EVALUATION OF WINDSHIELD FORWARD VISIBILITY

WITH AN

AIR BLAST RAIN REMOVAL NOZZLE

FOR THE

A3J-1 AIRPLANE

NORTH AMERICAN AVIATION INC

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NORTH AMERICAN AVIATION, INC.

COLUMBUS DIVISION COLUMBUS 16, OHIO

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EVALUATION OF WINDSHIELD FORWARD VISIBILITY WITH AN AIR BLAST RAIN REMOVAL NOZZLE FOR THE A3J-1 AIRPLANE

PREPARED BY THERMO LAB

APPROVED BY [signature]
CHIEF, AERO-THERMO SCIENCE

No. of Pages 27

REVISIONS

Date 12-28-59

DATE	REV. BY	PAGES AFFECTED	REMARKS
4-25-60	RCT	Page 10	Supply air pressure was 22.7 PSIG, should be 30.0 PSIG, which increased flow from 85 to 101 lb/min.

E D H 3:7 (REVISED 7-12-55)

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NORTH AMERICAN AVIATION, INC.
COLUMBUS DIVISION
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ABSTRACT

Full-scale laboratory testing of the A3J-1 windshield rain removal system was accomplished under simulated flight and rain intensity conditions. The original design of the rain removal air nozzles was shown to provide inadequate visibility. One of two nozzle design modifications tested was proven successful and the essential features of this design were incorporated in the production design.

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INDEX OF FIGURES

I. INTRODUCTION

A windshield rain removal system was required for the A3J-1 airplane to provide adequate forward visibility through the windshield during taxi, take-off, approach and landing in rain. Based on previous experience, the A3J-1 system was designed to pass engine bleed air through a ram air heat exchanger and suitable pressure control valve, and then eject the air through sonic nozzles at the forward edge of the windshield to provide clear windshield area. However, previous laboratory and flight test data was obtained on windshield configurations considerable different in geometry from that of the A3J-1. Also, most of the laboratory testing was performed with simulated rain of small or unknown drop size, which cast doubt on the results obtained.

It is important that the rain removal system provide adequate forward visibility with the lowest possible engine bleed airflow rate. Excessive airflow bleed from the engine for rain removal could reduce engine take-off thrust, reduce the quantity of air available for flap boundary layer control, or exceed the cooling capacity of the ram air heat exchanger.

The literature (References d, e, f, g, and h) indicate that air blast rain removal acts primarily by subjecting the rain drops to the shattering action of the high velocity air jet, and then deflecting the shattered drop fragments so that they miss the windshield entirely or impinge high upon the windshield in areas where visibility is not essential. The evaporation of water drops prior to and after impingement on the windshield is believed to have a less important secondary effect. The shattering and deflection of drops is considered to be a function of the jet velocity and the thickness of the jet. Previous test data indicates that sonic nozzle exit velocity produces more clearance than subsonic or supersonic exit velocities, and that the air pressure ratio should be such as to provide sonic flow. Since the speed of sound in air increases with temperature, it is considered desirable to use the highest feasible nozzle air temperature to increase air jet velocity, and secondarily to increase water evaporation. The thickness of the air jet at some distance from the nozzle exit would be a function of the airflow rate per unit width of windshield to be cleared, and it would be desirable to keep this to the minimum which would provide the required clearance.

I. INTRODUCTION (cont.)

The purpose of this test was to evaluate the A3J-1 windshield rain removal nozzle original design, to develop improved designs for incorporation in the airplane system, and to determine the effects of rain intensity, aircraft velocity, nozzle air pressure, nozzle air temperature and air flow per unit length of nozzle on forward visibility.

This test was requested by the Conditioning Systems Design Group. This report was written by R. C. Turner and M. H. Belgen. X2418

J. R. O'Dair, Group Leader
Airflow Laboratories

II. SUMMARY

The forward visibility with the original A3J-1 windshield rain removal nozzle design (Configuration A in Figure 5) was found to be inadequate under design conditions (carrier approach at 135 knots in heavy rain, with 30 psig nozzle air pressure and 275°F nozzle air temperature). A modified nozzle (Configuration B in Figure 5) provided satisfactory performance, not only at the design conditions, but at more severe conditions. The modified nozzle maintained adequate visibility at design conditions with approximately 16% less engine bleed airflow than the design flow of the original nozzle. As a result of this test, the rain removal nozzles were redesigned, and this change will be incorporated on Ship Number Six and subsequent.

Windshield visibility produced by the air blast rain removal system was found to be relatively independent of air velocity and liquid water content (Figure 11), to decrease with increase in rain drop size (Figure 10), and to increase with increase in nozzle pressure, temperature, or air weight flow rate (Figures 12 and 13).

A general interest motion picture relative to this test program is available (Reference i). It is believed that future rain removal development should be directed toward use of higher nozzle supply air temperatures, possibly with ram air jet pumping provisions in the nozzles if necessary to obtain tolerable windshield temperature levels.

III. DISCUSSION

A. Test Conditions

It was necessary to establish firm basis for comparison of the performance of the test nozzle configurations. This required that a set of design test conditions be established, taking into account the missions of the aircraft, predicted performance, probability of encountering various intensities of rain, and rain characteristics. In addition to the design conditions, a suitable range of the variables had to be established, so that the effect of the variables on system performance could be determined for a realistic operating regime. From a literature search and from consultation with the U. S. Weather Bureau and NAA Engineering Department Groups

III. DISCUSSION (cont.)

A. Test Conditions (cont.)

(A3J Project, Propulsion Systems, Aerodynamics, Advanced Design, and Flight Test), the following test conditions were established.

VARIABLES	DESIGN CONDITION	RANGE OF TEST CONDITIONS		
Flight Conditions:				
Airplane Angle of Attack, degrees	+6		+6	
Airplane Velocity, knots	135	135	170	200
Environmental Conditions:				
Rain Intensity	Heavy	Moderate	Heavy	Excessive
Rain Drop Size, in. diameter	0.059	0.039	0.059	0.083
Liquid Water Content, grains H_2O / Cu.Ft. Air	0.365	0.120	0.365	0.810
Rain Removal Nozzle Air Supply:				
Pressure, PSIG	30.0	22.7	30.0	37.3
Temperature, °F	275	275	425	500
Pilot's Eye Position:				
Water Plane, in.	+26	+23		+26
Buttock Plane, in.	0		0	
Fuselage Station, in.	+154		+154	

The design airplane six degree angle of attack and 135 knot velocity correspond with those which would be used with the A3J-1 airplane on the final landing approach to a CVA-38 aircraft carrier. This was selected because it was considered the flight condition most critical relative to forward visibility. The 135 to 200 knot test air velocity range corresponds approximately with the range for let-down prior to landing approach, landing wave-off, go-around, and other flight maneuvers during which some forward visibility is desirable. Forward visibility would be important at velocities less than 135 knots for ground taxi and take-off, but no tests were performed at these lower velocities because it was known that visibility would be better than was obtained at the

III. DISCUSSION (cont.)

A. Test Conditions (cont.)

selected test conditions. The six degree angle of attack was used for 170 and 200 knots to simplify the test set-up. Actual angles of attack corresponding to these velocities would be less than six degrees (with the aerodynamic configuration for landing), and the angle between the airstream and windshield would be greater. Thus actual visibility in flight at the higher velocities would be expected to be somewhat poorer than was observed during the tests.

The design rain intensity was selected as that classified as heavy. From a literature search and consultation with the U.S. Weather Bureau it was established that rain intensities more severe than this occur infrequently, are confined to small areas, and are of short duration. If a landing is attempted in extremely severe rain, it is expected that visibility will be inadequate, but usually such a rain condition will abate by the time a go-around and second landing attempt is made. The test range of rain intensities from moderate to excessive was selected to obtain data for the range from that most frequently encountered to that the most severe in which landing is likely to be attempted. The rain drop sizes and liquid water contents for the three test rain intensities were taken from a standard meteorology text (Reference a).

The environmental static pressure at the test section was not controlled, and was less than the local barometric pressure by the amount of conversion of static pressure to dynamic pressure in the inlet bellmouth and the amount of frictional pressure loss in the tunnel approach to the test section. Thus the static pressure in the test section varied with the barometric pressure and the test air velocity over a range from approximately 14.2 to 13.2 PSIA. This corresponds with flight altitudes from 1000 to 3000 feet, but the effect of this on test results was considered negligible.

The wind tunnel test section air temperature was room temperature (69 to 76°F) during the test runs. Incidence of natural rain is restricted to temperatures near room temperature and the minor variations of test air temperatures were considered to have a negligible effect on the test results.

The tunnel air humidity was not controlled or measured, and probably varied over a considerable range for various test runs. During natural rain the humidity is normally high, but can vary considerably also. In the general area where windshield clearance is obtained, the mixture of 275°F rain removal air with the

III. DISCUSSION (cont.)

A. Test Conditions (cont.)

room temperature tunnel air produces extremely low local relative humidities regardless of the tunnel air absolute humidity. Thus it is believed that wide variations of tunnel air humidity would have negligible effect on the test results.

The rain removal nozzle design air supply pressure of 30.0 PSIG was established from the specification for the pressure regulating valve located immediately upstream of the nozzle (Reference b). The test range of 22.7 to 37.3 PSIG was established arbitrarily as representing reasonable departure from the design point for the purpose of evaluating the effect of nozzle supply pressure on windshield visibility.

Under normal conditions, the airplane auxilliary supply air temperature is controlled to 300°F ± 10°F by the primary heat exchanger air temperature control system located at approximately station 524 (Reference c). Between this point and the rain removal nozzle at station 90, there is approximately 43 feet of uninsulated ducting in which a temperature drop of 25°F was expected at design airflow. On this basis the design nozzle supply air temperature was selected to be 275°F. The test range of 275 to 500°F covered the temperatures which could occur under the abnormal conditions of reduced primary heat exchanger cooling air flow with the pilot's control switch in the "override" position.

The nozzle supply air humidity was not controlled or measured, but the laboratory compressed air system used for the testing would be expected to supply air with approximately 10 grains of water per pound of air. Although this is lower than would normally be encountered in natural rain, it is believed that this would have a negligible effect on the test results because the mixture of 275°F rain removal air with room temperature tunnel air would produce extremely low local relative humidities regardless of nozzle supply air absolute humidity.

The design pilot's eye position was taken from A3J-1 design drawings. For a given clear area of windshield surface a decrease in the height of the pilot's eye position should provide an increase in the vertical extent of visibility. To determine the improvement of visibility produced by lowering the pilot's position, the alternate position was included. The three inch displacement was selected in consultation with A3J-1 test pilots, as a reasonable value in view of the available seat adjustment and the freedom of movement allowed the pilot by the seat harness. Some head movement to the side and

III. DISCUSSION (cont.)

A. Test Conditions (cont.)

forward would also be feasible, and this would improve the pilot's ability to utilize clear windshield area in viewing the landing mirror.

B. Test Set-Up

The test article consisted of a cockpit enclosure windshield frame assembly (247-31852) including the windshield glass (247-31853) and the windshield lower support frame assembly (247-31876), which contained the rain removal nozzle holes and air plenum. Three configurations of the frame assembly were tested (Figure 1).

The test article was mounted on a support fixture in an attitude simulating a six degree airplane angle of attack, and installed in an open circuit wind tunnel (Figure 2 and 3). The wind tunnel circuit consisted of an inlet bellmouth, a straight section for injection of water to simulate rain, the windshield test section, a diffuser, an air blower, an air throttle, and an outlet diffuser. The windshield rain removal nozzle supply air duct was connected to the laboratory heated compressed air system.

For rain simulation, de-ionized water was supplied by a pump to hypodermic needles on an oscillating rake in the wind channel immediately downstream of the inlet bellmouth. To measure simulated rain drop size, microflash photographic equipment was installed at a transparent tunnel wall section immediately upstream of the windshield. Considerable development was required to obtain adequate rain simulation and photographic recording of visibility (APPENDIX A).

To provide a standard reference field of vision for windshield forward visibility, target boards (black grid on white background) were set up in front of the inlet bellmouth and near the transparent section of the wind tunnel, and the interior of the tunnel straight section was painted white with black visual target lines to also appear as a grid from the pilot's eye position (Figure 4). Lighting was installed in the bottom of the tunnel to obtain adequate photographic recording. Black crosses were painted and small lights

III. DISCUSSION (cont.)

B. Test Set-Up (cont.)

installed at the points on the grid corresponding to the carrier landing mirror apparent positions for various distances aft of the carrier during landing approach.

C. Test Procedure

Prior to each test run water injection needles to simulate the desired rain condition were selected and installed, and the rake oscillation angle was set to approximate the proper liquid water content. The desired rain removal nozzle air weight flow was set up and dumped to atmosphere just upstream of the windshield frame air supply pipe. Laboratory air heaters were energized and controls set to obtain the required air temperature. Visibility-recording cameras were positioned and loaded.

When the required stabilized rain removal air temperature was attained, the tunnel drive blower was started and the blower outlet throttle was adjusted to obtain the tunnel dynamic pressure corresponding to the desired air velocity. The rain maker supply pump was started and the water pressure was adjusted to the value required to produce the desired rain drop size. Rain rake oscillation was then commenced and the tunnel illumination turned on.

Photographs were taken of the visibility through the windshield with rain on. Rain removal air was then turned on and the nozzle pressure was adjusted to the required value. Photographs and observations were then made of the visibility produced, and all data were recorded.

Forward visibility from the pilot's eye position through the windshield was recorded for each test condition by motion picture and/or still photography. Also, direct observations were made by design and laboratory personnel and engineering test pilots. The effectiveness of the rain removal system was judged on the ability of the observers to discern the visual targets.

D. Results

The data photographs show that configuration A, under design conditions, would not permit the pilot to clearly see

III. DISCUSSION (cont.)

D. Results (cont.)

the landing mirrors when he was nearer than about 500 feet aft of the carrier fantail (Figure 5). This configuration produced satisfactory visibility for the moderate rain condition only (Figure 6). Since the performance of this original design configuration was unsatisfactory, modifications were proposed.

It was apparent from the data photographs that the 5/32" diameter nozzle holes located between BP ± 4-5/6 and ± 12 were not contributing significantly to the overall nozzle performance. It was therefore decided to limit the placement of the nozzle holes between buttock planes ± 5-15/16 in the next series of tests. Configuration A hole spacing and total area was retained, which resulted in a nozzle hole diameter of 0.296 inches. Configurations B and C, which were entirely similar except for nozzle-to-windshield angle (Figure 1), were tested simultaneously, with B on the left side and C on the right side of the windshield centerline. This was considered feasible in that configuration A tests showed that the clearance patterns were symmetrical about the windshield centerline. The data photographs were printed to show configuration B and C results as if each configuration extended from buttock planes + 5-5/16 to - 5-5/16 and was tested separately.

The second series of tests showed that the inclined nozzles of configuration C produced clearance only slightly improved from that of configuration A at design conditions (Figure 5). The configuration B nozzles were superior to A and C under all conditions (Figures 5 to 9). In addition, the B nozzles produced adequate clearance with reduced nozzle air pressure and flow, with other conditions conforming to design values (Figure 5).

By stooping, the pilot can appreciably improve his utilization of the cleared portion of the windshield (Figure 14). This is considered important in permitting landings under more severe rain conditions and also in providing improved flight path visual detection capabilities at the higher let-down speeds and the expected lower airplane angles of attack.

The windshield frame assembly was redesigned September 3, 1958 (247-31876, Change D) to provide the essential features of test configuration B in the production articles. The change is to apply to ship number six and subsequent. Configuration B

III. DISCUSSION (cont.)

D. Results (cont.)

hole size and spacing were retained, but four additional holes were added on each side to increase the lateral extent of visibility in rain. Under design conditions of supply air pressure and temperature (30.0 PSIG downstream of the regulator and 300°F downstream of the primary heat exchanger), the revised design would provide approximately 101 lb/min. air flow to the windshield, assuming the increase in number of holes does not affect the overall discharge coefficient.

The effects on visibility of variation of rain drop size and liquid water content (rain rate), nozzle air pressure and temperature, and air velocity were found to be as follows:

Variable	Effect on Clearance	Reference Figure
Increased Rain Intensity	Pronounced decrease	10
Increased Flight Velocity	Insignificant change	11
Increased Nozzle Air Pressure	Slight increase	12
Increased Nozzle Air Temperature	Significant increase	13

Increased rain intensity, which involves increases in both drop size and liquid water content, produced decreased clearance. Increased velocity, which has the effect of increasing drop impingement velocity and liquid water content without affecting drop size, produced little effect on clearance. Therefore, it may be deduced that the size of the rain drops is the most important environmental factor to be considered in the design and testing of air blast rain removal systems.

Increased nozzle air pressure, which increases rain removal airflow rate as well as the pressure with a fixed nozzle configuration, produced onlv a slight increase of clearance, but the test range for this parameter was small. It is believed that clearance would not be greatly affected by nozzle pressure with a fixed airflow rate provided pressure ratios were adequate

III. DISCUSSION (cont.)

D. Results (cont.)

to assure sonic flow at the nozzle exit. Therefore the observed slight increase of clearance with nozzle pressure is attributed to the effect of the increased airflow rate rather than the increased pressure level. It is believed that increase of clearance with airflow rate for a constant nozzle pressure would be great in the low airflow range and slight in the high airflow range.

Increased nozzle air temperature, which also increases nozzle exit velocity and decreases airflow rate, produced a significant increase in clearance. Increased allowable air temperature and decreased required airflow are desirable from the standpoint of required heat exchanger size and engine bleed thrust penalty. Therefore, use of the highest feasible nozzle air temperature is desirable.

This project was conducted by R. C. Turner in the Thermo Lab from January 14, 1958, through April 16, 1958. The data contained in this report reflects status as of September 30, 1958. Original data for the project are recorded in Engineering Research Section Data Book Number 141, Pages 64-77, and Pages 142-299, and in Book 214, Pages 14-17 and 32-35.

IV. RECOMMENDATIONS

Jet air temperature increase is believed to promote system effectiveness by increasing the evaporation rate of the drop fragments in the jet and on the windshield after impingement, as well as by increasing jet velocity and decreasing the air weight flow requirement for a given nozzle area and pressure ratio. Use of high air temperatures for rain removal on turbo-jet powered aircraft has the added benefit of reducing engine compressor bleed air heat exchanger requirements and reducing the take-off thrust and range penalties imposed. Temperature limits are generally set by windshield material thermal limits, but airplane flight mach number increase also demands that better heat resistant windshield materials be developed. As such materials are made available, rain removal air temperatures could increase correspondingly.

It was implied above that air blast rain removal air

IV. RECOMMENDATIONS (cont.)

cooling requirements is a factor in engine bleed air heat exchanger design. It should be noted that the performance of such air-to-air exchangers is reduced under conditions of reduced cooling air flow. This condition is likely to occur during slow flight on approach to land, when the rain removal system would be simultaneously required if it is raining. It is therefore suggested that important improvements could be realized by the development of means of direct utilization of uncooled engine bleed air for air blast rain removal, providing windshield overheat prevention could be assured. It is also suggested that the use of uncooled bleed air as the motive fluid in an ejector-nozzle configuration could provide dual benefits in that both increased nozzle air weight flow and air jet cooling (windshield over-temperature protection) could be accomplished. It is recommended that consideration be given to these possibilities for future improvements in air blast windshield rain removal systems.

V. REFERENCES

a. Humphreys, W. J. - Physics of the Air. Third Edition McGraw-Hill Book Co., New York

b. Clark, W. - Equipment Specification: Valve, Air Pressure Regulating and Shut-Off, Anti-Ice. NAA Inc., Columbus, Ohio, NA5-6622A, 1957

c. Clark, W. and Passe, J. - Equipment Specification: Temperature Control System, Primary Heat Exchanger Air. NAA Inc., Columbus, Ohio, NA5-6593A, 1957

d. Slawsky, M. M. - Design Criterion for Air Jet Rain Removal Systems. U. S. Dept. of Commerce National Bureau of Standards, Washington D. C., NBS 4871, October 15, 1956

e. Malek, G. J. and Knapp, D. E. - Development of a Jet Blast Rain Removal System by Analysis and Test. Douglas Aircraft Co., Inc., Long Beach, California, March 26, 1957

f. Dunham, J. A. - Tests of Rain Removal on the Windshield and Side Panels Using Boundary Layer Anti-Icing System Air Discharge Nozzles. NAA, Inc., Los Angeles, California, NA-52-663, July 30, 1952

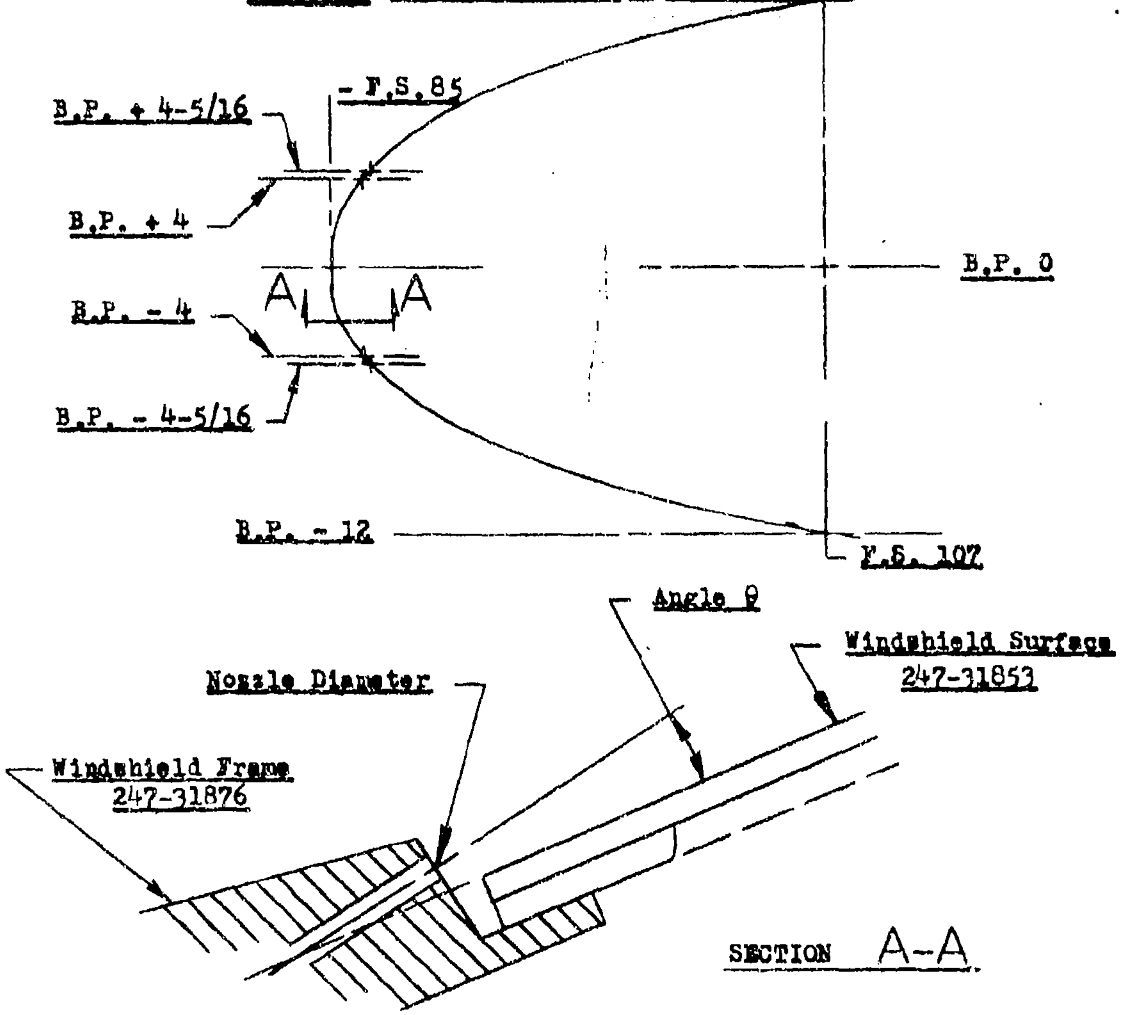
g. Ruggeri, R. S. - Preliminary Data on Rain Deflection from Aircraft Windshields by Means of High Velocity Jet Air Blast. NACA, Washington, D. C., RME55E17a, July 25, 1955

h. Kramer, O. G. - Analytical Results and Conclusions from the 1954-1955 Santa Susana Windshield Rain Removal Test Program. NAA Inc., Los Angeles, California, NA-54-455-1, June 6, 1957

i. Motion Picture, A3J-1 Rain Removal System Development and Test. NAA, Inc., Columbus, Ohio, Production Number 796, September, 1959

TEST NOZZLE CONFIGURATIONS

FIGURE 1

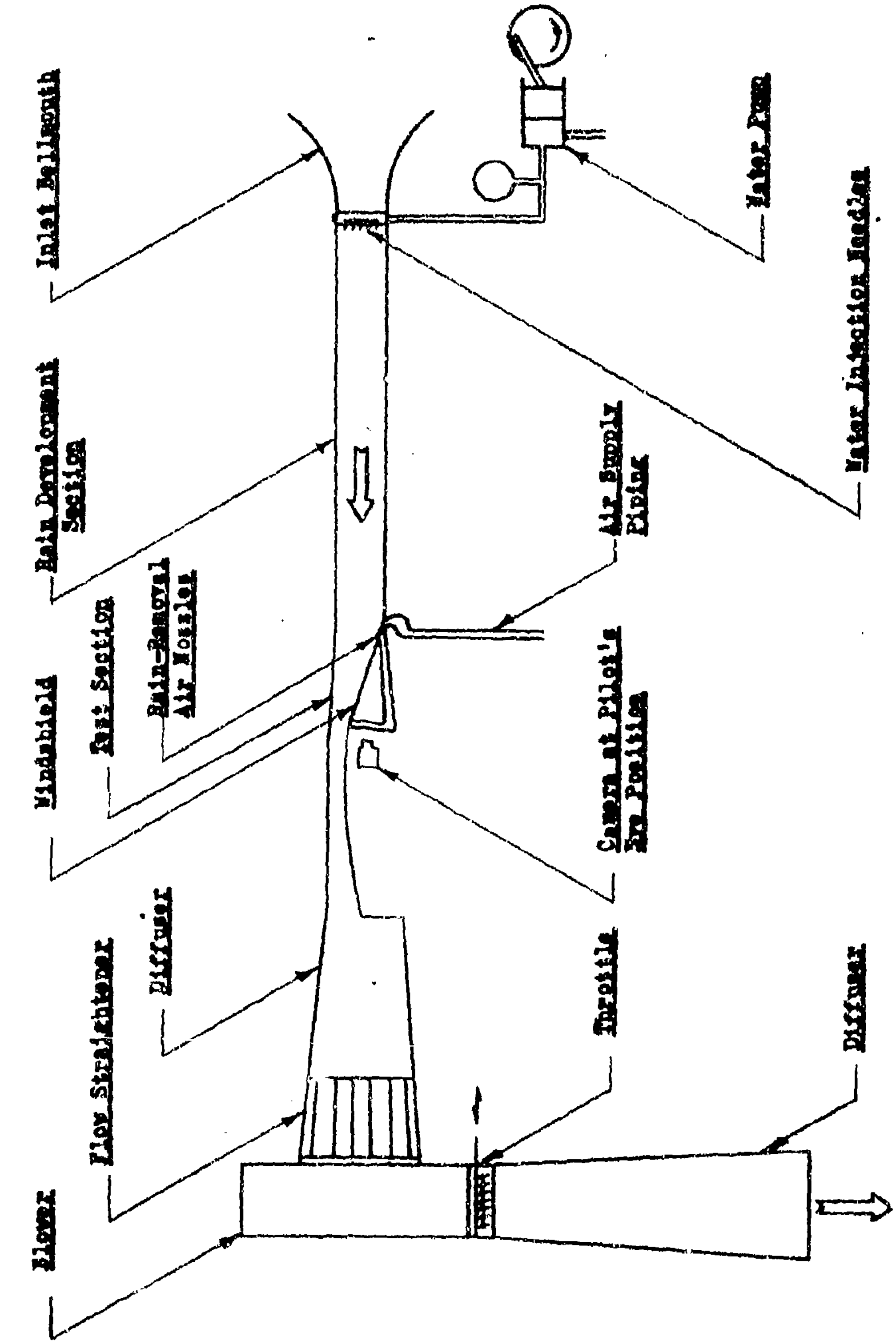


Note: Parts tested were in substantial accord with the drawings, except where modified for configuration changes.

Configuration -	Buttock Plane inches	No. of Holes -	Hole Diameter inches	Angle θ Degrees
A	+ 4 to - 4	20	0.250	0
A	± 4-5/16 to ± 12	42	5/32	0
B	+ 4 to - 4	20	0.296	0
B	± 4-5/16 to ± 5-15/16	10	0.296	0
B	± 5-15/16 to ± 12	None	-	-
C	+ 4 to - 4	20	0.296	10
C	± 4-5/16 to 5-9/16	8	0.296	10
C	± 5-15/16	2	0.296	0

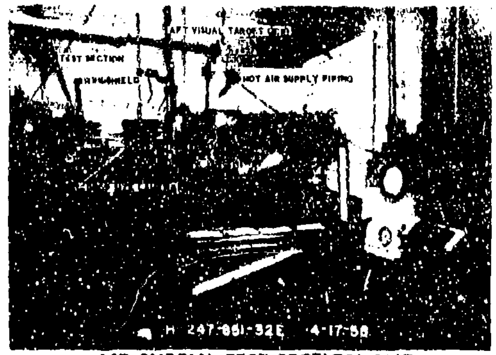
TEST SET-UP SCHEMATIC DRAWING

FIGURE 2



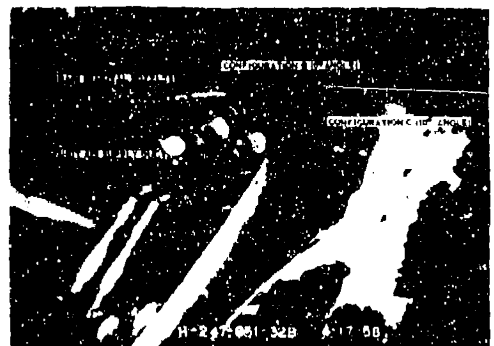
PHOTOGRAPHS OF TEST SET-UP FIGURE 3

RAIN DEVELOPMENT SECTION AND WATER SUPPLY PUMP

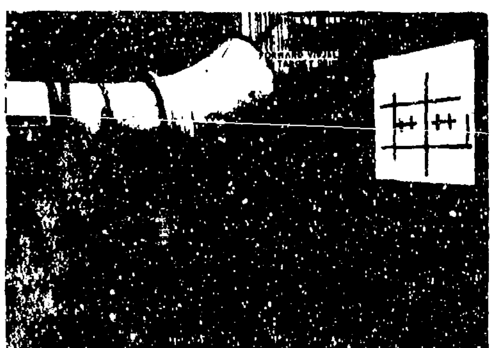


AIR SUPPLY, TEST SECTION AND INSTRUMENTATION

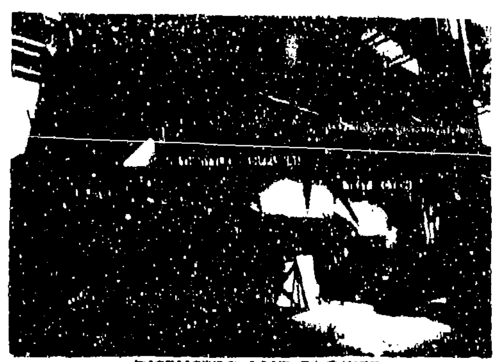
TEST SECTION



RAIN REMOVAL NOZZLES

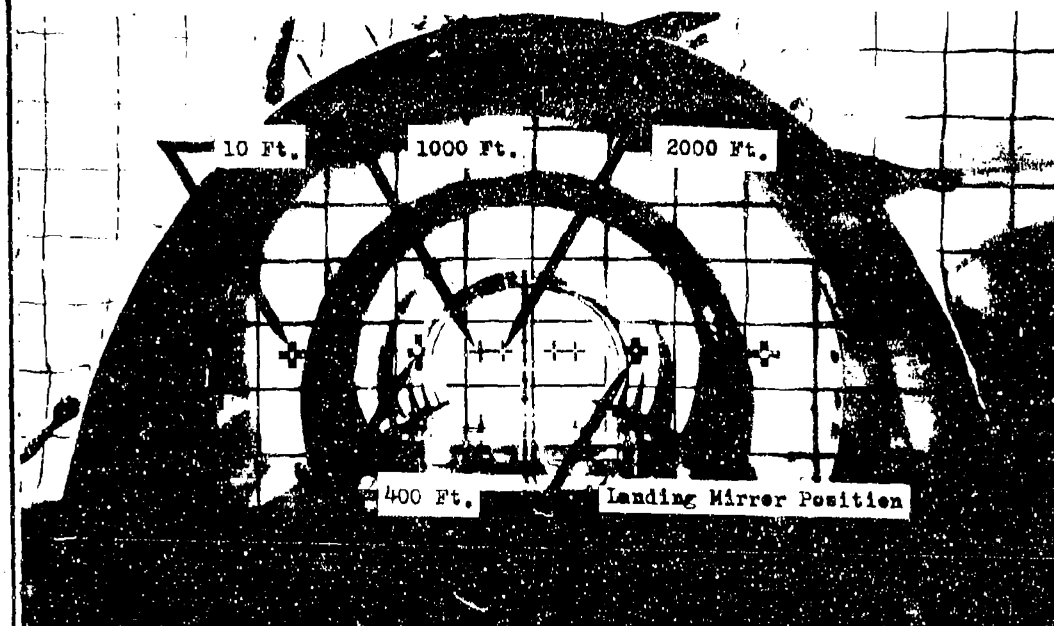


BELLMOUTH AND FORWARD TARGET BOARD

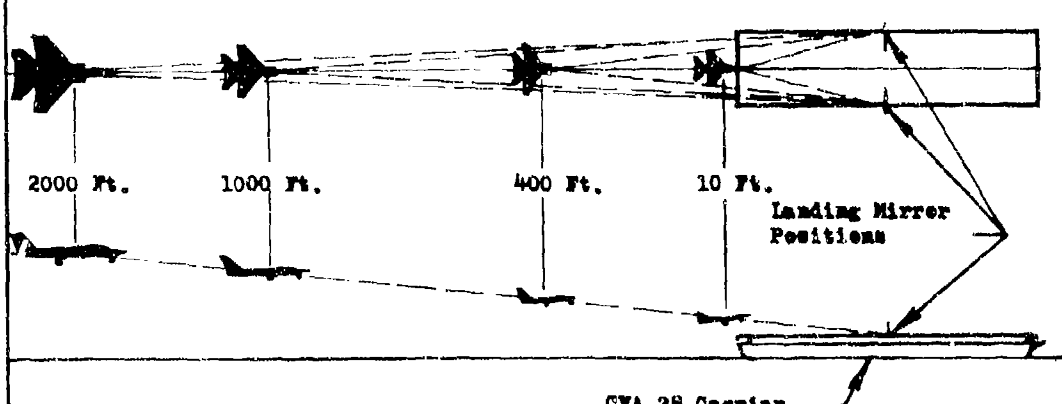


DIFFUSERS AND BLOWER

REFERENCE TARGETS FOR VISIBILITY EVALUATION FIGURE 4



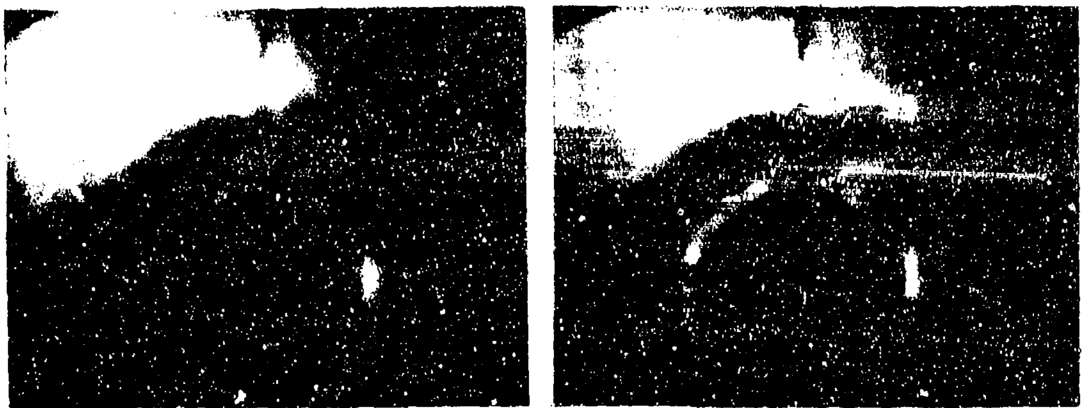
View Through Windshield from
Pilot's Normal Eye Position



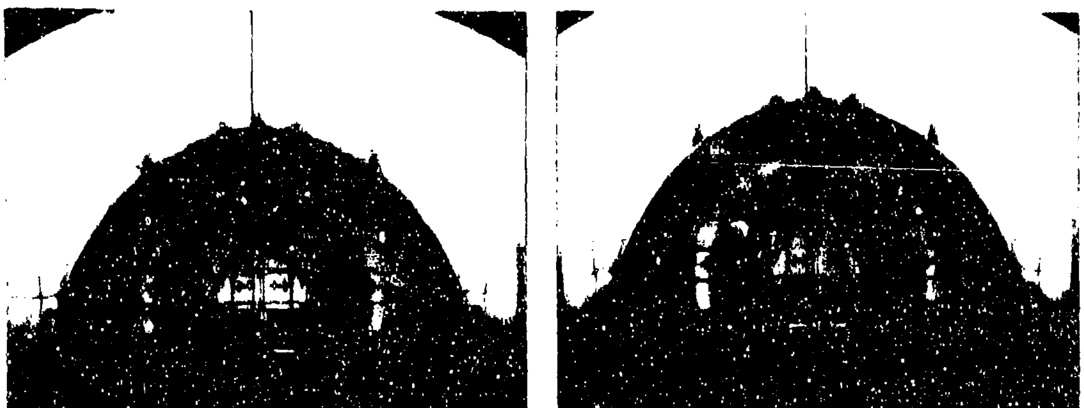
Schematic Diagram of Approach

WINDSHIELD VISIBILITY WITH HEAVY RAIN AT 135 KNOTS **FIGURE 5**

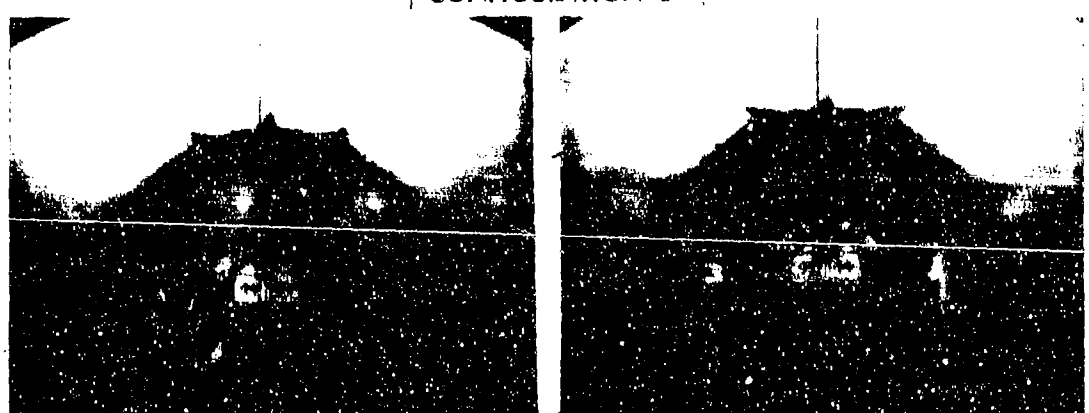
CONDITIONS: 275° F Nozzle Temperature, Camera at Pilot's Normal Eye Position



CONFIGURATION A



CONFIGURATION B

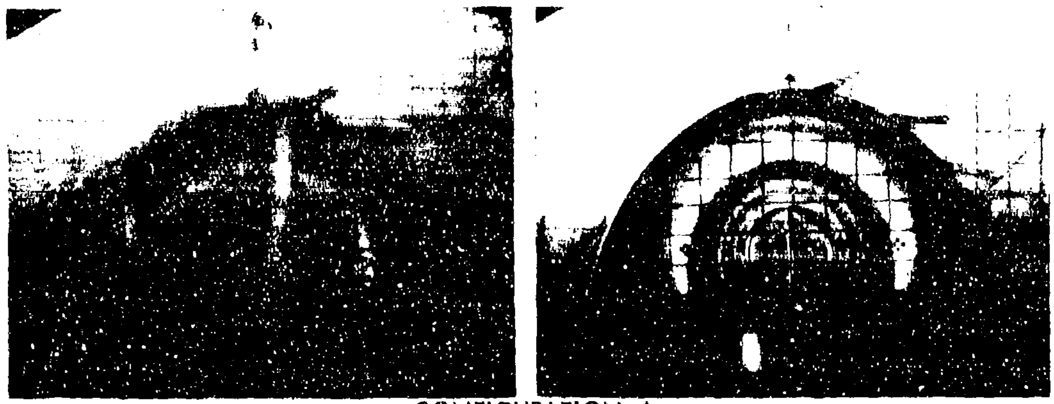


CONFIGURATION C

22.7 PSIG NOZZLE PRESSURE | 30.0 PSIG NOZZLE PRESSURE

WINDSHIELD VISIBILITY WITH MODERATE RAIN AT 135 KNOTS FIGURE 6

CONDITIONS: 275° F Nozzle Temperature, Camera at Pilot's Normal Eye Position



CONFIGURATION A

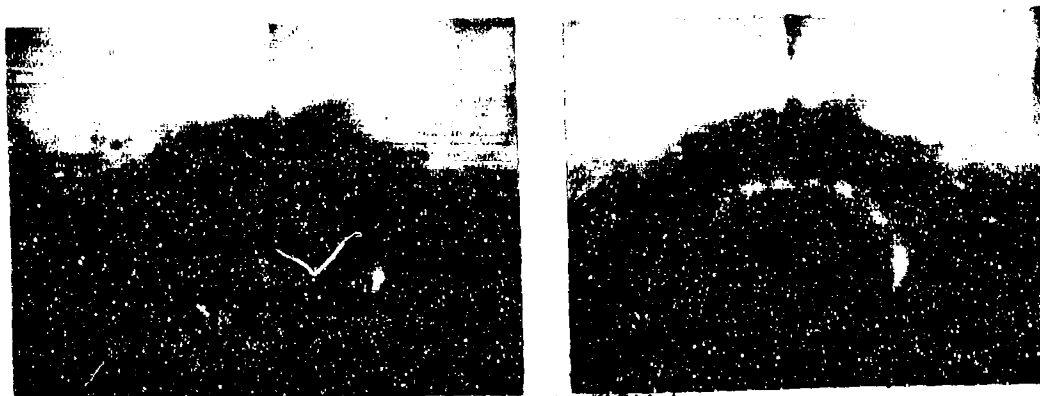
CONFIGURATION B

CONFIGURATION C

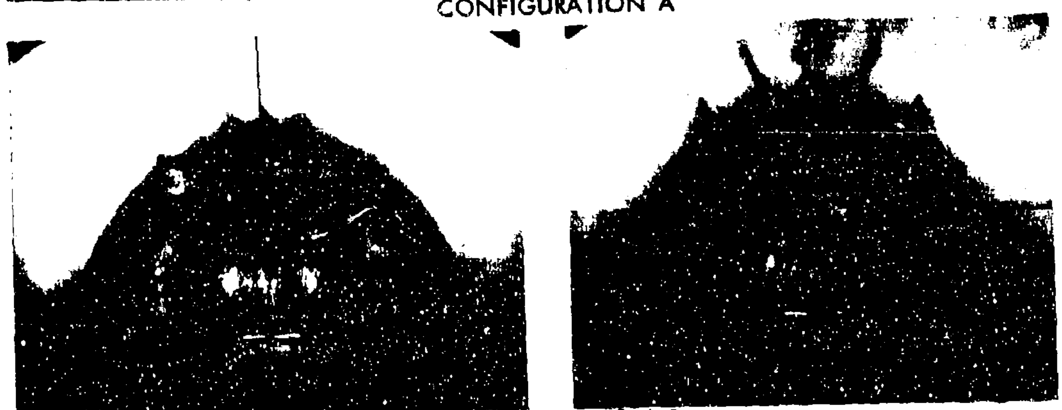
22.7 PSIG NOZZLE PRESSURE 30.0 PSIG NOZZLE PRESSURE

WINDSHIELD VISIBILITY WITH EXCESSIVE RAIN AT 135 KNOTS **FIGURE 7**

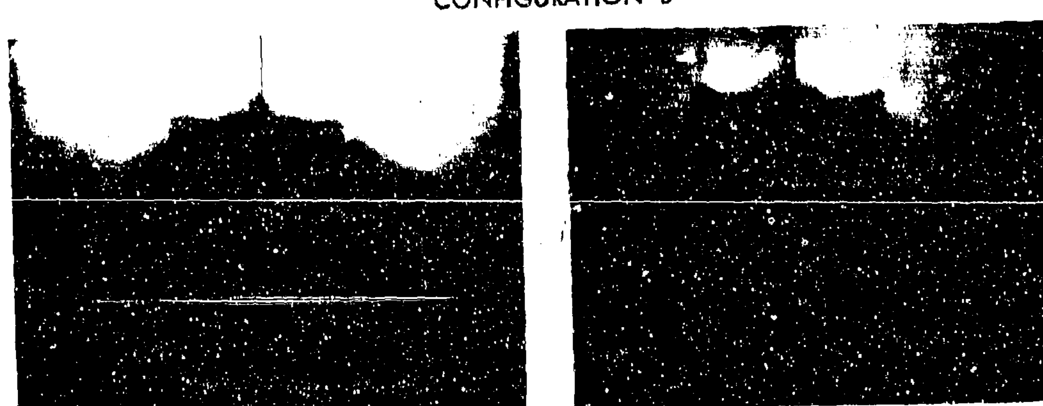
CONDITIONS: 275° F Nozzle Temperature, Camera at Pilot's Normal Eye Position



CONFIGURATION A



CONFIGURATION B

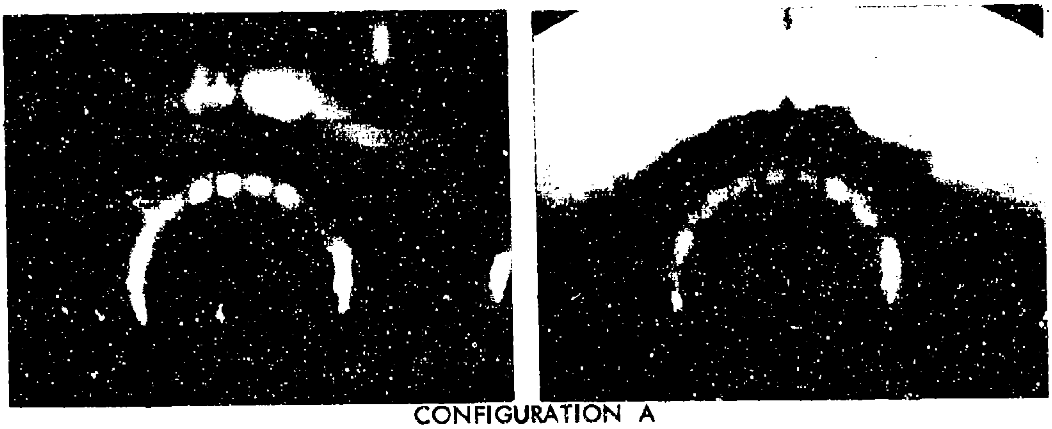


CONFIGURATION C

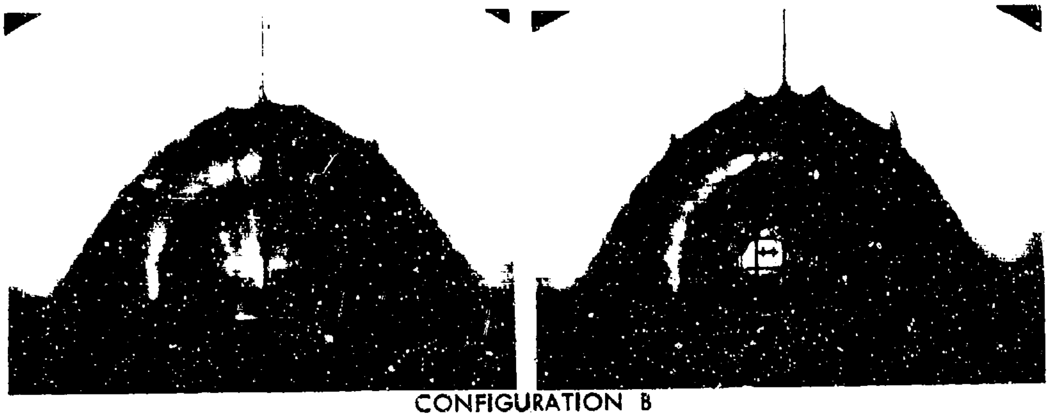
22.7 PSIG NOZZLE PRESSURE — 30.0 PSIG NOZZLE PRESSURE

WINDSHIELD VISIBILITY WITH HEAVY RAIN AT 170 KNOTS **FIGURE 8**

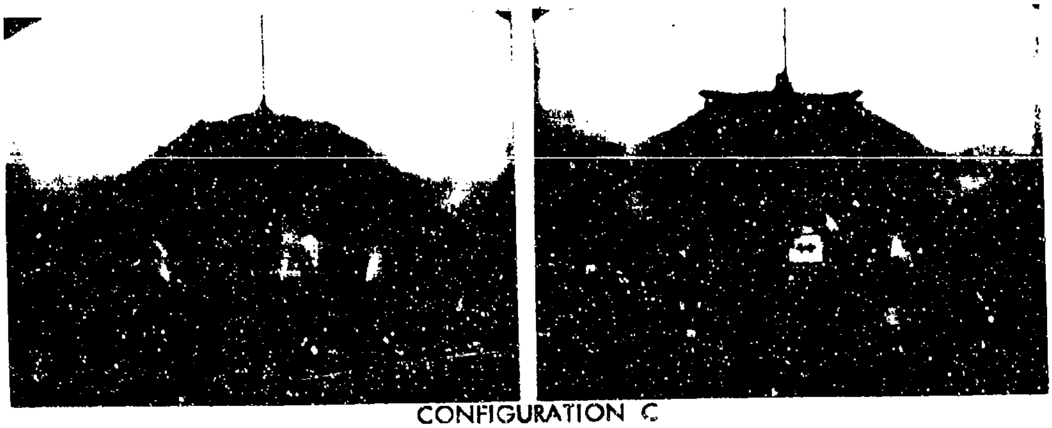
CONDITIONS: 275° F Nozzle Temperature, Camera at Pilot's Normal Eye Position



CONFIGURATION A



CONFIGURATION B



CONFIGURATION C

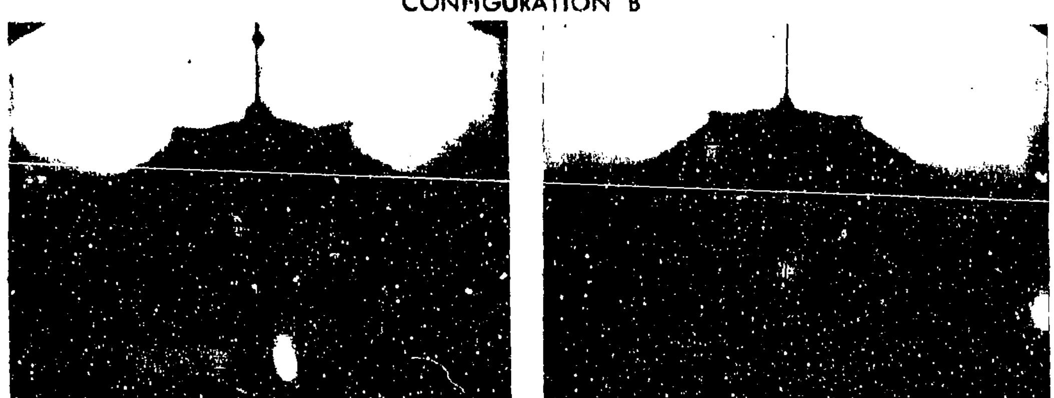
22.7 PSIG NOZZLE PRESSURE — 30.0 PSIG NOZZLE PRESSURE

WINDSHIELD VISIBILITY WITH HEAVY RAIN AT 200 KNOTS FIGURE 9

CONDITIONS: 275°F Nozzle Temperature, Camera at Pilot's Normal Eye Position

CONFIGURATION A

CONFIGURATION B

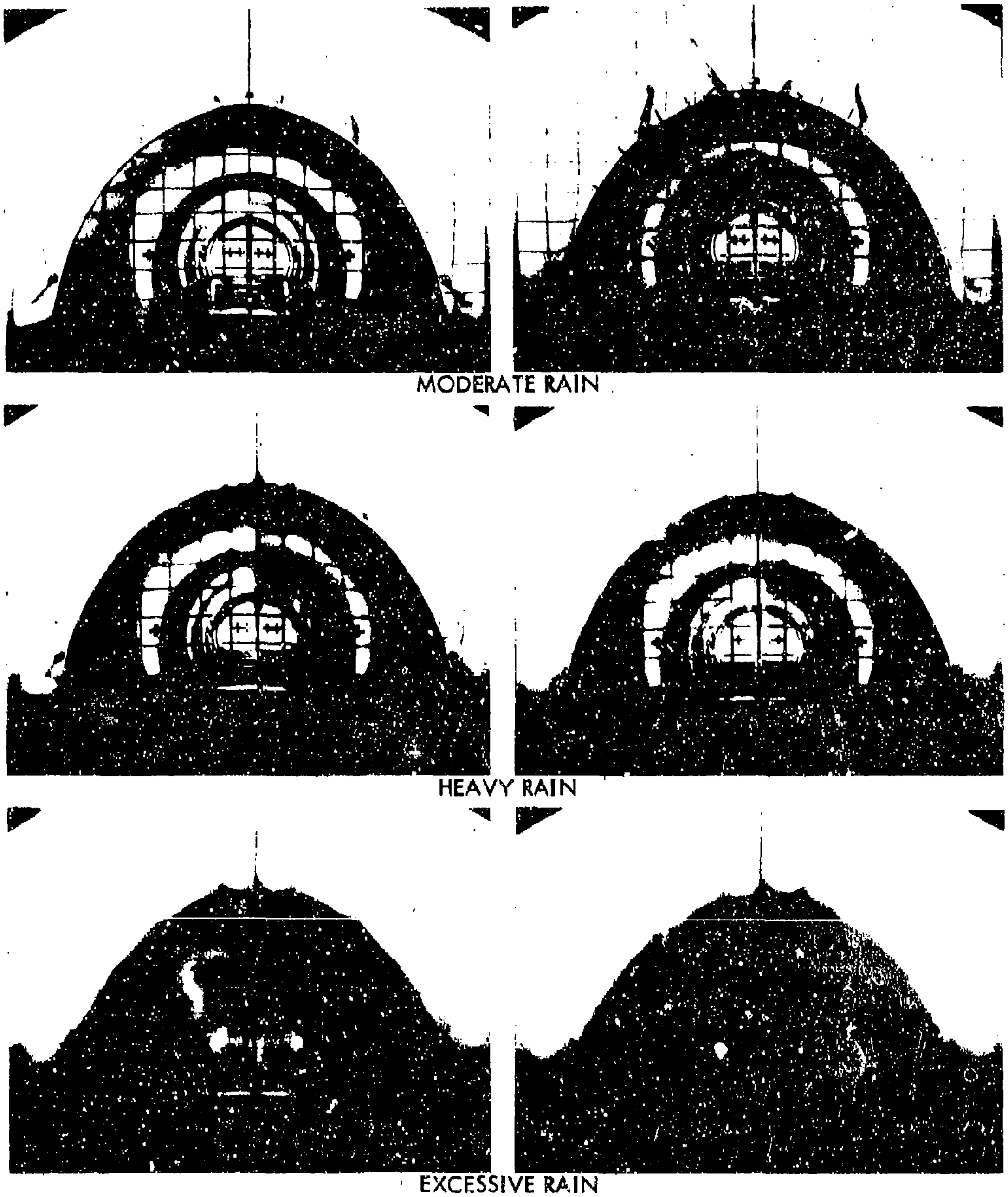


CONFIGURATION C

22.7 PSIG NOZZLE PRESSURE 30.0 PSIG NOZZLE PRESSURE

EFFECT OF VARIATION OF RAIN INTENSITY ON VISIBILITY FIGURE 10

CONDITIONS: 30.0 PSIG Nozzle Pressure, 275° F Nozzle Temperature, Configuration B
Camera at Pilot's Normal Eye Position

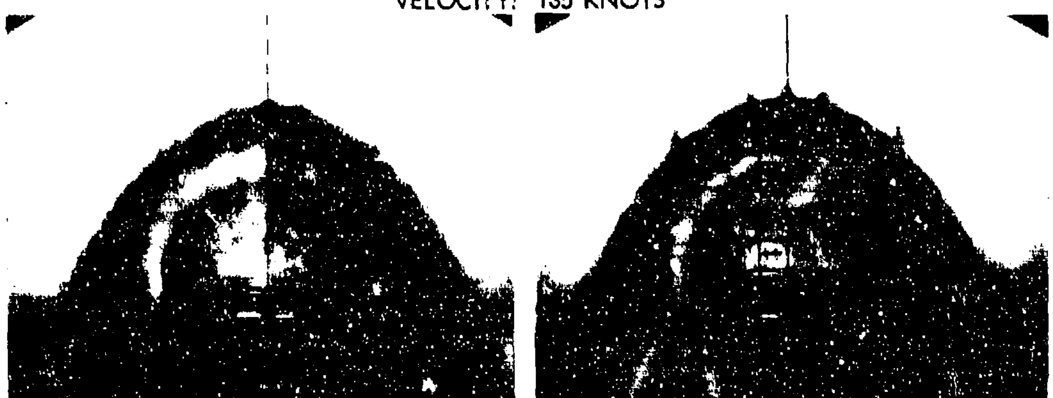


VELOCITY: 135 KNOTS VELOCITY: 200 KNOTS

EFFECT OF VARIATION OF AIR VELOCITY ON VISIBILITY FIGURE 11

CONDITIONS: Heavy Rain, 275° F Nozzle Temperature, Configuration B, Camera at Pilot's Normal Eye Position

VELOCITY: 135 KNOTS



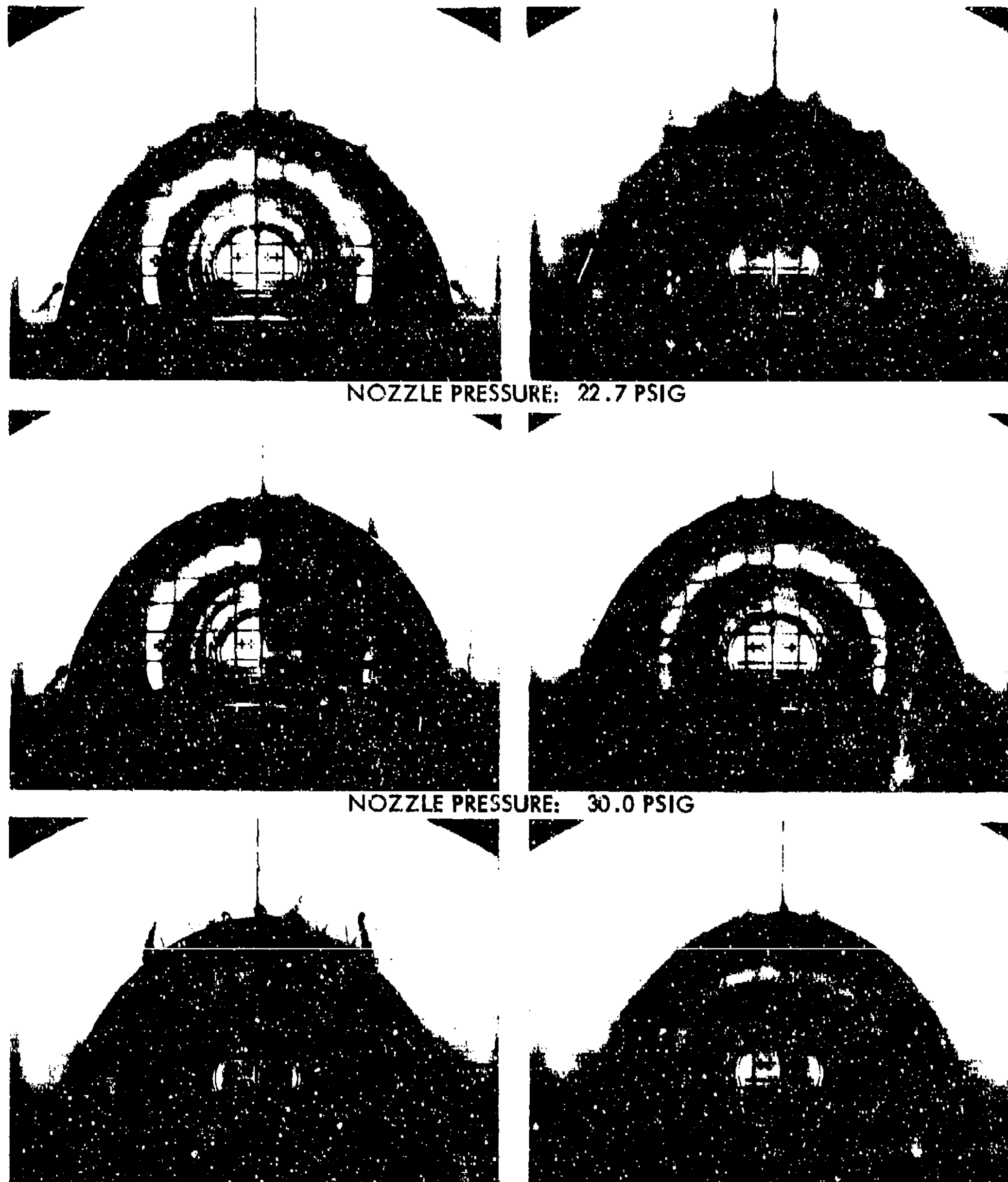
VELOCITY: 170 KNOTS

VELOCITY: 200 KNOTS

22.7 PSIG NOZZLE PRESSURE 30.0 PSIG NOZZLE PRESSURE

EFFECT OF VARIATION OF NOZZLE AIR PRESSURE ON VISIBILITY FIGURE 12

CONDITIONS: Heavy Rain, 275° F Nozzle Temperature, Configuration B
Camera at Pilot's Normal Eye Position



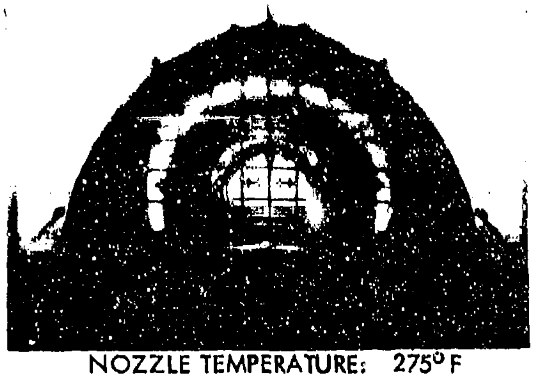
NOZZLE PRESSURE: 37.3 PSIG

VELOCITY: 135 KNOTS VELOCITY: 200 KNOTS

EFFECTS OF VARIATION OF NOZZLE AIR TEMPERATURE ON VISIBILITY

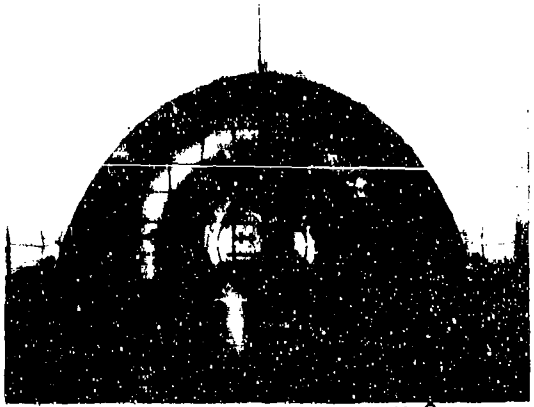
CONDITIONS: Heavy Rain, 135 Knots, 22.7 PSIG Nozzle Pressure, Configuration B, Camera at Pilot's Normal Eye Position

FIGURE 13



NOZZLE TEMPERATURE: 275° F

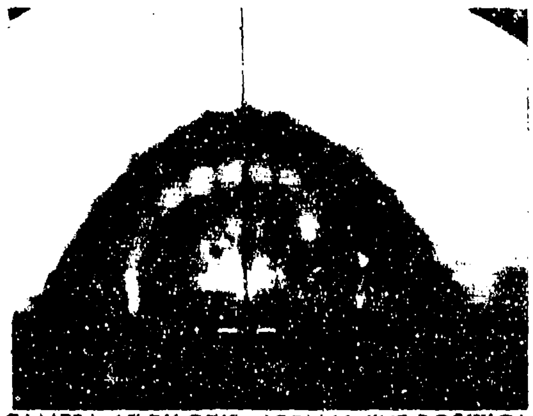
NOZZLE TEMPERATURE: 432° F



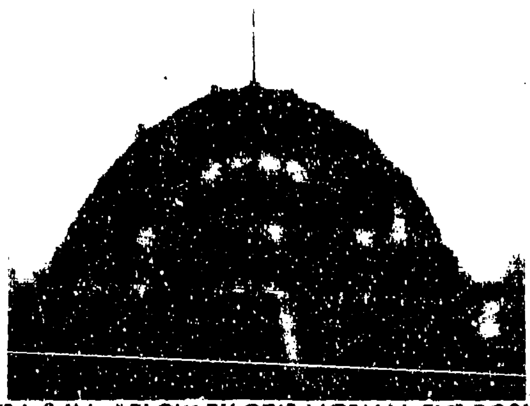
NOZZLE TEMPERATURE: 505° F

EFFECT OF VARIATION OF PILOT'S EYE POSITION ON VISIBILITY
FIGURE 14

CONDITIONS: Heavy Rain, 170 Knots, 22.7 PSIG Nozzle Pressure.
275°F Nozzle Temperature, Configuration B



CAMERA AT PILOT'S NORMAL EYE POSITION



CAMERA 3 IN. BELOW PILOT'S NORMAL EYE POSITION

APPENDIX A

WINDSHIELD RAIN REMOVAL TEST FACILITY DEVELOPMENT

(Pages A-1 through A-16)

APPENDIX A

SUMMARY

It was found that a stream of water drops of the size encountered in natural rain can be produced in 100 to 200 knot velocity air streams by injecting water at the same velocity as the air through small-bore needles with a length to diameter ratio of 90. The drops produced in this manner achieved spherical shape less than eight feet downstream of the water injection needle and retained uniform size twenty-four feet downstream.

It was found that accurate photographic recording of visibility under simulated rain conditions can be achieved by use of a uniformly lighted grid background of black lines on white with small electric lights to identify lines of vision used by the pilot during landing. With this technique a long exposure time (three seconds) and small aperture (f 32) were found to produce the most exact recording of visibility. The use of water free of minerals for the rain simulation and air free of oil for the rain removal supply system was found necessary to obtain consistent test results.

In future rain removal facilities it would be desirable to obtain more uniform dispersion of simulated rain water drops, to develop a method of determining drop size and dispersion with water injection needles in motion, and to ascertain if tunnel or rain removal supply air humidity have any appreciable effect on visibility produced by a rain removal system. It is believed that further development of the vibrating single water injection needle technique would produce more uniform drop dispersion, and it may be possible to prove that uniform dispersion is unnecessary. Several photographic and drop counting techniques appear promising for determining drop size and dispersion in the test section with the vibrating needle. With a closed circuit tunnel, control of air humidity appears to be feasible.

DISCUSSION

Preliminary Design

Tests of this nature, requiring airflow at flight velocities about a test article, can be performed either by moving the test article through the air (flight and sled testing) or by moving the air past the stationary test article (wind tunnel testing).

APPENDIX A

DISCUSSION (cont.)

Preliminary Design (cont.)

The wind tunnel approach was considered more feasible and economical than the alternate methods, although accurate rain simulation in a wind tunnel had not been achieved in earlier tests. Full scale testing was considered desirable to avoid consideration of unknown scale effects and to make use of available A3J-1 windshield assembly parts.

An open-circuit wind tunnel was selected instead of a closed-circuit configuration because it would cost less, test section aerodynamic flow uniformity could be more easily attained, and computations indicated that recirculation of rain drops might be a problem with a closed circuit configuration. A confined flow test section was selected instead of an open jet chamber because of lower cost and the fact that size of the open jet attainable with the available blower appeared to be marginal. Although it was known that the air flowing over the windshield in flight would be accelerated as it passed up the windshield, it was decided to provide an approximately constant flow area from the forward to the aft end of the windshield in the test set-up to reduce costs. This was considered acceptable because computations indicated that the air stream lines would have little effect on the trajectory of rain drops of the size encou[illegible] in natural rain, particularly along the forward edge of th[illegible]hield which was of most importance in this test.

With the open-circuit tunnel configuratic[illegible] not considered feasible to control the environmental [illegible]ity because of the extremely high tunnel air flow [illegible]omputations indicated that evaporation of water drops of th[illegible]ncountered in natural rain prior to entry into the rain rem[illegible]t air stream would not be appreciable. The available s[illegible] generation equipment was also inadequate for humidification of the rain removal nozzle hot air supply. Computations indicated that relative humidity in the mixed environmental and rain removal air stream would be extremely low both with and without simulation of air humidities expected in natural rain. Simulation of humidities was therefore considered unnecessary.

From reports of previous windshield rain removal testing, it was known that difficulties were to be expected with the simulation of natural rain drop sizes and dispersion in a wind

APPENDIX A

DISCUSSION (cont.)

Preliminary Design (cont.)

tunnel and with obtaining photographs indicating the true visibility through the windshield. Facility development testing was therefore considered necessary to solve these problems.

Water Injection Needle Development

Coincident with preliminary wind tunnel design, a literature search was conducted to determine methods of introducing water into a moving air stream to obtain simulated natural rain. The only successful technique discovered was that of Ruggeri, of NASA Lewis Lab, who had produced large sized drops in a small wind tunnel by ejecting a water jet into and parallel to the air stream in a constant-area section upstream of the test section. The diameter of the water jet, and the resulting drops, was controlled by the diameter of the ejecting tubular nozzle. The jet velocity was made to closely approach the air stream velocity by adjusting the water supply pressure; thus only small shear forces were exerted upon the water by the airstream and the jet of water was transformed by the action of surface tension into fairly uniformly-sized drops, travelling in line down the tunnel with the air stream.

To check and extend this work, a four-inch diameter open-circuit, open-jet test section wind tunnel, with variable-length constant-area sections upstream of the test section, was designed and constructed (Figure A-1). All test water injection needles were calibrated to determine their water flow rate vs. supply pressure characteristic so that water velocity at the needle exit could be controlled by adjusting the water supply pressure. A press-type cut-film camera and a two millionths second duration flash light was installed at the test section to record drop sizes. Experimentation showed that best photographic reproduction was obtained with the diffused flash source in line with the camera on the opposite side of the transparent-wall test section, thus providing back-lighting. With the camera position fixed and focused on the tunnel center line, a scale with 1/100 inch divisions, held on the tunnel center line, was photographed. Prints of this negative and the negatives of drops to be measured were then enlarged to the same magnification and the scale was used directly to determine drop diameters.

APPENDIX A

DISCUSSION (cont.)

Water Injection Needle Development (cont.)

Parameters investigated in the small tunnel were water injection needle bore length to inside diameter ratio (L/D), needle inside diameter, distance from needle exit to test section, air velocity, and water jet velocity. A needle L/D of 40 produced many drops of small diameter, but increasing the ratio to 90 and greater gave the desired condition of fewer drops that were larger and of fairly uniform size (Figure A-2). Water injection needles of 0.013, 0.027, and 0.039 inch diameter produced drop sizes closely approximating the 0.039, 0.059, and 0.083 inch diameter drops desired for simulation of moderate, heavy, and excessive rain conditions (Figure A-3). Drops had assumed a spherical shape eight feet downstream of the needle, and maintained this shape without appreciable break-up or agglomeration at a distance twenty-four feet downstream of the needle (Figure A-4). Since rain development tunnel lengths less than eight or greater than twenty-four feet were not being considered for this test, the exact limits of length for proper drop production were not determined. A variation of air velocity from 100 to 200 knots (with the water jet velocity equal to the air velocity) produced no appreciable change of drop size. A variation of the water pressure ratio from ten percent below to ten percent above that required for equal water jet and air stream velocities produced no appreciable change of drop size. On the basis of these test results, it was decided to use water injection needles of 0.013, 0.027, and 0.039 inches inside diameters with 90 L/D supplied with water at the pressures required to produce water velocities equal to the tunnel air velocities for all subsequent testing.

Drop Dispersion Equipment Development

It was thought that periodic, high frequency angular displacement of the water injection needles from the position parallel to the airflow direction would be required to disperse the drops over the test section. Such angular deflections should be as small as possible to reduce the shear forces exerted by the air on the water jets. Therefore the length of the tunnel constant-area rain development section was selected to be 24 feet, the maximum consistent with space available. It was decided to use an existing inlet bellmouth and duct with a segmented circular cross section of 3.65 square feet area for the rain development

APPENDIX A

DISCUSSION (cont.)

Drop Dispersion Equipment Development (cont.)

section. This duct was connected to the windshield test section with its induction air blower system.

Computations indicated that the water discharge rate from a single 0.027 inch diameter bore "heavy rain" water injection needle was approximately that necessary to produce the liquid water content in the test section which would simulate heavy rain. Therefore the first approach to rain drop dispersion was by inducing vibration of a single water injection needle. The needle was mounted on a 1/4 inch stainless steel tube and cantilever-supported on a fixed strut at a tunnel centerline (Figure A-5). Electromagnetic shaker units were mounted at 90° to each other and the tunnel centerline outside the tunnel and connected to the needle support tube by means of pushrods (Figure A-6). The shaker power supplies and controls were so arranged that the motion of the needle could be made to follow a variety of patterns, with good frequency and amplitude control. Several different needle vibration patterns were tried. Basically these patterns consisted of a 25 to 50 cps oval, figure eight, or multiple loop over the tunnel cross section with a 100 to 200 cps approximately simple harmonic motion superimposed.

Mechanical failure of needle-support tubes, needles and pushrods was encountered, and these problems precluded the use of higher vibration frequencies. With a 50 cps prime vibration mode at 200 knots tunnel velocity, water drops approaching the windshield from successive vibration cycles would be approximately 81 inches apart. For heavy rain a uniform drop spacing would be approximately 5 inches, and a vibration frequency of approximately 810 cps would be necessary to achieve this. However, observations of the windshield indicated that the vibration frequencies used were producing a uniform wetting of the windshield. At this time the vibration equipment had to be released for other testing, and it was decided to use a different method of drop dispersion. It is believed that the vibrating needle method showed promise, and should be considered for future rain simulation apparatus.

Larson of the WADC Equipment Laboratory had experimented with an apparatus, using Ruggeri's drop production method, capable of distributing the drops across a wind tunnel test section. This consisted of a vertically-mounted water supply manifold strut, in a streamlined housing. Water injection needles were mounted

APPENDIX A

DISCUSSION (cont.)

Drop Dispersion Equipment Development (cont.)

on the strut to form a rake of needles in a vertical plane. The manifold was mounted in bearings and oscillated in approximately simple harmonic motion, on its vertical axis by a drive system providing a range of frequency and amplitude. Spacing of the needles on the manifold was equivalent to the diameter of the natural dispersion of the drops in the tunnel from a fixed single needle. The needle rake therefore produced a vertical band of water drops at the test section. Oscillation of the manifold them produced a rapidly sweeping band of rain across the test section. The rake provided about ten times the required amount of water in the band. Proper average liquid water content values were provided by adjustment of the oscillation amplitude to have the curtain of rain in the test section for only 1/10th of the period, the water being directed to the tunnel walls during the remainder of the period.

The Los Angeles Division of NAA had constructed such an apparatus for F-100 windshield rain removal testing and this equipment was obtained for the A3J-1 testing. With some modification this apparatus was incorporated in the test wind tunnel (Figure A-7). Manifold oscillation frequency was limited to 20 cycles per second because of structural and vibration considerations. Photographs of the drops produced by this apparatus with the manifold stationary showed good agreement with the drop sizes obtained in the small tunnel. Photographs of drops with the manifold oscillating were not obtained because of difficulty in synchronizing the short duration photo flash with the incidence of drops in a particular portion of the tunnel. The appearance of the windshield with the simulated rain produced by this apparatus indicated that drop size and dispersion were satisfactory.

Visibility Recording Technique Development

During the first phase of the test program and for equal conditions, differences in the appearance of the rain on the windshield were noted. The differences were determined to be due to the fouling of the windshield surface by oil in the hot air supply and by deposition of the water soluable mineral salts present in the city water supply upon evaporation of the simulated rain on the windshield. An activated charcoal oil filter was provided to eliminate the first problem and the second was alleviated by the use of de-ionized water for the simulated rain. Also a

APPENDIX A

DISCUSSION (cont.)

Visibility Recording Technique Development (cont.)

program of frequent cleaning of the windshield was established.

Examination of the literature revealed that previous testing of this type relied primarily on the determination by visual inspection of the location and extent of dry, splattered, and completely wetted areas of the windshield to evaluate the performance of the rain removal system. In some tests photography of the windshield was used to provide a record of the appearance of rain upon the windshield. Also, illuminated objects forward of the tunnel entrance were photographed through the windshield to demonstrate and record the clarity of vision obtained through a small portion of the windshield. The techniques previously used were reviewed, and it was decided that rain removal system performance could be best recorded by photographing the pilot's field of vision forward through the portion of the windshield affected by the rain removal system.

Initial testing indicated that a sharp-contrast background with uniform lighting was necessary to obtain photographs indicating extent of clearance. The interior of the wind tunnel forward of the windshield and flat panels forward of the inlet bellmouth and forward of the transparent wall test section were painted a flat white. A transit was positioned at the pilot's eye position and used to construct a pattern of orthogonal grid lines in black paint over the white areas. Ports were cut in the floor of the rain development section of the wind tunnel and replaced with transparent plastic windows, through which electric illumination was provided to the tunnel interior. Since the carrier-landing approach operation was considered most critical in regard to requirements for visibility in rain, the visual target area was marked with black crosses and small electric lights at the carrier landing mirror system positions as they would appear to the pilot on approach at various distances from 2000 feet to 10 feet aft of the carrier fantail. The Landing Signal Officer position would appear to the pilot to be below the left mirror position and would therefore be visible to the pilot whenever this mirror position was visible.

A 4 x 5 Speed Graphic cut film camera with a 135 mm lens was positioned at the pilot's eye position for recording the vicibility.

APPENDIX A

DISCUSSION (cont.)

Visibility Recording Technique Development (cont.)

In view of the "sweeping band" method of rain drop dispersion it was felt that the camera exposure should be of relatively long duration to effectively totalize the visibility pattern, much as the human eye and brain totalizes series of instantaneous images. Consequently, neutral density lens filters were used to permit the setting of exposure time at three seconds. The camera iris diaphragm was set at F32 to produce the maximum depth of focus. Comparison by several individuals of the resulting photographs with the directly-observed view resulted in agreement that this photography method produced true records of the visibility through the windshield.

Motion pictures were also taken from the pilot's eye position. The necessary fast exposure exaggerated the effect of the "sweeping band" drop dispersion. Also, these films were inferior to the still photographs in detail and contrast.

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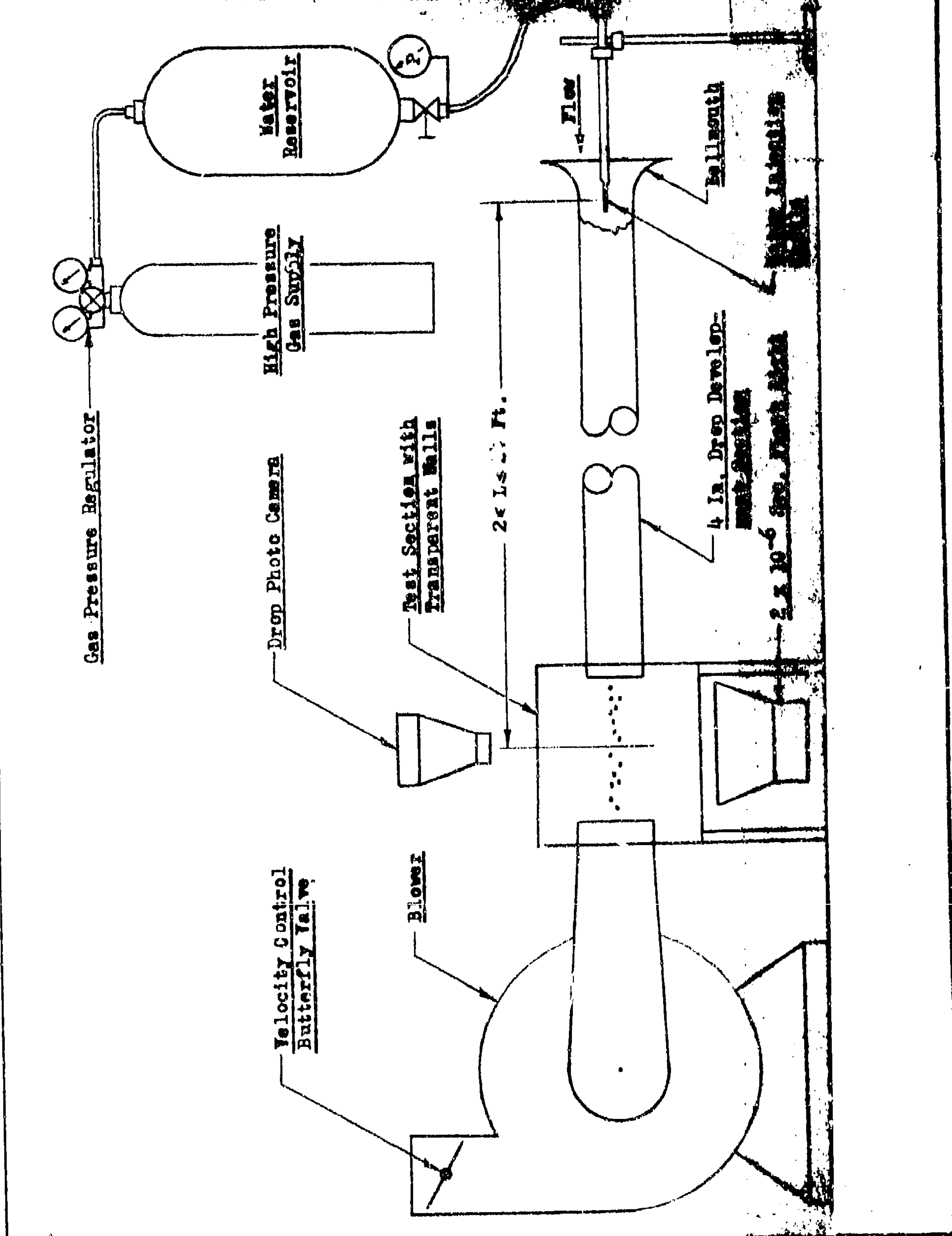

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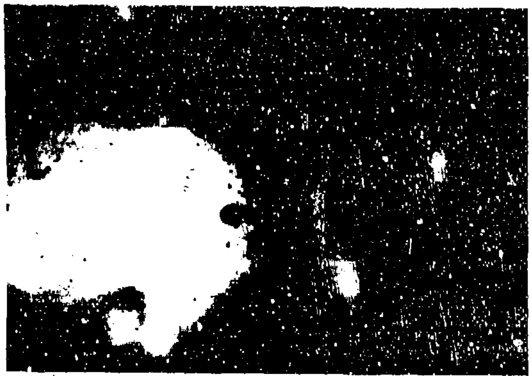
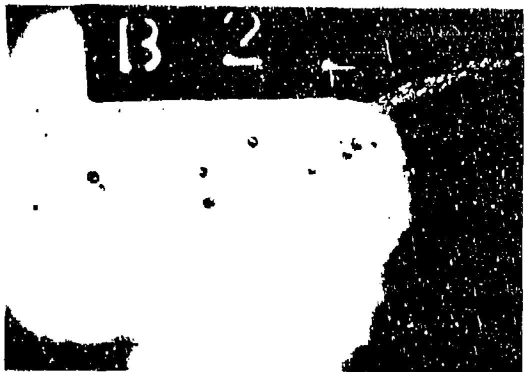
FIGURE A-2

EFFECT OF WATER INJECTION NEEDLE LENGTH TO DIAMETER RATIO ON DROP SIZE

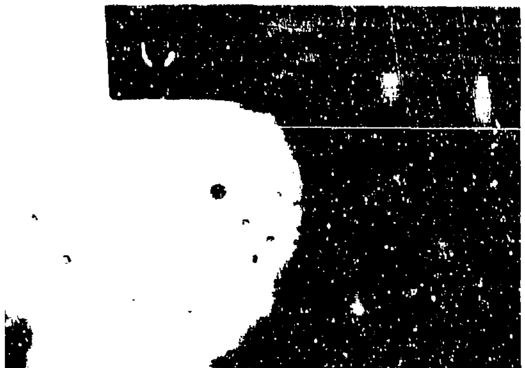
CONDITIONS: Velocity 150 Knots, Tunnel Length 24 Ft., Needle Inside Diameter 0.034 In.



L/D 40 MEAN DROP SIZE 0.036 IN.



L/D 90 MEAN DROP SIZE 0.083 IN.

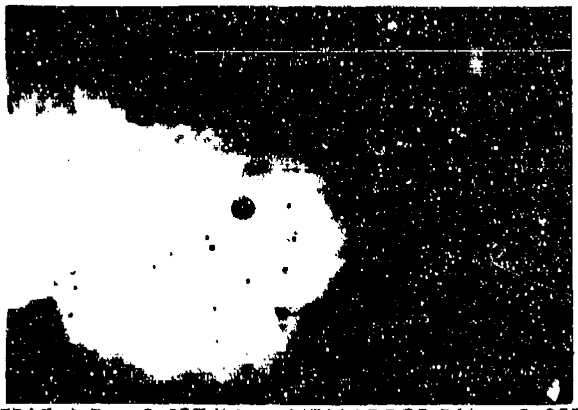


L/D 130 MEAN DROP SIZE 0.085 IN.

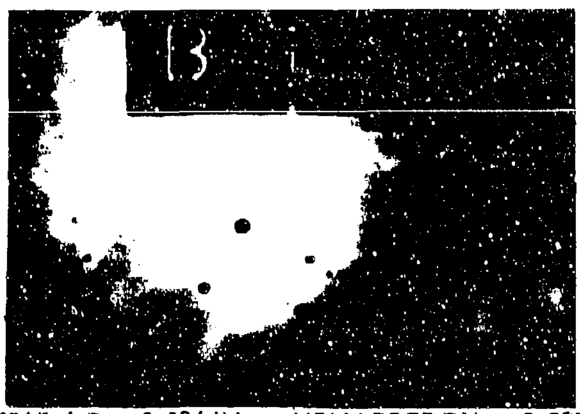
EFFECT OF SIZE OF WATER INJECTION NEEDLE ON DROP SIZE FIGURE A-3

CONDITIONS: Velocity 150 Knots, Tunnel Length 24 Ft., Needle L/D 90

NEEDLE I.D. 0.013 IN. MEAN DROP DIA. 0.035 IN.



NEEDLE I.D. 0.027 IN. MEAN DROP DIA. 0.055 IN.



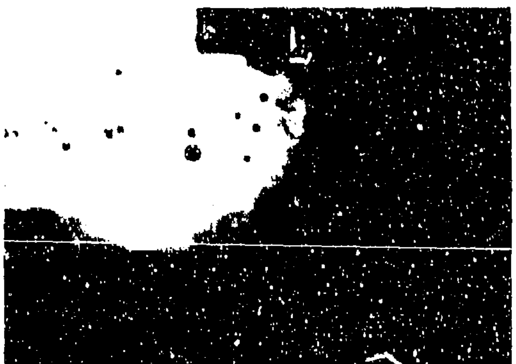
NEEDLE I.D. 0.034 IN. MEAN DROP DIA. 0.085 IN.

EFFECT OF DISTANCE FROM INJECTION NEEDLE ON DROP SIZE
FIGURE A-4

CONDITIONS: Velocity 150 Knots, Needle L/D 130, Needle I.D. 0.034 in.

DISTANCE FROM NEEDLE 2 FT.

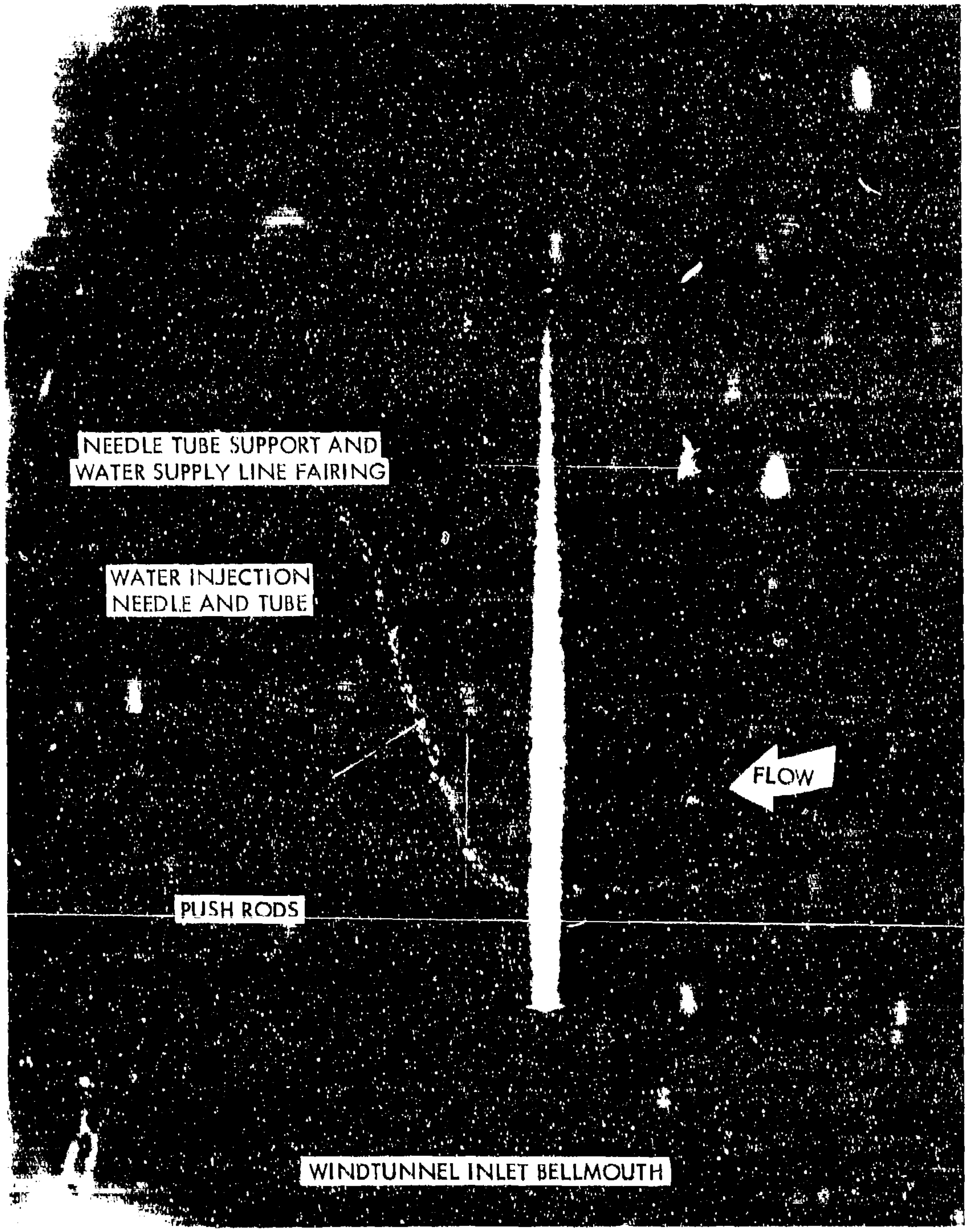
DISTANCE FROM NEEDLE 8 FT.
MEAN DROP DIA. 0.085 IN.



DISTANCE FROM NEEDLE 12 FT.
MEAN DROP SIZE 0.090 IN.

DISTANCE FROM NEEDLE 24 FT.
MEAN DROP SIZE 0.085 IN.

VIBRATING SINGLE-NEEDLE RAIN DISPERSION SET-UP FIGURE A-5



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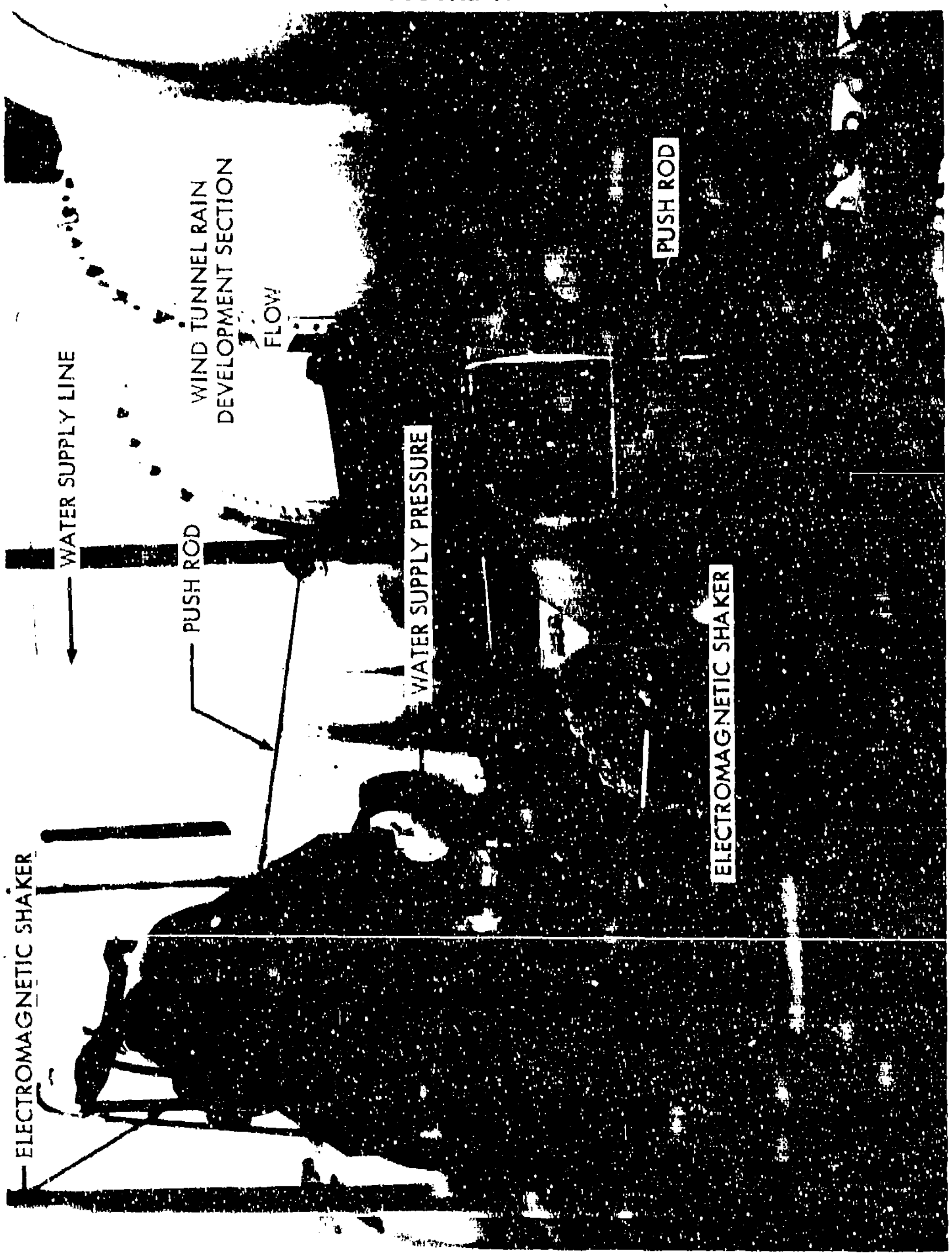
VIBRATING SINGLE-NEEDLE RAIN DISPERSION DRIVE ARRANGEMENT

FIGURE A-6



OSCILLATING RAKE RAINMAKER SET-UP FIGURE A-7