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REPORT NO. RN-TM-0559

WATER JET PENETRATION OF A HIGH-VELOCITY
GAS STREAM IN CROSS FLOW

MASTER

DECEMBER 1967

NUCLEAR PRODUCTS AND SERVICES GROUP

AEROJET-GENERAL CORPORATION

SACRAMENTO, CALIFORNIA

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WATER JET PENETRATION OF A HIGH-VELOCITY
GAS STREAM IN CROSS FLOW

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ABSTRACT

Data on water jet penetration into a high-velocity, cross-flow of gas were obtained for nozzles ranging from 0.0625 to 1.5 inches in diameter. The range of nozzle sizes tested necessitated two types of tests. The initial, or Phase I, tests (nozzles with diameters ranging from 0.0625 to 0.5 inch) were conducted in a two-dimensional test section with a window forming one side. The second series, or Phase II, tests (nozzles with diameters ranging from 0.25 to 1.5 inches) were conducted in the NASA Lewis Research Center six by nine foot Icing Research Tunnel. The gas streams penetrated in the small-nozzle tests were either nitrogen or hydrogen gases at ambient temperatures or heated to 1500°R. The large diameter nozzles were tested in the wind tunnel flowing air at 35 to 40°F. Expressions for predicting the profile and spread of the jet were empirically derived.

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I. SUMMARY

The penetration of water jets into a high-velocity, cross-flow of gas has been experimentally studied and empirical correlations developed which permit the prediction of performance of large diameter water nozzles.

Penetration can be represented by:

$$\frac{Z}{d} = 2.0 (q_w/q_a)^{0.5} (x/d)^{0.27},$$

for $x \leq Z$.

A jet of water injected into a flow of gas is bent by the flow and spreads. The jet spread was empirically correlated by the equation:

$$\frac{y}{d} = 2.6 \left(\frac{x}{d}\right)^{0.33},$$

for $7 < x < 22$.

Maximum penetration test data were correlated by the dimensional equation:

$$Z_{\max} = 4.0 (q_w/q_a)^{0.5} d^{0.7},$$

for $0.0625 < d < 0.5$,

where Z and d are expressed in inches.

II. INTRODUCTION

Scale-model testing and analysis of diffuser-ejector systems have contributed significantly toward the development of ETS-1 for NERVA technology engine testing. The advent of nuclear engines in the 5000 to 10,000 mw range has resulted in the initiation of a design effort for Engine/Stage Test Stands 2 and 3 (E/STS 2-3). Direct scaling of the diffuser-ejector system for ETS-1 to the demands of a 5000 to 10,000 mw engine indicated an overall diffuser-elbow system height of 135 to 190 feet. The fabrication costs of a convectively-cooled, scaled-up system were estimated to be prohibitive; therefore, alternative systems were investigated. The most economically feasible system appeared to be one wherein the gases were cooled in the subsonic-flow regions of the exhaust duct by direct injection of water. Cooling the gases prior to the time they contact the walls of the horizontal duct would reduce fabrication costs of the flow-turning elbow duct and the steam-ejector system downstream of the elbow and could result in a more reliable system.

Primary requirements were that the water injection system provide a minimum diffuser-exhaust duct overall height and that secondary cooling of the deflector and plenum be minimized. The cooling technique selected for study was the injection of water into the gas stream in an amount sufficient to cool the gas to an average temperature no greater than 1000°R. This would allow the use of uncooled carbon steel as the material of construction for the duct downstream of the region of injection and mixing. The test program was undertaken: (1) to determine if the direct injection of water into the stream would be practical, and (2) to arrive at an empirical relationship that could be used to size an arrangement of water injection ports or nozzles to cool the gas stream during tests of a 5000 or 10,000 mw engine. The location of the point of coolant injection was the subsonic-flow region at the exit plane of the diffuser.

To minimize duct length, the water must penetrate the gas stream and form a uniform dispersion. Several investigators have studied the problem of injecting liquids into high velocity gas flows. Chelko (Reference 1), an early investigator, studied the penetration characteristics of water discharged from nozzles 0.0135 to 0.0625 inch in diameter directed perpendicular to a 742 ft/sec air stream. The result of his analysis was an empirical expression relating penetration to the velocity and density ratios of the two streams. Fenn (Reference 2) investigated the penetration of a liquid-ammonia jet into an air stream and correlated his test data in a manner similar to Chelko. More recently Forde, Molder, and Szpiro (Reference 3) developed an analytical expression for the penetration of a liquid jet into a supersonic stream and compared it with data for penetration of water jets into a Mach 4 high-temperature air stream. Again, the sizes of orifices investigated were small and restricted in range.

Ingebo (Reference 4) in a recently completed study has correlated drop penetration data in terms of a Reynolds and Weber number relationship. The correlation resulting from this and previous investigations are all basically empirical and are of value for the particular range of test conditions evaluated.

An analytical study of the penetration characteristics of a liquid jet was recently published by Adelberg (Reference 5) which according to the author adequately represents certain test data, including data from References 1 and 2, for two postulated methods of jet breakup. Adelberg considers the surface of the jet as a point of origin of either acceleration or capillary waves. In general, if viscous forces are high (valid for large diameter jets and large dynamic pressures), waves will grow as acceleration waves; however, if the surface-tension forces exceed the viscous forces, then the surface waves are called capillary waves and penetration is characterized by a different equation. The experimental penetration data of the present study have not been compared with this analytical method at this time. Differences in the various empirical

equations led to a test program designed to extend the range of test data to include large-diameter nozzles, and to arrive at an empirical relationship that could be used to size an arrangement of injection nozzles to cool the hot gases and thereby protect an uncooled exhaust duct system for E/STS 2-3. The range of test variables included in this investigation are shown on Table 1.

In the Phase I program, water was injected at driving pressures of 50, 100, 150, and 200 psig, through nozzles of 0.0625, 0.125, 0.250, and 0.500 inch in diameter, into a subsonic flow of either hydrogen or nitrogen gas at ambient temperature or at 1500°R. The penetration characteristics were recorded by photographing the injection pattern through a plexiglas window of the test-section enclosure. Due to possible test-section influence or perturbation on the test results for the larger nozzles (especially the 0.5 inch nozzle), additional, or Phase II, tests were conducted in a wind tunnel.

In the Phase II program, a series of nozzles 0.25, 0.5, 0.75, 1.0, 1.25, and 1.50 inches in diameter were tested at driving pressures of 50, 100, 150, and 200 psi injecting into a 200 or 300 mph, 35 to 40°F air-stream. The 0.25 and 0.5 inch nozzles were tested in both facilities to evaluate any possible facility influence on the test results. Jet penetration and spreading characteristics in these tests again were determined from photographs of the jet plume taken through windows above and to one side of the jets.

The result of the test program is an empirical correlation which permits the prediction of jet penetration for nozzles ranging from 0.0625 through 1.5 inches over a range of gas and water velocities as a function of mixing length. In addition, a correlation for predicting jet spread was also generated.

TABLE 1

SUMMARY OF TEST CONDITIONS

Phase I Tests

Nozzle Diameter d in.	Water Dynamic Pressure q_w psia	Water Velocity V_w ft/sec	Gas	Gas Temperature T °R	Gas Velocity V_a ft/sec	Gas Density lb/ft ³	Gas Dynamic Pressure q_a psia
0.0625-0.5	31.5-172.5	63-145.5	Hydrogen	528-1686	1240-3954	.0022-.0083	0.17-3.78
			Nitrogen	496-1546	388-1342	.031 -.119	1.62-5.40

Phase II Tests

Nozzle Diameter d in.	Water Dynamic Pressure q_w psia	Water Velocity V_w ft/sec	Gas	Gas Temperature °R	Gas Mach No. M	Gas Dynamic Pressure q_a psia
0.25-1.5	29-142	62-139	Air	492-500	0.22-0.43	0.46-1.65

III. EXPERIMENTAL APPARATUS AND TEST PROCEDURE

Experimental testing was conducted in two phases using two different types of test installations. The first tests were conducted in a special two-dimensional test section, or enclosure, 3 inches wide and 20 inches high. Small nozzles to 0.5 inch in diameter were evaluated in this enclosure. Large nozzles from 0.25 to 1.5 inches in diameter were tested in the second phase of the program in a six-by-nine-foot wind tunnel.

A. PHASE I TESTS

A special test fixture, shown schematically on Figure 1, was fabricated for measuring jet penetration into a flow-field similar to that leaving the diffuser just upstream of the flow-turning elbow. The test section was 3 inches wide, 20 inches high, and was enclosed on one side with a 20 by 28 inch plexiglas window. The instrumentation for this test section included total-pressure rakes in two locations: one just upstream of the injection port and one near the exit-end of the test section. Static pressure taps were also located in these two planes. Ten thermocouples were located axially along the test section, 2 inches from the top, to measure temperature axially along the gas flow-path. The water-injection nozzles were mounted in the bottom of the test section, normal to the gas flow, in the middle of the 3-inch test section width and near the front end of the plexiglas window. Water flow to the nozzle was controlled by four solenoid valves and regulated by throttle valves preset to deliver water at the desired expulsion pressures. To generate the flow field, gaseous hydrogen or nitrogen from a high-pressure storage bottle farm was directed into a plenum from whence it passed through a multiorifice plate into the test section. A gas-fired, stored-energy heater was used to heat the gas for the high-temperature tests. The multiorifice plate was designed to generate a uniform Mach 0.7 gas flow-field. Figure 2 is a view of this test fixture. A high-speed camera and a strobe light were mounted in a protective box adjacent to the test section window. Test data were recorded on an oscillograph and photographed at the same time.

Figure 1 - VKC Test Installation

Figure 2 - Stream Penetration Test Fixture

The test procedure consisted of initiating water flow at the 50 psig level, starting and increasing gas flow until the desired stagnation pressure in the test section was reached, then recording data. The water pressure then was increased sequentially by actuating the solenoid valves in each line and the photography data-recording process repeated. Test data were taken for four water pressures. The complete data-recording process required approximately 30 seconds.

The nozzles tested in the laboratory facility were based upon a design which was reported in Reference 5 as giving good water penetration with minimum breakup in quiescent air. Figure 3 is a sketch of the maximum-penetration nozzle design. Figure 4 is a view of three of the maximum-penetration nozzles tested. The 0.25 and 0.5 inch nozzles were tested in Phase I and Phase II; the third or 0.75-inch nozzle was tested only in Phase II). Figure 5 is a typical view of water injection in the two-dimension test section.

B. PHASE II TESTS

A second series of tests to measure penetration from large diameter nozzles were conducted using the 6 by 9 foot Icing Research Tunnel at the NASA Lewis Research Center, Cleveland, Ohio. The test installation is shown schematically in Figure 6. The tests were made with four, standard smooth-bore fire-fighting nozzles shown in Figure 7 and the three maximum-penetration nozzles shown in Figure 5. Two 0.75 inch diameter nozzles, one of the maximum-penetration design and one the fire fighting nozzle, were tested to obtain a direct comparison on the effect of nozzle type on penetration. The nozzles were positioned in the floor of the wind tunnel to inject water normal to the air flow. Four cameras (two on the top of the tunnel looking down and two at the side looking across as shown in Figures 8 and 9, respectively) photographed the water jet. Pressure data were indicated by mercury or water manometers and recorded photographically. Pressure data included static and total pressures

Figure 3 - Maximum Penetration Nozzle Design

Figure 4 - Maximum Penetration Nozzles

Figure 5 - Water Injection from 0.25 in. Nozzle into
2-Dimensional Test Section

Figure 6 - Test Installation - Lewis Research Center
Wind Tunnel (6 x 9 ft Icing Research Tunnel)

Figure 7 - Fire Hose Nozzles with Various Diameter Replacement Tips

Figure 8 - Camera Installation on Top of Wind Tunnel

Figure 9 - Camera Installation at Side of Wind Tunnel

in the constant-flow-area test section. The manometer board is shown in Figure 10.

The water was supplied by an auxiliary pumper located adjacent to the wind tunnel facility. Water was pumped from the domestic water supply and carried to the tunnel by two 3-inch diameter fire hoses as shown in Figures 11 and 12. The centrifugal pump on the pumper was powered by an internal combustion engine. The optimum (dead-head) operating pressure was set by increasing the pump speed, then the supply valve opened and the throttle valve adjusted to give the desired discharge pressure. Figure 13 shows the shut-off valve, and the throttle valve above it, being adjusted. Once the throttle valve is set, the wind-tunnel operator regulates the tunnel speed (see Figure 14), the water flow is started and data taken.

Several pictures of the jet were taken prior to the time the tunnel became fogged. Approximately one minute after the initiation of water flow, water vapor or droplets in the air due to recirculated water vapor became so dense as to obstruct vision, at which time the throttle valve in the delivery line was set for the next test and the test terminated. Once a vapor cloud was generated, it persisted for some time even at low wind-tunnel speeds: hence the tunnel was operated at low speed (5 to 10 mph in the test section) for approximately 30 minutes between tests, or adjustments made in the throttle-valve setting, to permit the droplets to settle out on the floor or coalesce and collect on the walls or heat exchangers in the tunnel. Cameras were located at seven and 22 inches downstream of the nozzles. Jet penetration and spread were determined photographically. The scale for determining spread or penetration was based on a grid located on either the floor or wall of the test section, and corrected for the parallax resulting from improper positioning of the camera with respect to the edge of the water spray. Figure 15 is a typical view of a wind-tunnel test of the 1.5 inch nozzle, taken from one of the cameras mounted at the side of the wind tunnel. Figure 16 is a photograph of the nominal 1-inch diameter nozzle with a discharge pressure of 96 psig, as taken by the camera mounted on top of the wind tunnel.

Figure 10 - Wind Tunnel Manometer Board

Figure 11 - Fire Department Auxiliary Pumper

Figure 12 - Water Hoses Passing through Wind Tunnel Wall

Figure 13 - Water Control Valve Installation

Figure 14 - Wind Tunnel Control Console

Figure 15 - Water Jet Penetration from a 1.5 in. Fire Nozzle into
a 288 mph Air Stream. Water Discharge Pressure 50 psig.

Figure 16 - Typical View of Water Jet from Top of Wind Tunnel

IV. DATA ANALYSIS

Analysis of the test data was aimed at providing an empirical relationship that could be used to predict full-scale jet penetration. The test results from the Phase I and II tests included in the analysis are tabulated in Appendix A.

The method of analysis was patterned after that employed by Chelko in Reference 1. The main parameters of interest were the penetration and mixing lengths. Chelko found that the test variables which affected these parameters for the range of conditions covered in his test could be reduced to the density and velocity ratios of the water jets and the gas streams. This conclusion is also consistent with the findings of Fenn (Reference 2). The following equation characterized his data:

$$\frac{Z}{d} = K \left(\frac{V_w}{V_a} \right)^a \left(\frac{\rho_w}{\rho_a} \right)^b \left(\frac{x}{d} \right)^c \quad (1)$$

The magnitude of the exponents a, b, and c and the coefficient K were determined graphically. The penetration distances (Z) for different mixing lengths (X) were measured from photographs of the jets, and refer to points along the outer visible boundary of the liquid jet. Distortions and inaccuracies no doubt result from photographic interpretations and are reflected in the penetration measurements. The velocity and density of the gas stream were based on the total and static pressure-measurements made in the constant flow-area portion of the test section just upstream of the water-injection nozzle. The theoretical velocity of the water jet was adjusted to give an actual velocity based on a flow calibration of each nozzle for the discharge coefficient for each nozzle. Water density was assumed constant.

Chelko found that neither Reynolds number nor the viscosity ratio varied sufficiently in his tests to affect the results. Ingebo (Reference 4) included the affect of the liquid-jet-properties surface tension and viscosity in his

correlation of droplet penetration data. Since the temperature of the water in the jet was not varied in this test program, the influence of liquid properties on penetration was expected to be minimal.

Following the procedure of Chelko, the exponents of Equation (1) were evaluated graphically by plotting for the Phase I tests the variation of the penetration parameter Z/d , with velocity, (V_w/V_a) , and the density ratio, (ρ_w/ρ_a) , at a constant mixing length parameter, X/d . The penetration parameter was plotted as a function of the velocity ratio for the same mixing length parameter, permitting an evaluation of the velocity-ratio exponent, a . The penetration parameter divided by velocity ratio was then plotted as a function of the density ratio: when the value of the exponent b was found to be approximately 0.5, it became apparent that the product of the velocity ratio and the density ratio raised to the 0.5 power was equivalent to the square root of the dynamic pressure-ratio, (q_w/q_a) .

The exponent c was determined graphically in a similar manner and the coefficient K determined by plotting the penetration parameter as a function of the product of the square root of the dynamic pressure and the mixing length raised to the 0.27 power. Figure 17 is a plot of Phase I test data compared with the equation:

$$\frac{Z}{d} = 2.0 (q_w/q_a)^{0.5} \left(\frac{x}{d}\right)^{0.27} .$$

From these results it was deduced that penetration was neither strongly dependent on the type of gas (whether hydrogen or nitrogen) nor on temperature.

Some significant scatter about the mean line was noted: this was found to be data obtained primarily from large-diameter jets and the finding prompted the Phase II tests. The large-diameter nozzle tests were conducted in a wind tunnel where large quantities (as high as 800 gpm) of water could be released without adverse effects. The gas composition and temperature were not considered critical to future tests, and the NASA Icing Research Tunnel was

$$z/d = 2.0 (q_w/q_a)^{0.5} (x/d)^{0.27}$$

Figure 17 - Two-Dimensional Test Section Water Penetration Data

selected as the site for the Phase II tests. The Phase II data were graphically compared in the same manner as Phase I data and the result is shown in Figure 18, a plot of the NASA tunnel data with the "best-fit" equation. Figure 19 shows the results from the two facilities for the same nozzles, indicating a reasonably good comparison, as does the results from the two different nozzle designs which is shown by the comparison on Figure 20.

The effect of Mach number of the gas stream on jet penetration is indicated on Figure 21. A water jet injected into a cross-flow of gas is bent and spread by the aerodynamic forces of the gas stream. The spread or width of the water spray at various axial distances from the point of injection was estimated in the Phase I tests by observing the point where the jet appeared to intersect the window. This point in the high-temperature gas tests was interpreted to be the point where the surface of the plexiglas window was not softened by the flow of hot gas. In the Phase II tests the photographs taken from above the jets permitted a direct measure of the width, provided the distance from the wind-tunnel floor to the point of maximum width was known. Uncertainties therefore exist in the magnitude of the width of the jet due to uncertainties as to the point of maximum spray-width. The equation, which is considered to reasonably represent the test data, is a simple geometric relationship, independent of the gas or liquid jet properties. It is considered to be applicable for short mixing lengths, typically less than 22 inches. The jet profile, as indicated by Figure 16, resembles a parabola: however, the following equation was determined to reasonably represent the test data:

$$\frac{y}{d} = 2.6 \left(\frac{x}{d}\right)^{0.3},$$

where y = distance from the centerline to the edge of the jet.

This is illustrated by Figure 22, a plot of the Phase II data taken at mixing distances of seven and 22 inches, and the Phase I data evaluated at the point where the jet contacted the window, corresponding to a spread of 1.5 inches.

Figure 18 - Icing Research Tunnel Water Jet Penetration Data

Figure 19 - 1/4- and 1/2-in.-Dia Nozzle Water Jet Penetration Data

Type Nozzle

△ MAXIMUM PENETRATION

○ SMOOTH FIRE

$$z/d = 2.0 (q_w/q_a)^{0.5} (x/d)^{0.27}$$

Figure 20 - 3/4-in.-Dia Nozzle Water Jet Penetration Data

WATER PRESSURE 100 PSI

- VKC DATA: $M \geq 0.60$ (1/16 AND 1/8 IN. MAX. PENETRATION NOZZLES)
- ◇ VKC DATA: $M \approx 0.40$ (1/16, 1/4 AND 1/2 IN. MAX. PENETRATION NOZZLES)
- △ LRC DATA: $M \approx 0.27$ (1/4 AND 1/2 IN. MAX. PENETRATION NOZZLES)
- LRC DATA: $M \approx 0.40$ (FIRE AND MAX. PENETRATION NOZZLES)

Figure 21 - Mach. No. Effect on Water Jet Penetration

Figure 22 - Water Jet Spread in a Cross-Flow of High Velocity Gas

In Reference 4, Ingebo satisfactorily compared an analytical expression for predicting droplet penetration into a cross-flow of gas, with some experimental data of his own and that of Chelko (Reference 1). The maximum penetration data from this study was compared with the Ingebo equation, as shown on Figure 23. It appears that the small-diameter nozzle test data show relatively higher penetration than do the data for the large-diameter nozzles. A dimensional equation which appears to represent these maximum penetration data,

$$Z_m = 4.0 [q_w/q_a]^{0.5} d^{0.7},$$

where Z and d are in inches, is plotted in Figure 24. The test data from the Phase II tests were not compared with this equation since maximum penetration was not one of the measured parameters.

Figure 23 - Maximum Penetration Test Data Compared with Ingebo Equation (Reference 4)

Figure 24 - Maximum Penetration of a Liquid Jet into a Gas Stream

V. DISCUSSION OF RESULTS AND RECOMMENDATIONS

The penetration of water jets from water nozzles ranging in size from 0.0625 to 1.5 inches has been correlated by the empirical equation:

$$\frac{Z}{d} = 2.0 [q_w/q_a]^{0.5} \left(\frac{x}{d}\right)^{0.7} .$$

This equation should be limited to values of

$$x \leq Z .$$

Two types of nozzles were tested: the penetration of one nozzle (a maximum penetration nozzle) compared favorably with a standard fire-fighting nozzle, although differing significantly in design. The actual velocity and the theoretical velocity of the water jets were determined to be essentially the same for the fire nozzle, while the actual velocity of the maximum penetration nozzle was approximately 85% of the theoretical, based on actual flow calibrations. The flow-calibration data for the different nozzles are tabulated in Appendix B.

The width of the jet (for purposes of predicting regions of interaction between two adjacent jets or volume occupied by the water spray as a function of axial distance) can be estimated from the equation representing jet spread, $y/d = 2.6 (x/d)^{0.3}$.

The experimental data on which Chelko based his correlating equation were for tests in which the gas-stream velocity remained essentially constant and the liquid jet and nozzle diameters were the primary variable. In the more recent work by Ingebo, the gas velocity and density were varied. Combining these two data sources results in the following relationship for defining maximum penetration:

$$\frac{Z_m}{d} = 1.8 \left(\frac{Re}{We} \right)^{0.7},$$

which may be rewritten as:

$$\frac{Z_m}{d} = 1.8 \left[\frac{q_w \sigma}{q_a \mu_w v_w} \right]^{0.7}.$$

This equation is somewhat similar to the equation of this study except for the mixing length, x , which is not considered. This equation (which characterizes penetration in terms of the dynamic pressure ratio and the ratio of the surface tension forces to the viscous forces of the liquid jet) has been compared with the experimental test results. It appears from Figure 23 that the equation well represents the data for the small-diameter jets ($d \leq 0.125$), but essentially over-predicts all the larger-diameter data ($d > 0.5$). The equation which best predicts the maximum penetration of these same data is

$$Z_m = 4.0 [q_w/q_a]^{0.5} d^{0.7}.$$

The Phase I test data are compared with this equation in Figure 24. This equation represents all the different nozzle diameter data and suggests that the function of Reference 6 which compared maximum droplet diameter and nozzle diameter may not extend to large-diameter ($d > 0.5$) nozzles. This result suggests that an experimental study should be conducted to compare the results of maximum droplet-size generated for large-diameter nozzles with small nozzles to determine whether the relationship proposed in Reference 5 holds for increasing nozzle diameters.

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NOMENCLATURE

a, b, c, K	empirically-derived constants
d	nozzle diameter, in.
M	Mach number
P	static pressure, psia
q	dynamic pressure, psia
T _c	thermocouple
V	velocity, ft/sec
$\dot{w}$	weight flow rate, lb/sec
X	mixing length, in.
Y	mixing width, distance from centerline to edge of jet, normal to axis of the jet, in.
Z	penetration distance, in.
σ	surface tension, lb/sec ²
ρ	density, lb/ft ³
μ	viscosity, lb/ft sec

Subscripts

a	signifies air or gas
w	signifies water, or liquid
m	maximum

APPENDIX A

STREAM-PENETRATION EXPERIMENTAL TEST DATA

Phase I Tests

Stream-Penetration Experimental Test Data

Test Point Ref.	Water Nozzle Dia (d), in.	Discharge Coefficient C _D	Water Pressure (ΔP), psig	Gas Mach No. (M)	Total Temp of Gas (T _a), °R	Total Pressure of Gas (P _a), psia	Gas-Penetration Parameters Z/d for Various Mixing Lengths			Penetration Maximum Z _m	
							x/d = 8	x/d = 16	x/d = 32		
Nitrogen Gas Stream											
A-1	140-33	1/16	.886	48	0.60	500	19.36	12.8	17.45	20.4	1.5
	140-34	1/16	.886	101	0.62	500	19.74	17.6	23.2	29.1	2.0
	140-35	1/16	.886	163	0.66	500	20.38	16.0	22.1	26.2	1.9
	141-37	1/8	.85	48	0.61	496	19.53	12.8	16.0	18.9	2.3
	141-38	1/8	.85	101	0.61	496	19.69	14.5	19.2	24.1	4.0
	141-39	1/8	.85	159	0.60	496	19.90	17.4	23.2	30.5	5.0
	141-40	1/8	.85	211	0.60	496	19.90	20.3	26.4	33.4	5.6
	148-45	1/2	.851	59	0.47	535	20.57	14.0	17.2	*	11.0
	148-46	1/2	.851	108	0.41	532	20.45	17.2	23.0	*	14.2
	148-47	1/2	.851	152	0.39	535	21.03	20.2	27.2	*	17.2
	148-48	1/2	.851	203	0.34	537	21.66	21.0	31.4	*	--
	146A-64A	1/16	.886	49	0.64	1400	19.4	12.2	18.3	21.4	1.4
	146A-63A	1/16	.886	111	0.66	1513	19.7	15.3	21.4	27.5	1.8
	146A-62A	1/16	.886	165	0.66	1454	19.9	19.6	24.4	28.1	1.9
	146A-61A	1/16	.886	211	0.68	1365	20.1	21.4	29.4	33.6	2.5
	146B-64B	1/16	.886	51	0.68	1500	20.3	15.3	17.1	18.4	1.3
	146B-63B	1/16	.886	117	0.70	1525	20.7	15.3	22.0	30.6	1.6
	146B-62B	1/16	.886	173	0.72	1538	21.0	15.3	23.8	31.8	2.5
	146B-61B	1/16	.886	220	0.72	1546	21.0	18.3	27.5	34.9	2.4
	145-60	1/8	.85	50	0.65	1450	19.4	12.2	15.9	18.4	2.3
	145-59	1/8	.85	103	0.67	1496	19.7	13.8	18.4	22.4	3.0
	145-58	1/8	.85	163	0.69	1487	20.0	17.1	19.9	28.0	3.9
	145-57	1/8	.85	220	0.70	1492	20.0	18.9	24.5	30.3	3.9
	143-56	1/4	.855	47	0.52	1445	17.55	11.6	14.2	15.6	3.9
	143-55	1/4	.855	95	0.53	1454	17.7	14.0	16.8	22.0	5.7
	143-54	1/4	.855	161	0.52	1456	17.68	17.6	19.9	24.4	7.0
	143-53	1/4	.855	198	0.52	1458	17.7	19.1	23.0	26.4	8.4
	144-52	1/2	.851	54	0.38	1483	18.6	12.2	14.4	*	9.6
	144-51	1/2	.851	100	0.41	1479	18.88	14.5	17.0	*	13.4

Test Point Ref.	Water Nozzle Dia	Discharge Coefficient C_D	Water Pressure (ΔP), psig	Gas Mach No. (M)	Total Temp of Gas (T_a), °R	Total Pressure of Gas (P_a), psia	Gas-Penetration Parameters Z/d for Various Mixing Lengths			Penetration Maximum Z _m
	(d), in.						x/d = 8	x/d = 16	x/d = 32	
Hydrogen Gas Stream										
147-2A	1/16	.886	110	0.41	659	15.84	32.0	35.2	44.8	3.4
147-3A	1/16	.886	178	0.34	659	15.78	35.2	41.6	48.0	3.8
147-4A	1/16	.886	216	0.32	659	15.68	44.8	57.6	70.5	6.9
150-1B	1/16	.886	46	0.50	537	17.55	16.0	22.4	25.6	1.8
150-2B	1/16	.886	105	0.60	537	18.17	19.2	25.6	32.0	2.5
150-3B	1/16	.886	156	0.51	537	18.13	25.6	32.0	38.4	3.1
150-4B	1/16	.886	196	0.53	537	18.24	25.6	35.2	40.0	2.8
181-1A	1/16	.886	42	0.41	528	17.04	17.6	22.4	27.2	2.5
151-5A	1/8	.85	49	0.53	537	18.45	15.2	17.6	22.4	3.2
151-6A	1/8	.85	100	0.58	537	18.17	16.0	25.6	28.8	4.2
151-7A	1/8	.85	157	0.46	533	17.89	24.0	30.4	35.2	6.8
151-8A	1/8	.85	215	0.44	533	17.87	28.0	35.2	41.6	8.2
152-5B	1/8	.85	46	0.55	555	18.77	14.4	16.8	20.0	2.9
152-6B	1/8	.85	96	0.55	550	19.03	20.8	24.0	28.8	4.0
152-7B	1/8	.85	150	0.54	546	19.24	20.0	25.6	32.0	5.8
157-8C	1/8	.85	202	0.54	528	19.36	20.8	28.8	36.0	6.5
153-9	1/4	.855	45	0.46	542	18.80	13.6	19.2	24.0	6.8
153-10	1/4	.855	95	0.44	537	19.46	20.4	27.2	33.6	10.0
153-11	1/4	.855	160	0.42	537	20.01	22.4	32.0	36.8	12.8
153-12A	1/4	.855	205	0.41	537	20.28	29.6	36.0	40.0	--
182-12B	1/4	.855	208	0.42	535	19.76	17.6	23.2	26.4	7.5
154-14B	1/2	.851	106	0.28	528	22.33	22.8	26.4	*	16.8
192-30	1/16	.886	156	0.55	1584	19.48	24.0	32.0	38.4	2.8
192-29	1/16	.886	199	0.54	1572	19.26	22.4	36.8	44.8	3.0
191-28	1/8	.85	68	0.50	1652	19.53	16.0	22.4	26.4	3.5
191-27	1/8	.85	120	0.48	1678	19.56	22.4	28.8	36.0	4.9
191-26	1/8	.85	167	0.47	1661	19.60	28.0	34.4	39.2	6.0
191-25	1/8	.85	199	0.47	1627	19.54	28.0	36.8	42.4	6.6
190-24	1/4	.855	52	0.48	1674	21.18	15.2	16.8	26.0	6.5
190-22	1/4	.855	173	0.47	1674	22.68	25.2	33.6	39.2	9.0
190-21	1/4	.855	216	0.45	1629	22.45	25.6	30.4	38.0	10.2
190-23	1/4	.855	108	0.44	1686	21.67	22.4	27.2	31.2	9.9

Test Point Ref.	Water Nozzle Dia (d), in.	Discharge Coefficient C_D	Water Pressure (ΔP), psig	Gas Mach No. (M)	Total Temp of Gas (T_a), °R	Total Pressure of Gas (P_a), psia	Gas-Penetration Parameters Z/d for Various Mixing Lengths			Penetration Maximum Z_m
							x/d = 8	x/d = 16	x/d = 32	
<u>Hydrogen Gas Stream</u>										
189-20	1/2	.851	60	0.46	1508	24.49	14.4	18.4	*	9.6
188-19	1/2	.851	110	0.37	1550	29.78	19.6	23.6	*	15.2
187-18	1/2	.851	166	0.32	1565	26.81	23.2	28.0	*	16.2
186-17B	1/2	.851	212	0.27	1580	28.55	23.6	29.6	*	16.6
193-32B	1/16	.886	53	0.38	1665	16.60	19.2	32.0	48.0	-
193-29B	1/16	.886	205	0.38	1648	16.60	41.6	64.0	97.6	-
194-32A	1/16	.886	49	0.24	1597	15.20	24.0	38.4	54.4	-
194-29A	1/16	.886	198	0.22	1589	15.20	56.0	91.3	133.0	-
199-29C	1/16	.886	197	0.15	1551	14.81	96.0	131.0	176.0	-
199-32C	1/16	.886	64	0.13	1500	14.72	48.0	83.2	123.0	12.1
200-32C	1/16	.886	68	0.14	1496	14.70	64.0	112.0	190.5	-
200-29C	1/16	.886	195	0.17	1534	14.80	48.0	96.0	157.0	-
196-20A	1/2	.851	66	0.20	1479	17.40	28.0	33.0	*	19.7
196-20B	1/2	.851	68	0.27	1590	19.50	21.2	27.8	*	14.0
195-17B	1/2	.851	207	0.41	1500	23.20	31.0	*	*	-

*Unable to read photograph

Phase II Tests

Stream Penetration Experimental Test Data

Run No.	Nozzle dia. d in.	Discharge Coefficient C_D	Nozzle Water Pressures ΔP psig	Mach No. M	Temp. T_a $^{\circ}R$	Dynamic Pressure q_a psia	Water Jet Dynamic Pressure q_w psia	Jet Penetration and Spread Y for Mixing Lengths of 7 in.		Jet Penetration and Spread Z for Mixing Length of 22 in.		Nozzle Type
								Z in.	Y in.	Z in.	Y in.	
1a	1.502	.981	70	0.37	495	1.235	72.75	32.5	6.3	44.3	10.3	Fire
1b	1.502	.981	70	0.31	495	0.867	72.75	-	-	46.5	-	Fire
2a	1.502	.981	70	0.22	498	0.467	72.75	-	-	-	-	Fire
3a	1.502	.981	58	-	494	-	60.3	30.1	6.0	42.2	12.3	Fire
3'a	1.502	.981	40	0.40	497	1.435	41.6	24.0	5.4	33.1	8.5	Fire
3'b	1.502	.981	40	0.39	497	1.364	41.6	34.7	4.9	32.8	9.0	Fire
4a	1.502	.981	50	0.27	492	0.702	52.0	41.8	6.8	58.0	-	Fire
4'a	1.502	.981	42	0.26	495	0.652	43.7	36.6	5.6	-	7.9	Fire
4'b	1.502	.981	42	0.23	495	0.510	43.7	37.9	5.3	-	9.8	Fire
5a	1.236	.953	112	0.39	497	1.361	106.6	36.2	5.8	48.3	9.3	Fire
6a	1.236	.953	90	0.38	495	1.291	85.5	29.5	5.9	43.7	-	Fire
6'a	1.236	.953	100	0.40	496	1.431	95.2	33.1	4.6	44.9	7.3	Fire
6'b	1.236	.953	100	0.37	496	1.224	95.2	33.2	4.9	46.9	7.2	Fire
7a	1.236	.953	82	0.40	495.5	1.417	78.0	29.2	5.7	39.6	7.9	Fire
8a	1.236	.953	50	0.40	494.5	1.416	47.5	21.9	5.9	30.8	8.3	Fire
9a	1.128	.948	140	0.39	494.5	1.347	130.0	35.5	5.9	-	-	Fire
10a	1.128	.948	92	0.40	496	1.417	85.5	27.4	5.3	36.9	8.5	Fire
10b	1.128	.948	92	0.39	496	1.347	85.5	29.9	-	-	-	Fire
11a	1.128	.948	48	0.41	498	1.505	44.6	17.2	5.8	24.0	8.4	Fire
11b	1.128	.948	48	0.40	498	1.433	44.6	18.8	-	29.8	7.0	Fire

A-4

Run No.	Nozzle dia. in.	Discharge Coefficient C_D	Nozzle Water Pressures ΔP psig	Mach No. M	Temp. T_a $^{\circ}R$	Dynamic Pressure q_a psia	Water Jet Dynamic Pressure q_w psia	Jet Penetration and Spread Y for Mixing Lengths of 7 in.		Jet Penetration and Spread Z for Mixing Length of 22 in.		Nozzle Type
								Z	Y	Z	Y	
								in.	in.	in.	in.	
12a	0.73	1.008	142	0.41	498	1.505	142	27.7	4.1	36.6	6.9	Fire
13a	0.73	1.008	100	0.41	496	1.505	100	21.5	4.3	28.1	5.6	Fire
13b	0.73	1.008	100	0.41	496	1.505	100	24.8	4.1	30.2	6.0	Fire
14a	0.73	1.008	50	0.42	496	1.580	50	15.1	4.1	19.5	4.5	Fire
14b	0.73	1.008	50	0.41	496	1.505	50	15.4	4.0	20.3	5.3	Fire
15a	0.75	.842	100	0.42	496	1.586	70.9	21.4	4.0	30.1	5.9	AGC
15b	0.75	.842	100	0.42	496	1.586	70.9	19.3	-	25.9	-	AGC
16a	0.75	.842	63	0.42	497	1.586	44.6	15.9	4.0	20.8	5.8	AGC
17a	0.75	.842	146	0.41	496.5	1.514	103.4	24.6	4.4	33.1	-	AGC
18a	0.50	.851	140	0.42	496	1.574	101.8	17.9	3.4	23.9	5.2	AGC
18b	0.50	.851	140	0.41	496	1.500	101.8	15.9	-	-	-	AGC
18'a	0.50	.851	140	0.42	493	1.57	101.8	17.4	3.4	22.7	4.5	AGC
18'b	0.50	.851	140	0.42	493	1.57	101.8	17.3	-	-	-	AGC
19a	0.50	.851	105	0.42	494	1.569	76.2	15.5	3.8	16.9	5.2	AGC
20a	0.50	.851	86	0.27	493	0.697	62.4	18.7	2.9	23.4	5.9	AGC
20b	0.50	.851	86	0.27	493	0.697	62.4	20.2	3.2	26.7	4.5	AGC
21a	0.50	.851	40	0.41	498	1.499	29.0	8.8	3.4	15.5	3.9	AGC
21b	0.50	.851	40	0.41	498	1.499	29.0	-	-	12.5	3.8	AGC
21'a	0.50	.851	62	0.42	495	1.586	45.0	-	-	-	-	AGC
21'b	0.50	.851	62	0.42	495	1.586	45.0	-	-	-	-	AGC
22a	0.50	.851	42	0.27	492	0.697	30.5	14.1	3.3	17.2	4.5	AGC

A-5

	Run No.	Nozzle dia. d in.	Discharge Coefficient C _D	Nozzle Water Pressures ΔP psig	Mach No. M	Temp. T _a °R	Dynamic Pressure q _a psia	Water Jet Dynamic Pressure q _w psia	Jet Penetration and Spread Y for		Jet Penetration and Spread Z for		Nozzle Type
									Mixing Lengths of 7 in.		Mixing Length of 22 in.		
									Z in.	Y in.	Z in.	Z in.	
A-6	22'a	0.50	.851	57	0.27	498	0.704	41.4	15.3	3.2	20.2	4.2	AGC
	22'b	0.50	.851	57	0.27	498	0.704	41.4	-	-	21.5	4.2	AGC
	23a	0.50	.851	144	0.27	493	0.697	104.5	24.9	3.2	34.5	-	AGC
	23b	0.50	.851	144	0.27	493	0.697	104.5	-	-	35.1	5.0	AGC
	24a	0.25	.855	40	0.42	493	1.576	29.3	5.5	-	1.9	-	AGC
	24'a	0.25	.855	46	0.42	498	1.577	33.64	8.3	-	1.9	-	AGC
	25a	0.25	.855	50	.28	497	0.752	36.6	8.7	-	1.9	-	AGC
	26a	0.25	.855	126	.43	495	1.651	92.3	9.7	2.0	11.5	-	AGC
	26'a	0.25	.855	100	0.43	496	1.651	732	8.6	1.8	10.2	-	AGC
	27a	0.25	.855	108	0.27	497	0.70	79.0	12.9	2.0	16.4	-	AGC
	27b	0.25	.855	108	0.27	497	0.70	79.0	13.4	-	-	-	AGC
	28a	0.25	.855	140	0.43	495	1.652	102.4	9.8	-	2.0	-	AGC
	28b	0.25	.855	140	0.43	495	1.652	102.4	-	-	12.4	-	AGC
	29a	0.25	.855	142	0.27	500	0.70	104.0	14.8	2.1	19.8	-	AGC
29b	0.25	.855	142	0.27	500	0.70	104.0	-	-	19.7	-	AGC	

NOTES: - (1) Water temperature approximately 40°F for all tests.

(2) Run number with a prime ' denotes a repeat test. The letters refer to the picture sequence. Four pictures were taken, but only the first one or two will be used in the analysis.

APPENDIX B
NOZZLE CALIBRATION DATA

Nozzle Calibration Data

Nozzle Type	Inlet Pressure psig	Nom. Nozzle Dia. in	Water Flow Rate, lb/sec				
			0.0625	0.125	0.25	0.5	0.75
Maximum Penetration	50		0.1015	0.3955	1.5802	6.2634	13.52
	100		0.1431	0.5537	2.2066	8.8106	19.55
	150		0.1755	0.6767	2.6979	10.7538	23.89
	200		0.2024	0.7798	3.1141	12.4232	27.58
		Nom. Nozzle Dia. in	0.75	1.00	1.25	1.50	
Smooth Bore Fire Nozzle	50		15.86	37.17	43.90	69.04	
	100		22.18	50.25	61.63	96.85	
	150		26.81	61.34	75.39	117.97	
	200		30.82	70.71	86.86	126.72	

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