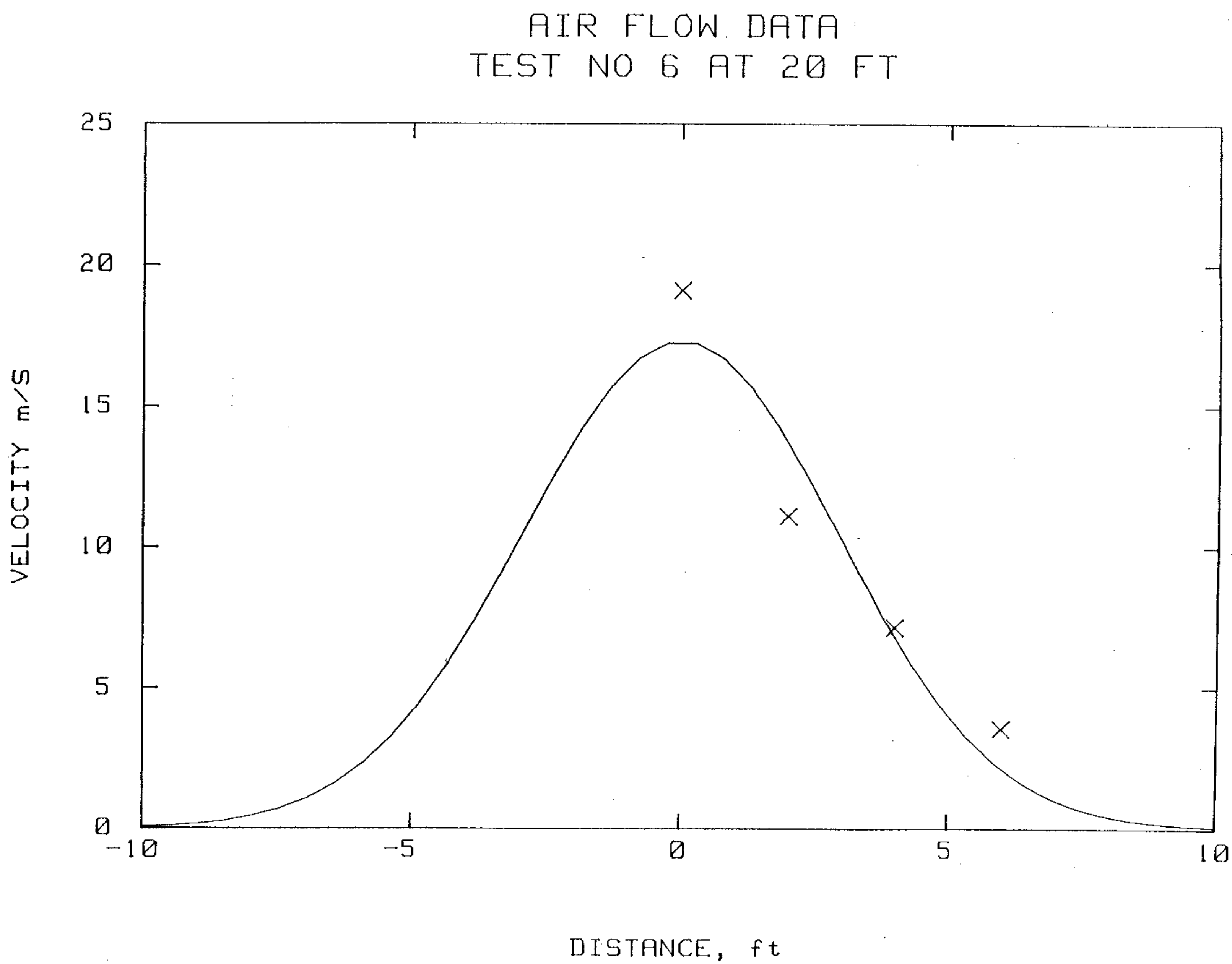

AIR FLOW DATA
TEST NO 5 AT 10 FT
VELOCITY m/S
DISTANCE, ft
25
20
15
10
5
0
-10
-5
0
5
10

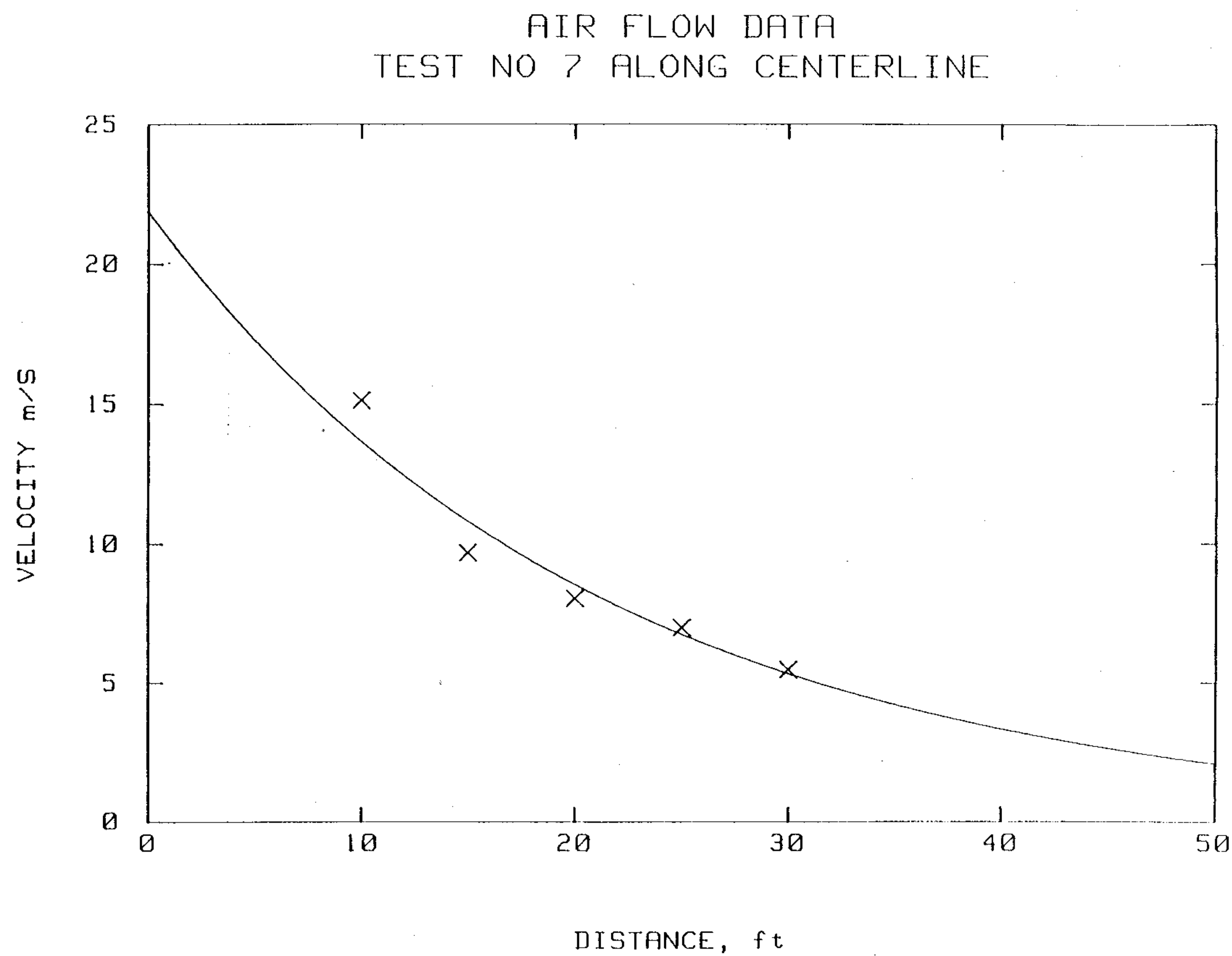

AIR FLOW DATA
TEST NO 5 AT 20 FT
VELOCITY m/S
DISTANCE, ft
0
5
10
15
20
25
-10
-5
0
5
10

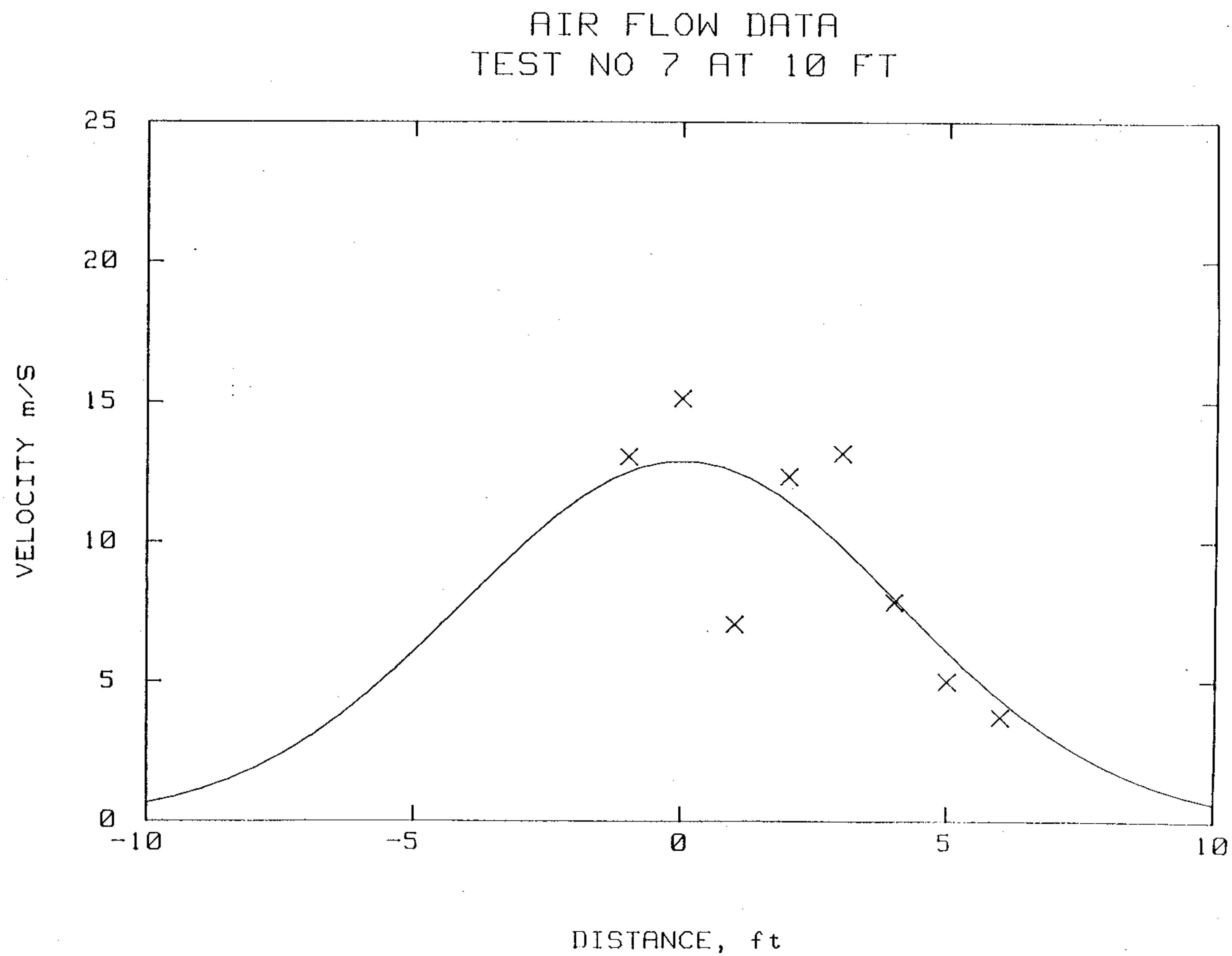
AIR FLOW DATA
TEST NO 6 ALONG CENTERLINE

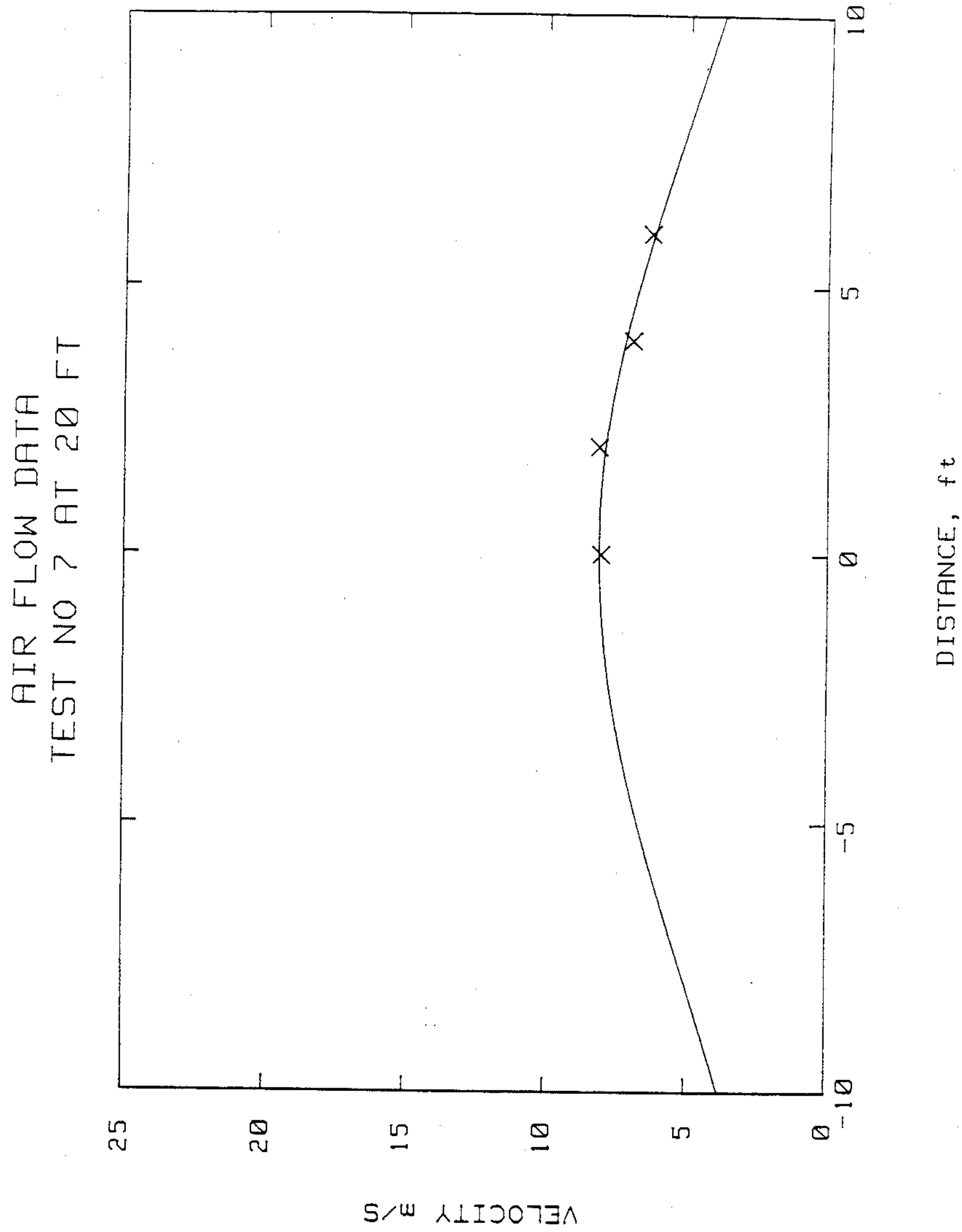



AIR FLOW DATA
TEST NO 6 AT 10 FT
VELOCITY m/S
DISTANCE, ft
25
20
15
10
5
0
-10
-5
0
5
10

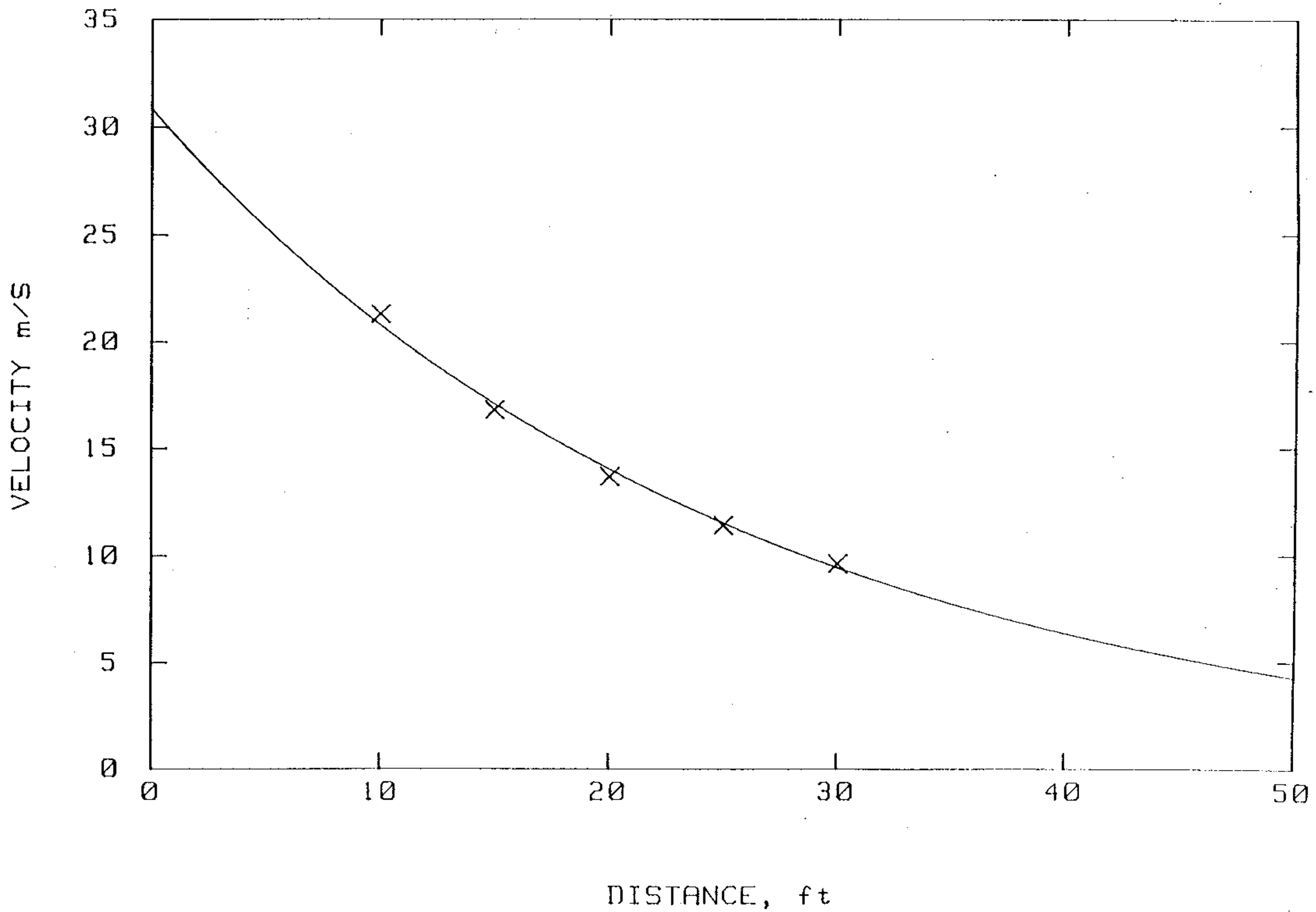

AIR FLOW DATA
TEST NO 6 AT 20 FT
VELOCITY m/S
25
20
15
10
5
0
−10
−5
0
5
10
DISTANCE, ft


AIR FLOW DATA
TEST NO 7 ALONG CENTERLINE
VELOCITY m/S
0
5
10
15
20
25
0
10
20
30
40
50
DISTANCE, ft

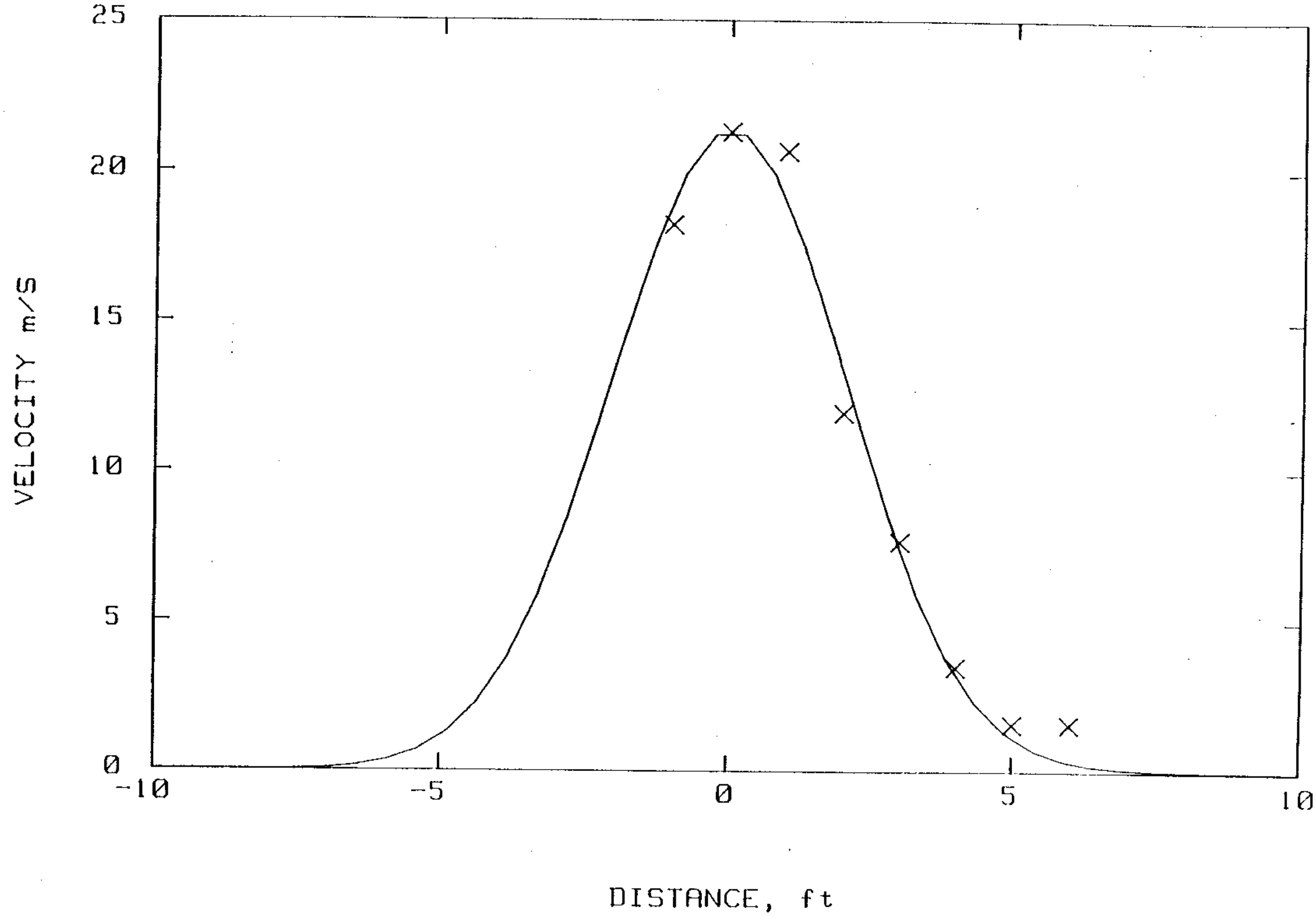

AIR FLOW DATA
TEST NO 7 AT 10 FT
VELOCITY m/S
25
20
15
10
5
0
-10
-5
0
5
10
DISTANCE, ft

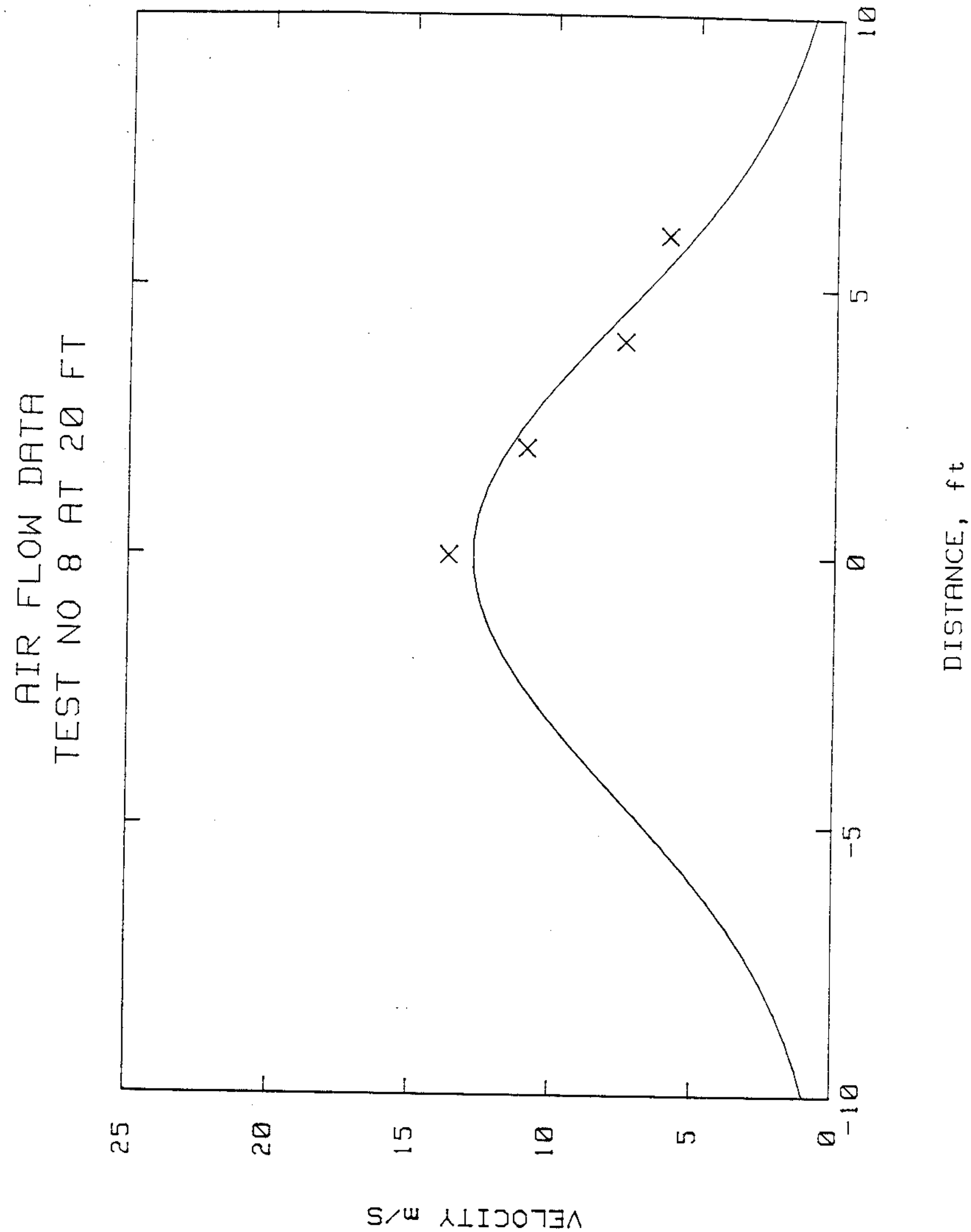

AIR FLOW DATA
TEST NO 7 AT 20 FT
VELOCITY m/S
DISTANCE, ft
0
5
10
15
20
25
-10
-5
0
5
10

AIR FLOW DATA
TEST NO 8 ALONG CENTERLINE

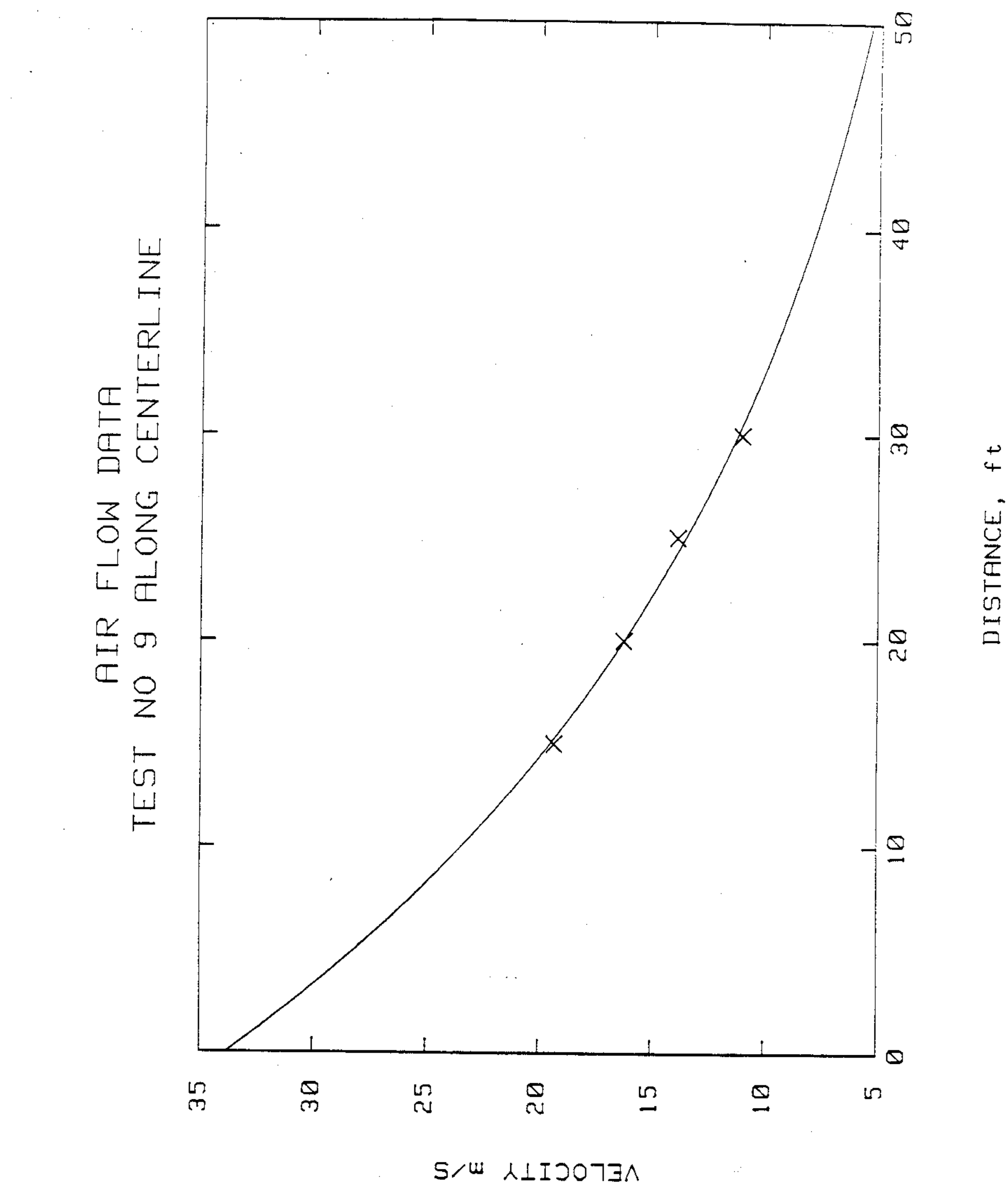


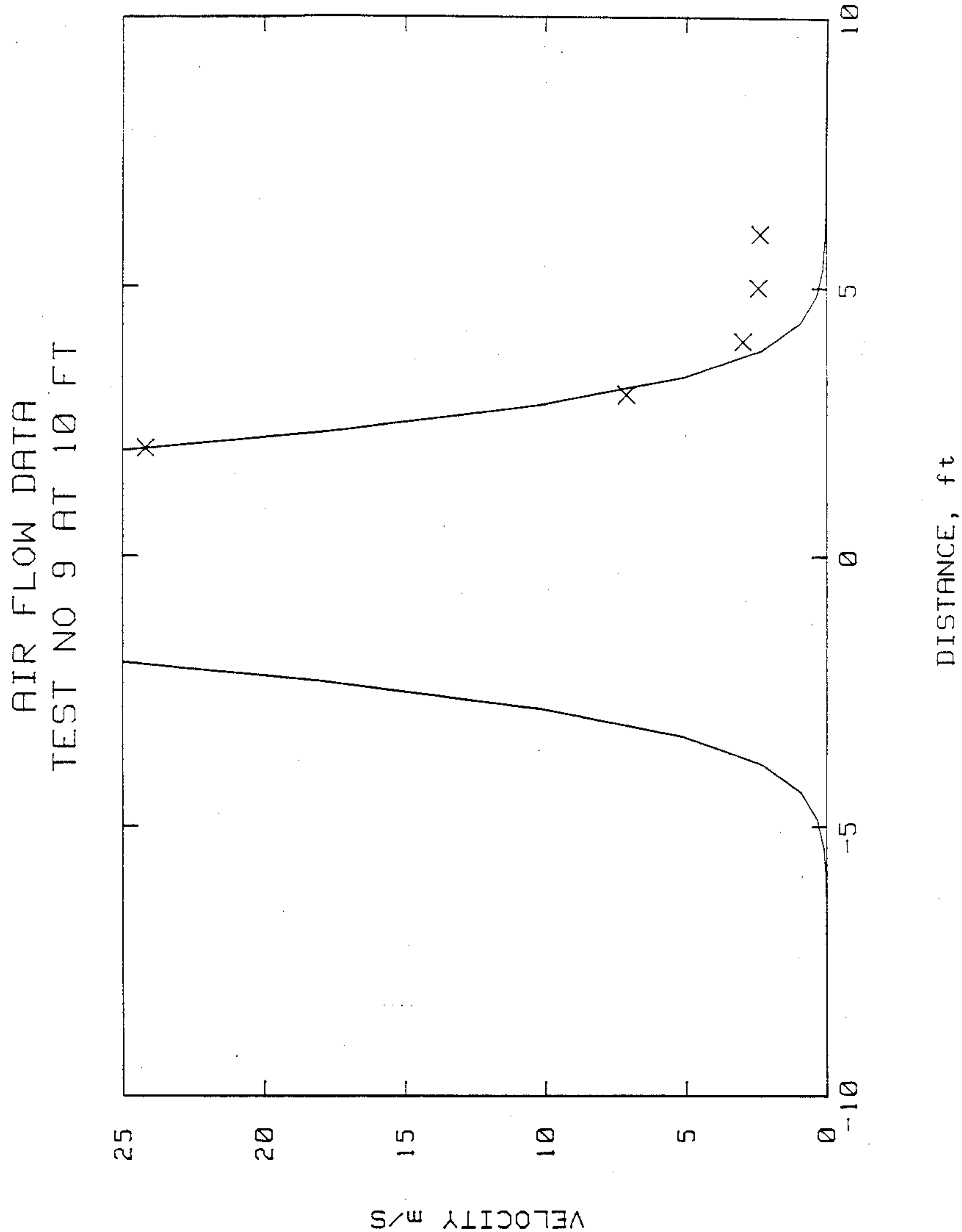
AIR FLOW DATA
TEST NO 8 AT 10 FT

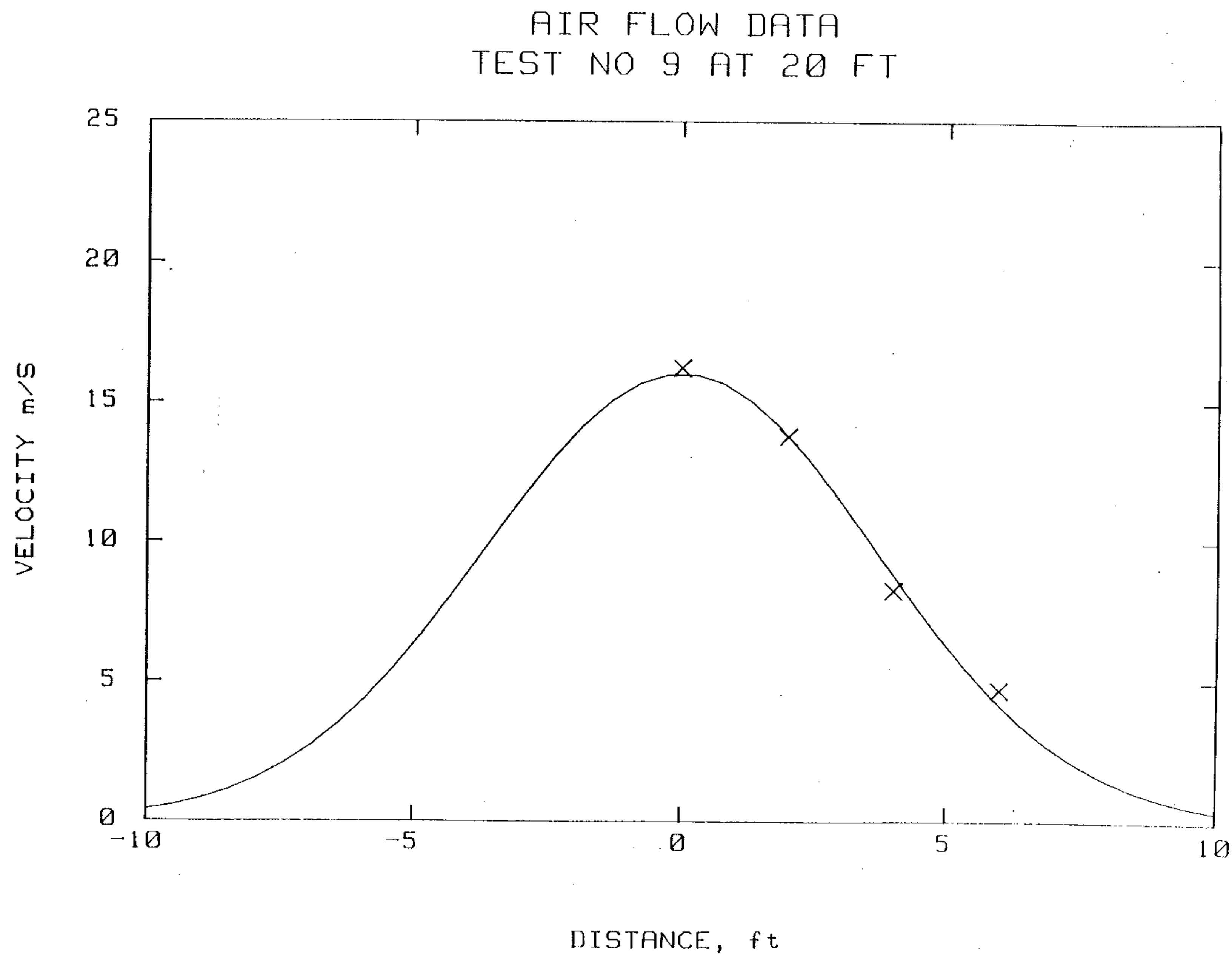


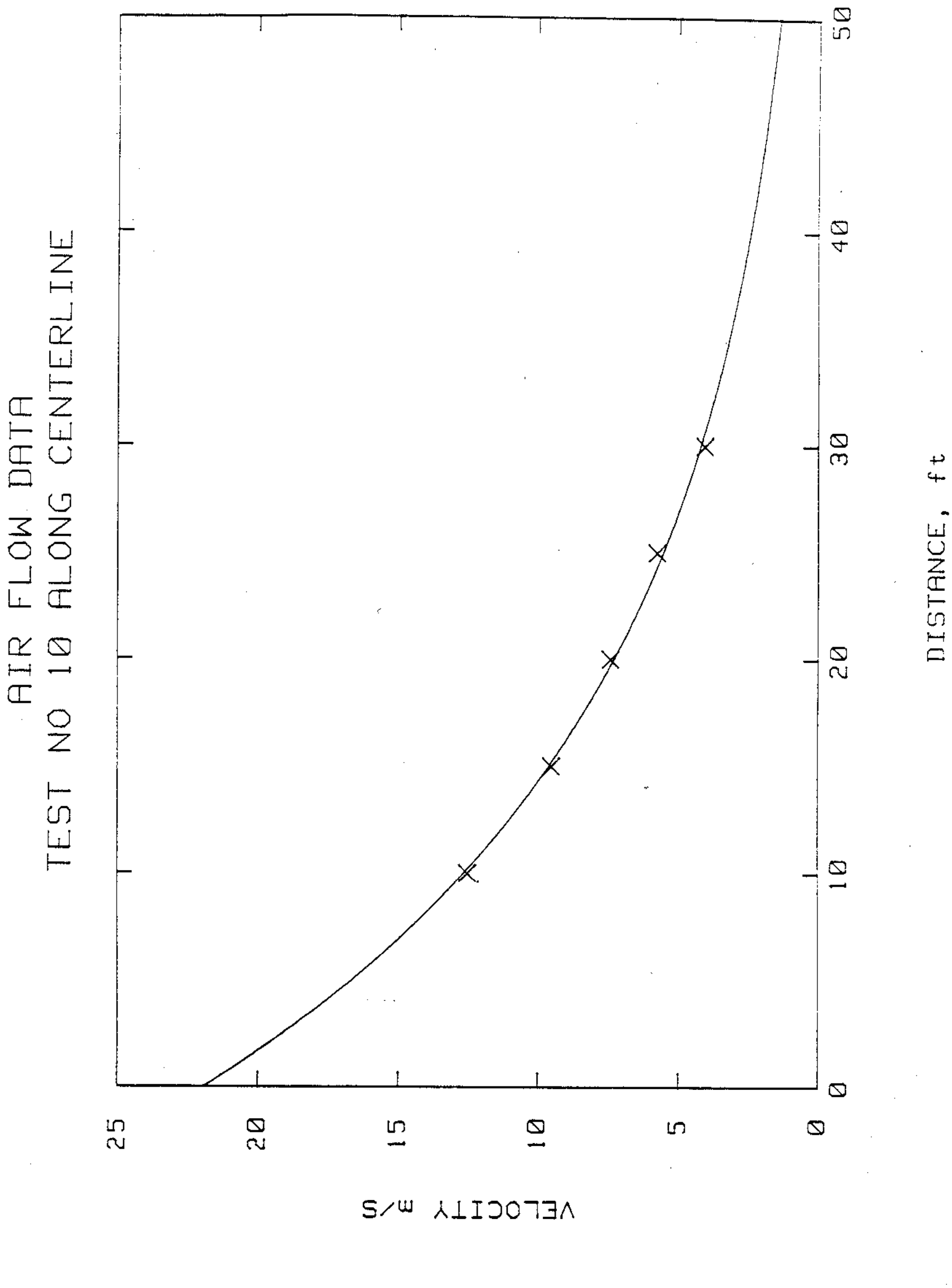


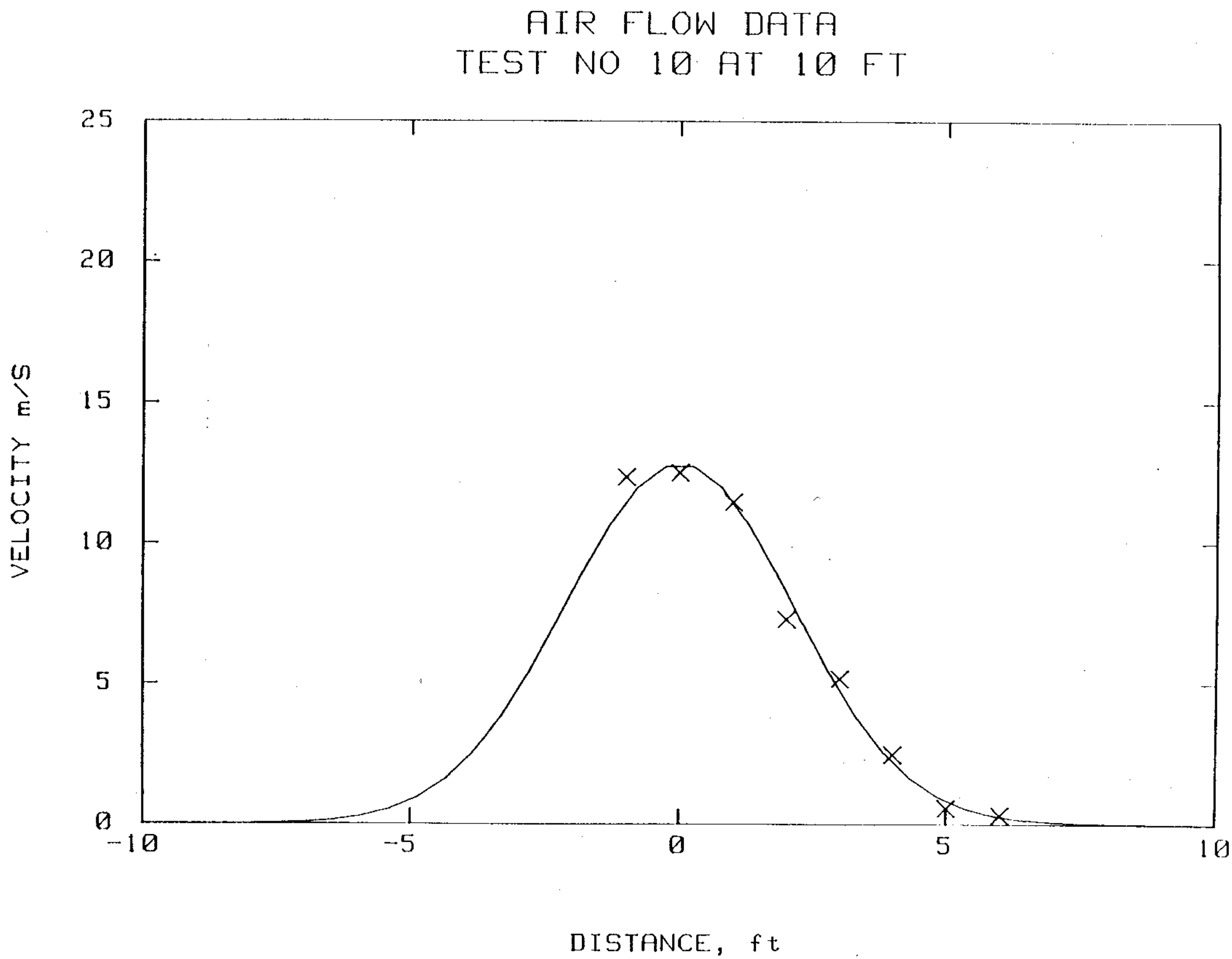
AIR FLOW DATA
TEST NO 8 AT 20 FT
VELOCITY m/S
DISTANCE, ft
0
5
10
15
20
25
-10
-5
0
5
10

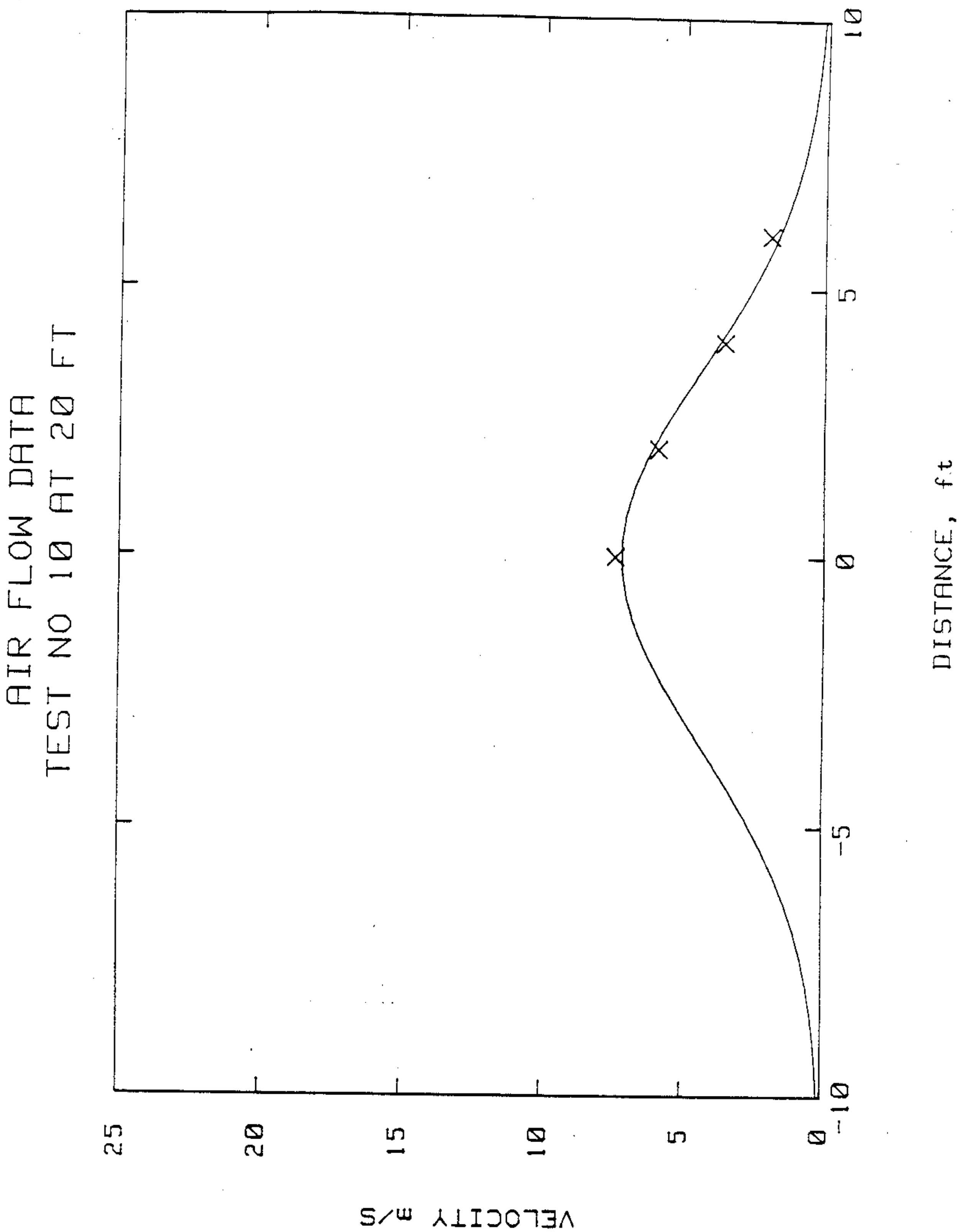

AIR FLOW DATA
TEST NO 9 ALONG CENTERLINE
VELOCITY m/S
35
30
25
20
15
10
5
DISTANCE, ft
0
10
20
30
40
50


AIR FLOW DATA
TEST NO 9 AT 10 FT
DISTANCE, ft
VELOCITY m/S
-10
-5
0
5
10
25
20
15
10
5
0


AIR FLOW DATA
TEST NO 9 AT 20 FT
VELOCITY m/S
25
20
15
10
5
0
-10
-5
0
5
10
DISTANCE, ft


AIR FLOW DATA
TEST NO 10 ALONG CENTERLINE
VELOCITY m/S
DISTANCE, ft
0
5
10
15
20
25
0
10
20
30
40
50


AIR FLOW DATA
TEST NO 10 AT 10 FT
VELOCITY m/S
25
20
15
10
5
0
-10
-5
0
5
10
DISTANCE, ft


AIR FLOW DATA
TEST NO 10 AT 20 FT
VELOCITY m/S
DISTANCE, ft
25
20
15
10
5
0
-10
-5
0
5
10

APPENDIX C

CALCULATION OF OPTIMUM SPACING FOR MULTIPLE NOZZLE CONFIGURATIONS

The optimum spacing for each nozzle type was defined by an iterative process. The summed velocity distribution is:

$$\text{SUMVEL} = \sum_{i=0}^{40} \left\{ \sum_{n=-1}^{2} \nu[x - i * \frac{\text{SIGMA}}{40} (1-2n) - 4n * \text{SIGMA}] \right\}$$

where ν(x) is the normal velocity equation from Section 3.2. Spacing is defined as:

$$\text{SPACING} = 4 * \text{SIGMA} (1 - i/40)$$

This means that 40 iteration steps were required to overlap nozzles which were initially a distance of 4 SIGMA apart. The ratio of trough velocity to peak velocity in the summed distribution is always greater than 90 percent after 17 iterations:

$$\nu(2\ \text{SIGMA})/\nu \left(i * \frac{\text{SIGMA}}{20} \right) \geq 0.90$$

Therefore optimum spacing is 2.3*SIGMA. A summary of optimum spacings derived for the tested nozzles is tabulated in the following.

However, the selected spacing is dependent on the distance downstream from the nozzle. A uniform distribution at 3.05 m (10 feet) corresponds to a severely peaked distribution at 6.1 m (20 feet) for the same spacing.

The following tabulated data give the trough velocity between two adjacent jets, the peak velocity along the centreline of a jet, the ratio of the two velocities and the average velocity for every iteration step. Starting from a spacing of 4 SIGMA (i.e. iteration 0) and reducing the spacing by 1/40th sigma for every subsequent iteration step, provides the information necessary to calculate the spacing for any desired velocity fluctuation. The last few iteration steps are theoretical and have no practical meaning since a minimum spacing will be imposed by design considerations of a multiple-nozzle line.

Following the tables, velocity profile plots are presented for the base cases for a distance from the nozzles of 3.05 (10 ft) and 6.10 m (20 ft). The higher velocity curves represent the closer distance to the nozzles.

SUMMARY OF MULTIPLE NOZZLE OPTIMUM SPACINGS

TEST NO.	NOZZLE TYPE	PRESSURE (kPa)	*OPTIMUM SPACING AT 3.05 m (m)	OPTIMUM SPACING AT 6.10 m (m)
1	40-20	13790	1.942	3.577
2	25-20	13790	.973	2.323
3	40-10	13790	1.494	2.448
4	65-20	13790	3.868	-
5	25-10	13790	1.022	2.027
6	25-40	13790	1.024	2.056
7	65-30	13790	2.852	5.690
8	40-40	13790	1.442	3.084
9	40-60	13790	1.061	2.565

* Criteria for optimum is that trough velocity is within 10 percent of peak velocity:

$$V(2\ SIGMA)/\ V(delta\ X) \leq 0.900$$

NOTE that velocity values are derived from cross-section data only and are not corrected by centre-line velocity distributions.

TEST: 1 at 3.05 Meters

Iteration	V(2sigma) (Meters/Sec)	V(deltax) (Meters/Sec)	V(2sigma)/V(deltax)	Ave Vel (Meters/Sec)
0	4.276	15.807	.270	10.042
1	4.719	15.812	.298	10.266
2	5.196	15.820	.328	10.508
3	5.707	15.830	.361	10.769
4	6.252	15.845	.395	11.049
5	6.833	15.866	.431	11.349
6	7.448	15.894	.469	11.671
7	8.099	15.933	.508	12.016
8	8.784	15.986	.550	12.385
9	9.505	16.055	.592	12.780
10	10.258	16.148	.635	13.203
11	11.044	16.268	.679	13.656
12	11.862	16.424	.722	14.143
13	12.710	16.622	.765	14.666
14	13.587	16.872	.805	15.230
15	14.492	17.185	.843	15.839
16	15.427	17.570	.878	16.498
17	16.391	18.040	.909	17.216
18	17.389	18.607	.935	17.998
19	18.426	19.282	.956	18.854
20	19.513	20.078	.972	19.796
21	20.664	21.005	.984	20.834
22	21.897	22.073	.992	21.985
23	23.238	23.294	.998	23.266
24	24.715	24.675	1.002	24.695
25	26.362	26.229	1.005	26.295
26	28.212	27.967	1.009	28.090
27	30.297	29.906	1.013	30.101
28	32.641	32.062	1.018	32.351
29	35.257	34.454	1.023	34.856
30	38.138	37.097	1.028	37.617
31	41.252	39.995	1.031	40.624
32	44.543	43.130	1.033	43.836
33	47.921	46.454	1.032	47.188
34	51.275	49.875	1.028	50.575
35	54.469	53.259	1.023	53.864
36	57.357	56.432	1.016	56.894
37	59.791	59.194	1.010	59.493
38	61.639	61.347	1.005	61.493
39	62.794	62.716	1.001	62.755
40	63.187	63.187	1.000	63.187

SPACING: 1.942 Meters

TEST: 1 at 6.10 Meters

Iteration	V(2sigma) (Meters/Sec)	V(deltax) (Meters/Sec)	V(2sigma)/V(deltax)	Ave Vel (Meters/Sec)
0	2.217	8.195	.270	5.206
1	2.447	8.197	.298	5.322
2	2.694	8.201	.328	5.448
3	2.959	8.207	.361	5.583
4	3.241	8.214	.395	5.728
5	3.542	8.225	.431	5.884
6	3.861	8.240	.469	6.051
7	4.199	8.260	.508	6.229
8	4.554	8.287	.550	6.421
9	4.927	8.323	.592	6.625
10	5.318	8.371	.635	6.845
11	5.726	8.434	.679	7.080
12	6.149	8.514	.722	7.332
13	6.589	8.617	.765	7.603
14	7.044	8.747	.805	7.895
15	7.513	8.909	.843	8.211
16	7.997	9.109	.878	8.553
17	8.497	9.352	.909	8.925
18	9.015	9.646	.935	9.330
19	9.553	9.996	.956	9.774
20	10.116	10.409	.972	10.262
21	10.713	10.889	.984	10.801
22	11.352	11.443	.992	11.398
23	12.047	12.076	.998	12.061
24	12.813	12.792	1.002	12.802
25	13.666	13.598	1.005	13.632
26	14.625	14.499	1.009	14.562
27	15.706	15.504	1.013	15.605
28	16.922	16.621	1.018	16.772
29	18.278	17.861	1.023	18.070
30	19.771	19.232	1.028	19.501
31	21.386	20.734	1.031	21.060
32	23.092	22.359	1.033	22.726
33	24.843	24.082	1.032	24.463
34	26.582	25.856	1.028	26.219
35	28.238	27.610	1.023	27.924
36	29.735	29.255	1.016	29.495
37	30.997	30.687	1.010	30.842
38	31.955	31.803	1.005	31.879
39	32.553	32.513	1.001	32.533
40	32.757	32.757	1.000	32.757

SPACING: 3.577 Meters

TEST: 2 at 3.05 Meters

Iteration	V(2sigma) (Meters/Sec)	V(deltax) (Meters/Sec)	V(2sigma)/V(deltax)	Ave Vel (Meters/Sec)
0	5.335	19.723	.270	12.529
1	5.888	19.729	.298	12.809
2	6.483	19.738	.328	13.111
3	7.121	19.752	.361	13.436
4	7.801	19.770	.395	13.786
5	8.525	19.796	.431	14.160
6	9.293	19.831	.469	14.562
7	10.105	19.880	.508	14.992
8	10.960	19.945	.550	15.453
9	11.859	20.032	.592	15.946
10	12.799	20.147	.635	16.473
11	13.780	20.298	.679	17.039
12	14.800	20.492	.722	17.646
13	15.858	20.739	.765	18.299
14	16.952	21.052	.805	19.002
15	18.082	21.442	.843	19.762
16	19.248	21.923	.878	20.585
17	20.451	22.509	.909	21.480
18	21.696	23.216	.935	22.456
19	22.991	24.058	.956	23.524
20	24.347	25.051	.972	24.699
21	25.782	26.207	.984	25.995
22	27.321	27.541	.992	27.431
23	28.994	29.063	.998	29.029
24	30.837	30.787	1.002	30.812
25	32.891	32.726	1.005	32.809
26	35.199	34.895	1.009	35.047
27	37.801	37.313	1.013	37.557
28	40.727	40.003	1.018	40.365
29	43.991	42.988	1.023	43.489
30	47.585	46.286	1.028	46.935
31	51.471	49.902	1.031	50.686
32	55.576	53.814	1.033	54.695
33	59.792	57.960	1.032	58.876
34	63.976	62.229	1.028	63.103
35	67.961	66.451	1.023	67.206
36	71.564	70.410	1.016	70.987
37	74.601	73.857	1.010	74.229
38	76.907	76.542	1.005	76.725
39	78.348	78.251	1.001	78.300
40	78.838	78.838	1.000	78.838

SPACING: .973 Meters

TEST: 2 at 6.10 Meters

Iteration	V(2sigma) (Meters/Sec)	V(deltax) (Meters/Sec)	V(2sigma)/V(deltax)	Ave Vel (Meters/Sec)
0	3.191	11.796	.270	7.493
1	3.522	11.800	.298	7.661
2	3.878	11.806	.328	7.842
3	4.259	11.813	.361	8.036
4	4.666	11.824	.395	8.245
5	5.099	11.840	.431	8.469
6	5.558	11.861	.469	8.710
7	6.044	11.890	.508	8.967
8	6.555	11.929	.550	9.242
9	7.093	11.981	.592	9.537
10	7.655	12.050	.635	9.853
11	8.242	12.140	.679	10.191
12	8.852	12.256	.722	10.554
13	9.485	12.404	.765	10.944
14	10.139	12.591	.805	11.365
15	10.815	12.824	.843	11.820
16	11.512	13.112	.878	12.312
17	12.232	13.463	.909	12.847
18	12.976	13.886	.935	13.431
19	13.751	14.389	.956	14.070
20	14.562	14.983	.972	14.772
21	15.421	15.675	.984	15.548
22	16.341	16.472	.992	16.407
23	17.341	17.383	.998	17.362
24	18.444	18.414	1.002	18.429
25	19.672	19.574	1.005	19.623
26	21.053	20.871	1.009	20.962
27	22.609	22.317	1.013	22.463
28	24.359	23.926	1.018	24.142
29	26.311	25.711	1.023	26.011
30	28.461	27.684	1.028	28.072
31	30.785	29.846	1.031	30.316
32	33.240	32.186	1.033	32.713
33	35.761	34.666	1.032	35.214
34	38.264	37.219	1.028	37.742
35	40.648	39.745	1.023	40.196
36	42.803	42.112	1.016	42.458
37	44.619	44.174	1.010	44.397
38	45.998	45.780	1.005	45.889
39	46.860	46.802	1.001	46.831
40	47.153	47.153	1.000	47.153

SPACING: 2.323 Meters

TEST: 3 at 3.05 Meters

Iteration	V(2sigma) (Meters/Sec)	V(deltax) (Meters/Sec)	V(2sigma)/V(deltax)	Ave Vel (Meters/Sec)
0	3.465	12.811	.270	8.138
1	3.825	12.815	.298	8.320
2	4.211	12.821	.328	8.516
3	4.625	12.829	.361	8.727
4	5.067	12.841	.395	8.954
5	5.537	12.858	.431	9.198
6	6.036	12.881	.469	9.459
7	6.564	12.913	.508	9.738
8	7.119	12.955	.550	10.037
9	7.703	13.012	.592	10.357
10	8.314	13.087	.635	10.700
11	8.951	13.184	.679	11.067
12	9.613	13.310	.722	11.462
13	10.301	13.471	.765	11.886
14	11.011	13.674	.805	12.343
15	11.745	13.927	.843	12.836
16	12.502	14.240	.878	13.371
17	13.284	14.621	.909	13.952
18	14.092	15.080	.935	14.586
19	14.933	15.627	.956	15.280
20	15.814	16.272	.972	16.043
21	16.747	17.023	.984	16.885
22	17.746	17.889	.992	17.818
23	18.833	18.878	.998	18.855
24	20.030	19.998	1.002	20.014
25	21.364	21.257	1.005	21.311
26	22.864	22.666	1.009	22.765
27	24.553	24.237	1.013	24.395
28	26.454	25.984	1.018	26.219
29	28.574	27.922	1.023	28.248
30	30.908	30.065	1.028	30.486
31	33.432	32.413	1.031	32.923
32	36.099	34.954	1.033	35.527
33	38.837	37.648	1.032	38.242
34	41.555	40.420	1.028	40.988
35	44.144	43.163	1.023	43.653
36	46.484	45.734	1.016	46.109
37	48.457	47.973	1.010	48.215
38	49.954	49.718	1.005	49.836
39	50.890	50.828	1.001	50.859
40	51.209	51.209	1.000	51.209

SPACING: 1.494 Meters

TEST: 3 at 6.10 Meters

Iteration	V(2sigma) (Meters/Sec)	V(deltax) (Meters/Sec)	V(2sigma)/V(deltax)	Ave Vel (Meters/Sec)
0	1.944	7.188	.270	4.566
1	2.146	7.190	.298	4.668
2	2.363	7.193	.328	4.778
3	2.595	7.198	.361	4.897
4	2.843	7.205	.395	5.024
5	3.107	7.214	.431	5.161
6	3.387	7.227	.469	5.307
7	3.683	7.245	.508	5.464
8	3.994	7.269	.550	5.631
9	4.322	7.300	.592	5.811
10	4.664	7.342	.635	6.003
11	5.022	7.397	.679	6.210
12	5.394	7.468	.722	6.431
13	5.779	7.558	.765	6.669
14	6.178	7.672	.805	6.925
15	6.590	7.814	.843	7.202
16	7.015	7.989	.878	7.502
17	7.453	8.203	.909	7.828
18	7.907	8.461	.935	8.184
19	8.378	8.768	.956	8.573
20	8.873	9.129	.972	9.001
21	9.396	9.551	.984	9.473
22	9.957	10.037	.992	9.997
23	10.566	10.592	.998	10.579
24	11.238	11.220	1.002	11.229
25	11.987	11.926	1.005	11.957
26	12.828	12.717	1.009	12.772
27	13.776	13.598	1.013	13.687
28	14.842	14.578	1.018	14.710
29	16.032	15.666	1.023	15.849
30	17.341	16.868	1.028	17.105
31	18.758	18.186	1.031	18.472
32	20.254	19.611	1.033	19.933
33	21.790	21.123	1.032	21.456
34	23.315	22.678	1.028	22.997
35	24.767	24.217	1.023	24.492
36	26.080	25.660	1.016	25.870
37	27.187	26.916	1.010	27.052
38	28.027	27.894	1.005	27.961
39	28.553	28.517	1.001	28.535
40	28.731	28.731	1.000	28.731

SPACING: 2.448 Meters

TEST: 4 at 3.05 Meters

Iteration	V(2sigma) (Meters/Sec)	V(deltax) (Meters/Sec)	V(2sigma)/V(deltax)	Ave Vel (Meters/Sec)
0	1.974	7.297	.270	4.635
1	2.179	7.299	.298	4.739
2	2.399	7.303	.328	4.851
3	2.635	7.308	.361	4.971
4	2.886	7.315	.395	5.100
5	3.154	7.324	.431	5.239
6	3.438	7.337	.469	5.388
7	3.739	7.355	.508	5.547
8	4.055	7.379	.550	5.717
9	4.388	7.412	.592	5.900
10	4.735	7.454	.635	6.095
11	5.098	7.510	.679	6.304
12	5.476	7.582	.722	6.529
13	5.867	7.673	.765	6.770
14	6.272	7.789	.805	7.030
15	6.690	7.933	.843	7.312
16	7.121	8.111	.878	7.616
17	7.567	8.328	.909	7.947
18	8.027	8.590	.935	8.308
19	8.506	8.901	.956	8.704
20	9.008	9.268	.972	9.138
21	9.539	9.696	.984	9.618
22	10.108	10.190	.992	10.149
23	10.727	10.753	.998	10.740
24	11.409	11.391	1.002	11.400
25	12.169	12.108	1.005	12.139
26	13.023	12.911	1.009	12.967
27	13.986	13.805	1.013	13.896
28	15.068	14.801	1.018	14.934
29	16.276	15.905	1.023	16.090
30	17.606	17.125	1.028	17.365
31	19.043	18.463	1.031	18.753
32	20.562	19.910	1.033	20.236
33	22.122	21.444	1.032	21.783
34	23.670	23.024	1.028	23.347
35	25.145	24.586	1.023	24.865
36	26.478	26.051	1.016	26.264
37	27.601	27.326	1.010	27.464
38	28.454	28.319	1.005	28.387
39	28.987	28.952	1.001	28.970
40	29.169	29.169	1.000	29.169

SPACING: 3.868 Meters

TEST: 5 at 3.05 Meters

Iteration	V(2sigma) (Meters/Sec)	V(deltax) (Meters/Sec)	V(2sigma)/V(deltax)	Ave Vel (Meters/Sec)
0	4.256	15.736	.270	9.996
1	4.698	15.741	.298	10.219
2	5.173	15.748	.328	10.460
3	5.681	15.759	.361	10.720
4	6.224	15.773	.395	10.999
5	6.802	15.794	.431	11.298
6	7.414	15.822	.469	11.618
7	8.062	15.861	.508	11.962
8	8.745	15.913	.550	12.329
9	9.461	15.983	.592	12.722
10	10.212	16.075	.635	13.143
11	10.994	16.194	.679	13.594
12	11.808	16.349	.722	14.079
13	12.652	16.547	.765	14.599
14	13.525	16.796	.805	15.161
15	14.427	17.107	.843	15.767
16	15.357	17.491	.878	16.424
17	16.317	17.959	.909	17.138
18	17.310	18.523	.935	17.916
19	18.343	19.195	.956	18.769
20	19.425	19.987	.972	19.706
21	20.570	20.909	.984	20.740
22	21.798	21.973	.992	21.886
23	23.133	23.188	.998	23.160
24	24.603	24.563	1.002	24.583
25	26.242	26.110	1.005	26.176
26	28.084	27.841	1.009	27.962
27	30.159	29.770	1.013	29.965
28	32.493	31.916	1.018	32.205
29	35.098	34.298	1.023	34.698
30	37.965	36.929	1.028	37.447
31	41.066	39.814	1.031	40.440
32	44.341	42.935	1.033	43.638
33	47.704	46.243	1.032	46.974
34	51.043	49.649	1.028	50.346
35	54.223	53.018	1.023	53.620
36	57.097	56.176	1.016	56.637
37	59.520	58.926	1.010	59.223
38	61.360	61.069	1.005	61.214
39	62.509	62.432	1.001	62.471
40	62.901	62.901	1.000	62.901

SPACING: 1.022 Meters

TEST: 5 at 6.10 Meters

Iteration	V(Zsigma) (Meters/Sec)	V(deltax) (Meters/Sec)	V(Zsigma)/V(deltax)	Ave Vel (Meters/Sec)
0	2.307	8.528	.270	5.417
1	2.546	8.531	.298	5.538
2	2.803	8.535	.328	5.669
3	3.079	8.540	.361	5.810
4	3.373	8.548	.395	5.961
5	3.686	8.559	.431	6.123
6	4.018	8.575	.469	6.296
7	4.369	8.596	.508	6.482
8	4.739	8.624	.550	6.682
9	5.128	8.662	.592	6.895
10	5.534	8.711	.635	7.123
11	5.958	8.776	.679	7.367
12	6.399	8.860	.722	7.630
13	6.857	8.967	.765	7.912
14	7.330	9.102	.805	8.216
15	7.818	9.271	.843	8.545
16	8.322	9.479	.878	8.901
17	8.843	9.733	.909	9.288
18	9.381	10.038	.935	9.710
19	9.941	10.403	.956	10.172
20	10.527	10.832	.972	10.679
21	11.148	11.332	.984	11.240
22	11.813	11.908	.992	11.861
23	12.537	12.567	.998	12.552
24	13.333	13.312	1.002	13.323
25	14.222	14.150	1.005	14.186
26	15.220	15.088	1.009	15.154
27	16.345	16.134	1.013	16.239
28	17.610	17.297	1.018	17.453
29	19.021	18.587	1.023	18.804
30	20.575	20.013	1.028	20.294
31	22.255	21.577	1.031	21.916
32	24.030	23.268	1.033	23.649
33	25.853	25.061	1.032	25.457
34	27.662	26.907	1.028	27.285
35	29.385	28.733	1.023	29.059
36	30.943	30.444	1.016	30.694
37	32.257	31.935	1.010	32.096
38	33.253	33.096	1.005	33.175
39	33.876	33.835	1.001	33.856
40	34.088	34.088	1.000	34.088

SPACING: 2.027 Meters

TEST: 6 at 3.05 Meters

Iteration	V(2sigma) (Meters/Sec)	V(deltax) (Meters/Sec)	V(2sigma)/V(deltax)	Ave Vel (Meters/Sec)
0	8.033	29.699	.270	18.866
1	8.867	29.708	.298	19.288
2	9.763	29.722	.328	19.742
3	10.722	29.742	.361	20.232
4	11.747	29.770	.395	20.758
5	12.837	29.808	.431	21.323
6	13.993	29.862	.469	21.928
7	15.216	29.935	.508	22.575
8	16.504	30.033	.550	23.269
9	17.857	30.165	.592	24.011
10	19.273	30.338	.635	24.805
11	20.750	30.564	.679	25.657
12	22.286	30.856	.722	26.571
13	23.879	31.229	.765	27.554
14	25.527	31.700	.805	28.613
15	27.228	32.287	.843	29.757
16	28.983	33.011	.878	30.997
17	30.795	33.894	.909	32.345
18	32.670	34.959	.935	33.814
19	34.619	36.227	.956	35.423
20	36.661	37.722	.972	37.192
21	38.823	39.463	.984	39.143
22	41.140	41.471	.992	41.306
23	43.659	43.763	.998	43.711
24	46.434	46.359	1.002	46.397
25	49.528	49.279	1.005	49.403
26	53.003	52.545	1.009	52.774
27	56.921	56.186	1.013	56.554
28	61.326	60.237	1.018	60.781
29	66.241	64.731	1.023	65.486
30	71.653	69.697	1.028	70.675
31	77.504	75.142	1.031	76.323
32	83.686	81.032	1.033	82.359
33	90.034	87.276	1.032	88.655
34	96.335	93.704	1.028	95.020
35	102.336	100.062	1.023	101.199
36	107.761	106.023	1.016	106.892
37	112.335	111.214	1.010	111.774
38	115.806	115.257	1.005	115.532
39	117.976	117.831	1.001	117.903
40	118.714	118.714	1.000	118.714

SPACING: 1.024 Meters

TEST: 6 at 6.10 Meters

Iteration	V(2sigma) (Meters/Sec)	V(deltax) (Meters/Sec)	V(2sigma)/V(deltax)	Ave Vel (Meters/Sec)
0	4.685	17.322	.270	11.004
1	5.172	17.327	.298	11.250
2	5.694	17.336	.328	11.515
3	6.254	17.347	.361	11.800
4	6.851	17.363	.395	12.107
5	7.487	17.386	.431	12.437
6	8.162	17.417	.469	12.789
7	8.875	17.460	.508	13.167
8	9.626	17.517	.550	13.572
9	10.415	17.594	.592	14.004
10	11.241	17.695	.635	14.468
11	12.103	17.827	.679	14.965
12	12.999	17.997	.722	15.498
13	13.928	18.215	.765	16.071
14	14.889	18.489	.805	16.689
15	15.881	18.831	.843	17.356
16	16.905	19.254	.878	18.079
17	17.961	19.769	.909	18.865
18	19.055	20.390	.935	19.722
19	20.192	21.130	.956	20.661
20	21.383	22.001	.972	21.692
21	22.644	23.017	.984	22.830
22	23.995	24.188	.992	24.092
23	25.464	25.525	.998	25.495
24	27.083	27.039	1.002	27.061
25	28.887	28.742	1.005	28.815
26	30.915	30.647	1.009	30.781
27	33.199	32.771	1.013	32.985
28	35.769	35.134	1.018	35.451
29	38.636	37.755	1.023	38.195
30	41.792	40.651	1.028	41.222
31	45.205	43.827	1.031	44.516
32	48.810	47.263	1.033	48.037
33	52.513	50.905	1.032	51.709
34	56.188	54.654	1.028	55.421
35	59.688	58.362	1.023	59.025
36	62.852	61.839	1.016	62.346
37	65.520	64.866	1.010	65.193
38	67.545	67.225	1.005	67.385
39	68.810	68.726	1.001	68.768
40	69.241	69.241	1.000	69.241

SPACING: 2.056 Meters

TEST: 7 at 3.05 Meters

Iteration	V(2sigma) (Meters/Sec)	V(deltax) (Meters/Sec)	V(2sigma)/V(deltax)	Ave Vel (Meters/Sec)
0	3.489	12.900	.270	8.195
1	3.851	12.904	.298	8.378
2	4.241	12.910	.328	8.575
3	4.657	12.919	.361	8.788
4	5.102	12.931	.395	9.017
5	5.576	12.948	.431	9.262
6	6.078	12.971	.469	9.525
7	6.609	13.003	.508	9.806
8	7.169	13.045	.550	10.107
9	7.756	13.102	.592	10.429
10	8.371	13.178	.635	10.775
11	9.013	13.276	.679	11.144
12	9.680	13.403	.722	11.542
13	10.372	13.565	.765	11.968
14	11.088	13.769	.805	12.429
15	11.827	14.024	.843	12.925
16	12.589	14.339	.878	13.464
17	13.376	14.722	.909	14.049
18	14.190	15.185	.935	14.688
19	15.037	15.736	.956	15.386
20	15.924	16.385	.972	16.155
21	16.863	17.141	.984	17.002
22	17.870	18.013	.992	17.942
23	18.964	19.009	.998	18.987
24	20.169	20.137	1.002	20.153
25	21.513	21.405	1.005	21.459
26	23.023	22.823	1.009	22.923
27	24.724	24.405	1.013	24.565
28	26.638	26.165	1.018	26.401
29	28.773	28.117	1.023	28.445
30	31.123	30.274	1.028	30.699
31	33.665	32.639	1.031	33.152
32	36.350	35.197	1.033	35.774
33	39.107	37.910	1.032	38.508
34	41.844	40.701	1.028	41.273
35	44.451	43.463	1.023	43.957
36	46.807	46.052	1.016	46.430
37	48.794	48.307	1.010	48.550
38	50.302	50.063	1.005	50.183
39	51.244	51.181	1.001	51.213
40	51.565	51.565	1.000	51.565

SPACING: 2.852 Meters

TEST: 7 at 6.10 Meters

Iteration	V(2sigma) (Meters/Sec)	V(deltax) (Meters/Sec)	V(2sigma)/V(deltax)	Ave Vel (Meters/Sec)
0	2.196	8.116	.270	5.157
1	2.424	8.120	.298	5.272
2	2.668	8.124	.328	5.396
3	2.931	8.129	.361	5.530
4	3.211	8.137	.395	5.674
5	3.509	8.148	.431	5.823
6	3.825	8.162	.469	5.994
7	4.159	8.182	.508	6.171
8	4.511	8.209	.550	6.360
9	4.881	8.245	.592	6.563
10	5.268	8.292	.635	6.780
11	5.672	8.354	.679	7.013
12	6.092	8.434	.722	7.263
13	6.527	8.536	.765	7.531
14	6.977	8.665	.805	7.821
15	7.442	8.825	.843	8.134
16	7.922	9.023	.878	8.473
17	8.417	9.264	.909	8.841
18	8.930	9.555	.935	9.243
19	9.463	9.902	.956	9.682
20	10.021	10.311	.972	10.166
21	10.612	10.787	.984	10.699
22	11.245	11.335	.992	11.290
23	11.934	11.962	.998	11.948
24	12.692	12.672	1.002	12.682
25	13.538	13.470	1.005	13.504
26	14.488	14.362	1.009	14.425
27	15.558	15.358	1.013	15.458
28	16.763	16.465	1.018	16.614
29	18.106	17.693	1.023	17.900
30	19.585	19.051	1.028	19.318
31	21.185	20.539	1.031	20.862
32	22.874	22.149	1.033	22.512
33	24.609	23.856	1.032	24.233
34	26.332	25.613	1.028	25.972
35	27.972	27.350	1.023	27.661
36	29.455	28.980	1.016	29.217
37	30.705	30.398	1.010	30.552
38	31.654	31.504	1.005	31.579
39	32.247	32.207	1.001	32.227
40	32.449	32.449	1.000	32.449

SPACING: 5.690 Meters

TEST: 8 at 3.05 Meters

Iteration	V(2sigma) (Meters/Sec)	V(deltax) (Meters/Sec)	V(2sigma)/V(deltax)	Ave Vel (Meters/Sec)
0	5.787	21.395	.270	13.591
1	6.388	21.402	.298	13.895
2	7.033	21.412	.328	14.223
3	7.724	21.426	.361	14.575
4	8.463	21.446	.395	14.954
5	9.248	21.474	.431	15.361
6	10.081	21.513	.469	15.797
7	10.962	21.565	.508	16.264
8	11.890	21.636	.550	16.763
9	12.864	21.731	.592	17.298
10	13.884	21.856	.635	17.870
11	14.949	22.019	.679	18.484
12	16.055	22.229	.722	19.142
13	17.203	22.498	.765	19.850
14	18.390	22.837	.805	20.613
15	19.616	23.260	.843	21.438
16	20.880	23.781	.878	22.331
17	22.185	24.418	.909	23.301
18	23.536	25.185	.935	24.360
19	24.940	26.099	.956	25.519
20	26.411	27.175	.972	26.793
21	27.969	28.430	.984	28.199
22	29.638	29.876	.992	29.757
23	31.453	31.528	.998	31.490
24	33.452	33.398	1.002	33.425
25	35.680	35.501	1.005	35.591
26	38.184	37.854	1.009	38.019
27	41.006	40.477	1.013	40.742
28	44.180	43.395	1.018	43.788
29	47.721	46.633	1.023	47.177
30	51.620	50.211	1.028	50.915
31	55.835	54.133	1.031	54.984
32	60.288	58.377	1.033	59.333
33	64.862	62.875	1.032	63.868
34	69.401	67.506	1.028	68.453
35	73.724	72.086	1.023	72.905
36	77.633	76.381	1.016	77.007
37	80.927	80.120	1.010	80.524
38	83.429	83.033	1.005	83.231
39	84.992	84.887	1.001	84.939
40	85.523	85.523	1.000	85.523

SPACING: 1.442 Meters

TEST: 8 at 6.10 Meters

Iteration	V(2sigma) (Meters/Sec)	V(deltax) (Meters/Sec)	V(2sigma)/V(deltax)	Ave Vel (Meters/Sec)
0	3.461	12.796	.270	8.129
1	3.821	12.801	.298	8.311
2	4.207	12.807	.328	8.507
3	4.620	12.815	.361	8.718
4	5.061	12.827	.395	8.944
5	5.531	12.844	.431	9.188
6	6.029	12.867	.469	9.448
7	6.556	12.898	.508	9.727
8	7.111	12.941	.550	10.026
9	7.694	12.997	.592	10.346
10	8.304	13.072	.635	10.688
11	8.941	13.170	.679	11.055
12	9.603	13.295	.722	11.449
13	10.289	13.456	.765	11.872
14	10.999	13.659	.805	12.329
15	11.732	13.912	.843	12.822
16	12.488	14.224	.878	13.356
17	13.269	14.604	.909	13.937
18	14.077	15.063	.935	14.570
19	14.917	15.610	.956	15.263
20	15.797	16.253	.972	16.025
21	16.728	17.004	.984	16.866
22	17.727	17.869	.992	17.798
23	18.812	18.857	.998	18.834
24	20.008	19.975	1.002	19.991
25	21.340	21.233	1.005	21.287
26	22.838	22.640	1.009	22.739
27	24.526	24.210	1.013	24.368
28	26.424	25.955	1.018	26.189
29	28.542	27.891	1.023	28.217
30	30.874	30.031	1.028	30.452
31	33.395	32.377	1.031	32.886
32	36.058	34.915	1.033	35.487
33	38.794	37.606	1.032	38.200
34	41.509	40.375	1.028	40.942
35	44.095	43.115	1.023	43.605
36	46.432	45.683	1.016	46.058
37	48.403	47.920	1.010	48.161
38	49.899	49.662	1.005	49.780
39	50.833	50.771	1.001	50.802
40	51.152	51.152	1.000	51.152

SPACING: 3.084 Meters

TEST: 9 at 3.05 Meters

Iteration	V(2sigma) (Meters/Sec)	V(deltax) (Meters/Sec)	V(2sigma)/V(deltax)	Ave Vel (Meters/Sec)
0	15.546	57.473	.270	36.510
1	17.159	57.492	.298	37.326
2	18.893	57.519	.328	38.206
3	20.750	57.557	.361	39.154
4	22.733	57.611	.395	40.172
5	24.842	57.686	.431	41.264
6	27.080	57.790	.469	42.435
7	29.446	57.931	.508	43.689
8	31.939	58.121	.550	45.030
9	34.557	58.375	.592	46.466
10	37.297	58.711	.635	48.004
11	40.156	59.149	.679	49.652
12	43.129	59.714	.722	51.421
13	46.212	60.435	.765	53.323
14	49.400	61.346	.805	55.373
15	52.693	62.482	.843	57.587
16	56.089	63.884	.878	59.986
17	59.595	65.593	.909	62.594
18	63.223	67.653	.935	65.438
19	66.996	70.108	.956	68.552
20	70.948	73.000	.972	71.974
21	75.131	76.370	.984	75.751
22	79.616	80.255	.992	79.936
23	84.490	84.692	.998	84.591
24	89.861	89.716	1.002	89.788
25	95.847	95.366	1.005	95.606
26	102.573	101.686	1.009	102.130
27	110.155	108.733	1.013	109.444
28	118.680	116.572	1.018	117.626
29	128.191	125.269	1.023	126.730
30	138.665	134.880	1.028	136.772
31	149.988	145.416	1.031	147.702
32	161.951	156.816	1.033	159.384
33	174.236	168.900	1.032	171.568
34	186.430	181.338	1.028	183.884
35	198.044	193.643	1.023	195.843
36	208.542	205.179	1.016	206.861
37	217.393	215.223	1.010	216.308
38	224.112	223.049	1.005	223.580
39	228.311	228.029	1.001	228.170
40	229.739	229.739	1.000	229.739

SPACING: 1.061 Meters

TEST: 9 - at 6.10 Meters

Iteration	V(2sigma) (Meters/Sec)	V(deltax) (Meters/Sec)	V(2sigma)/V(deltax)	Ave Vel (Meters/Sec)
0	4.338	16.037	.270	10.187
1	4.788	16.042	.298	10.415
2	5.272	16.049	.328	10.660
3	5.790	16.060	.361	10.925
4	6.343	16.075	.395	11.209
5	6.932	16.096	.431	11.514
6	7.556	16.125	.469	11.840
7	8.216	16.164	.508	12.190
8	8.912	16.217	.550	12.565
9	9.642	16.288	.592	12.965
10	10.407	16.382	.635	13.394
11	11.205	16.504	.679	13.854
12	12.034	16.662	.722	14.348
13	12.894	16.863	.765	14.879
14	13.784	17.117	.805	15.451
15	14.703	17.434	.843	16.068
16	15.650	17.825	.878	16.738
17	16.629	18.302	.909	17.465
18	17.641	18.877	.935	18.259
19	18.694	19.562	.956	19.128
20	19.796	20.369	.972	20.083
21	20.964	21.309	.984	21.136
22	22.215	22.393	.992	22.304
23	23.575	23.631	.998	23.603
24	25.074	25.033	1.002	25.053
25	26.744	26.610	1.005	26.677
26	28.621	28.373	1.009	28.497
27	30.736	30.340	1.013	30.538
28	33.115	32.527	1.018	32.821
29	35.769	34.954	1.023	35.361
30	38.691	37.635	1.028	38.163
31	41.851	40.575	1.031	41.213
32	45.189	43.756	1.033	44.472
33	48.617	47.128	1.032	47.872
34	52.019	50.598	1.028	51.309
35	55.259	54.032	1.023	54.646
36	58.189	57.250	1.016	57.720
37	60.659	60.053	1.010	60.356
38	62.533	62.237	1.005	62.385
39	63.705	63.626	1.001	63.666
40	64.103	64.103	1.000	64.103

SPACING: 2.565 Meters

TEST: 10 at 3.05 Meters

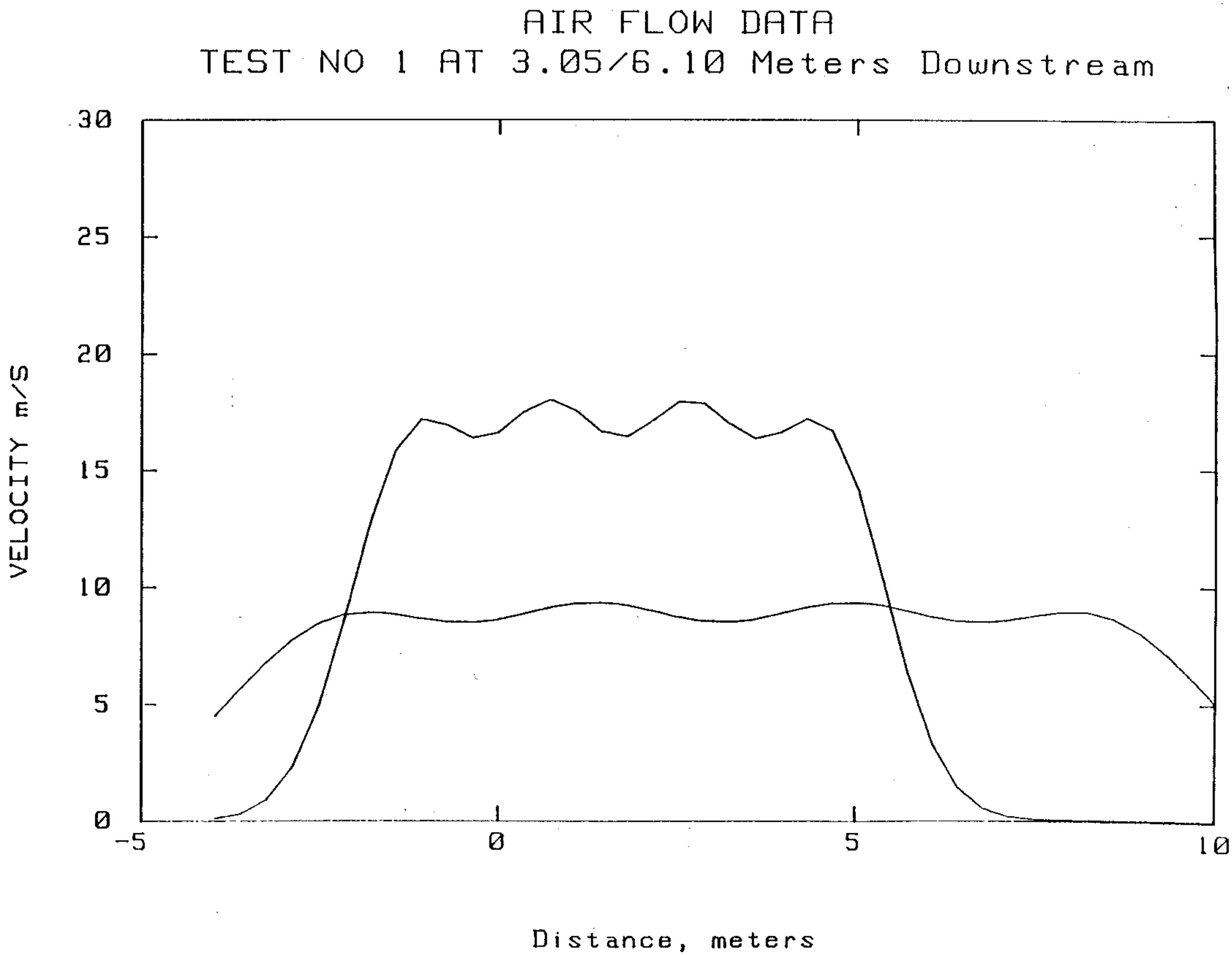
Iteration	V(2sigma) (Meters/Sec)	V(deltax) (Meters/Sec)	V(2sigma)/V(deltax)	Ave Vel (Meters/Sec)
0	3.465	12.811	.270	8.138
1	3.825	12.815	.298	8.320
2	4.211	12.821	.328	8.516
3	4.625	12.829	.361	8.727
4	5.067	12.841	.395	8.954
5	5.537	12.858	.431	9.198
6	6.036	12.881	.469	9.459
7	6.564	12.913	.508	9.738
8	7.119	12.955	.550	10.037
9	7.703	13.012	.592	10.357
10	8.314	13.087	.635	10.700
11	8.951	13.184	.679	11.067
12	9.613	13.310	.722	11.462
13	10.301	13.471	.765	11.886
14	11.011	13.674	.805	12.343
15	11.745	13.927	.843	12.836
16	12.502	14.240	.878	13.371
17	13.284	14.621	.909	13.952
18	14.092	15.080	.935	14.586
19	14.933	15.627	.956	15.280
20	15.814	16.272	.972	16.043
21	16.747	17.023	.984	16.885
22	17.746	17.889	.992	17.818
23	18.833	18.878	.998	18.855
24	20.030	19.998	1.002	20.014
25	21.364	21.257	1.005	21.311
26	22.864	22.666	1.009	22.765
27	24.553	24.237	1.013	24.395
28	26.454	25.984	1.018	26.219
29	28.574	27.922	1.023	28.248
30	30.908	30.065	1.028	30.486
31	33.432	32.413	1.031	32.923
32	36.099	34.954	1.033	35.527
33	38.837	37.648	1.032	38.242
34	41.555	40.420	1.028	40.988
35	44.144	43.163	1.023	43.653
36	46.484	45.734	1.016	46.109
37	48.457	47.973	1.010	48.215
38	49.954	49.718	1.005	49.836
39	50.890	50.828	1.001	50.859
40	51.209	51.209	1.000	51.209

SPACING: 1.494 Meters

TEST: 10 at 6.10 Meters

Iteration	V(2sigma) (Meters/Sec)	V(deltax) (Meters/Sec)	V(2sigma)/V(deltax)	Ave Vel (Meters/Sec)
0	1.944	7.188	.270	4.566
1	2.146	7.190	.298	4.668
2	2.363	7.193	.328	4.778
3	2.595	7.198	.361	4.897
4	2.843	7.205	.395	5.024
5	3.107	7.214	.431	5.161
6	3.387	7.227	.469	5.307
7	3.683	7.245	.508	5.464
8	3.994	7.269	.550	5.631
9	4.322	7.300	.592	5.811
10	4.664	7.342	.635	6.003
11	5.022	7.397	.679	6.210
12	5.394	7.468	.722	6.431
13	5.779	7.558	.765	6.669
14	6.178	7.672	.805	6.925
15	6.590	7.814	.843	7.202
16	7.015	7.989	.878	7.502
17	7.453	8.203	.909	7.828
18	7.907	8.461	.935	8.184
19	8.378	8.768	.956	8.573
20	8.873	9.129	.972	9.001
21	9.396	9.551	.984	9.473
22	9.957	10.037	.992	9.997
23	10.566	10.592	.998	10.579
24	11.238	11.220	1.002	11.229
25	11.987	11.926	1.005	11.957
26	12.828	12.717	1.009	12.772
27	13.776	13.598	1.013	13.687
28	14.842	14.578	1.018	14.710
29	16.032	15.666	1.023	15.849
30	17.341	16.868	1.028	17.105
31	18.758	18.186	1.031	18.472
32	20.254	19.611	1.033	19.933
33	21.790	21.123	1.032	21.456
34	23.315	22.678	1.028	22.997
35	24.767	24.217	1.023	24.492
36	26.080	25.660	1.016	25.870
37	27.187	26.916	1.010	27.052
38	28.027	27.894	1.005	27.961
39	28.553	28.517	1.001	28.535
40	28.731	28.731	1.000	28.731

SPACING: 2.448 Meters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VELOCITY m/S
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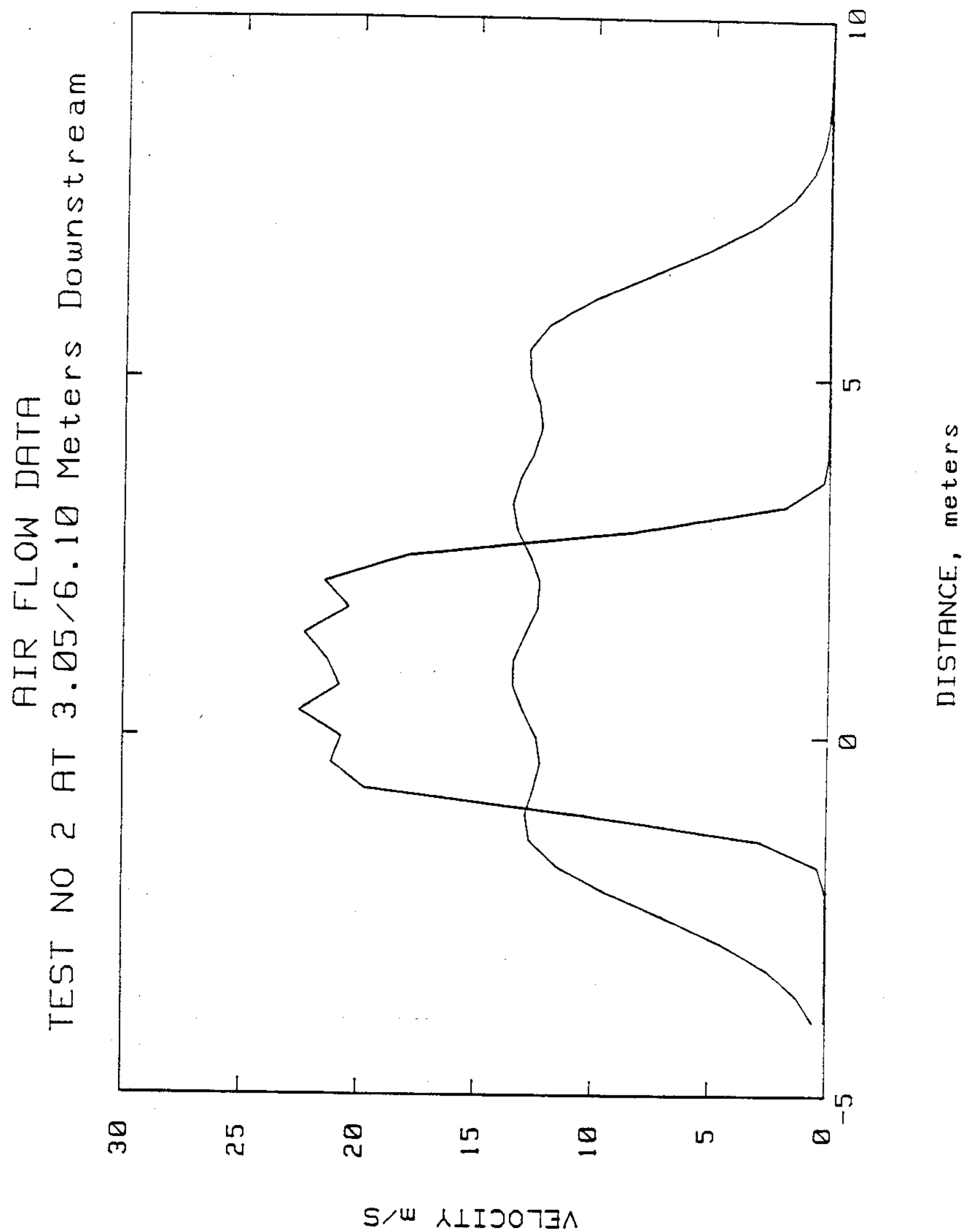
25
20
15
10
5
0
-5
0
5
10
Distance, meters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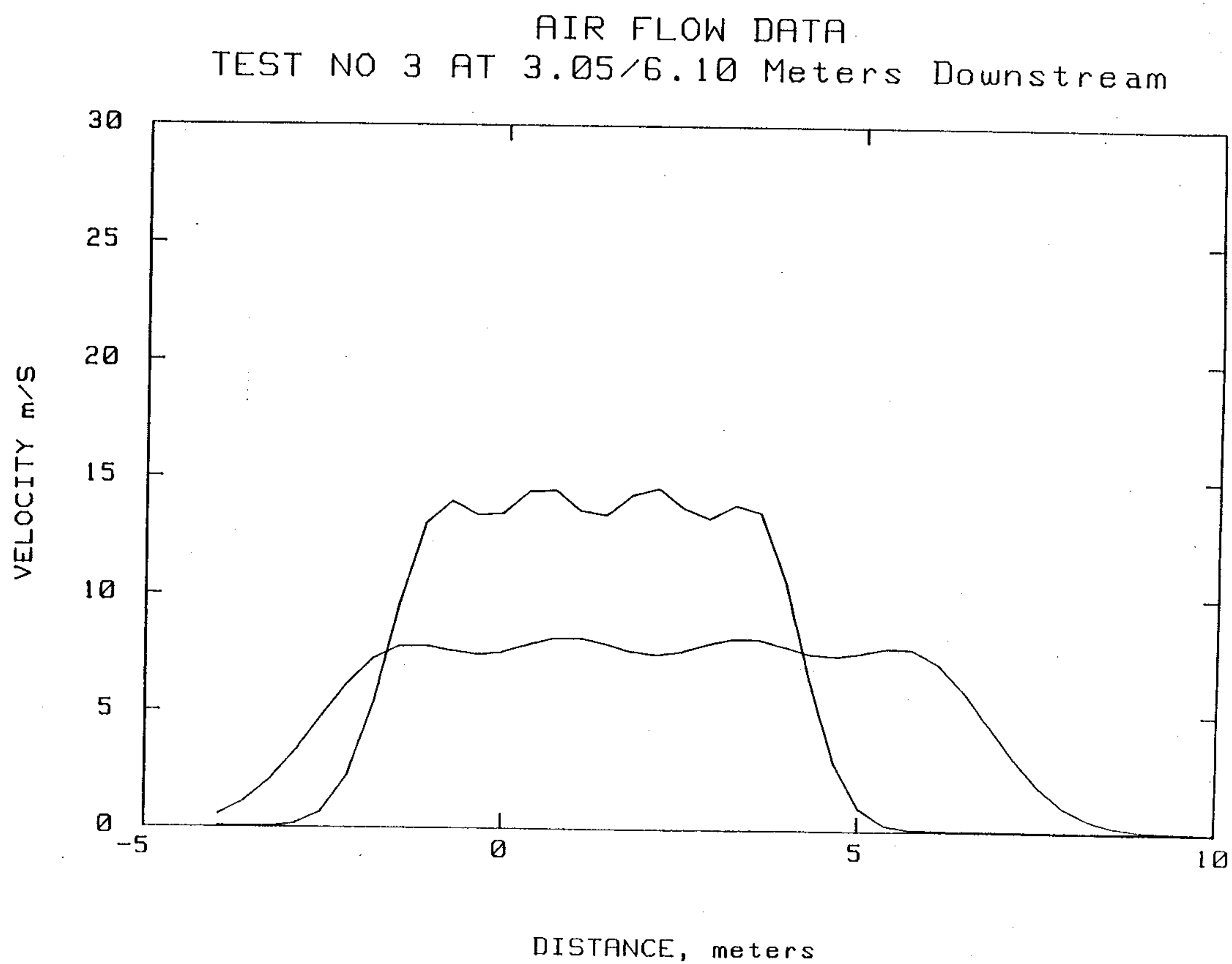
10
15
20
25
30
-5
0
5
10
DISTANCE, meters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VELOCITY m/S
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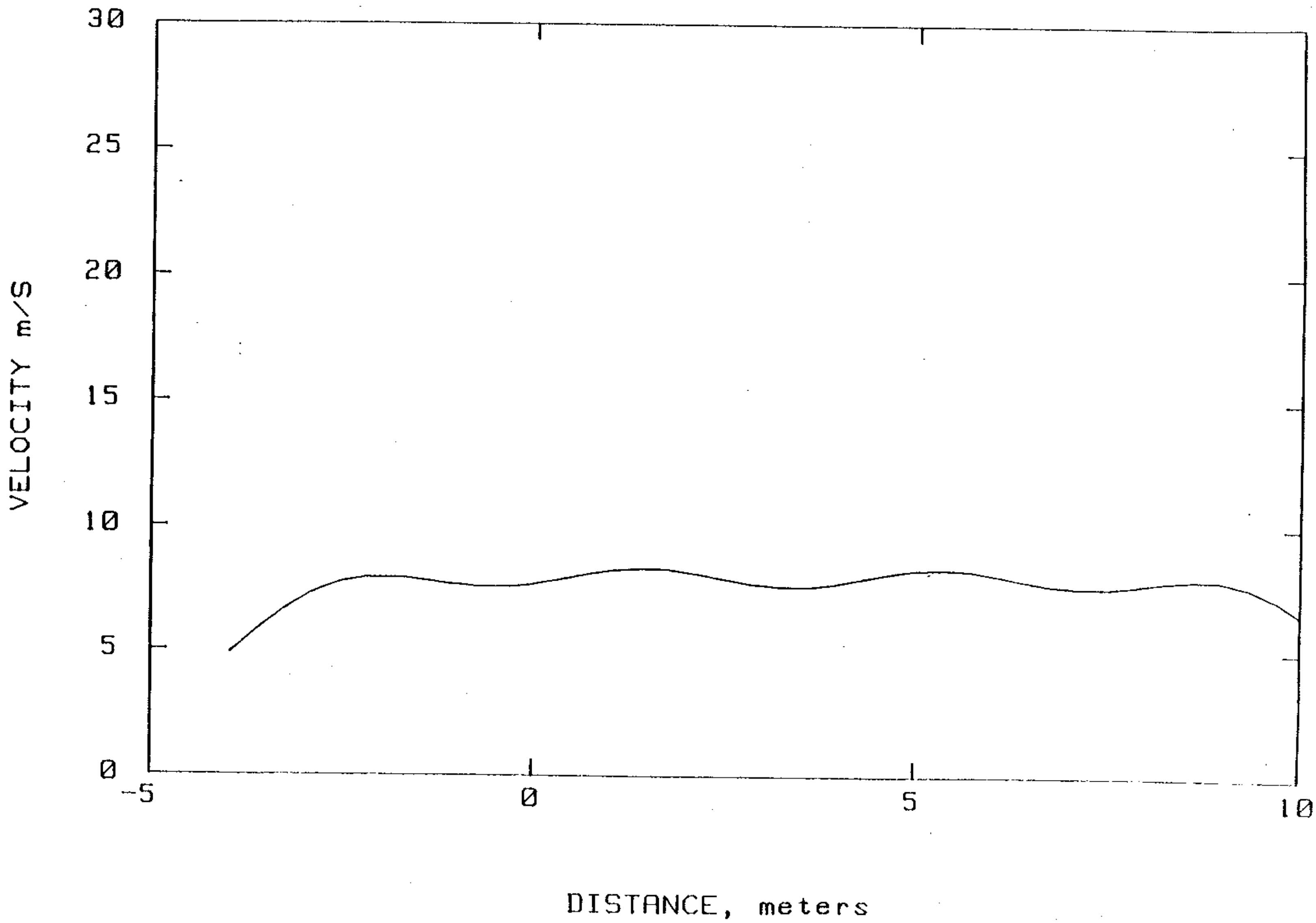
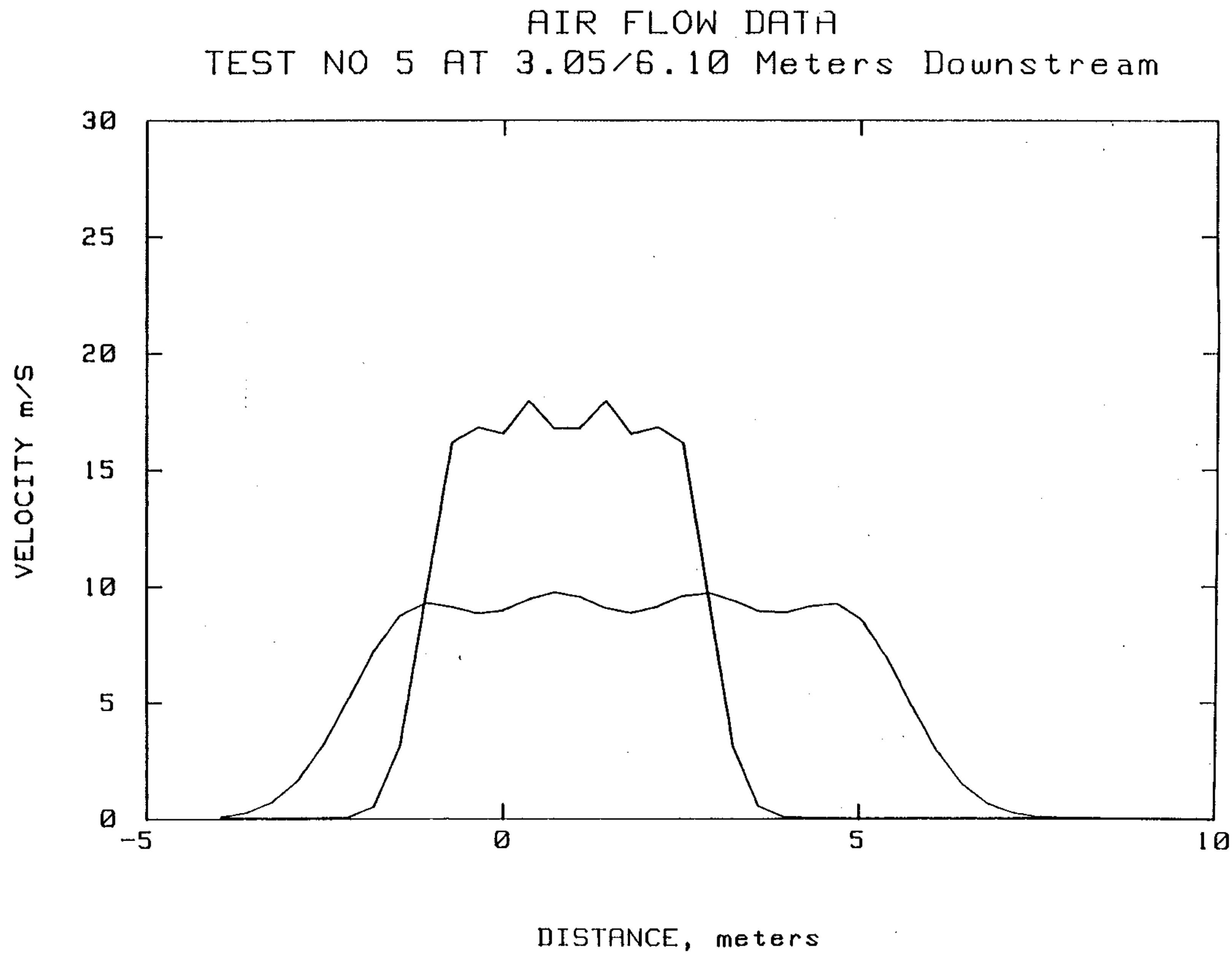
25
20
15
10
5
0
-5
0
5
10
DISTANCE, meters

AIR FLOW DATA
TEST NO 4 AT 3.05/6.10 Meters Downstream




AIR FLOW DATA
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VELOCITY m/S
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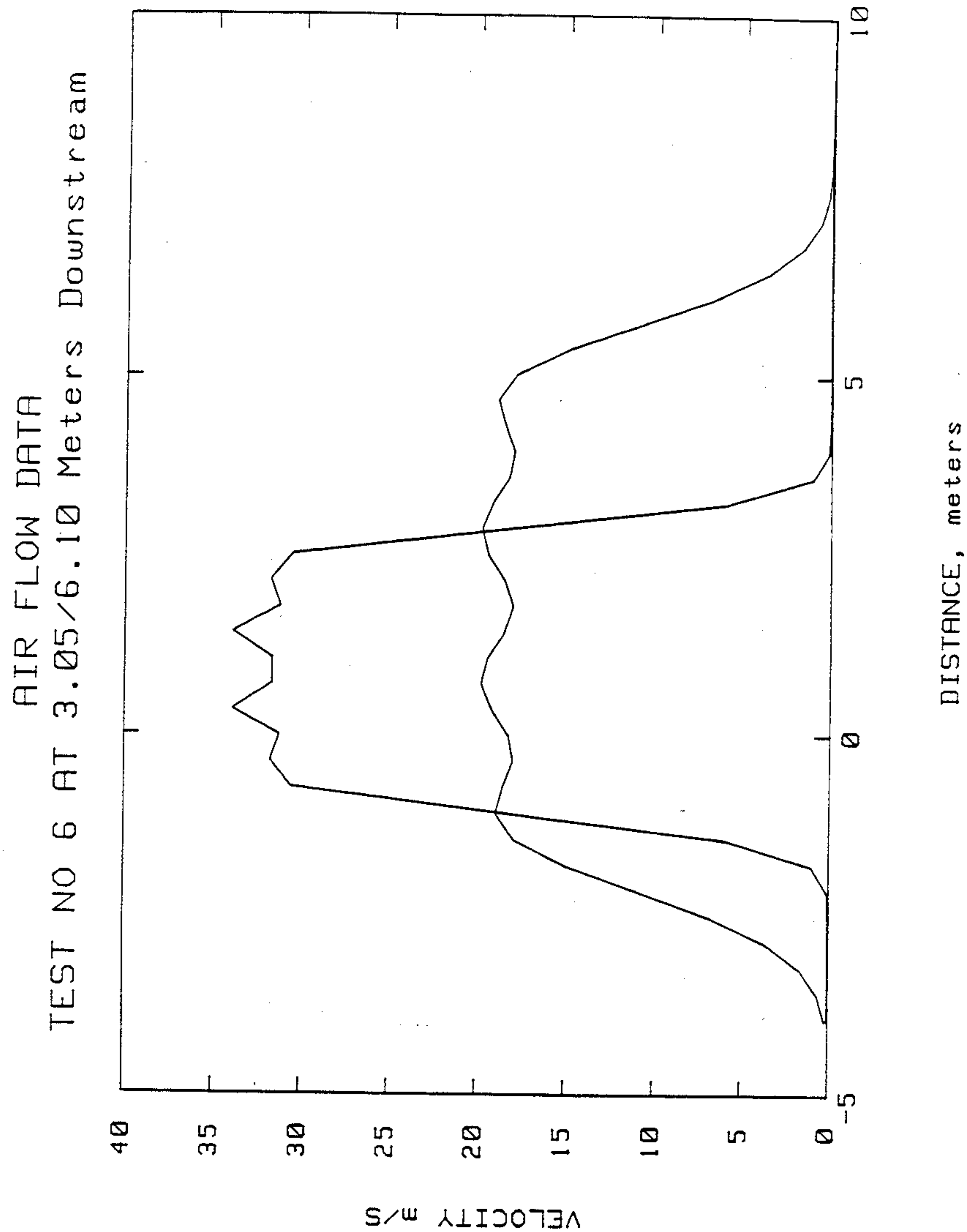
25
20
15
10
5
0
-5
0
5
10
DISTANCE, meters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VELOCITY m/S
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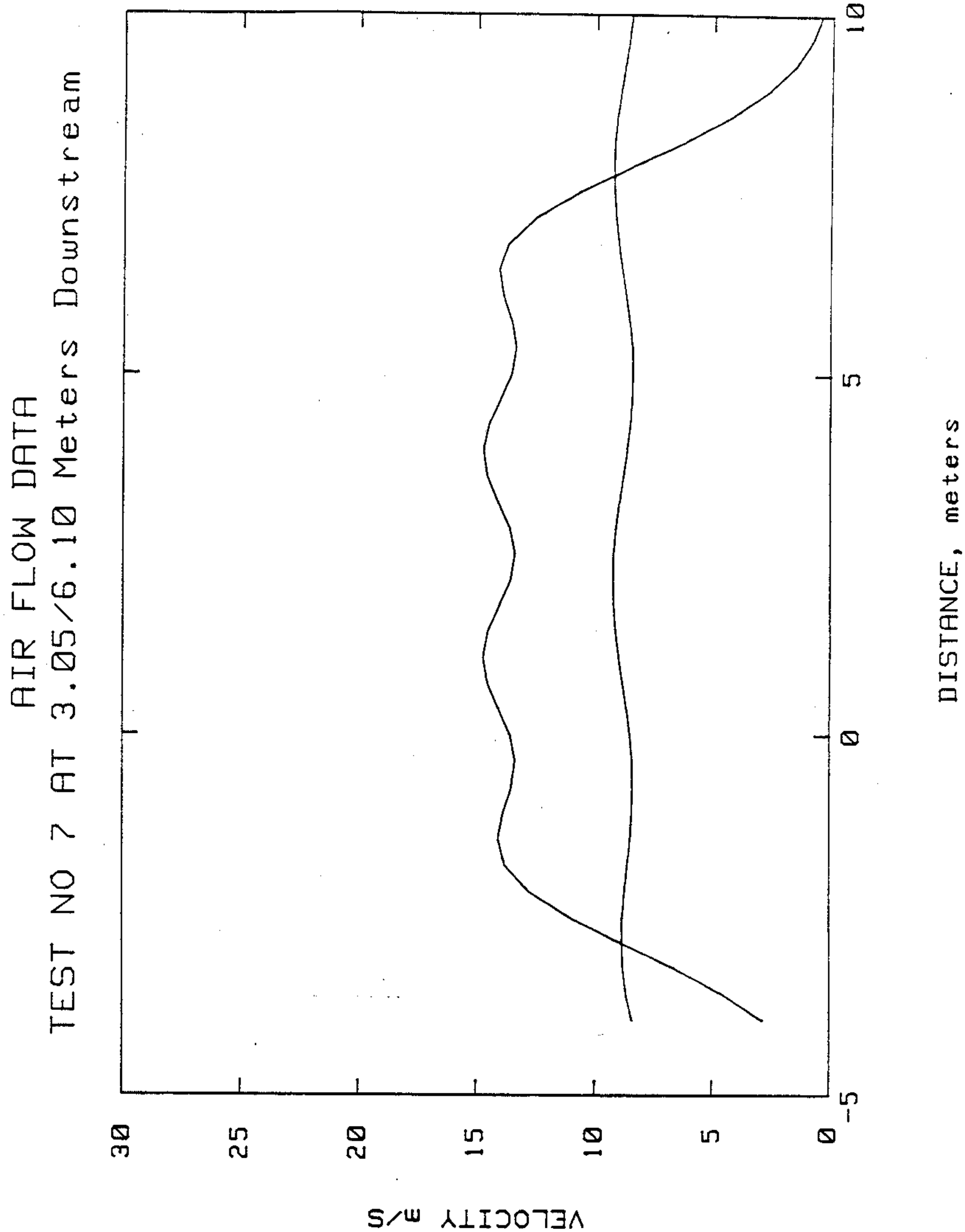
5
10
15
20
25
30
35
40
DISTANCE, meters
-5
0
5
10


AIR FLOW DATA
TEST NO 7 AT 3.05/6.10 Meters Downstream
VELOCITY m/S
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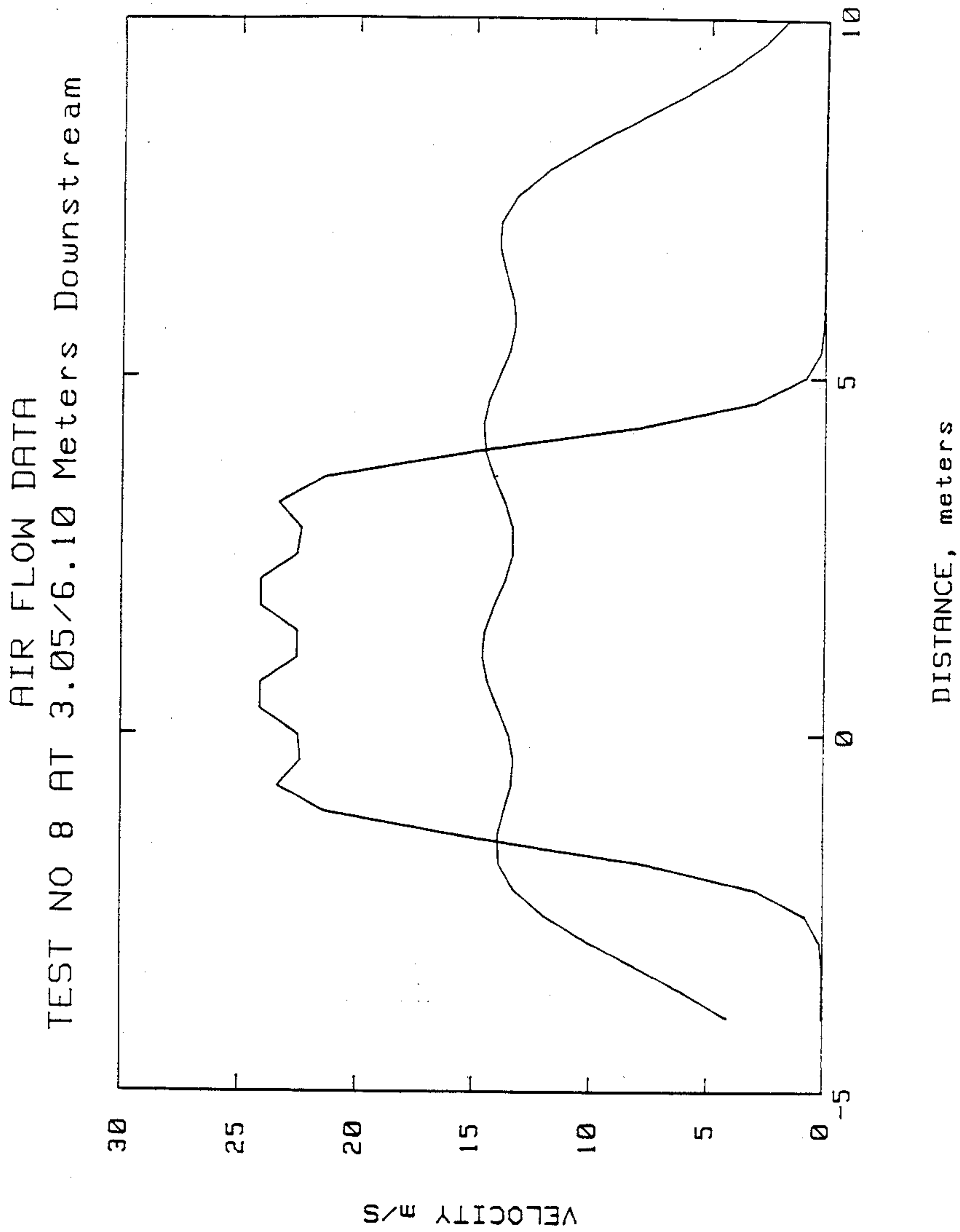
10
15
20
25
30
-5
0
5
10
DISTANCE, meters


AIR FLOW DATA
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VELOCITY m/S
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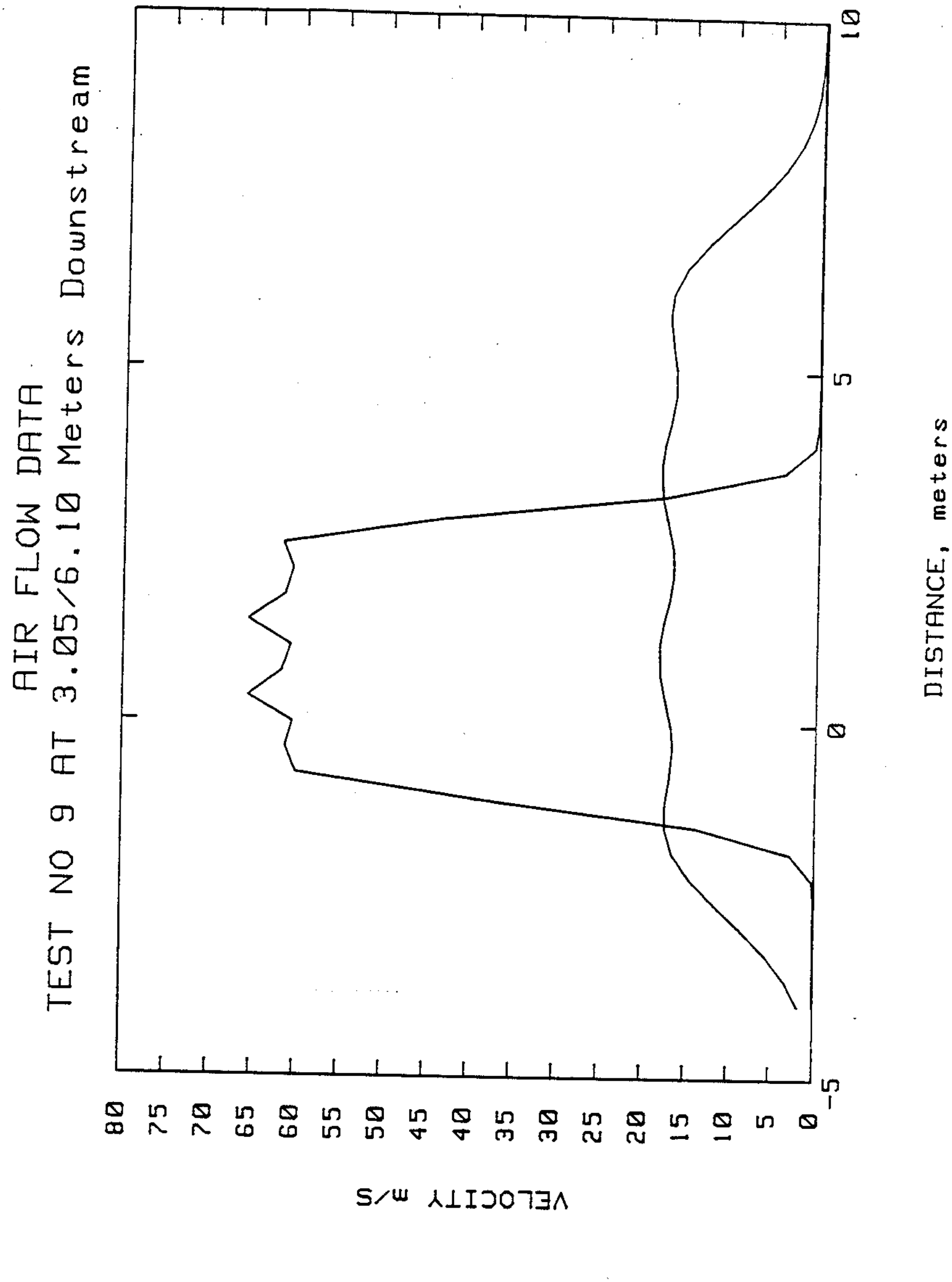
15
20
25
30
DISTANCE, meters
-5
0
5
10


AIR FLOW DATA
TEST NO 9 AT 3.05/6.10 Meters Downstream
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5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
DISTANCE, meters
-5
0
5
10