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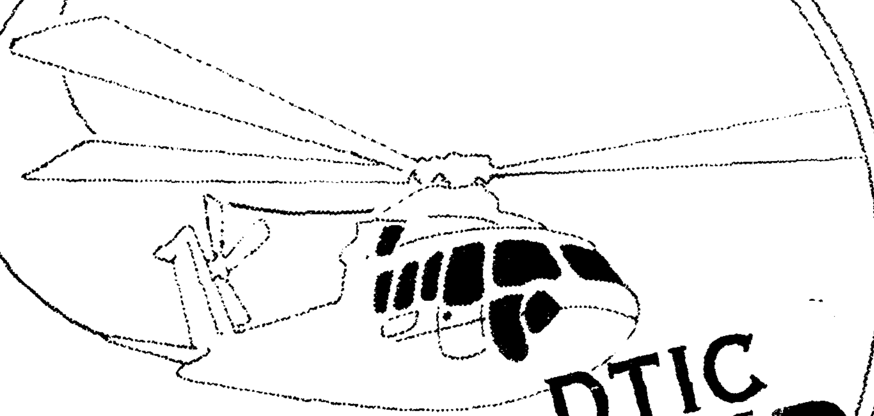
Icing Cloud Simulator for Use In Helicopter Engine Induction System Ice Protection Testing



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16. Abstract

Aircraft with Airborne Icing Spraying Systems (AISS) have been used for some time to generate icing clouds into which test aircraft could be flown to show compliance with the requirements of FAR XX.1093. However, the spray arrays used and the relatively large distance between the AISS and aircraft parts to be tested precluded small droplet sizes at high liquid water content at most atmospheric conditions. Some of these shortcomings were overcome by mounting the AISS directly on the test aircraft. This proved to be a very efficient method to develop and certify individual aircraft components.

This report describes the methodology and test procedure used with an AISS mounted on a test aircraft to show compliance with FAR 29.1093 for the newly developed inlet of the Bell 222/250-C30G helicopter conversion. Development and certification testing was accomplished in a 4-week period.

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PREFACE

The test equipment described in this report was designed and built for and by Heli-Air, Inc. of Broussard, LA. Flight tests were conducted in International Falls, Minnesota and Ames, Iowa. Tyron Millard and Wayne Barbini represented the Rotorcraft Directorate of the Southwest Region of the Federal Aviation Administration (FAA). Harry Harr, designated engineering representative of Global Helicopters, coordinated Heli-Air's efforts with the FAA and recorded aircraft parameters and liquid water content during testing. Dave Brown of Heli-Air, Inc., piloted the aircraft. Paul Graham and John Eastes (Heli-Air), under the direction of Dave Brown, kept the helicopter flying as well as provided video and still picture coverage of the tests in progress. The author operated the spray rig and photographed the icing cloud droplet samples captured on oil slides. The aircraft tested was a modified Bell 222A helicopter.

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SYMBOLS AND ABBREVIATIONS

AA_2 - Air Exit Area into Nozzle Mixing Chamber

AA_3 - Net Effective Nozzle Exit Area for Air

A_3 - Nozzle Exit Area

A_c - Icing Cloud Area

AW_2 - Water Exit Area into Nozzle Mixing Chamber

C_D - Water Droplet Drag Coefficient

C_V - Discharge Coefficient

D_W - Water Droplet Diameter

dV/dt - Rate of Change of Water Droplet Velocity

FAA - Federal Aviation Administration

FAR - Federal Aviation Regulation

FOD - Foreign Object Damage

g - Gravitational Constant

GPH - Gallons Per Hour

Hc - Heat Transfer Coefficient

IFR - Instrument Flight Rules

k - Specific Heat Ratio

KIAS - Knots Indicated Air Speed

LWC - Liquid Water Content

MVD - Mean Volume Diameter

N - Number of Steps to Calculate Jet Core Velocity and Temperature

N_U - Nusselt Number

OAT - Outside Air Temperature

PA_1 - Nozzle Air Supply Pressure

P_2 - Mixing Chamber Pressure

PW_1 - Nozzle Water Supply Pressure

P_R - Prandtle Number

R_C - Temperature Recovery Factor

R_g - Gas Constant for Air

R_N - Reynolds Number

$T\infty$ - Remote Air Temperature

TA_1 - Nozzle Supply Air Temperature

TA_2 - Mixing Chamber Air Temperature (Isentropic)

TA_2' - Mixing Chamber Air Temperature (Actual)

TA_J - Jet Core Air Temperature

TOT - Turbine Outlet Temperature

TW_J - Jet Core Water Droplet Temperature

VA_J - Jet Core Velocity of Air

VA_2 - Air Velocity Into Mixing Chamber

$V\infty$ - Remote Air Velocity (Aircraft)

V_R - Relative Velocity between Water Droplet and Jet Core Air Velocity

VW_J - Water Droplet Velocity in Jet Core

W_A - Airflow Rate through Nozzle

w_A - Specific Weight of Air

w_W - Specific Weight of Water

X - Distance Along Jet Core Measured Downstream of Nozzle Exit

EXECUTIVE SUMMARY

Airborne Icing Spray Systems (AISS) have proved to be valuable tools in the development and certification process of complete aircraft as well as aircraft components. This report details the design methodology and test procedure of an AISS mounted directly on the test aircraft. The system was used to develop and show compliance with the requirements of Federal Aviation Regulations (FAR) 29.1093 for a new engine inlet on the Bell 222/250-C30G helicopter conversion.

This AISS design entailed investigation of available bleed air and water supplies, spray nozzle performance in terms of required water and bleed air quantities, pressures and temperatures to generate the desired droplet sizes, droplet size distribution, droplet impact temperature and velocities, icing cloud freezable liquid water content, etc., all for various atmospheric conditions and airspeeds. Computer code was generated to facilitate the design process.

It was found that the entire FAR Part 29, Appendix C envelope could be simulated with the nozzle arrangement and systems controls provided. The entire development and certification testing was accomplished within a 4-week period. This was due to the fact that the system was self-sufficient and therefore operationally and logistically very flexible.

1. INTRODUCTION.

In early 1988, the design process of replacing the two LTS-101 engines in the Bell 222 helicopter with Allison 250-C30G engines was initiated by Heli-Air, Inc. of Louisiana. Due to the different air inlet configuration of these engines, the air induction system had to be redesigned. Part of the Supplemental Type Certificate (STC) work was, therefore, to show compliance with the requirements of Federal Aviation Regulation (FAR) Part 29, paragraph 1093, dealing with induction system ice protection. Due to a tight schedule and budgetary considerations, it was decided to avoid, if possible, icing tunnel schedules and/or the high costs of currently used ground or airborne icing cloud generators.

Previous experience by the author with small arrays of spray nozzles used on the ground in appropriate weather conditions had been shown to perform in a satisfactory manner for small turboprop air induction systems. However, this could not be said of a similar setup used on a helicopter. Rotor wash and lack of a sufficient horizontal wind-component made it difficult to control the icing cloud produced, let alone simulate forward airspeed. It was therefore concluded that for this case a cost effective and workable icing rig should be airborne, necessarily self-sufficient, and mounted on the aircraft whose air induction system was to be tested.

This report describes the design process for such a spray rig, as well as results obtained using this system. The nozzle array considered was to be sized to adequately cover the starboard engine inlet with an icing cloud sufficiently variable to cover atmospheric icing as detailed in FAR Part 29, Appendix C. The following items were considered before the spray rig configuration was finalized:

1. Sufficiency of available bleed air in terms of volume, temperature, and pressure.

2. Nozzle performance and control requirements.

3. Droplet impingement temperatures and velocity.

2. DISCUSSION.

2.1 BLEED AIR.

The maximum extractable bleed air for the Allison 250-C30G engines is 4.5 percent of the airflow rate. To estimate the minimum amount of bleed air available, power required was assumed to be 235 hp/engine. At this power setting, the Allison 250-C30G engine performance program gives the bleed airflow rates, pressures and temperatures as shown on figure 1.

2.2 SPRAY NOZZLE.

The spray nozzles used were manufactured by the Spraying Systems Company of Wheaton, IL. The particular setup selected (after some bench tests) consisted of fluid cap 40100 and air cap 1401110 (figure 2). At a water flow rate of 2.5 GPH, this internal mix nozzle produced water droplets in the size range required (figure 3). Manufacturer supplied test data was used to relate water pressure, P_{W_1}, air supply pressure, P_{A_1} and water flow rate, GPH, as follows:

$$P_{W_1} = .572\ P_{A_1} + 2.56\ GPH - 7.4$$

The mixing chamber pressure, STA 2, was calculated from:

$$P_2 = P_{W_1} - (.00232\ GPH/A_{W_1})^2/2\ g\ w_W$$

The compressible flow equation was then used to calculate airflow rates and mixing chamber inlet velocity.

Let $R = (P_2/P_{A_1})$

$C_1 = (2)(g)(k/k-1)$

$C_2 = 2/k$

$C_3 = (k-1)/k$

Then

$$W_A = P_{A_1}\ C_V A\ A_2\ [(C_1/R_g\ T_{A_1})(R^{C2})(1-R^{C3})]^{1/2}$$

And

$$V_{A_2} = [C_1 R_g T_{A_1}\ (1-R^{C3})]^{1/2}$$

Based on experimental data, the discharge coefficient, C_V, was determined to be .7. A temperature recovery factor of .9 was assumed.

$$RC = (T_{A_1} - T_{A_2}') / (T_{A_1} - T_{A_2}) = .9$$

To be on the conservative side as far as target impact temperatures are concerned, the nozzle air exit temperature was assumed to be equal to mixing chamber inlet temperature. The nozzle air exit velocity was based on the net mixing chamber exit area, that is:

$$A_{A_3} = A_3 - A_W$$

2.3 DROPLET IMPINGEMENT TEMPERATURE.

The following assumptions were made regarding the droplet path to the target.

a. A spray nozzle rake of sufficient size could be mounted about 7 feet ahead of the engine inlet.

b. The water droplets are spherical.

c. The Reynolds number is low enough such that the droplet drag coefficient is approximated by:

$$C_D = 24 / R_N$$

d. The velocity and temperature decay of the jet core are approximated by:

$$V_{A_J} = (6D_3 / X (V_{A_3} - V_\infty)) + V_\infty$$

$$T_{A_J} = (5D_3 / X (T_{A_3} - T_\infty)) + T_\infty$$

To be on the conservative side, jet core parameters have been used to compute target impact conditions.

2.4 IMPACT VELOCITY.

The change in droplet velocity is given by:

$$dV/dt = \text{droplet drag/droplet mass}$$
$$= (3/4)(w_A/w_W)(C_D/D_W)\ V_R$$

Substituting assumption "C", and assuming the viscosity to be constant over the temperature range in question, this equation reduces to:

$$dV/dt = 18\ \mu\ (V_R / D^2_W)$$

In the interval, delta X, bounded by station 1 and 2, the average relative velocity, V_R, is estimated as follows:

$$V_R = (V_{A_{J1}} + V_{A_{J2}} - V_{W_{J1}} - V_{W_{J2}})/2$$

And the corresponding time increment:

$$(t_2 - t_1) = 2\ (X_2 - X_1)/(V_{W_2} - V_{W_1})$$

Where $(X_2 - X_1) = (\text{distance to target})/N$
Combining yields

$$0 = V^2{}_{W_{J2}} + 18\ \mu\ (X_2 - X_1)\ V_{W_{J2}} / D^2_W$$

$$-[\ V^2{}_{W_{J1}} + 18\ \mu\ (X_2 - X_1)(V_{A_{J1}} + V_{A_{J2}} - V_{W_{J1}}) / D^2_W\ ]$$

This can now be solved for $V_{W_{J2}}$.

2.4.1 Water Impact Temperature.

For the purpose of this investigation, only worst case conditions are investigated to assure that prescribed icing conditions are satisfied. It was therefore decided that evaporative cooling of the water droplet will be ignored.

The same step size has been used as for the velocity calculations. The initial droplet temperature was assumed to be the water supply temperature (heating in the mixing chamber of the nozzles has been ignored). The droplet temperature exposed to the jet core and airstream is evaluated for each step using the solution to the transient heat transfer equation

$$T_{W_{J2}} = (T_{W_{J1}} - T_{A_{JAV}})e^{-([(H_C A_S)/(w_W V)]t} + T_{A_{JAV}}$$

Where

$$H_C = N_U k/D_W$$

The Nusselt number, N_U, for a sphere, is given by:

$$N_U = 2 + (.4R_N^{1/2} + .06\ R_N^{2/3})(P_R)^{.4}$$

The Prandtl number, P_R, for the case on hand was assumed to be .71. Reynolds and Nusselts numbers are based on the diameter of the water droplet.

The computer code on figure 4 has been used to calculate the temperature and velocity of a water droplet traveling along the jet core. Figure 5 gives the characteristics of a 25 m particle while figure 6 shows temperatures and velocity of a 45 m droplet. The last column in the tabulations shows the differential speed between jet core and water droplet.

As shown, essentially ambient conditions exist 3 to 4 feet past the spray rake, especially if one remembers that the data shown are based on a temperature and velocity decay of a smooth nozzle. The highly turbulent spray nozzle exit conditions should provide a much earlier and more uniform particle stabilization than what this math model indicates.

2.5 SPRAY RIG DESIGN AND CONTROLS.

The total amount of water to generate the appropriate icing cloud is given by:

$$GPH = .045\ gr\ V_\infty\ A_C\ /\ \sqrt{\delta}$$

The nozzle configuration selected runs best at water flow rates of 2.5 GPH. A curve fit to experimental data (figure 1) yields the air pressure required to operate this nozzle as a function of desired droplet size in microns.

$$P_{A_1} = .094\ D^2_W - 6.64\ D_W + 132.2$$

The corresponding water pressure to force a flow of 2.5 GPH is given by:

$$P_{W_1} = .572*P_{A_1} - 1$$

Using these relationships, computer code was generated (Figure 7) to yield optimum rake configurations for each required condition. For the worst case, the number of nozzles required at 2.5 GPH/nozzle was 30 (see figure 8). To be able to generate all required icing clouds, a spray array of 34 nozzles was devised which allowed the operation of uniformly spaced nozzles in groups of 9, 25, and 34. Figure 9 shows the final rake configuration. Bleed air enters the vertical distribution trunk (3) at (1) feeding all nozzles. Water enters two separate sets of passages supplying the 9 and 25 nozzles groups [(5) and (4) at (2)]. The shroud (6) helps to dampen rake-caused turbulence as well as to direct the icing cloud. Figure 10 details the distribution system to spray nozzle sets (4) and (5). Water as well as air passages are designed to minimize differences in pressure drops to each nozzle. A schematic of the test equipment setup is shown on figure 11. A metering pump (2) delivers water at a constant flow rate from the 30 gallon water tank (1), via a filter (5), and a flow meter (8) to the spray rig. An accumulator (3) downstream of the pump smoothes out the variable supply pressure. Bleed air pressure and waterflow rates were predetermined and could be preset using metering valve (7) and bypass valve (9) in conjunction with gate valve (2) on the air supply side.

Bleed air was also used to power the LWC meter mounted forward of the engine inlet. Air and water temperatures and pressures were measured at the spray rig. A shock mounted microscope provided a means to determine droplet sizes captured on oil slides during individual runs.

3. AIRCRAFT CONFIGURATION AND TEST SETUP.

The aircraft configuration and test setup is schematically shown on figure 12. Figures 13, 14, and 15 show configuration photos of the test aircraft.

3.1 INDUCTION SYSTEM.

Air enters the inlet plenum (figure 12) through a perforated metal screen (5) and an alternate air passage (6). From there it flows through a coarse FOD screen (7) via a converging duct (8) to the Bellmouth of the Allison 250-C30G engine (10).

During icing conditions, the perforated metal screen (5) acts as a valve by freezing over within seconds and thus forcing all the air to flow through the alternate air passage (6). It is expected that inertial separation of water particles and air will keep the plenum ice free. Although some run through with large droplet sizes and near freezing temperatures will occur before screen (5) freezes over, the amount of internal ice buildup was expected to be minimal. In any case, FOD screen (7) is expected to protect the engines from any ice breaking loose from screen (5) or entering through the air bypass (6) when the rotorcraft reenters nonicing conditions.

3.2 TEST SETUP.

The spray rig (1) was mounted on top of the cabin over the pilot's seat (figure 12). The shroud and flap attached to the top trailing edge of the shroud were made adjustable to allow centering of the icing cloud on the #2 engine inlet screen (5). The liquid water content sensor (2) was mounted near the top of the gearbox cowl. An 8-inch-long, 1/4-inch-diameter rod (3) installed perpendicular to the gearbox ahead of the inlet demonstrated ice accretion rates and ice shapes during testing.

Spray rig presssure and temperatures were measured at the rake's water and bleed air inlets. To monitor the ice cloud's temperature history, thermocouples were located at the trailing edge of the 8-inch rod at (4) and at the FOD screen (7).

OAT was recorded using a thermocouple located within 2 inches of the ship OAT sensor. A single pitot-static tube (9) ahead of the engine bell mouth (10) was used to estimate inlet losses under icing conditions. To sample droplet sizes, an oil slide could be exposed to the icing cloud through a tube in the cabin roof just ahead of the inlet. Mirrors mounted ahead of the spray rig allowed the pilot to observe the location of the icing cloud. A mirror located on the top of the starboard winglet made it possible to film the inlet screen and the 8-inch rod from the cabin while a test was in progress. All spray rig controls were located in the cabin.

4. TEST CONDITIONS.

The Bell Helicopter Model 222 is not certified to fly into known icing conditions. The air induction system certification was therefore based on the concept of limited exposure associated with escape from inadvertent icing encounters.

Since the physical size of the icing clouds to be traversed has been defined, the total amount of ice accretion for a given catch efficiency is a function of the freezing water fraction (LWC) only, whereas the ice accretion rate for a given LWC and catch efficiency in the externals of the inlet is proportional to the ship's airspeed, internal ice buildup in the air induction system is a function of the engines volumetric air consumption. To minimize the effects of the icing conditions, one should therefore fly the helicopter at the low speed end of the drag curve. The less efficient inertial water removal from the combustion air at low forward speeds is expected to be secondary. At higher speeds, screen run through and/or projected higher inlet losses may become critical. For the above reason, the minimum IFR speed of 50 KIAS appears to be a practical initial penetration speed.

Table 1 shows the proposed test conditions and estimates total ice accretion while on condition. Conditions (1)-(5) are flown at just below freezing temperature. Conditions (1) and (2) are flown at max ice accretion rates. Condition (3) checks for potential problems in case of nonrecognition of icing conditions. Seventy-five KIAS is deemed a reasonable average speed for flight in prevailing atmospheric conditions. Conditions (4) and (5) are the worst cases for water flow through on screen #1. Conditions (6) and (7) are run at lower temperatures to show the effects of ice shapes.

5. DATA ACQUISITION.

Flight test data included the following parameters:
Aircraft Data:

OAT	-	Outside Air Temperature
VI	-	Indicated Airspeeds
TQ	-	Torque (both engines)
HP	-	Altitude (Pressure)
TOT	-	Turbine Outlet Temperature (both engines)
N_1	-	Compressor Speed
GW	-	Gross Weight
PSI-PSS	-	Inlet Static Pressure
PTI-PSS	-	Inlet Total Pressure
PTS-PSS	-	Ship Total Pressure

Spray Rig:

LWC	-	Freezable Liquid Water Content
WFR	-	Water Flow Rate
TNA	-	Air Temp (Nozzle Inlet)
PNA	-	Air Press (Nozzle Inlet)
TNW	-	Water Temp (Nozzle Inlet)
THS_1	-	Icing Wand Temperature (Icing Cloud)
THS_2	-	Coarse Screen Temp (Inlet Air Temp)
PNW	-	Water Press (Nozzle Inlet)

6. RESULTS OF TESTING.

6.1 INTRODUCTION.

Company testing conducted between February 23 and March 13, 1989, confirmed the predicted capabilities of the aircraft mounted, self-contained spray rig. Limited icing tests during this period also established sufficient confidence in the air induction system design to start FAA testing. All testing was done March 13 through 15, 1989, in International Falls, Minnesota, and on March 18 and 19 in Ames, Iowa. FAA representatives of the Rotorcraft Certification Directorate of the Southwest Region witnessed the conduct of the tests.

The aircraft tested was a modified Bell 222A with the following deviations:

a. LTS-101 engines were replaced with Allison 250-C30G engines.
b. Different exhaust system.
c. Different inlet system.
d. Ice rig mounted on top of forward cabin.

Figures 14 and 15 give an overview of the test aircraft while figure 13 shows the two outer screens ("small" on the left side, "large" on the right side) tested.

Engineering judgement based on early test results dictated changes in the proposed test plan. Table 2 shows actual conditions flown. Table 3 summaries the raw test data taken during the FAA witnessed test period.

6.2 SUMMARY OF TESTING CONCLUSIONS.

The FAA representatives concurred that based on the observed test results, the air induction system flown will adequately protect the engines from detrimental ice buildup during inadvertent flight into icing conditions. Subsequent analysis of droplet size and LWC's showed that these parameters were essentially within specified limits. The TOT margins were also found to be sufficient. It was, therefore, concluded that the Bell 222A/Allison 250-C30G as configured meets the requirements of FAR Part 29, Appendix C of the CFR's.

6.3 OPERATIONAL NOTES.

All test points were run near maximum gross weight. To maximize bleed air available to the spray rig, all test conditions were flown with the landing gear extended.

The time duration of each test point was determined by the time required to transverse sequentially a standard stratiform and cumuliform cloud as defined in Part 29, Appendix C. Since the Ludlum limit reduces the useful range of the freezable liquid water content meter to 2 gm/m^3 and because cumuliform clouds may reach up to 3 gm/m^3, the time to simulate these conditions was increased by a factor of 1.5 and the target LWC was reduced to a measurable 2 gm/m^3. Furthermore, 1 minute was added to allow for a problem recognition time.

	KIAS	OAT °F	MVD	LWC	TIME	mm ICE ACRETION
1	50	26–31	15–25	1.8–2.0	5.3	15.9
			15–25	0.5–0.8	21.9	22.0
2	100	26–31	15–25	1.8–2.0	3.2	17.6
			15–25	0.5–0.8	11.4	24.0
3	75	26–31	15–25	0.5–0.8	30.0	42.0
4	50	26–31	35–50	0.5–.75	5.3	5.3
			35–50	.15–.30	21.9	8.8
5	100	26–31	35–50	0.5–.75	3.2	6.2
			35–50	.15–.30	11.4	6.6
6	50	10–15	15–25	1.8–2.0	5.3	15.9
			15–25	0.5–0.8	21.9	22.0
7	100	10–15	15–25	1.8–2.0	3.2	17.6
			15–25	0.5–0.8	11.4	24.0

Table 1. Proposed Test Conditions

COND.	KIAS	OAT	TIME	LWC	MVD
5C	75	16.2	30.0	1.02	21
9B	50	31	22.0	1.77	42
5A	50	16.6	5.3	2.62	19
			21.7	1.28	22
5B	100	14.7	6.4	2.13	28
			12.4	0.71	25
5E	50	16.7	5.3	1.34	58
			21.9		
5D	100	18.7	6.4	0.80	40
			12.4	0.58	41
8A		23.6	40.0	0.88	43
9A		32.0	30.0	2.10	
7A	50	−4	5.3	2.46	19
			21.9	1.08	17
7B	100	−2	6.4	1.74	25
			12.4	0.71	25
6A	50	10.5	27.0	1.94	26
6B	50	14	21.9	1.12	25
			5.3	1.86	25
6D	50	15	21.9	0.90	29
			5.3	2.15	21

Table 2. Actual Test Conditions Flown

HELI-AIR INCORPORATED

RAW DATA

DATE	COND	CONFIG	OAT	KIAS	ALT	rh %	MVD	LWC*	TIME	TQ%	N1%	TOT	Pt SHP	Pt DUCT	Ps DUCT	ROD T7	[illegible] T2	[illegible] T3	[illegible] T4	BLEED AIR T5	FRAMES MVD	ICE ACCRETION FRAMES
3/13/88	5A	small	18.0	50	2250	83	small	1.55	5.30	48.5	87.4	550	–	–	–	17.8	–	16.9	137	254	1–3	2–15
		scr.	18.0	50	2250	83	small	0.76	21.7	41.0	87.4	600	–	>-27.0	>-27.0	17.8	–	16.9	137	254	4–7	
3/13/88	5B	small	14.7	100	2000	70	small	0.54	12.4	51.0	88.0	570	–	-2.0	–	14.9	28.0	14.1	128	241	8–10	10–23
		scr.	14.7	100	2000	70	small	1.63	8.40	51.0	98.4	600	–	>-27.0	>-27.0	17.2	28.0	14.1	110	243	11–13	
3/13/88	5C	small	18.2	75	2500	90	small	0.66	38.0	41.0	88.7	550	+2.5	-2.3	–	18.7	30.2	15.6	138	235	2–5	24–30
		scr.	–	75	2500	90	small	–	–	–	–	540	+2.5	-14.0	-17.0	–	–	–	–	–	–	
3/13/88	5D	small	18.7	100	3000	65	large	0.44	12.4	52.0	90.0	585	+4.0	–	–	19.0	17.6	17.6	72	56	8–11	31–34
		scr.	18.7	100	3000	65	large	0.61	8.40	52.0	90.0	586	+4.0	-21.0	-28.0	18.0	17.6	17.5	63	48	12–16	
3/13/88	5E	small	18.7	50	3000	80	large	0.50	21.9	41.0	86.0	510	+1.2	–	–	17.3	18.5	15.1	45	82	10–15	33–36A
		scr.	18.0	50	3000	80	large	0.78	5.30	41.0	86.0	550	+1.2	-18.0	-21.5	18.8	16.0	15.1	45	58	24–25	
3/14/88	4A	large	18.5	50	4000	36	small	1.15	27.0	48.0	85.4	500	+1.2	–	–	12.2	18.3	9.60	86	107	1–2	3–5
		scr	–	–	–	–	–	–	–	–	–	506	+1.2	[illegible]	-13.0	–	–	–	–	–	–	
3/14/88	4B	large	14.0	50	2000	81	small	0.71	21.9	40.0	86.0	540	–	–	–	–	–	–	–	–	3–7	4–6
		scr.	14.0	50	2000	81	small	1.10	5.30	38.0	85.0	546	–	-25.0	-27.0	–	–	–	–	–	8–12	
3/14/88	4D	large	15.0	50	2250	42	small	0.53	21.9	38.0	88.0	546	–	–	–	–	–	–	–	–	5–8	–
		scr.	15.0	50	2250	42	small	1.27	6.30	38.0	88.0	550	–	–	–	–	–	–	–	–	7–12	
3/16/88	7A	small	-4.0	50	3000	71	small	0.64	21.9	38.0	84.0	486	–	–	–	–	–	–	–	–	1–4	9–13
		scr	-4.0	50	3000	71	small	1.40	5.30	38.0	84.0	510	–	-24.0	–	–	–	–	–	–	5–12	
3/16/88	7B	small	-1.0	100	3200	41	small	0.54	12.4	52.0	–	550	–	–	–	–	–	–	–	–	1–4	14–17
		scr.	-1.0	100	3200	41	small	1.03	8.40	52.0	–	570	–	-27.0	–	–	–	–	–	–	5–12	
3/18/88	8A	small	23.8	0	–	40	small	0.84	48.0	50.0	–	–	–	-2.0	–	21.6	38.0	30.7	125	133	–	–
		scr.	–	–	–	–	small	–	–	–	–	–	–	-12.0	-17.0	–	–	–	–	–	–	
3/19/88	9A	small	32.0	0	–	50	large	0.44	30.0	50.0	88.0	500	–	-2.5	–	28.6	31.4	27.0	125	133	1–12	–
		scr.	–	–	–	–	–	–	–	–	–	570	–	-12.0	-17.0	–	–	–	–	–	–	
3/19/88	9B	small	31.0	50	1300	–	large	1.06	22.0	38.0	85.0	–	–	-2.5	–	29.1	31.6	28.6	77	150	–	–
		scr.	–	–	–	–	–	–	–	–	–	–	–	-11.0	-15.0	–	–	–	–	–	–	

Table 3. Bell 222/Allison 250-C30G Ice Test Results.

Since LWC meter readings are considered indeterminate above -5°C, near freezing temperature data were obtained by running equivalent water-flow rates.

The following is a typical flight profile:

1. Aircraft is fueled up to max gross weight.

2. After engine startup, bleed air is feed into air and water supply lines to prevent system freeze-ups.

3. The estimated water-flow rate required for the first part of the test is set during climb-out.

4. Aircraft climbs to the desired OAT level and then levels out at the test airspeed.

5. Bleed air pressure is then set to estimated value and water is directed into spray rig.

6. Bleed air to water line is disconnected.

7. Water-flow rate is now adjusted if required to desired liquid water meter reading.

8. Using oil slides, ice cloud droplet samples are taken, checked for size and photographed using a shock mounted microscope. If necessary, bleed air pressure is adjusted and above procedure is repeated.

9. All required aircraft and spray rig data are manually recorded. Videos of the inlet screen are taken through the aft cabin window.

10. Steps 8 through 10 are repeated for the second part of the conditions.

11. After all required data are taken, the water supply line and water passages in the spray rig are purged with bleed air.

12. After landing, the ice buildup on various inductions system parts is observed and photographically documented.

6.4 DROPLET QUALITY.

Oil slide pictures taken during FAA testing have been placed on file at Heli-Air. Even though the time lapse between obtaining the droplet sample and taking the picture was only about 5 seconds, some droplet size distortion due to coalescence a.. evaporation could be observed. While the latter increases MVD somewhat, the former may result in very large drops which will not only significantly increase MVD, but will also result in a rather lopsided and erratic droplet size distribution. For this reason, it was decided to ignore the two largest droplets on each slide as far as MVD tabulations and calculations were concerned.

Figure 16 shows the droplet sizes measured for each test condition versus liquid water content. By and large, this figure shows that droplet size targets have been met, and that nozzle performance could be controlled within the tested liquid water contents.

Figure 17 shows that the droplet size distributions of the "small" droplet runs compare fairly well to that found in a "standard" stratiform cloud.

6.5 TEMPERATURE.

The ice cloud air temperature was measured by an aft facing thermocouple mounted on the 8-inch-long rod (item 4, figure 12) and a thermocouple on the inner screen of the engine inlet. As expected, the former temperature reads slightly higher, and the latter temperature somewhat lower than OAT. This effect is assumed to be mainly due to evaporation.

From ice shapes observed and calculations, one may conclude that water droplet impact temperatures were sufficiently close to ambient temperatures, and that these ice tests did simulate natural icing conditions fairly well.

6.6 INLET PERFORMANCE.

6.6.1 Photographic and Visual Records.

The ice buildup on the inlet screen was observed and photographed using a video camera via a wing mounted mirror. The videos are on file at Heli-Air.

After each condition, the aircraft landed and the photographs shown in figures 18 through 24 were taken.

A summary of observations based on visual and photographic evidence is presented in table 4. The tabulated open areas are estimated from the photographs.

6.6.2 Inlet Losses.

Table 5 shows the temperature rise caused by ice buildup on the air induction system. Inlet losses were deduced from various observations. Estimates under "average" values demonstrate sufficient temperature margins to fly the aircraft even under the most severe icing conditions for the time interval anticipated.

7. CONCLUSION/OBSERVATIONS.

The inlet loss data obtained during these tests were rather sketchy and only moderately verifiable. Nevertheless, the effects of various parameters on the inlet configuration tested could be evaluated.

The overall effect of an increase in airspeed showed a small decrease in inlet losses. This is, as expected, particularly true for the larger droplet sizes. The difference in blockage due to ice buildup on the inlet slot and inner

RUN	OUTER SCREEN	% OPEN	BYPASS GAP	% OPEN	INNER SCREEN	% OPEN
5A	Pressure loss in excess of 27" - Granular rime ice.	0	Distinct secondary stagnation stream line-	75	4" elliptical area with ~15' ice build-up upon wire - very little bridging.	95
5B	Heavier ice build-up than previous run. Coarser rime ice which appeared to be self-clearing. Pressure loss in excess of 27". Max loss appears to be somewhat less than for run 5A.	6	Less pronounced stagnation stream line. More ice build-up on aft section of gap	95	About the same as Run 5A. Some bridging.	85
5C	Intermediate amount of ice build-up of rather finely structured rime ice. Screen was self cleaning around the perif-ery.	9	Ice shape similar to Run 5B.	95	Wire ice build-up extensive over a larger area, but there was no bridging.	93
5D	Larger amount of very coarse and porous, almost translucent rime ice.	10	Only a small amount of ice on gap surface.	100	No ice on inner screen.	100
5E	About the same amount of ice build-up as run 5D, but with a much finer, still porous rime ice structure.	2	Fair amount of ice on gap surface rather uniformly distrib-uted.	90	Considerable ice build-up on inner screen, but relatively little bridging.	70
6A	Screen sheds ice during test. Rel-atively low ice accumulation with large open areas.	20	Almost completely ice free	100	Slight frost on wires.	98
6B	Higher ice accumulation - Less shedding.	8	Some ice accumulation.	100	Very little frost on screen wires.	99
6D	No photograph.	-	-	-	-	-

Table 4. Bell 222/Allison 250-C30G Ice Build-Up Test Results Summary - Sheet 1 of 2

RUN	OUTER SCREEN	% OPEN	BYPASS GAP	% OPEN	INNER SCREEN	% OPEN
7A	Very fluffy rime ice which circum-cised easily on contact. Shedding during run.	0	Pronounced stag-nation line build-up on forward part of gap area.	85	Considerable ice build-up over approximately 80% of screen area but without bridging.	65
7B	Same as 7A.	0	Two ice ridges in gap. Appears to be worse than Run 7A.	80	Significant amount of screen is iced over.	65
8A	Screen completely covered with rime ice.	0	Only small ridge of ice on forward part of gap.	98	Center part iced over, clean around perimeter.	55
9A	Glaze ice over entire screen.	0	Essentially ice free except for small area on top.	100	About 20% clear, 50% iced up, but no bridging and about 30% brok-en off.	50
9B	Same as 9A.	0	Clear gap.	100	Slightly iced up.	98

Table 4. Bell 222/Allison 250-C30G Ice Build-Up Test Results Summary - Sheet 2 of 2

COND	TOT RISE – °C			
	A	B	C	AVERAGE
5A	40	41	20	34
5B	43	34	30	36
5C	15	19	–	17
5D	25	21	20	22
5E	18	29	40	29
6A	10	7	5	7
6B	30	8	5	14
7A	29	29	15	24
7B	33	34	20	29
8A	12	19	–	16
9A	12	19	–	16
9B	11	21	–	16

NOTE:

A – The total pressure loss as measured by a single duct-mounted pitot tube and the engine performance deck are the basis for these values.

B – This TOT rise is based on estimated open areas and the engine deck.

C – Measured temperature rise. (Pilots TOT gage.)

Table 5. Bell 222/Allison 250-C30G Inlet Losses due to Icing

screen apparently more than offset the inherently higher losses associated with the aft facing slot. It is therefore concluded that the aircraft should, if inadvertent ice penetration occurs, fly at about 60 to 70 KIAS. Since this range is near maximum endurance speed for most conditions, lower power requirements will also tend to increase the already large TOT margins.

The results obtained clearly show the much higher inertial separation efficiencies for the larger droplet sizes if compared at constant airspeeds.

Conditions flown at just below freezing temperatures are generally assumed to be critical for screened inlets. This appears to be the case, especially with large droplet sizes. Current test results show, however, that this is not necessarily true. The very fine mesh outer screen was very quickly closed off by a layer of glaze ice. Any runback was then apparently shed externally.

The effect of slot configuration was evaluated by testing two different screen sizes. The larger screen was designed to minimize slot losses under icing conditions and maximize droplet separation efficiency. It was clearly the better screen.

Since, on a two-engine helicopter, power demands per engine are relatively low, the 34°F maximum TOT temperature rise allows sufficient margin to assure adequate engine performance throughout the flight envelope.

To check if remelting of ice accumulations acquired during an inadvertent icing encounter would affect engine performance, a test point equivalent to run 5A was flown. After landing, the iced up engine was kept running at 40 percent torque levels while the inlet was deiced using a portable heater. No adverse engine reactions were observed.

8. REFERENCES.

1. Federal Aviation Administration "Certification of Transport Category Rotorcraft," Advisory Circular AC-29-2A paragraph 532.

2. Federal Aviation Regulations Part 29 paragraph 1093 (b)(1)(i)

3. Federal Aviation Regulation Part 25, Appendix C

4. Leigh Instrument LTD "Operational Manual, MK12B Ice Detector System IDU-3B," Careton Place, Ontario, Canada.

5. "Spray Nozzle and Accessories," Industrial Catalog 27, Spraying Systems CO., North Avenue at Scmale Road, Wheaton, IL.

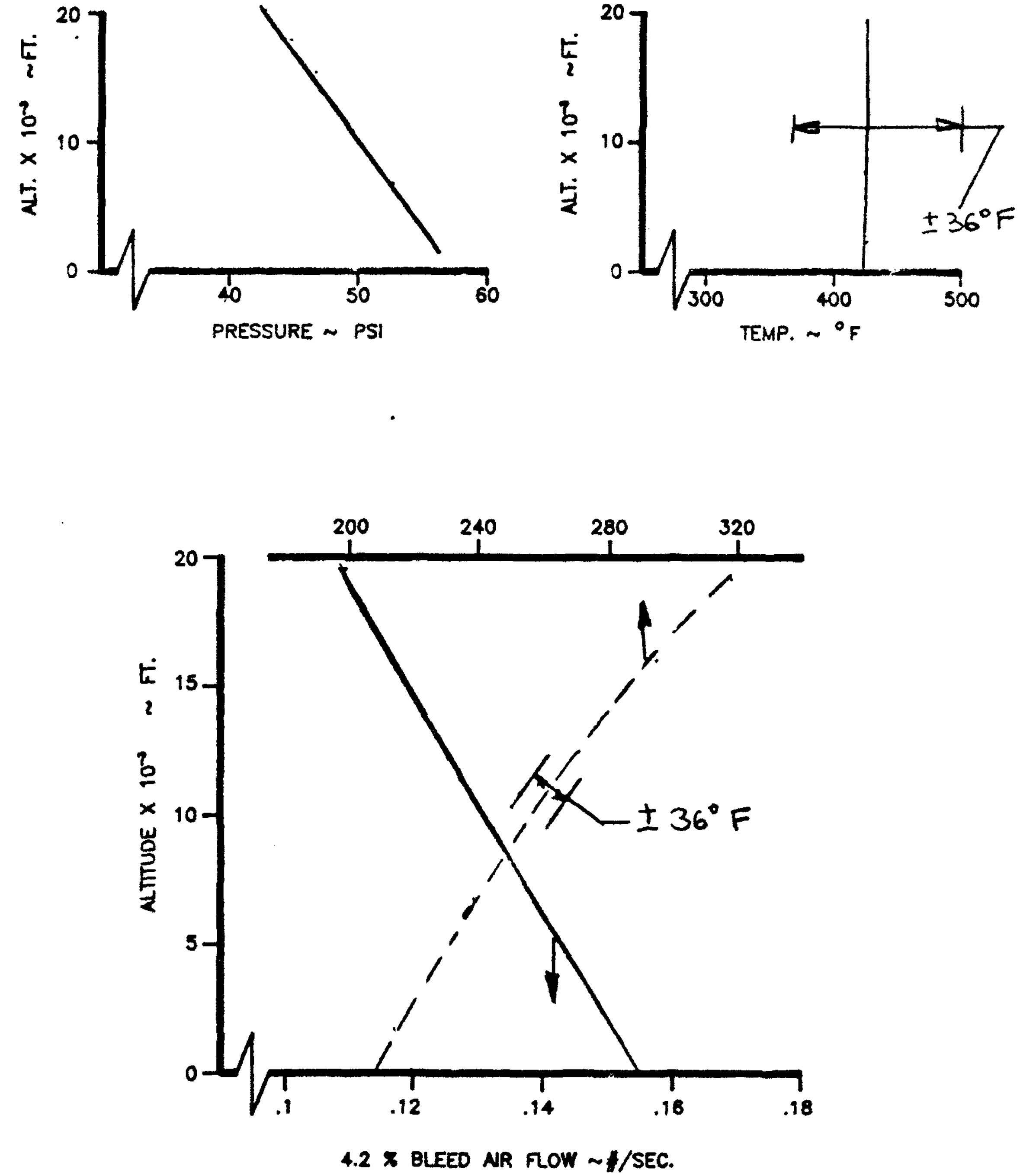


Figure 1. Available Bleed Air per Engine at 60 KIAS - 4.2% Bleed, Std. Day.

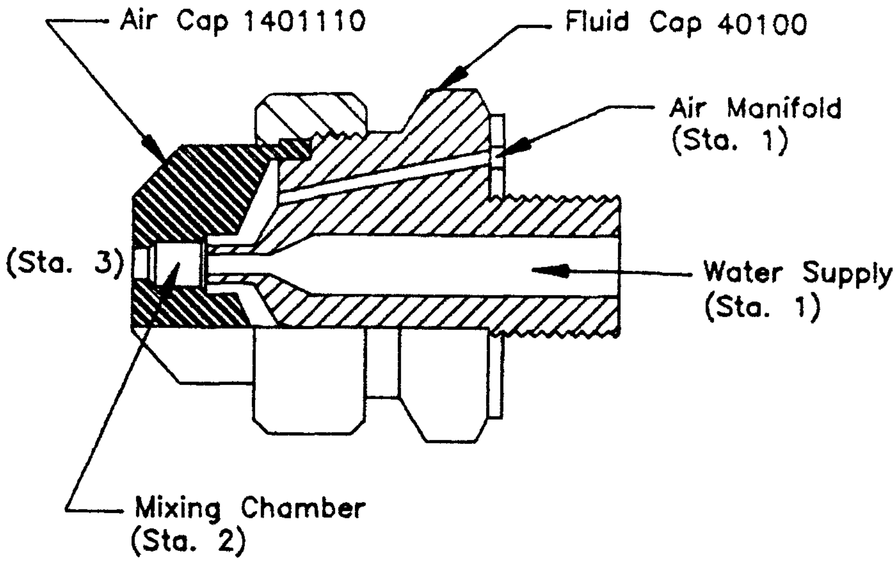


Figure 2. Spray Nozzle

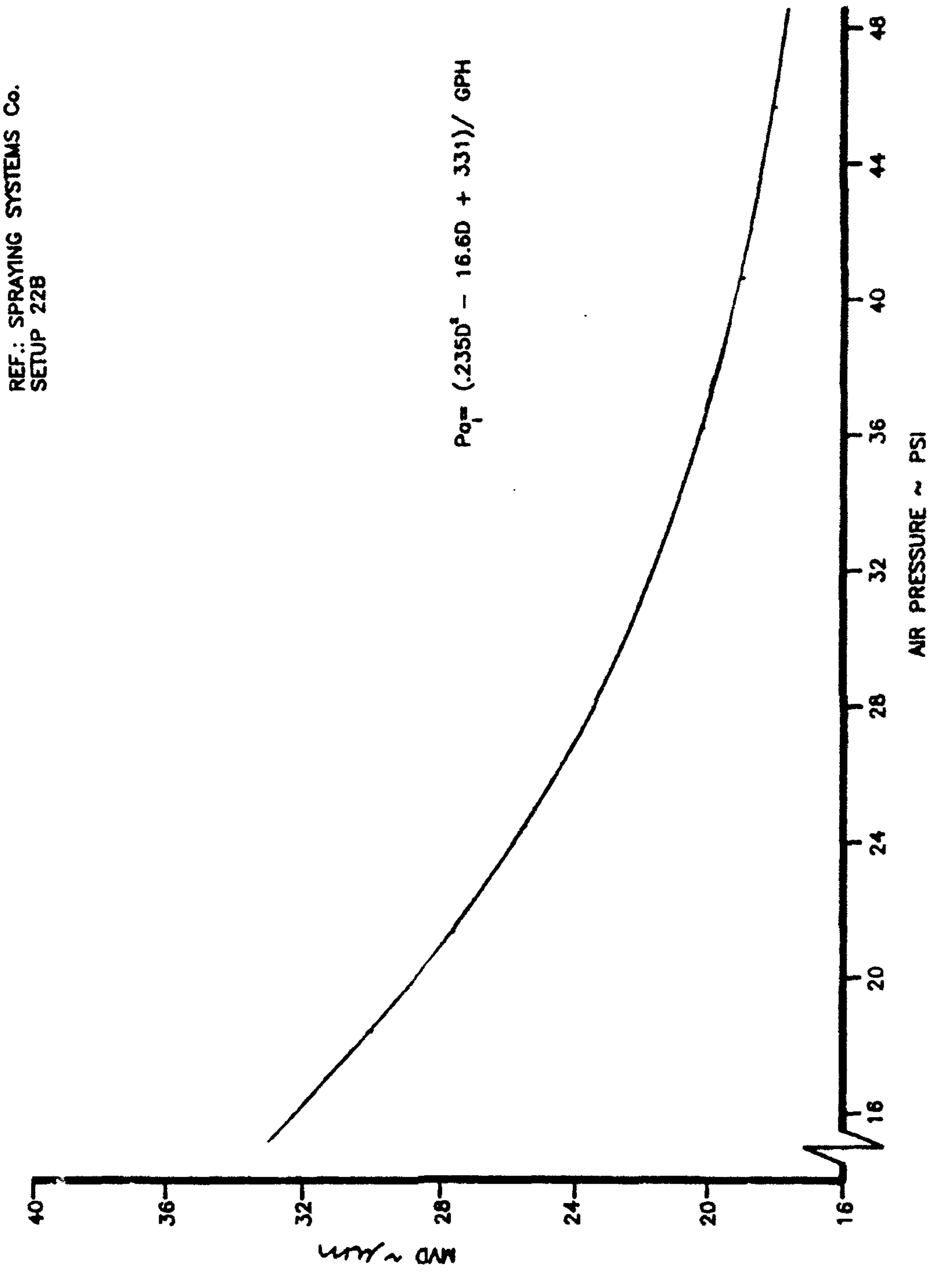


Figure 3. Spray Nozzle Performance (GPH = 2.5)

```
5 CLS
10 REM          ICE TEST RIG EVALUATION
20 REM
30 REM X=INDEX ON AIR SUPPLY PRESSURE            (PA1)      (MAX=N)
40 REM Y=INDEX ON NUMBER OF STEPS (JET PATH)                (MAX=M)
50 REM
60 REM *************** INITIAL CONDITIONS *******************************
70 REM
80 INPUT"WATER FLOW RATE PER NOZZLE                         [GPH]       =";GPH
90 INPUT"INITIAL WATER TEMPERATURE            (RAKE)        [DEG F]     =";TO
100 INPUT"INITIAL BLEED AIR TEMPERATURE       (RAKE)        [DEG F]     =";TA1
110 INPUT"AIRSPEED                                          [KIAS]      =";VO
130 INPUT"DISTANCE TO TARGET                                [INCHES]    =";XF
140 INPUT"WATER DROPLET SIZE                                [MICRONS]   =";D
150 INPUT"PRESSURE ALTITUDE                                 [FT]        =";HP
155 INPUT"OAT                                               [DEG F]     =";OAT
160 N=1
170 M=100
175 DIM E(M+2,11)
180 RC=.9                       :REM TEMPERATUR RECOVERY FACTOR AT STA 2
190 DPA1=10                     :REM AIR SUPPLY PRESSURE INCREMENTS
200 RX=53.3                     :REM GAS CONSTANT (AIR)
210 CP=.24                      :REM SPECIFIC HEAT (AIR)
220 PO=30                       :REM STARTING AIR SUPPLY PRESSURE
230 ROH=62.4                    :REM WATER DENSITY
240 VIS=3.5E-07                 :REM AVERAGE AIR VISCOSITY
250 PR=.71                      :REM PRANDL NUMBER
260 K=1.4
270 KH=.0273
280 G=32.2
285 K1=18*3.5E-07/(ROH*3.2808E-06^2)
286 E1=2.7183
290 REM
300 REM ***************** NOZZLE DIMENSIONS ********************************
310 REM *                                                                   *
311 REM * THE NOZZLE USED FOR THIS PROGRAM WAS OF THE INTERNAL MIX TYPE     *
312 REM *     AND WAS MANUFACTURED BY THE SPRAYING SYSTEMS COMPANY          *
313 REM *                         SETUP  22B                                *
314 REM *********************************************************************
320 D1=.04                          :REM WATER PASSAGE EXIT DIAMETER     (STA 2)
330 D2=.1                           :REM AIR ANNULUS INNER DIAMETER      (STA 2)
340 D3=.14                          :REM AIR ANNULUS OUTER DIAMETER      (STA 2)
350 D4=.11                          :REM NOZZLE EXIT DIAMETER            (STA 3)
360 A1=(.7854*D1^2)/144             :REM WATER NOZZLE EXIT AREA          (STA 2)
370 A2=(.7854*(D3^2-D2^2))/144      :REM AIR NOZZLE EXIT AREA            (STA 2)
380 A3=(.7854*D4^2)/144             :REM COMBINED NOZZLE EXIT AREA       (STA 3)
390 REM
400 REM ****************** CALCULATIONS OF NOZZLE EXIT CONDITIONS **********
410 REM
420 THET=1-HP*6.875E-06
430 DELT=THET^5.2561
440 SIGMA=THET^4.2561
450 VR=VO*1.688/SQR(SIGMA)
460 P2=2116*DELT
470 A=2*G*K/(K-1)
```

Figure 4. Code to calculate droplet impact conditions, Sheet 1 of 3.

```
480 C1=2/K
490 C2=(K-1)/K
500 T=TA1+460
505 TA=OAT+460
510 PA1=PO
520 WW=8.345*GPH/3600
530 VW2=WW/(ROH*A1)
531       LPRINT"                    ICE RIG EVALUATION - PATH"
532       LPRINT
535      LPRINT"X","V[DRPLT]","T[DRPLT]","VA[DELTA]"
536      LPRINT"[INCHES]","[KIAS]","[DEG F]","[KIAS]"
540 FOR X=1 TO N
550   PA1=PA1+DPA1
560   PW1=.572*PA1+2.56*GPH-7.4
570   PW=PW1*144+P2
580   PC=PW-((WW/A1)^2)/(2*G*ROH)
590   P1=PA1*144+P2
600   R=PC/P1
610   TA2=T*(1-RC*(1-R^C2))
620   WA=.7*P1*A2*SQR((A*R^C1/(RX*T))*(1-R^C2))
630   CFM=WA*RX*TA2*60/P2
640   VA2=SQR(A*RX*T*(1-R^C2))
650   M2=VA2/(49.1*SQR(T))
660   REM
670   REM LET TA2=TA3 (CONSERVATIVE FOR IMPACT TEMPERATURES)
680   REM
690   VA3=WA*TA2*RX/(PC*(A3-A1))
695  GOSUB 3000
700  E(X,5)=PA1
705  E(X,6)=PW1
710  E(X,7)=VA3
720  E(X,8)=VWI
730  E(X,9)=TWI
735  E(X,10)=CFM
740 NEXT X
800 OPEN "LPT1:"AS #1
805 PRINT#1,
810 REM PRINT#1,"                    ICE TEST RIG EVALUATION"
820 PRINT#1,
830 PRINT#1,"WATER FLOW RATE PER NOZZLE                  [GPH]       =";GPH
840 PRINT#1,"INITIAL WATER TEMPERATURE AT RAKE           [DEG F]     =";TO
850 PRINT#1,"INITIAL BLEED AIR TEMPERATURE AT RAKE       [DEG F]     =";TA1
860 PRINT#1,"AIRSPEED                                    [KIAS]      =";VO
880 PRINT#1,"DISTANCE TO TARGET                          [INCHES]    =";XF
890 PRINT#1,"PRESSURE ALTITUDE                           [FT]        =";HP
900 PRINT#1,"OAT                                         [DEG F]     =";OAT
910 PRINT#1,"WATER DROPLET SIZE                          [MICRONS]   =";D
920 PRINT#1,
930 PRINT#1,"PA1","PW1","VA[EXIT]","CFM"
940 FOR S=1 TO N
950   PRINT#1,E(S,5),E(S,6),E(S,7),E(S,10)
960 NEXT S
970 PRINT#1,
980 PRINT#1,"PA1","V[IMPACT]","T[IMPACT]"
990 FOR S=1 TO N
```

Figure 4. Code to calculate droplet impact conditions, Sheet 2 of 3.

```
1000   PRINT#1,E(S,5),(E(S,8)*SQR(SIGMA)/1.688),(E(S,9)-460)
1010 NEXT S
1020 END
3000 REM
3010 REM ***************** ROUND JET TRAJECTORY *****************************
3020 REM
3030 B1=.174533*B
3040 V=VA3
3060 DX=XF/M
3070 FOR S=1 TO M
3080  U=1
3120  S1=S1+DX
3130  KJ=1
3150  KJ=6*D4/S1
3160  IF KJ>1 THEN KJ=1
3170  IF KJ>1 THEN KJ1=1 ELSE KJ1=5*KJ/6
3180  TJ=KJ1*(TA2-TA)+TA                          :REM JET CORE TEMPERATURE
3190  VAJ=KJ*(VA3-VR)+VR                          :REM JET CORE VELOCITY (MAX)
3240  E(S,0)=S1
3250  E(S,1)=VAJ
3255  E(S,2)=TJ
3270 NEXT S
3271 V=VA3
3272 S1=0
3273 TJ=TA2
3280 REM
3290 REM ************** WATER DROPLET VEL.& TEMP **************************
3300 REM
3310 REM
3320 E(0,1)=VA3-VR            :REM NOZZLE EXIT VELOCITY OF AIR
3330 E(0,2)=TA2               :REM NOZZLE EXIT TEMPERATURE OF AIR
3340 E(0,3)=VW2               :REM NOZZLE EXIT VELOCITY OF WATER
3350 E(0,4)=T0+460            :REM NOZZLE EXIT TEMPERATURE OF WATER
3360 FOR S=1 TO M
3370  BJ=K1*E(S,0)/D^2
3380  CJ=E(S-1,3)^2+BJ*(E(S,1)+E(S-1,1)-E(S-1,3))
3390  E(S,3)=.5*(-BJ+SQR(BJ^2+4*CJ))              :REM VW=DROPLET VELOSITY AT S
3400  VARW=(E(S,1)+E(S-1,1)-E(S,3)-E(S-1,3))/2    :REM AVERAGE DIFFERENCE IN VEL
3410  TAJ=(E(S-1,2)+E(S,2))/2                     :REM AVERAGE JET CORE TEMP.
3420  RN=(P2/TAJ)*ABS(VARW)*D/183.1               :REM AVERAGE REYNOLDS NUMBER
3430  NU=2+(.4*RN^(1/2)+.06*RN^(2/3))*PR^.4       :REM AVERAGE PRANDL NUMBER
3440  HC=4!*NU/D                                  :REM AVERAGE FILM COEFFICIENT
3450  VWA=(E(S,3)+E(S-1,3))/2                     :REM AVERAGE JET CORE VELOCITY
3460  TT=DX/VWA                                   :REM TIME REQIRED TO TRAV. DX
3470  L=29322*HC*TT/D
3475  IF L>80 THEN L=80
3480  E(S,4)=(E(S-1,4)-TAJ)*E1^(-L) +TAJ          :REM IMPACT TEMPERATURE
3481 PRINT E1,E1^(-L),E(S-1,4)-TAJ,HC
3482  VWI=E(S,3)
3488  TWI=E(S,4)
3489 LPRINT E(S,0),(VWI*SQR(SIGMA)/1.688),(TWI-460),(VARW*SQR(SIGMA)/1.688)
3490 NEXT S
3500 RETURN
```

Figure 4. Code to calculate droplet impact conditions, Sheet 3 of 3.

ICE RIG EVALUATION - PATH

X (INCHES)	V(DRPLT) (KIAS)	T(DRPLT) (DEG F)	VA(DELTA) (KIAS)
.84	59.84319	144.8601	263.8968
1.68	88.08549	92.9057	155.329
2.52	100.0037	59.54901	55.5628
3.36	104.5867	47.17063	17.43
4.2	104.3653	40.92877	-.6879428
5.04	100.9033	35.95783	-6.806996
5.88	95.52702	32.85324	-11.21811
6.720001	89.43914	30.66956	-10.46642
7.560001	83.62683	29.02826	-8.31089
8.400001	78.71036	27.74457	-5.934724
9.240001	74.88055	26.71121	-3.976306
10.08	72.00606	25.86029	-2.616312
10.92	69.83205	25.14658	-1.763785
11.76	68.12875	24.53912	-1.248089
12.6	66.74041	24.01575	-.9282106
13.44	65.57326	23.56024	-.7176945
14.28	64.57107	23.16025	-.5705069
15.12	63.6977	22.80625	-.4627868
15.96	62.92807	22.49072	-.3814021
16.8	62.24375	22.20773	-.3184703
17.64	61.63067	21.95255	-.2689126
18.48	61.07786	21.72119	-.2292804
19.32	60.57656	21.5105	-.1971725
20.16	60.11969	21.31784	-.1708473
21	59.70147	21.14093	-.1490514
21.84	59.31706	20.978	-.1308447
22.68	58.96247	20.82739	-.1155029
23.52	58.63429	20.68778	-.1024929
24.36	58.32961	20.55798	-9.137926E-02
25.2	58.04598	20.43707	-8.181608E-02
26.04	57.78124	20.32407	-7.354698E-02
26.88	57.53359	20.21826	-6.637255E-02
27.72	57.30133	20.11902	-6.009341E-02
28.56	57.08312	20.0257	-5.458339E-02
29.4	56.87769	19.93781	-4.974076E-02
30.24	56.68391	19.85486	-.0454475
31.08	56.50087	19.77649	-.0416385
31.92001	56.32764	19.7023	-3.824866E-02
32.76	56.16346	19.63196	-3.520879E-02
33.6	56.00765	19.56519	-.0324904
34.44	55.85955	19.50174	-.0300406
35.28	55.71863	19.44138	-2.783089E-02
36.12	55.58438	19.38382	-2.584094E-02
36.96	55.4563	19.32895	-2.403411E-02
37.8	55.33399	19.27655	-2.238599E-02
38.64	55.21709	19.22641	-2.088843E-02
39.48	55.10521	19.17847	-1.952517E-02
40.32	54.99805	19.13254	-1.827992E-02
41.16	54.8953	19.0885	-1.713234E-02
42.00001	54.79673	19.04623	-1.607429E-02
42.84001	54.70206	19.00568	-.0151139
43.68001	54.61106	18.96671	-1.422676E-02
45.36001	54.43924	18.8731	-1.264375E-02
46.20001	54.35809	18.85831	-1.193973E-02
47.04001	54.27986	18.8248	-1.128049E-02
47.88001	54.20438	18.79245	-1.067821E-02
48.72001	54.13154	18.76123	-1.011663E-02
49.56001	54.06115	18.73114	-9.587599E-03
50.40001	53.99317	18.70197	-9.107406E-03
51.24001	53.92742	18.67383	-8.659767E-03
52.08001	53.86378	18.64658	-8.228406E-03
52.92001	53.8022	18.62021	-7.829602E-03
53.76001	53.74255	18.5947	-7.455213E-03
54.60001	53.68474	18.56992	-7.105241E-03
55.44001	53.62869	18.5459	-6.767478E-03
56.28001	53.57434	18.52268	-6.454131E-03
57.12001	53.52159	18.50009	-6.173339E-03
57.96001	53.47037	18.47818	-5.900687E-03
58.80001	53.42064	18.45686	-5.648382E-03
59.64001	53.37228	18.43619	-5.400146E-03
60.48001	53.32533	18.41608	-5.176327E-03
61.32001	53.27961	18.39652	-4.964716E-03
62.16001	53.23519	18.37753	-4.761244E-03
63.00001	53.19187	18.35901	-4.557772E-03
63.84001	53.14981	18.341	-4.374648E-03
64.68001	53.10874	18.32346	-.0042078
65.52001	53.06881	18.3064	-4.036884E-03
66.36	53.02986	18.28973	-3.890384E-03
67.2	52.99188	18.2735	-3.735745E-03
68.04	52.95485	18.25766	-3.589246E-03
68.87999	52.91873	18.24222	-3.459023E-03
69.71999	52.88351	18.22714	-3.345079E-03
70.55998	52.8491	18.21243	-3.231135E-03
71.39998	52.8155	18.19809	-3.109052E-03
72.23998	52.78268	18.18405	-2.995107E-03
73.07997	52.75061	18.17038	-2.881163E-03
73.91997	52.7193	18.15698	-2.775358E-03
74.75996	52.68869	18.14392	-.0026899
75.59996	52.65874	18.1311	-2.596302E-03
76.43996	52.62951	18.11862	-2.523052E-03
77.27995	52.60083	18.10638	-2.433525E-03
78.11995	52.57283	18.09442	-2.343997E-03
78.95995	52.54542	18.0827	-2.278886E-03
79.79995	52.51856	18.07123	-2.205636E-03
80.63994	52.49229	18.06003	-2.132386E-03
81.47994	52.46657	18.04904	-2.075414E-03
82.31993	52.44133	18.0383	-2.010303E-03
83.15993	52.41666	18.02771	-1.953331E-03
83.99992	52.39244	18.0174	-1.896359E-03

WATER FLOW RATE PER NOZZLE	(GPH)	= 2.5
INITIAL WATER TEMPERATURE AT RAKE	(DEG F)	= 85
INITIAL BLEED AIR TEMPERATURE AT RAKE	(DEG F)	= 250
AIRSPEED	(KIAS)	= 50
DISTANCE TO TARGET	(INCHES)	= 84
PRESSURE ALTITUDE	(FT)	= 7000
OAT	(DEG F)	= 17
WATER DROPLET SIZE	(MICRONS)	= 25

PA1	PW1	VA(EXIT)	CFM
40	21.88	664.1588	6.532487

PA1	V(IMPACT)	T(IMPACT)
40	52.39244	18.0174

Figure 5. Droplet Trajectory Calculations, MVD = 25

CE RIG EVALUATION - PATH

X [INCHES]	V[DRPLT] [KIAS]	T[DRPLT] [DEG F]	VA[DELTA] [KIAS]
.84	34.3581	146.7588	276.6393
1.68	52.19845	98.63892	186.0151
2.52	62.24992	68.27704	92.38322
3.36	69.08386	56.58417	54.05829
4.2	73.7838	50.31189	32.35418
5.04	76.84468	46.38144	18.51303
5.88	78.58034	43.69678	9.284528
6.720001	79.23455	41.785	3.109218
7.560001	79.02078	40.29089	-.9055682
8.400001	78.13728	38.8186	-3.345157
9.240001	76.77113	37.62149	-4.635059
10.08	75.09626	36.67215	-5.106703
10.92	73.26801	35.90766	-5.026865
11.76	71.4165	35.27756	-4.609947
12.6	69.64105	34.74698	-4.022409
13.44	68.00776	34.29251	-3.385265
14.28	66.5511	33.89777	-2.777769
15.12	65.2795	33.55094	-2.243706
15.96	64.18311	33.24329	-1.79983
16.8	63.24174	32.9682	-1.444989
17.64	62.43143	32.72052	-1.168287
18.48	61.72892	32.49619	-.955191
19.32	61.11391	32.29199	-.7913757
20.16	60.56983	32.10538	-.6645924
21	60.0837	31.93411	-.5652411
21.84	59.64549	31.77646	-.4861759
22.68	59.2475	31.63083	-.4222308
23.52	58.88374	31.49594	-.369731
24.36	58.54951	31.3707	-.3260557
25.2	58.24106	31.25403	-.2893086
26.04	57.95526	31.14517	-.258092
26.88	57.68954	31.04334	-.2313497
27.72	57.44175	30.94785	-.2082739
28.56	57.21004	30.85819	-.1882502
29.4	56.99281	30.7738	-.1707577
30.24	56.78872	30.69425	-.1554078
31.08	56.59655	30.61914	-.141879
31.92001	56.41525	30.5481	-.1298945
32.76	56.24391	30.48081	-.1192427
33.6	56.0817	30.41696	-.1097446
34.44	55.92789	30.35632	-.1012354
35.28	55.78183	30.29865	-9.359508E-02
36.12	55.64293	30.24375	-8.671568E-02
36.96	55.51067	30.19141	-8.049758E-02
37.8	55.38458	30.14142	-7.486343E-02
38.64	55.26422	30.09369	-6.974816E-02
39.48	55.14921	30.04804	-6.509271E-02
40.32	55.03918	30.0043	-6.084423E-02
41.16	54.93384	29.96243	-5.696198E-02
42.00001	54.83287	29.92227	-5.340733E-02
42.84001	54.73599	29.88373	-.0501477
43.68001	54.64297	29.84671	-4.714242E-02
45.36001	54.46759	29.77683	-4.102366E-02
46.20001	54.38483	29.74384	-3.946135E-02
47.04001	54.30511	29.71204	-3.727403E-02
47.88001	54.22827	29.6814	-3.524948E-02
48.72001	54.15415	29.65183	-.0333694
49.56001	54.08261	29.62326	-3.162158E-02
50.40001	54.0135	29.5957	-2.999584E-02
51.24001	53.94671	29.56906	-2.847183E-02
52.08001	53.88214	29.54328	-.0270577
52.92001	53.81966	29.51831	-.0257331
53.76001	53.75918	29.49414	-2.449396E-02
54.60001	53.70058	29.47077	-.0233362
55.44001	53.64381	29.44812	-2.224559E-02
56.28001	53.58875	29.42612	-.0212262
57.12001	53.53536	29.40479	-2.026581E-02
57.96001	53.48354	29.3841	-1.936646E-02
58.80001	53.43321	29.36398	-1.852002E-02
59.64001	53.38433	29.34445	-1.771427E-02
60.48001	53.33685	29.3255	-1.696142E-02
61.32001	53.29067	29.30704	-1.625334E-02
62.16001	53.24575	29.28909	-1.557374E-02
63.00001	53.20206	29.27164	-1.493484E-02
63.84001	53.15954	29.25467	-1.433664E-02
64.68001	53.11814	29.23813	-1.377098E-02
65.52001	53.0778	29.22202	-1.322568E-02
66.36	53.03852	29.20633	-1.271293E-02
67.2	53.00022	29.19104	-1.223274E-02
68.04	52.96287	29.17615	-1.176475E-02
68.87999	52.92646	29.16159	-1.133339E-02
69.71999	52.89092	29.1474	-1.091831E-02
70.55998	52.85624	29.13358	-1.051136E-02
71.39998	52.82241	29.12006	-1.013697E-02
72.23998	52.78934	29.10687	-9.778863E-03
73.07997	52.75705	29.094	-9.428891E-03
73.91997	52.72552	29.08136	-9.103336E-03
74.75996	52.69469	29.06906	-8.798128E-03
75.59996	52.66454	29.05704	-8.496989E-03
76.43996	52.63507	29.04529	-8.216198E-03
77.27995	52.60626	29.03378	-7.943546E-03
78.11995	52.57807	29.02252	-7.687171E-03
78.95995	52.55049	29.01151	-7.438935E-03
79.79995	52.52348	29.00076	-7.198838E-03
80.63994	52.49703	28.99021	-6.962811E-03
81.47994	52.47116	28.97989	-6.743061E-03
82.31993	52.4458	28.96976	-6.539589E-03
83.15993	52.42096	28.95984	-6.336117E-03
83.99992	52.39663	28.95014	-6.140784E-03

WATER FLOW RATE PER NOZZLE	[GPH]	= 2.5
INITIAL WATER TEMPERATURE AT RAKE	[DEG F]	= 85
INITIAL BLEED AIR TEMPERATURE AT RAKE	[DEG F]	= 250
AIRSPEED	[KIAS]	= 50
DISTANCE TO TARGET	[INCHES]	= 84
PRESSURE ALTITUDE	[FT]	= 7000
OAT	[DEG F]	= 28
WATER DROPLET SIZE	[MICRONS]	= 45

PAI	PWI	VA[EXIT]	CFM
40	21.88	664.1588	6.532487

PAI	V[IMPACT]	T[IMPACT]
40	52.39663	28.95014

Figure 6. Droplet Trajectory Calculations, MVD = 45

```
10 REM
20 REM "      ESTIMATED ICE RIG SETTINGS"
30 REM
40 CLS
50 INPUT"GRAMS OF WATER PER M^3                              [GRAM]    =";GR
70 INPUT"ICING CLOUD SIZE                                    [FT^2]    =";AC
80 INPUT"AIRSPEED                                            [KIAS]    =";V
90 INPUT"OAT                                                 [DEG F]   =";OAT
100 INPUT"ALTITUDE                                            [FT]      =";HP
110 INPUT"DESIRED DROPLET DIAMETER                            [MICRONS]=";D
115 INPUT"BLEED AIR TEMPERATURE                               [DEG F]   =";TA1
120 RG=53.3
130 K=1.4
140 G=32.2
141 D1=.04
143 D2=.1
145 D3=.14
147 D4=.11
150 THET=1-HP*6.875E-06
160 DELT=THET^5.2561
170 SIGMA=DELT*518/(460+OAT)
200 GPHT=.0455*GR*V*AC/SQR(SIGMA)
201 N=GPHT/2.5
205 GPH=2.5
210 PA1=(9.399999E-02*D^2-6.64*D+132.2)*GPH/2.5
220 PW1=.572*PA1+2.56*GPH-7.4
230 WA=.0766*SQR(SIGMA)*V*1.688*AC
240 P2=2116*DELT
250 A1=(.7854*D1^2)/144
260 A2=(.7854*D2^2)/144
270 A3=(.7854*D3^2)/144
280 A4=(.7854*D4^2)/144
290 P2=2116*DELT
300 A=2*G*K/(K-1)
310 C1=2/K
320 C2=(K-1)/K
330 T=460+TA1
340 WW=8.345*2.5/3600
350 PW=PW1*144+P2
355 P1=PA1*144+P2
360 PC=PW-((WW/A1)^2)/(G*62.3*2)
370 R=PC/P1
380 TA2=T*(1-.9*(1-R^C2))
390 WA1=.7*P1*A2*SQR((A*R^C1/(RG*T))*(1-R^C2))
400 CFM=WA1*RG*TA2*60*N/P2
2350 LPRINT
2400 LPRINT
2450 LPRINT" *************** TEST PARAMETERS *****************"
2500 LPRINT
2550 LPRINT"GRAMS OF WATER PER M^2                     [GRAM]     =";GR
2600 LPRINT"ESTIMATED ICING CLOUD SIZE                 [FT^2]     =";AC
2650 LPRINT"AIRSPEED                                   [KIAS]     =";V
2700 LPRINT"OAT                                        [DEG F]    =";OAT
2750 LPRINT"DROPLET SIZE                               [MICRONS]  =";D
2755 LPRINT"BLEED AIR RAKE TEMPERATURE                 [DEG F]    =";TA1
2800 LPRINT
2850 LPRINT
2900 LPRINT" *************** ICE RIG CONFIGURATION ************"
2950 LPRINT
3000 LPRINT"OPTIMUM NUMBER OF NOZZLES                             =";N
3100 LPRINT"BLEED AIR PRESSURE AT NOZZLE               [PSI]      =";PA1
3200 LPRINT"WATER SUPPLY PRESSURE AT NOZZLE            [PSI]      =";PW1
3210 LPRINT"WATER FLOW RATE                            [%]        =";(1.38*GPHT)
3300 LPRINT"FLOW RATE OF ICING CLOUD AT INLET          [#/SEC]    =";WA
3350 LPRINT"BLEED AIR FLOW REQUIRED                    [CFM]      =";CFM
3400 END
```

Figure 7. Design Code for Ice Rig

```
************** TEST PARAMETERS ****************

GRAMS OF WATER PER M^2             [GRAM]      = 2.5
ESTIMATED ICING CLOUD SIZE         [FT^2]      = 6
AIRSPEED                           [KIAS]      = 100
OAT                                [DEG F]     = 17
DROPLET SIZE                       [MICRONS]   = 20
BLEED AIR RAKE TEMPERATURE         [DEG F]     = 250

************** ICE RIG CONFIGURATION ************

OPTIMUM NUMBER OF NOZZLES                      = 29.82291
BLEED AIR PRESSURE AT NOZZLE       [PSI]       = 36.99999
WATER SUPPLY PRESSURE AT NOZZLE    [PSI]       = 20.16399
WATER FLOW RATE                    [%]         = 102.889
FLOW RATE OF ICING CLOUD AT INLET  [#/SEC]     = 71.01745
BLEED AIR FLOW REQUIRED            [CFM]       = 191.0099
```

Figure 8. Typical Output from Design Code (Figure 7).

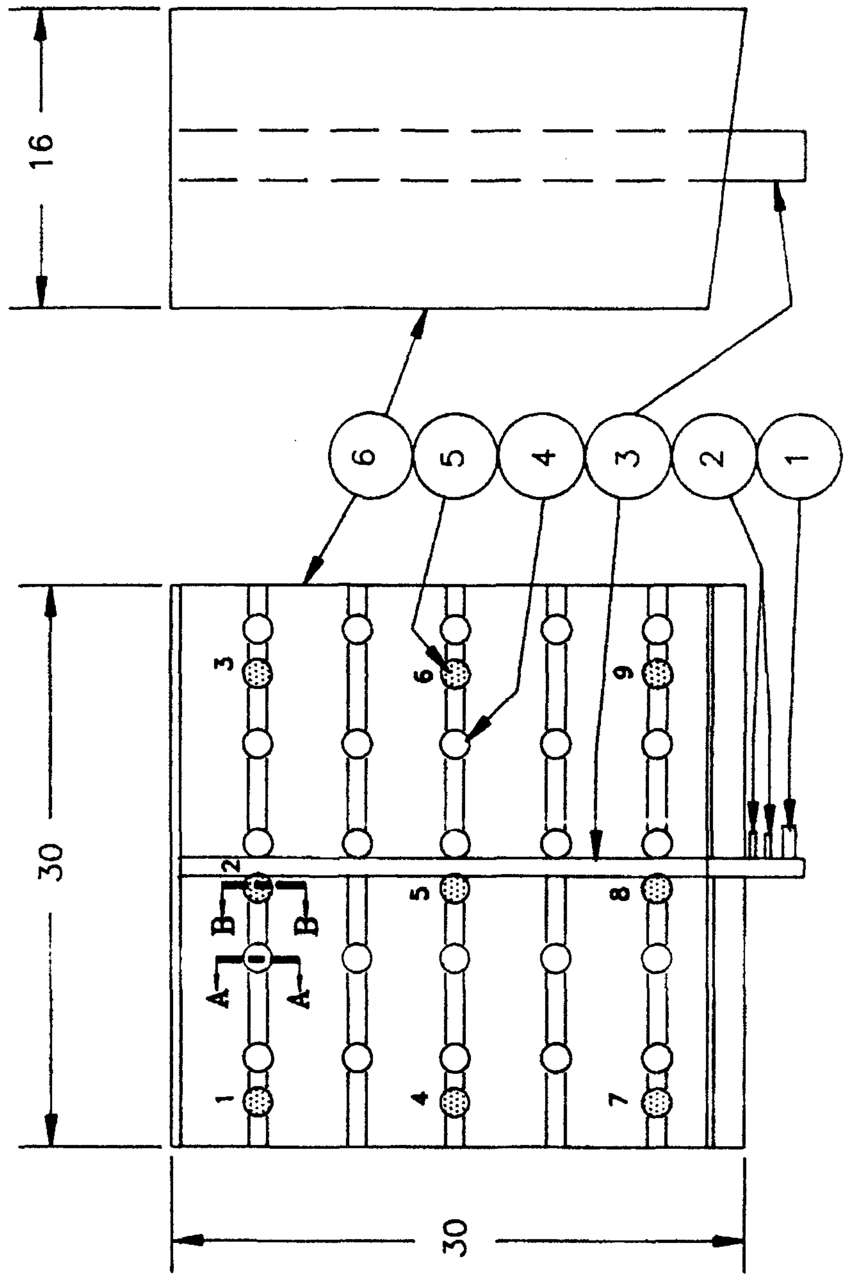
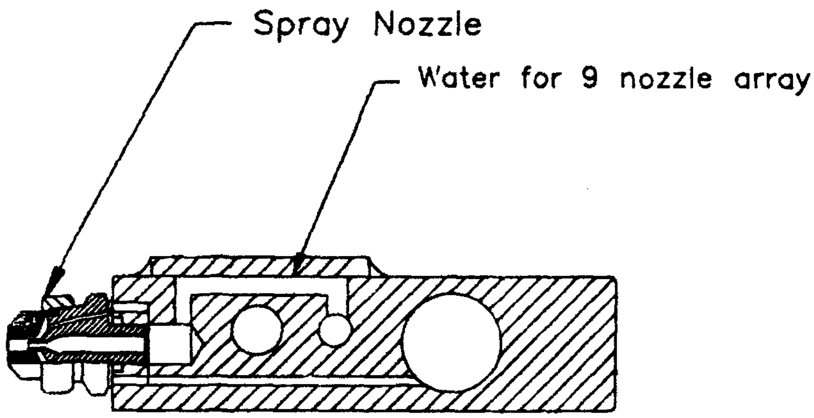
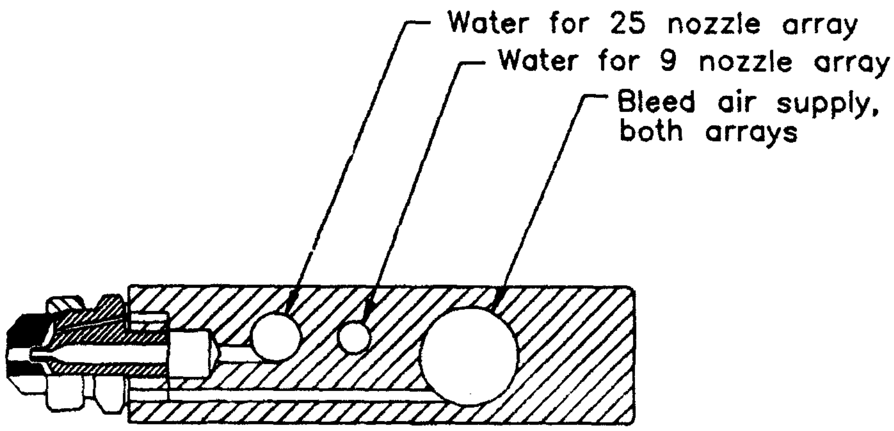


Figure 9. Spray Rake Configuration

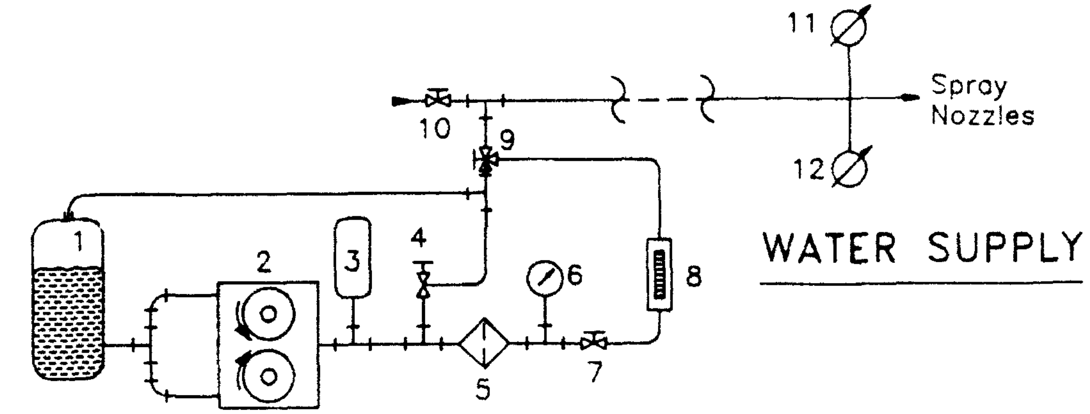


SECTION A-A

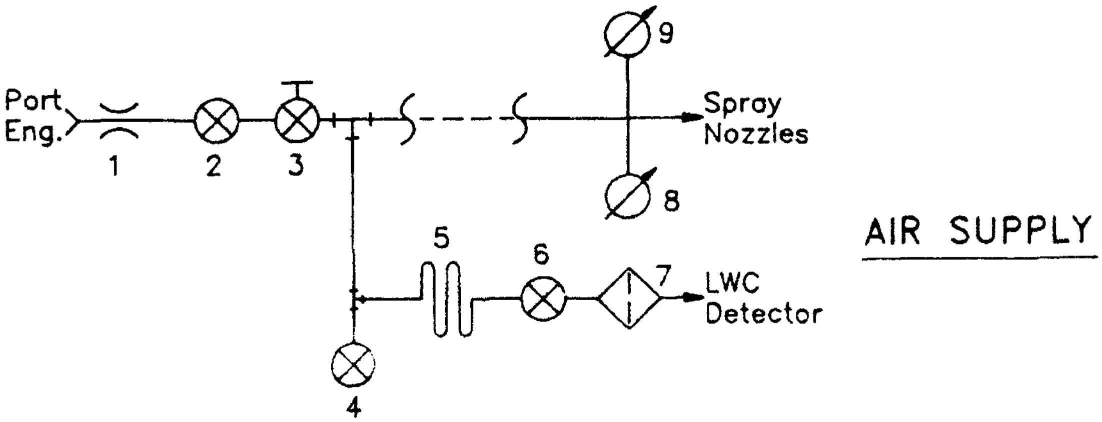


SECTION B-B

Figure 10. Nozzle Feed Details



1. 30 gallon ventilated water tank
2. Double-acting, variable, positive displacement water pump
3. Accumulator
4. Pressure relief valve
5. Water filter
6. Pressure guage
7. Metering valve
8. Flow meter
9. Three-way valve
10. Bleed-air shut-off valve
11. Thermocouple
12. Pressure pick-up



1. Bleed air orifice (d = 0.435 in.)
2. Bleed air shut-off
3. Bleed air control valve
4. Water trap
5. Cooling coils
6. Shut off valve
7. Filter for LWC meter (see inst. man.)
8. Thermocouple
9. Pressure pick-up

Figure 11. Test Equipment Schematic

* Patent Pending

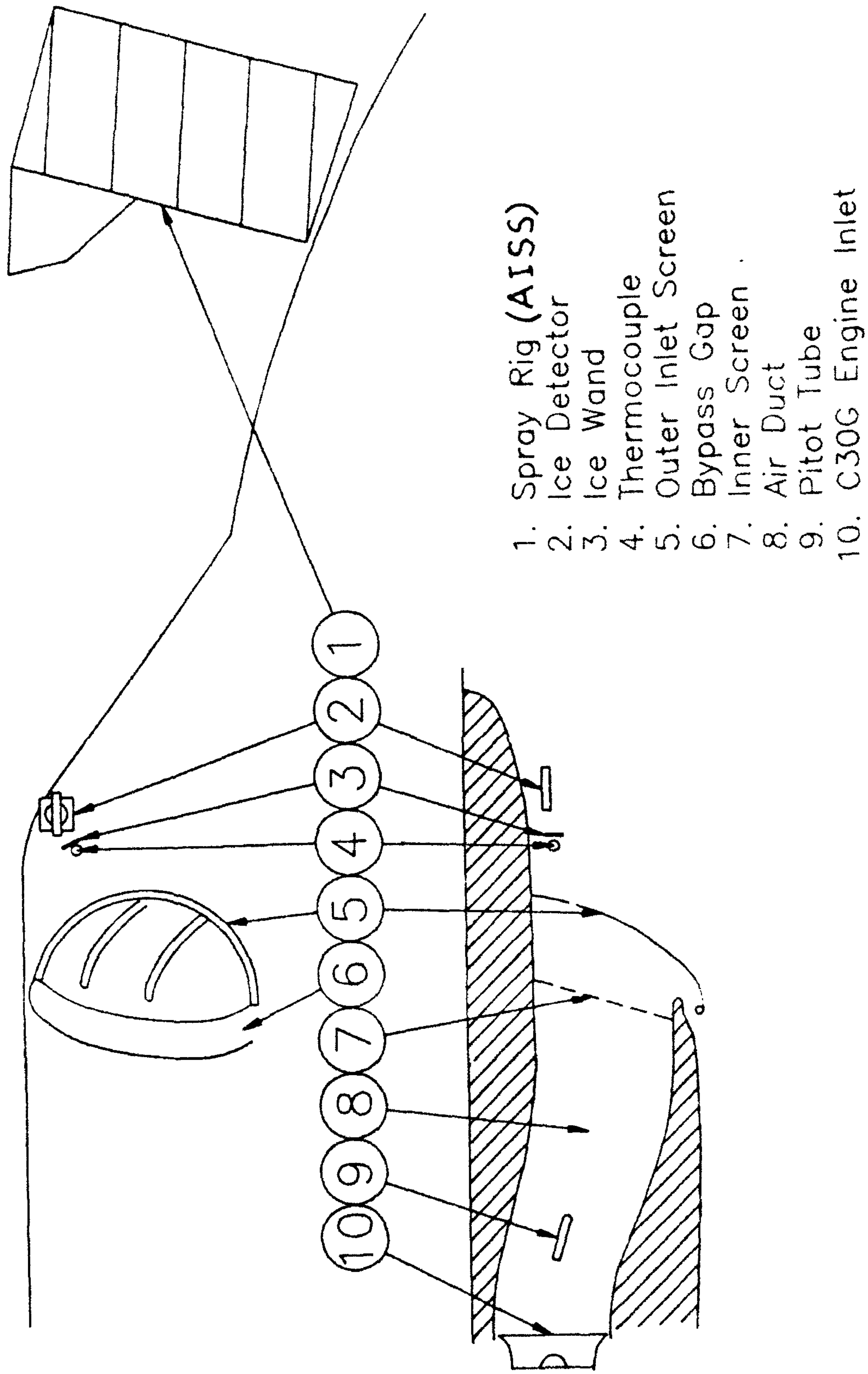


Figure 12. Test Aircraft Configuration and Set Up (Schematic)

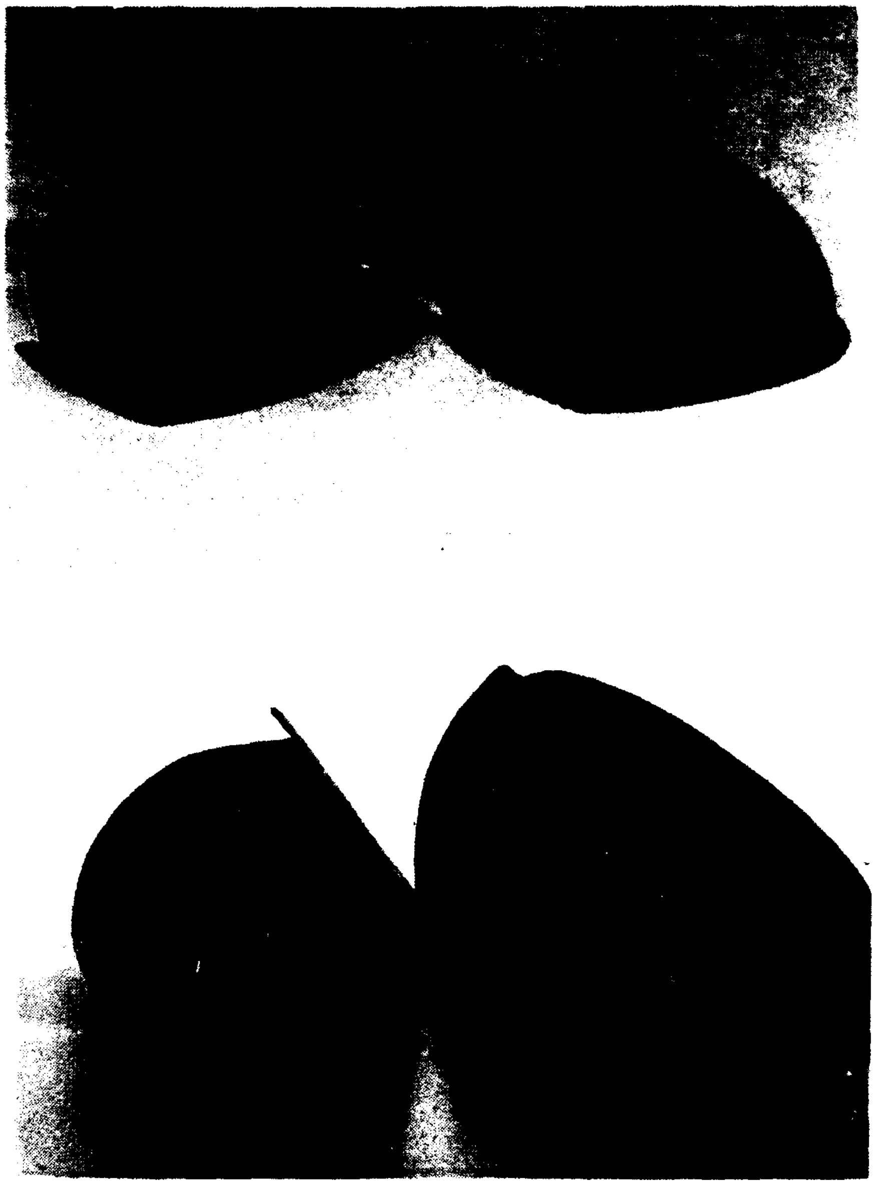


Figure 13. Inlet Screens

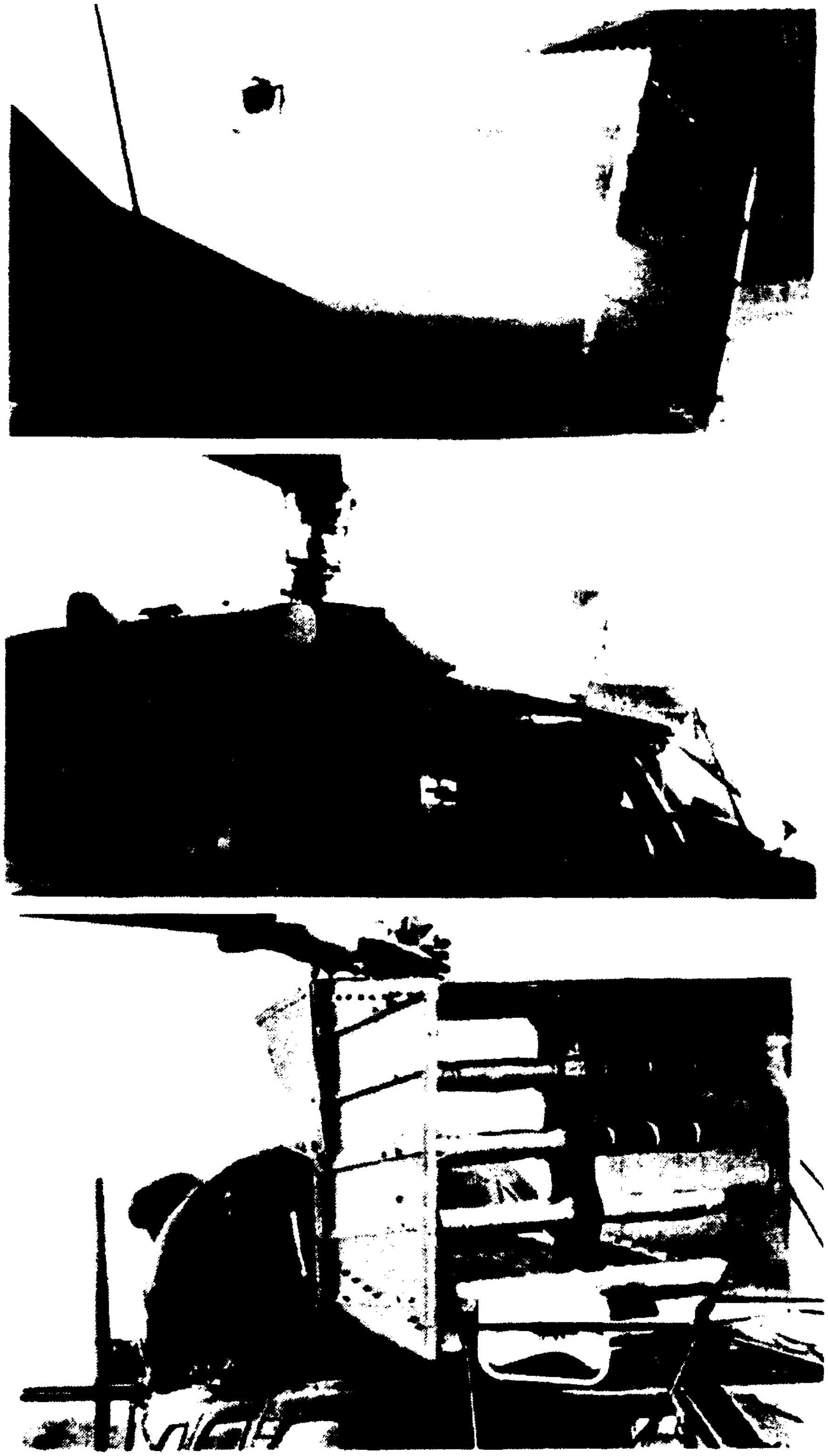


Figure 14. Test Aircraft Configuration Photos.
(Spray Rig)

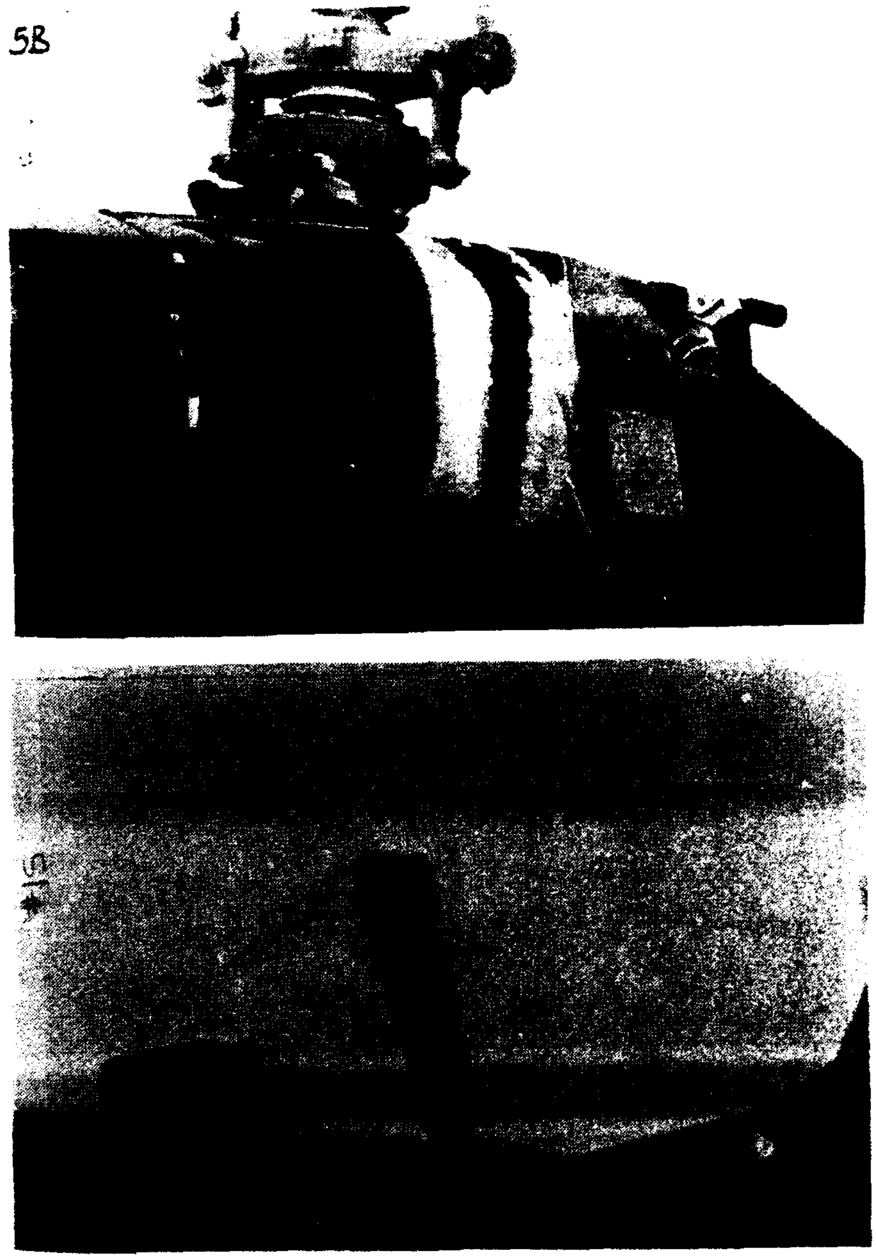


Figure 15. Test Aircraft Configuration Photos.
(Engine Inlet)

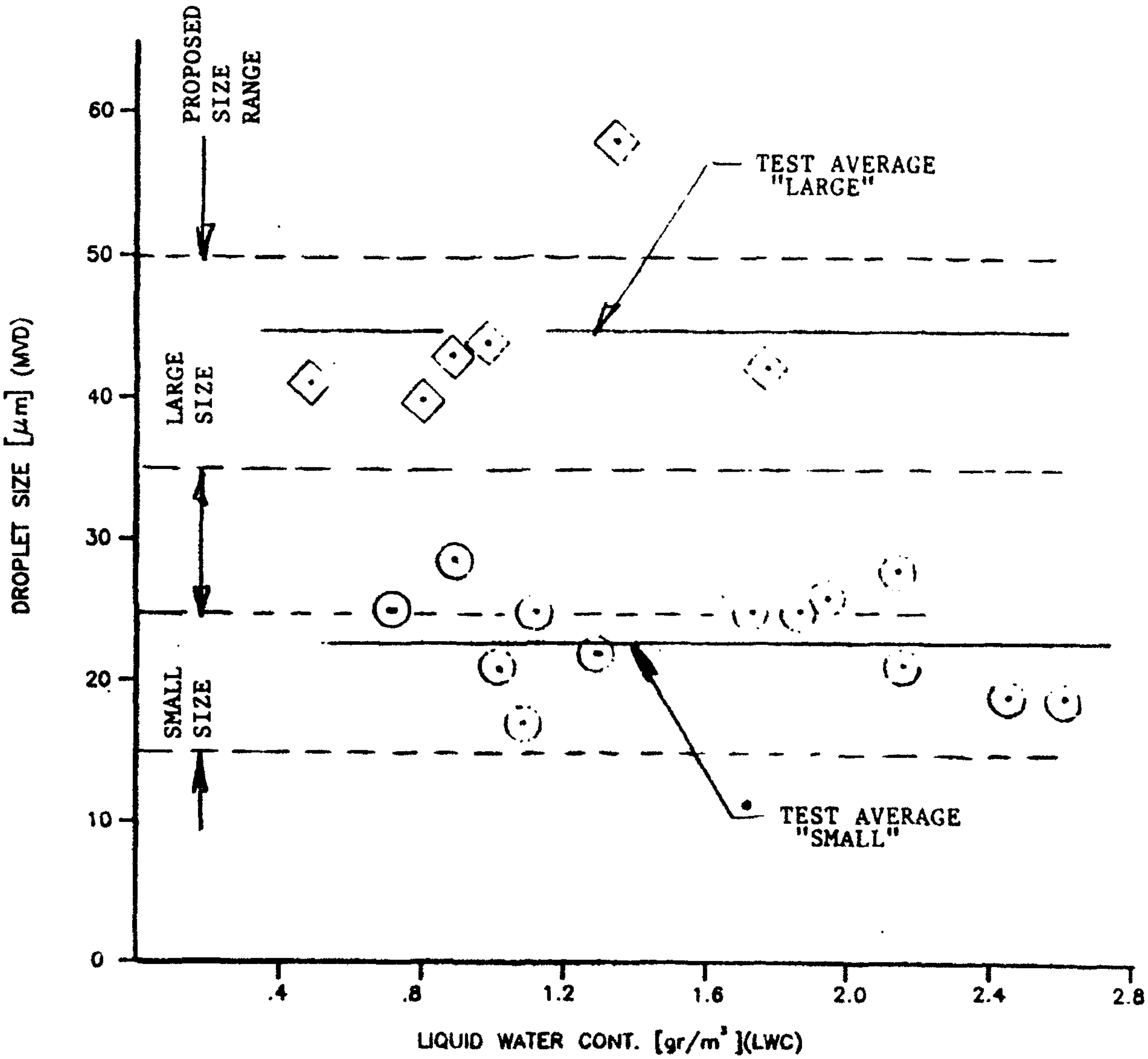
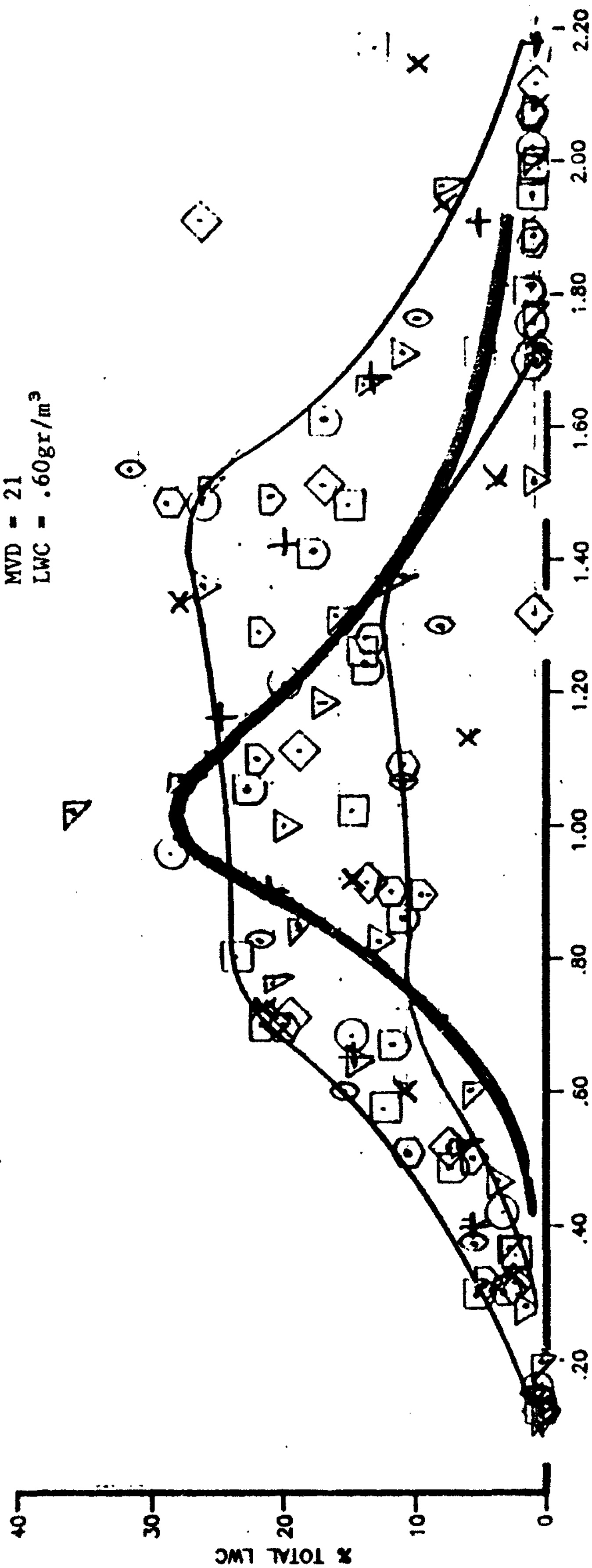


Figure 16. Actual Rake Performance



SYM	FRAME	MVD	LWC
○	FRAME #1	19 µm	2.6
□	FRAME #2	22 µm	1.3
◇	FRAME #3	25 µm	.7
▷	FRAME #4	28 µm	2.1
▽	FRAME #5	21 µm	1.0
	FRAME #10	26 µm	1.9
	FRAME #11	25 µm	1.1
	FRAME #12	25 µm	1.9
	FRAME #14	21 µm	2.2
	FRAME #15	17 µm	1.1
+	FRAME #16	20 µm	2.5
×	FRAME #17	26 µm	.71

Figure 17. Droplet Size Distribution

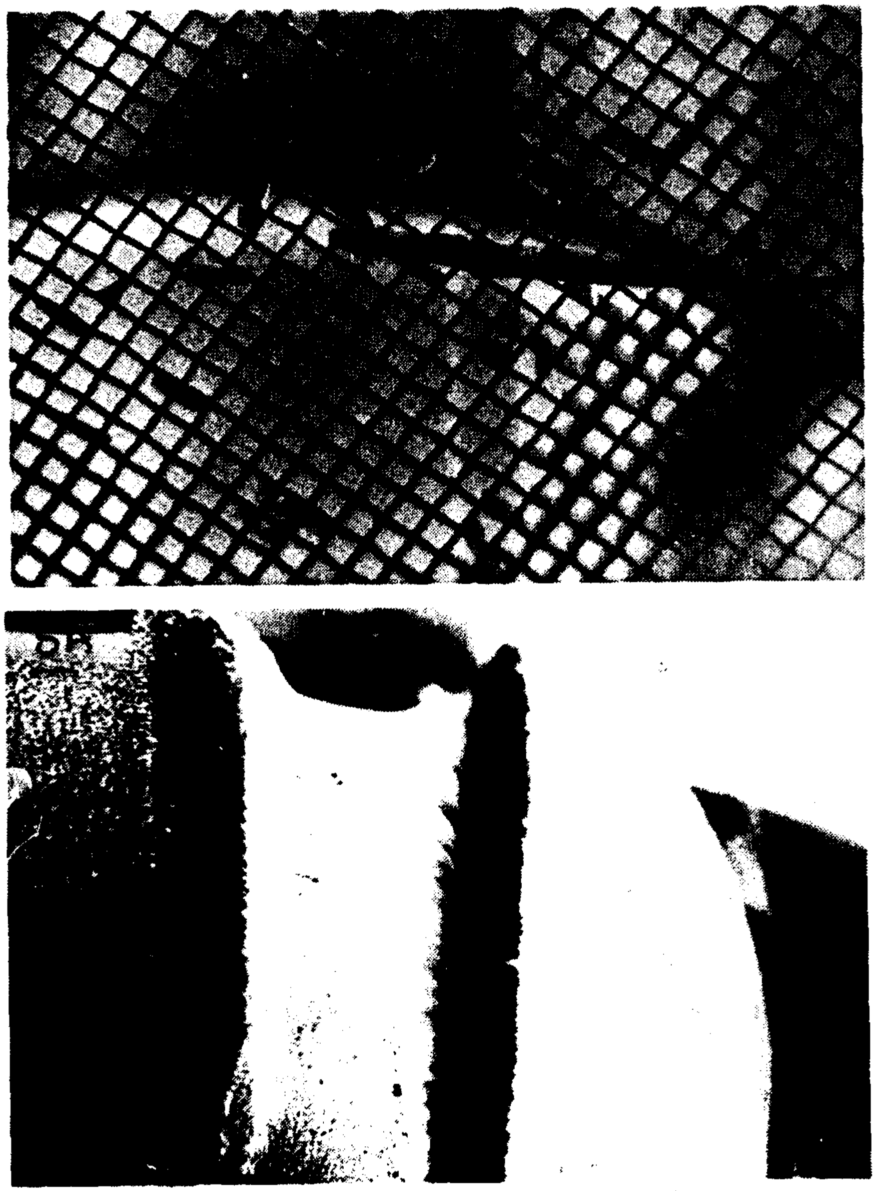


Figure 18. RUN 5A, Maximum Inlet Ice Build Up.
MVD = 26, KIAS = 50, OAT = 17°F

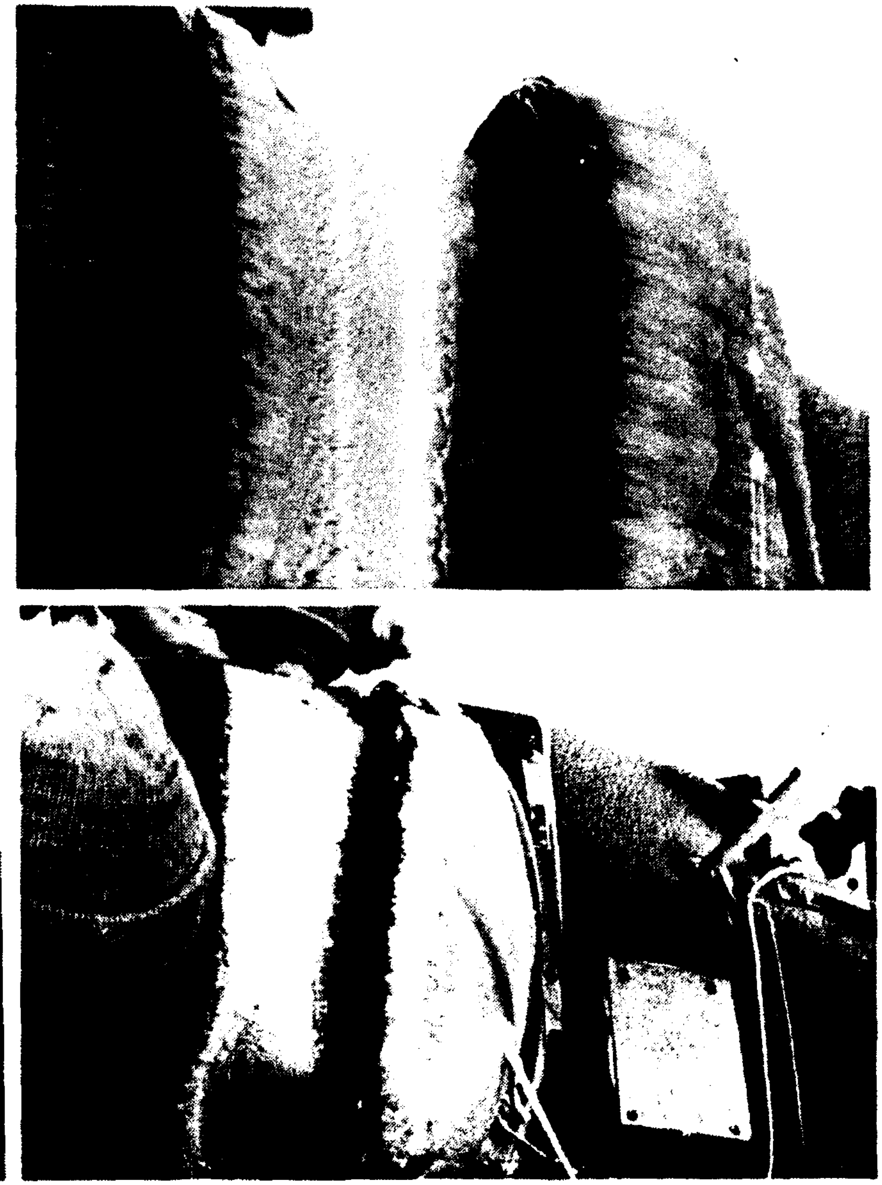


Figure 19. RUN 5B, Maximum Inlet Ice Build Up.
MVD = 26, KIAS = 100, OAT = 15°F

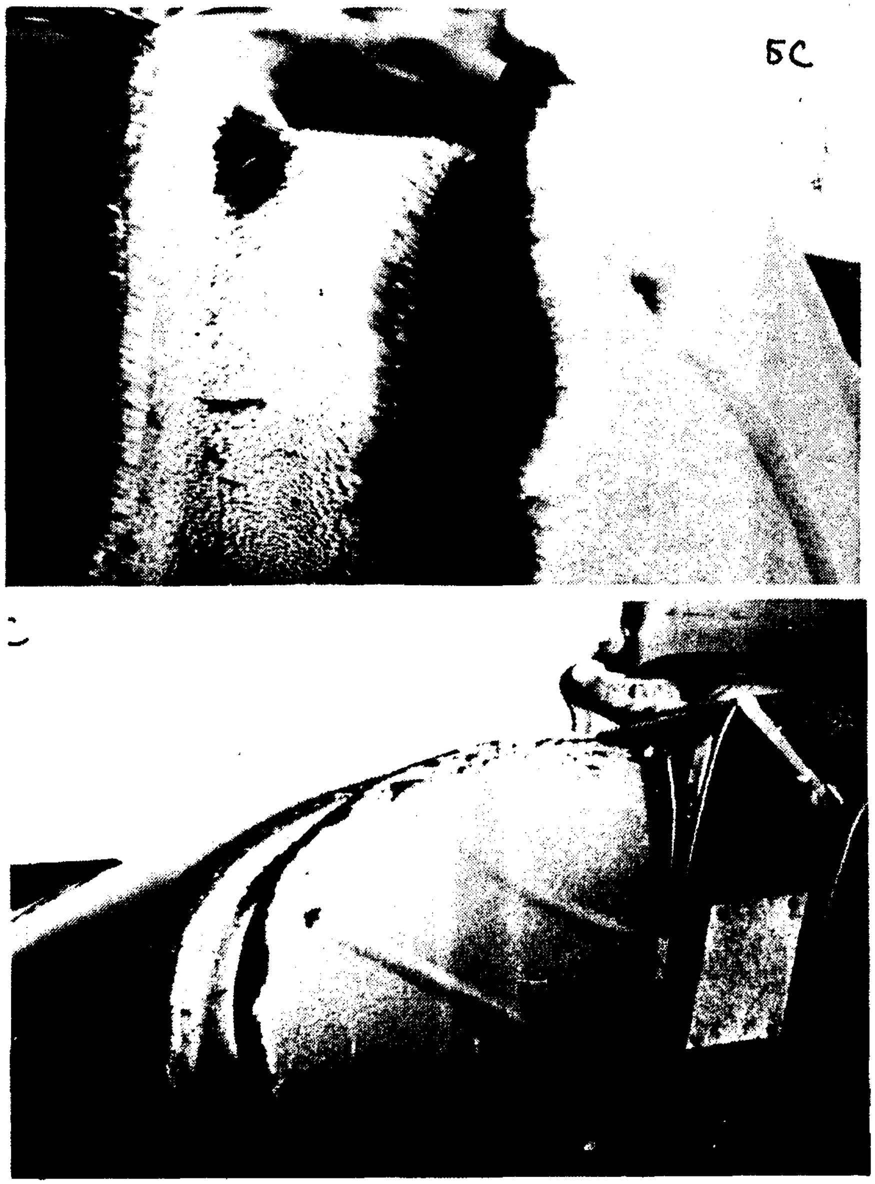


Figure 20. RUN 5C, Maximum Inlet Ice Build Up.
MVD - 21, KIAS = 75, OAT - 16°F

Figure 21. RUN 5D, Maximum Inlet Ice Build Up.
MVD - 40, KIAS - 100, OAT - 19°F

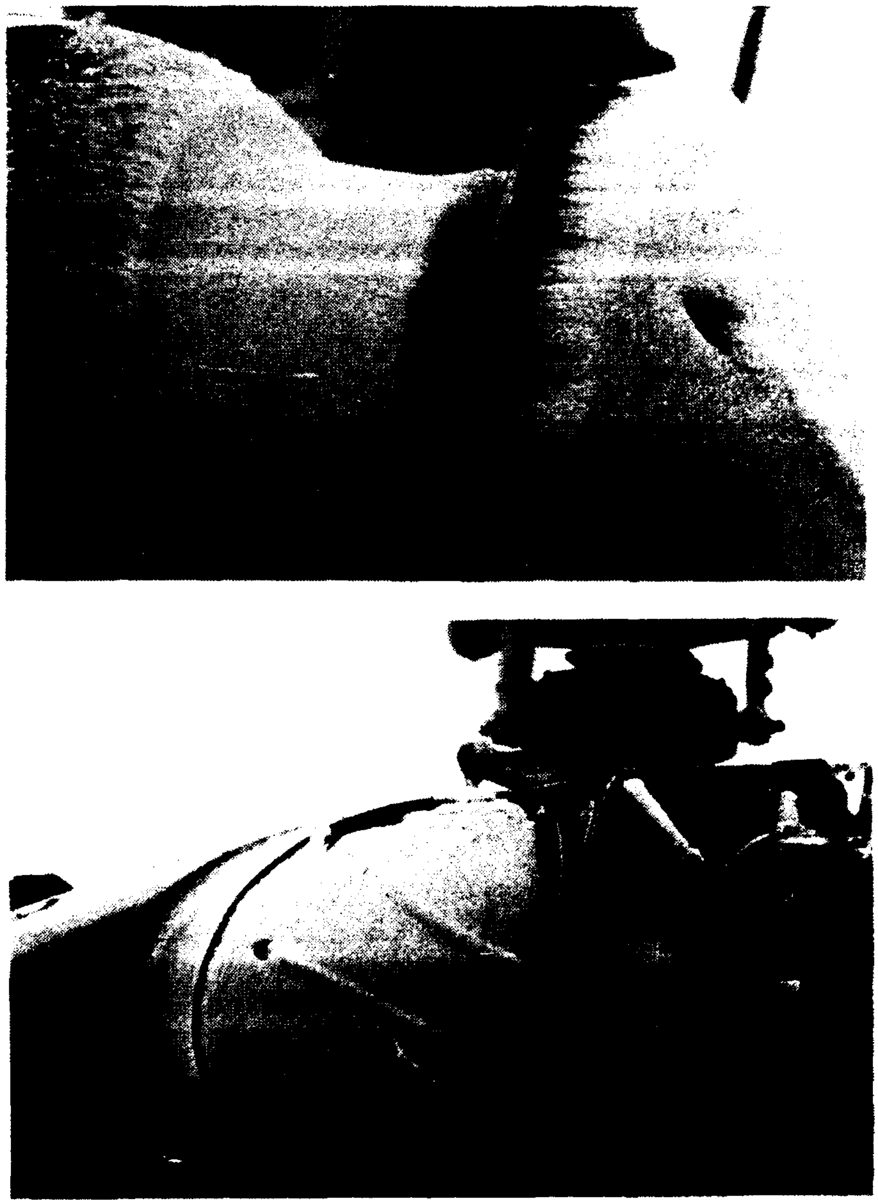


Figure 22. RUN 5E, Maximum Inlet Ice Build Up.
MVD = 58, KIAS = 50, OAT = 17°F

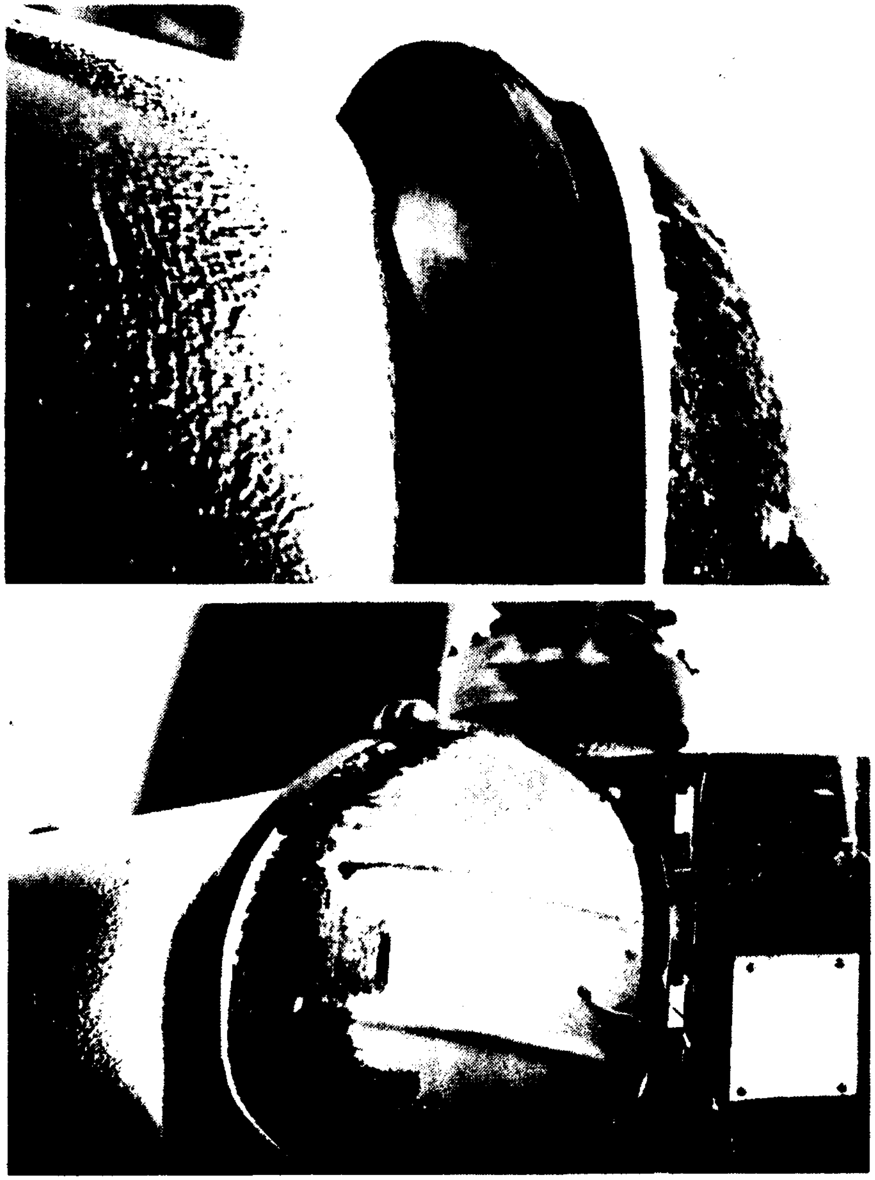


Figure 23. RUN 6A, Maximum Inlet Ice Build Up.
MVD = 26, KIAS = 50, OAT = 11°F

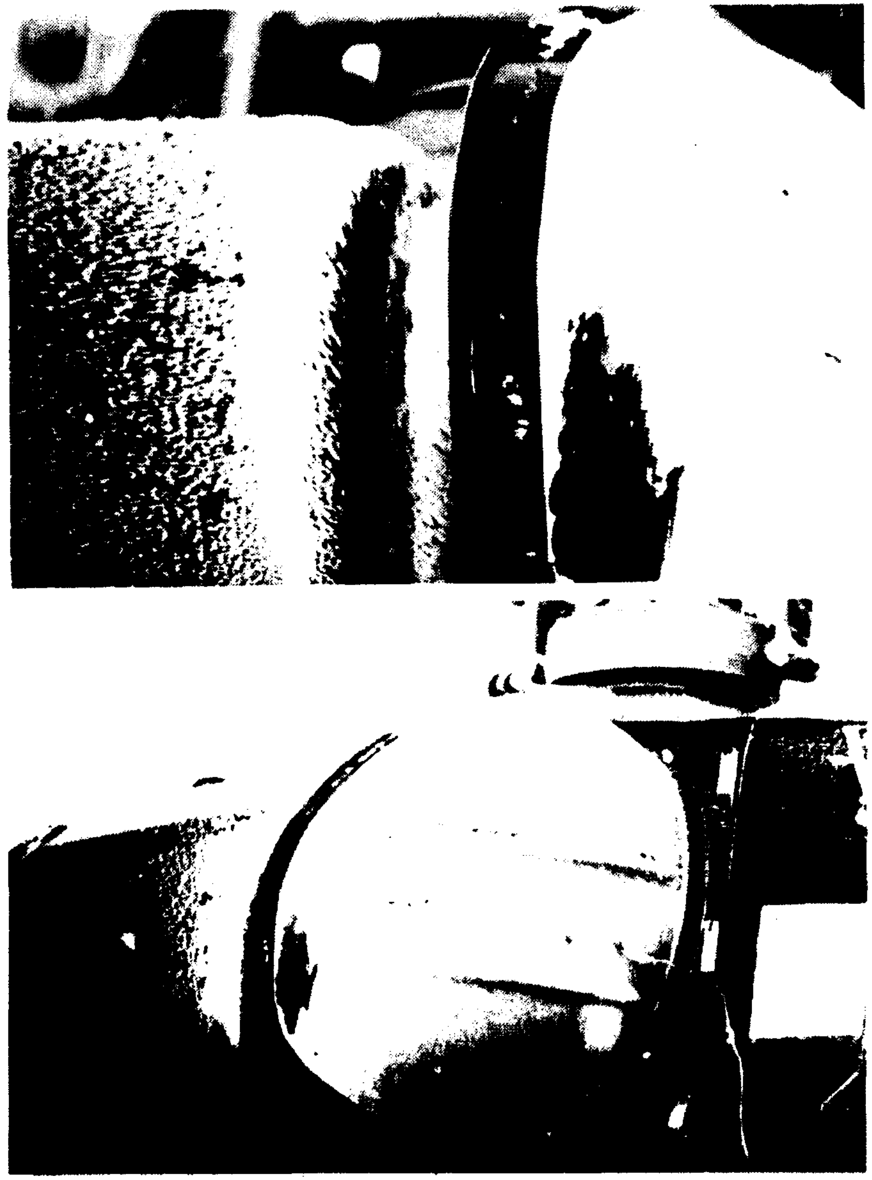


Figure 24. RUN 6B, Maximum Inlet Ice Build Up.
MVD = 25, KIAS = 50, OAT = 14°F

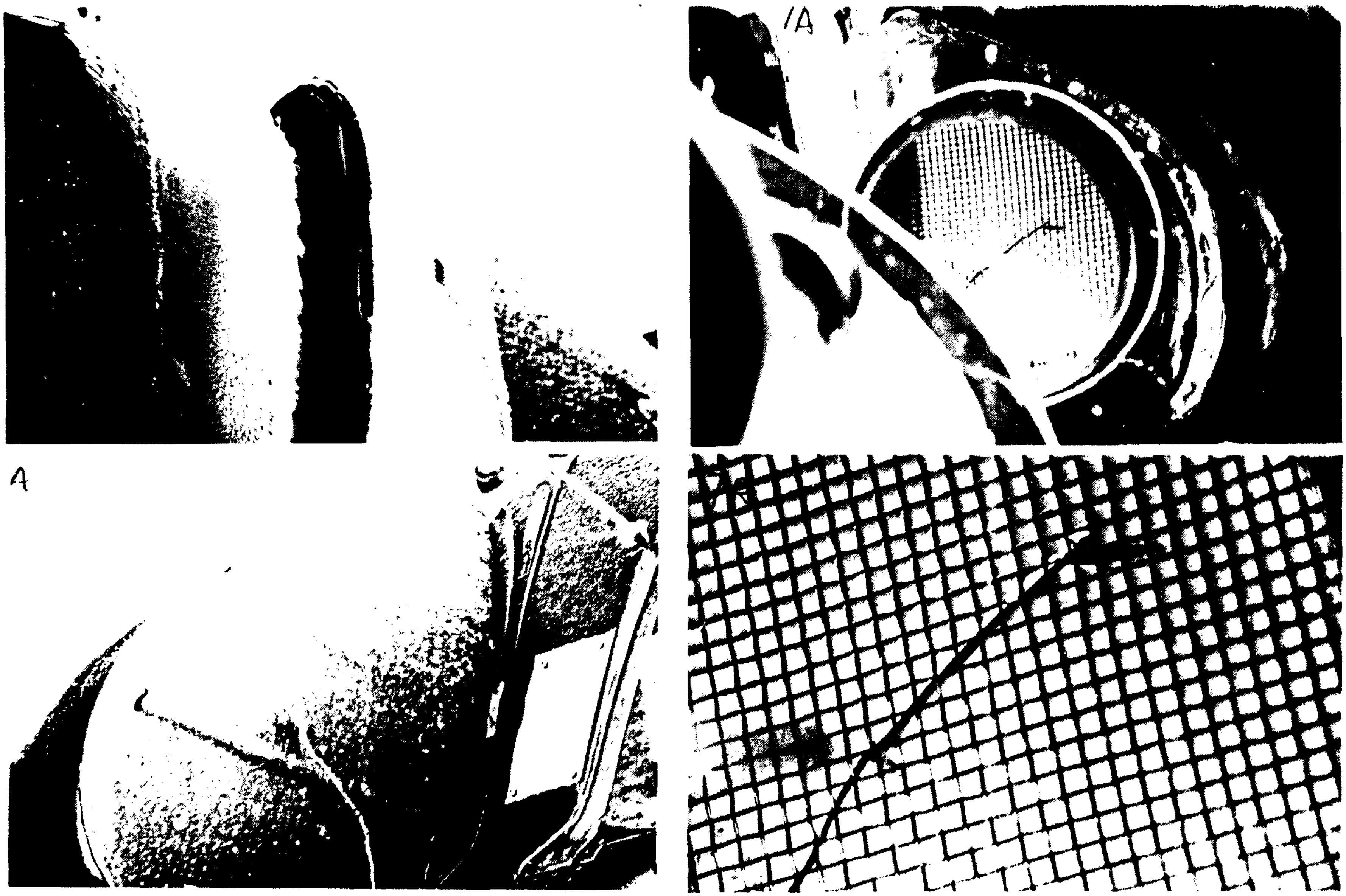


Figure 25. RUN 7A, Maximum Inlet Ice Build Up.
MVD 18, KIAS = 50, OAT 4°F

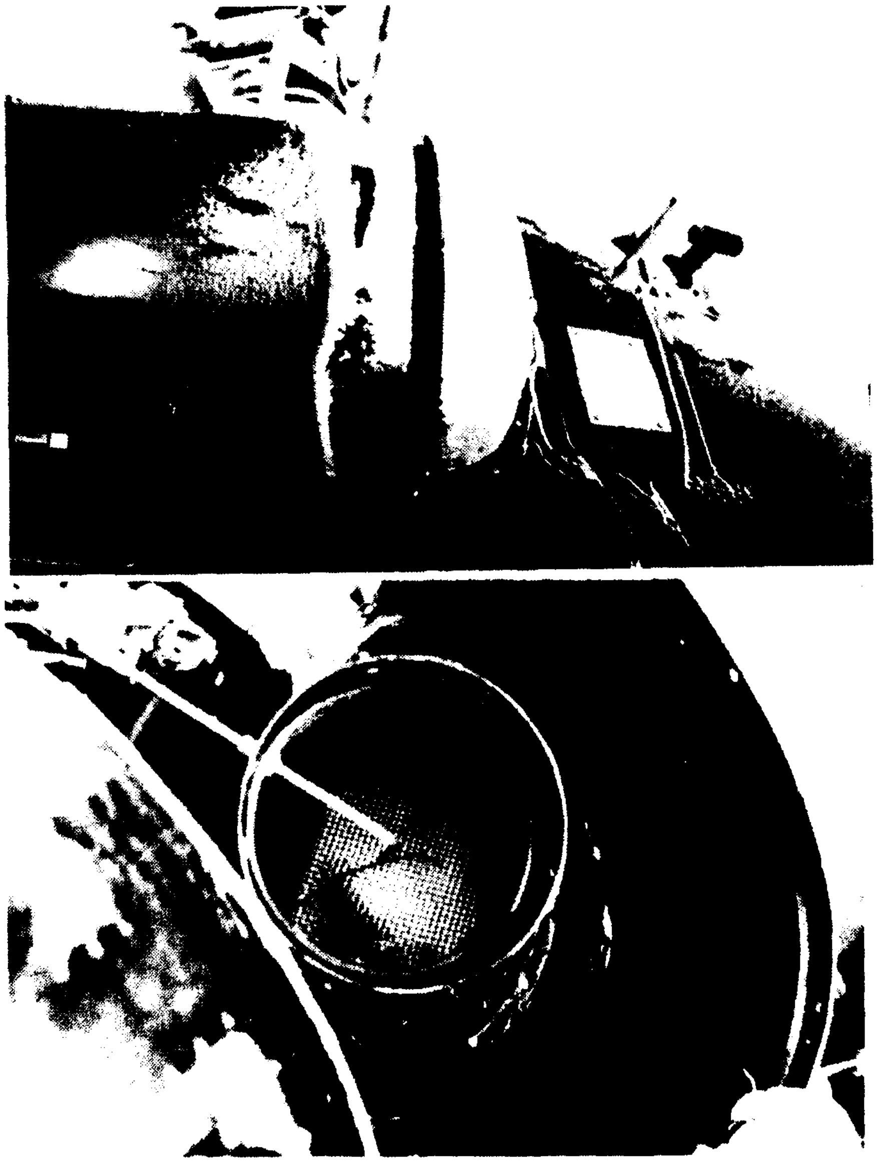


Figure 26. RUN 7B, Maximum Inlet Ice Build Up.
MVD = 25, KIAS = 100, OAT = -2°F

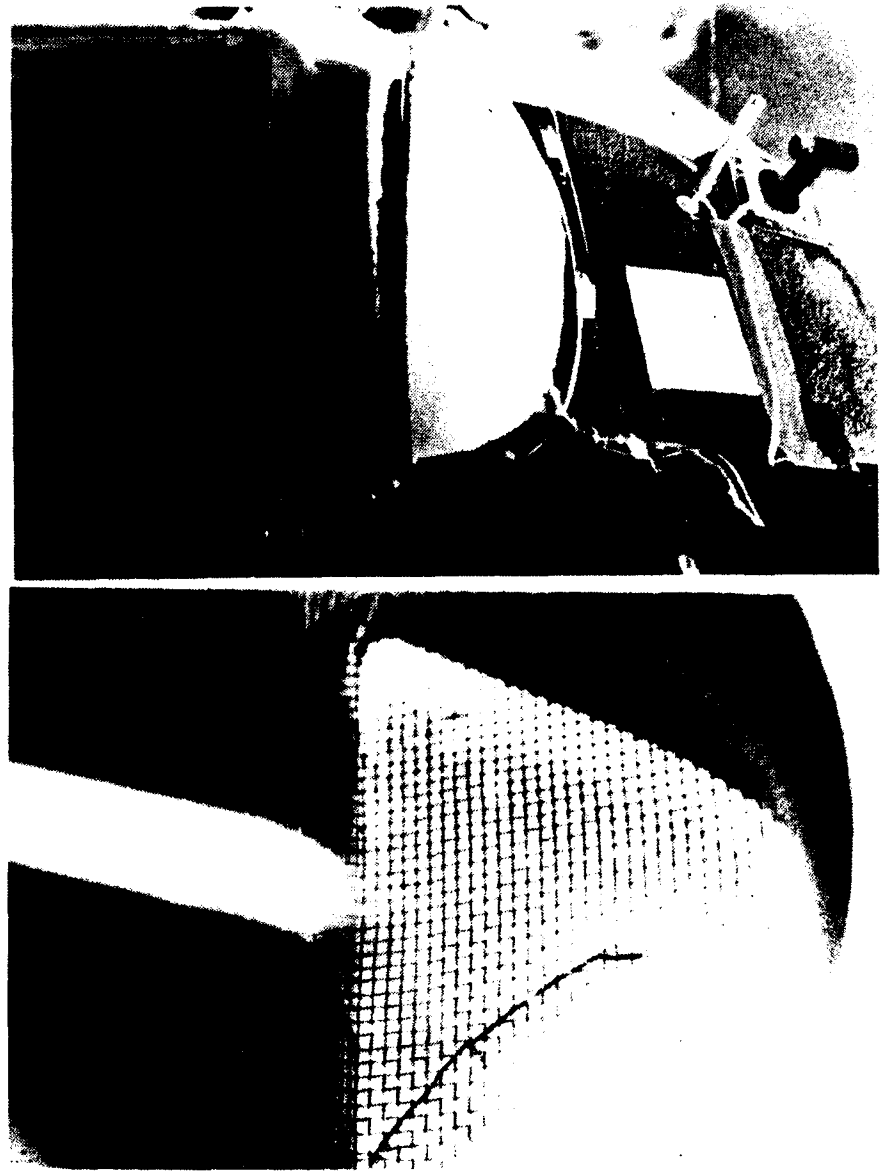


Figure 27. RUN 8A, Maximum Inlet Ice Build Up.
MVD = 43, GROUND RUN, OAT = 24°F

Figure 28. RUN 9A, Maximum Inlet Ice Build Up.
MVD = N.A, GROUND RUN, OAT = 32°F

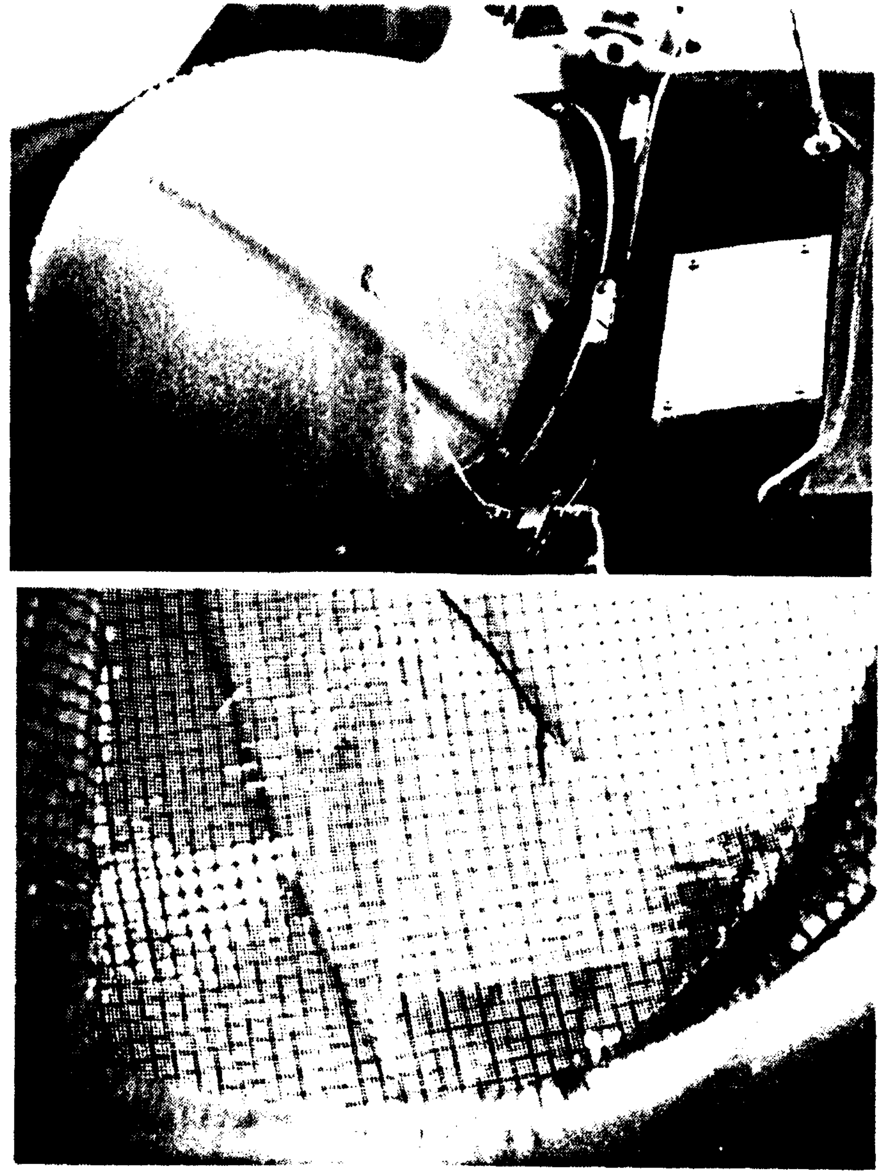


Figure 29. RUN 9B, Maximum Inlet Ice Build Up.
MVD = [illegible], [illegible] .50, OAT 31°F