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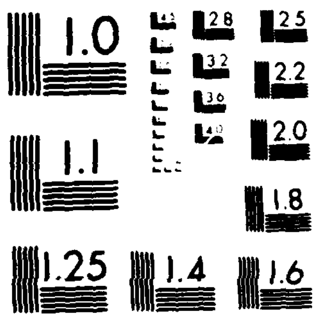

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AFFTC-TIM-83-2

REVIEW AND ASSESSMENT OF USAF and U.S. ARMY (HISS) ARTIFICIAL ICING CLOUD STUDIES

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FINAL REPORT

MARCH 1983

AIR FORCE FLIGHT TEST CENTER

EDWARDS AIR FORCE BASE, CALIFORNIA

AIR FORCE SYSTEMS COMMAND

UNITED STATES AIR FORCE

A F F T C

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S. H. Schwartz
Faculty Advisor

This report has been reviewed and is approved for publication:

EDWARD B. RUSS[illegible] [illegible]lonel, USAF
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This report reviews the results of articicial icing cloud studies which have been conducted by the USAF and U.S. Army. An attempt was made to evaluate the quality, validty, and the direction of work performed thus far, and to suggest ways to improve the experimental procedures and present fresh ways to view the problem of artificial icing of aircraft in flight.

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1.0 INTRODUCTION

Aircraft icing and methods for its prevention and removal has been an ongoing subject of investigation by the U.S. military establishment. As a result, the testing and certification of ice protection systems is an important part of the design and operation of fixed wing aircraft and helicopters. In the past five years effort has been stepped up by the Air Force and the Army to create artificial icing conditions in order to simulate ice accretion on various types of aircraft. The successful simulation of the natural icing clouds could enable tests to be performed without waiting for proper meterological conditions.

Most of the recent inflight testing by the USAF and the Army has been carried out separately at the Edwards Air Force Base. The USAF study was directed at the fixed wing aircraft, while the tests performed by the Army were centered on helicopters. In both investigations the artificial cloud ~~was~~ generated by an airplane or a helicopter spraying water through a bank of nozzles towed directly behind the aircraft. A trailing test aircraft was flown into the spray cloud; icing was induced on various surfaces of the test aircraft by exposing selected surfaces. In the flight tests conducted in the late 1970's, it was found that the droplets from the artificial cloud were too large, and the clouds were too small in size. In order to reduce the droplet size extensive work was performed in the N.A.S.A. Lewis icing wind tunnel to select a more appropriate nozzle to achieve smaller droplet sizes, and to evaluate the effects of nozzle orientation and various flow parameters on the nature of artificially generated clouds.

A design clinic team of graduate students ~~in the~~ Mechanical and Chemical Engineering Department at the California State University~~, Northridge~~ has undertaken a study of the USAF inflight and wind tunnel test programs. The purpose of this study was to review the accumulated data and the experimental methods involved. An attempt was made to evaluate the quality, validity, and the direction of the work performed thus far, and to suggest ways to improve the experimental procedure and possibly present fresh ways to view the problem.

2.0 DESCRIPTION OF THE EXPERIMENTAL PROGRAM:

2.1 Definitions of Terms:

Prior to undertaking and evaluating the experimental data, it is necessary to introduce the parameters by which the performance of the tests are measured. The performance of the tests which in essence is a measure of degree of success in simulating natural icing clouds, is established by means of two parameters; the liquid water content (LWC), and the median volumetric diameter (MVD). The MVD by definition is a droplet size for which half of the total mass in the cloud is contained in droplets smaller than the MVD droplet, and the other half is contained in droplets larger than the MVD droplet.

The MVD is a useful parameter in evaluating the artificial cloud since in natural icing clouds it is often found that much of the mass is concentrated closely around the median volumetric diameter. The liquid water content is also an important variable because it is a measure of the mass of the water contained in a given volume of air; it strongly affects the degree of the ice accretion.

The liquid water content is a calculated parameter and is obtained by measuring the air velocity in the measuring cavity of the probe, the cross-sectional area of the cavity, and the size and number of droplets passing through the cavity for a given period of time. In the LWC calculations, the air velocity was employed rather than the droplet velocity as it was assumed that the droplet velocity will be close to that of the air stream, at a reasonable distance from the nozzle, due to the small size of the droplets involved. The LWC can be defined in the following formulation, introducing a predetermined electronic calibration factor.

LWC = Water Flow Rate/(Air Speed * Area) * F * C

where

LWC - gm/m**3

Flow rate - Gallons/min

Airspeed - Knots

Cross-sectional area - ft

C - units conversion factor

F - calibration factor

2.2 WIND TUNNEL TESTS:

2.2.1 Introduction

Both the USAF and the Army have conducted wind tunnel tests as a preliminary to actual inflight simulation tests. The purpose of the tests was to develop improved spray systems to be used in the inflight program. Both services independently ran their tests in the Icing Research Tunnel at the NASA Lewis Research Center in Cleveland, Ohio. In addition to trying to achieve water droplet median volumetric diameters within the 15-40 micron range, tests were also run to study the effects of the water mixture ratio and the air flow rates, water and air pressures, ambient temperature, velocity of object, and humidity on the spray cloud.

2.2.2 Spray Nozzles and Nozzle Banks:

Even though the two separate programs used different nozzle boom configurations, the nozzles used in each program were generally the same. The Army Hiss program of nozzle testing (1) was an extensive one and covered a wide variety of nozzles. Principal nozzles evaluated in each program were the Baseline Nozzles manufactured by the All American Manufacturing Co., Spray Systems 1/4J nozzles manufactured by the Spray Systems Co., and the Sonicore nozzles.

The U.S. Army test used a full scale 9 ft. section of the HISS spray boom with provisions for 13 nozzles. The nozzles were oriented upward, downward, aft directly behind the boom, and aft above the boom. The USAF used an entirely different spray rig. Theirs was primarily made of several concentric rings of nozzles as opposed to the Army spray boom where the nozzles projected outward from a straight piece of pipe. Figures 1 and 2 illustrate the types of the nozzle rigs used in each of the programs.

2.2.3 Instrumentation:

The instrumentation used was primarily for measuring the spray characteristics which included the drop size distribution, the MVD, the LWC, total temperature, and the tunnel air speed. The HISS instrument traverse unit was located at a standoff distance (distance downstream from nozzles) of 21.5 ft. while the USAF instrumentation standoff distance was only 2-3 ft. which is too close to make any judgement of the effectiveness of

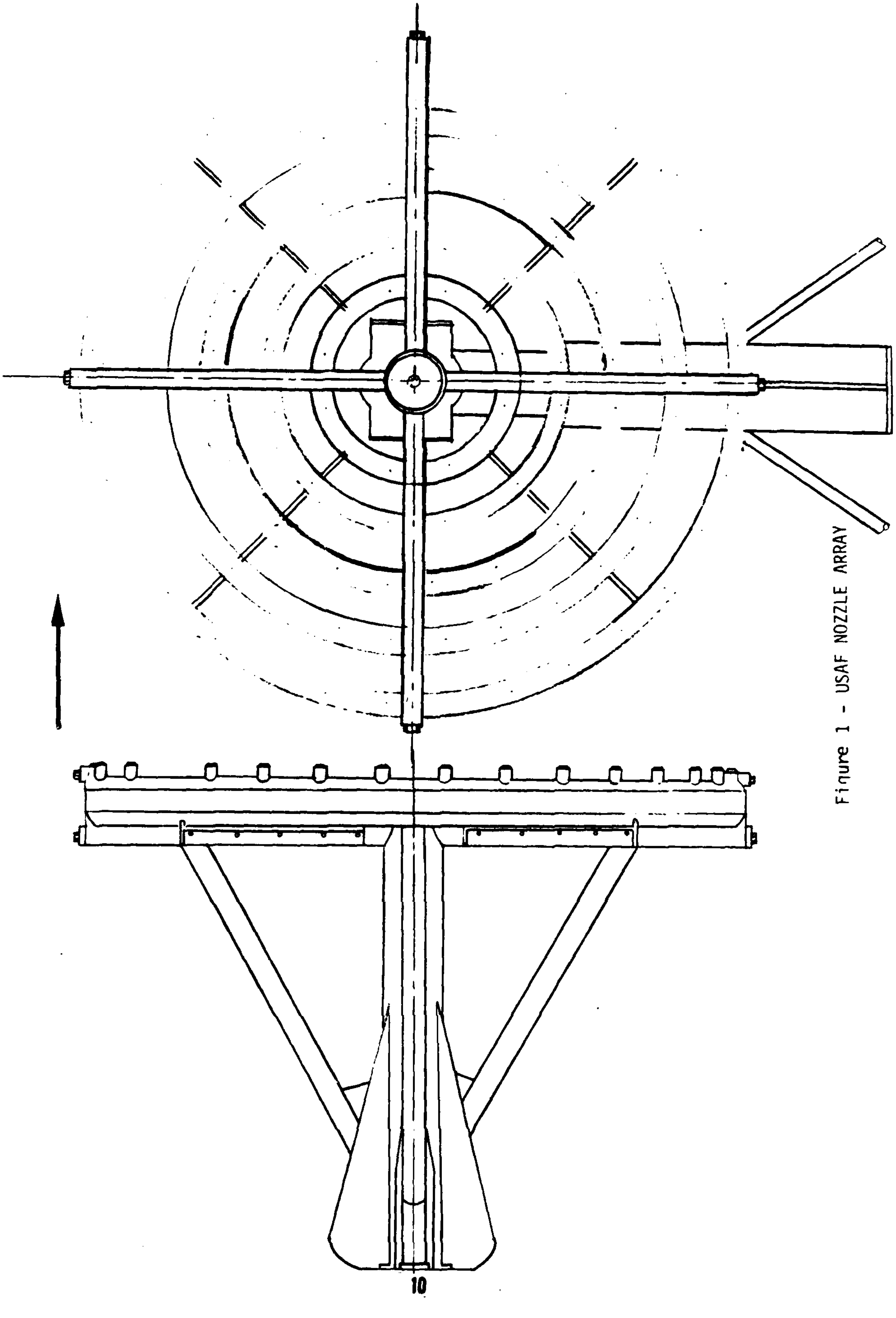


Figure 1 - USAF NOZZLE ARRAY

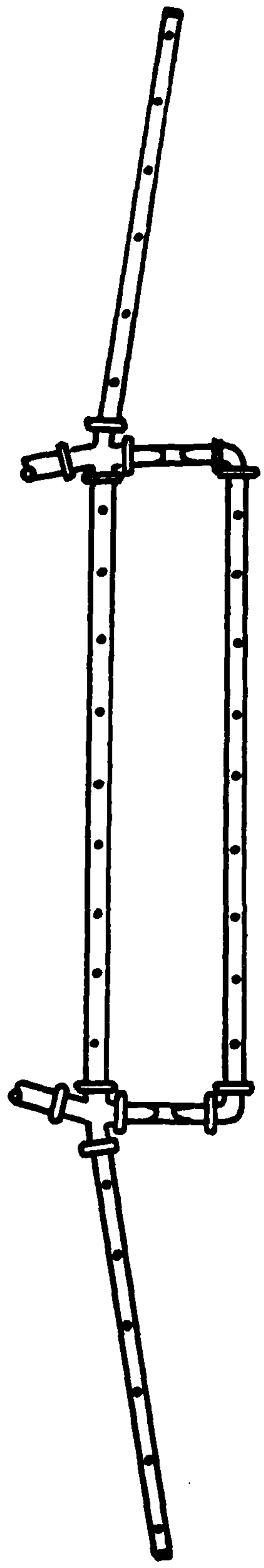


Figure 2 - HISS SPRAY BOOM

dispersal.

During the ice simulation tests the MVD was determined from measurements of water droplets in the test clouds. This was accomplished by means of laser probes which directly counted and measured the droplet diameters. A good understanding of the basic working principles is important due to the fact that the instrumentation has an important bearing on the LWC and MVD which are calculated from the droplet measurement data.

The laser probes employed during the icing tests were all provided by the MRI Corporation, which also lent its technical support to the data acquisition and analysis. The laser probes can be classified basically into two types: the scattering type and the laser shadowing type probes. The former was used principally to measure small droplets, while the latter was best suited to measure larger droplets. The laser scattering probe operates by measuring the laser light attenuation caused by passing water droplets, while the laser shadowing probe measures the size of the droplets by determining the sizes of shadows projected onto an array of photo diodes. Therefore by means of proper calibration the actual sizes of the droplets can be determined. The probes used during these tests were much different from the methods employed during the mid 1950's by NASA which conducted numerous analyses of aircraft icing (2,3). Prior to the laser probes, the MVD and the LWC were measured by the rotating cylinder method, and by hot wire anemometry notably the Johnson-Williams liquid water content meter which is still used to a limited extent for smaller water droplets. In spite of the advanced state of technology of the laser probes, there is an inherent source of instrument error associated with the probes, which has a significant impact on the calculations of LWC.

An incorrect determination of LWC could most likely result due to incorrect determination of the droplet concentration of the water droplets. Incorrect counting of the water droplets usually results in an under estimation of the LWC; especially at high flow velocities and high droplet concentrations. This is normally to be expected; however there is an additional impact due to the electronic circuitry of the probes and the instrumentation for data acquisition. The error results from the fact that it takes a finite time for the microprocessor to convert the analog signal into digital form and transfer it into storage tapes. During this short period the device is essentially blacked out, and this results in an underestimation of LWC. This problem is especially acute if larger droplets are present in the airstream. The uncertainty in the overall LWC has been determined to be between 10 and 20% (4).

Table 1 lists the various probes and their basic description.

2.3 DISCUSSION OF THE WIND TUNNEL RESULTS:

The experimental results obtained from the KC-135 wind tunnel test (Figure 3) are quite striking. It can be seen that there are large fluctuations of MVD, and LWC across the lateral traverse of the wind tunnel. The data obtained were random, the LWC determined through the laser probes and the Johnson-Williams

Table 1: INSTRUMENTATION DESCRIPTION

	ASP:	CPS:	PPS:
Number of channels	15	15	15
Size Range	3 - 45 microns	20 - 300 microns	140 - 2100 microns
Size Resolution	3 microns		
Maximum Part. Rate	100 KHZ	-	-
Coincidence Error	<1% W/ 1000/CM3	-	-
Max. Part. Vel.	125 m/s	250 knots	250 knots
Environmental	$(-40^{\circ}C)$ to $40^{\circ}C$ Hum: 10-100%	$(-60^{\circ}C)$ to $50^{\circ}C$ Hum: 10-100%	$(-60^{\circ}C)$ to $50^{\circ}C$
Sample Area	0.653 (mm)**2	-	-
Maximum Aper.	-	6.5 cm	6.5 cm
Altitude	0-40,000FT.	0-40,000 FT.	0-40,000 FT.
Dimensions	Airfoil L=24"	Cylin. L=28" Dia.=6.5" Optical Extension L=20", D=1"	Cylin. L=28" Dia.=6.5" Optical Extension L=10", D=1"

1) ASP (Axially Scattering Probe)-
   Drop sizing device using laser scattering technique.

2) PPS (Precipitation Particle Spectrometer)-
   Drop sizing device using laser shadowing technique.

3) CPS (Cloud Particle Spectrometer)-
   Drop sizing device using laser shadowing technique.

4) J-W (Johnson Williams Liquid Water Content Indicator)-
   Measures LWC using hot wire anenometry.

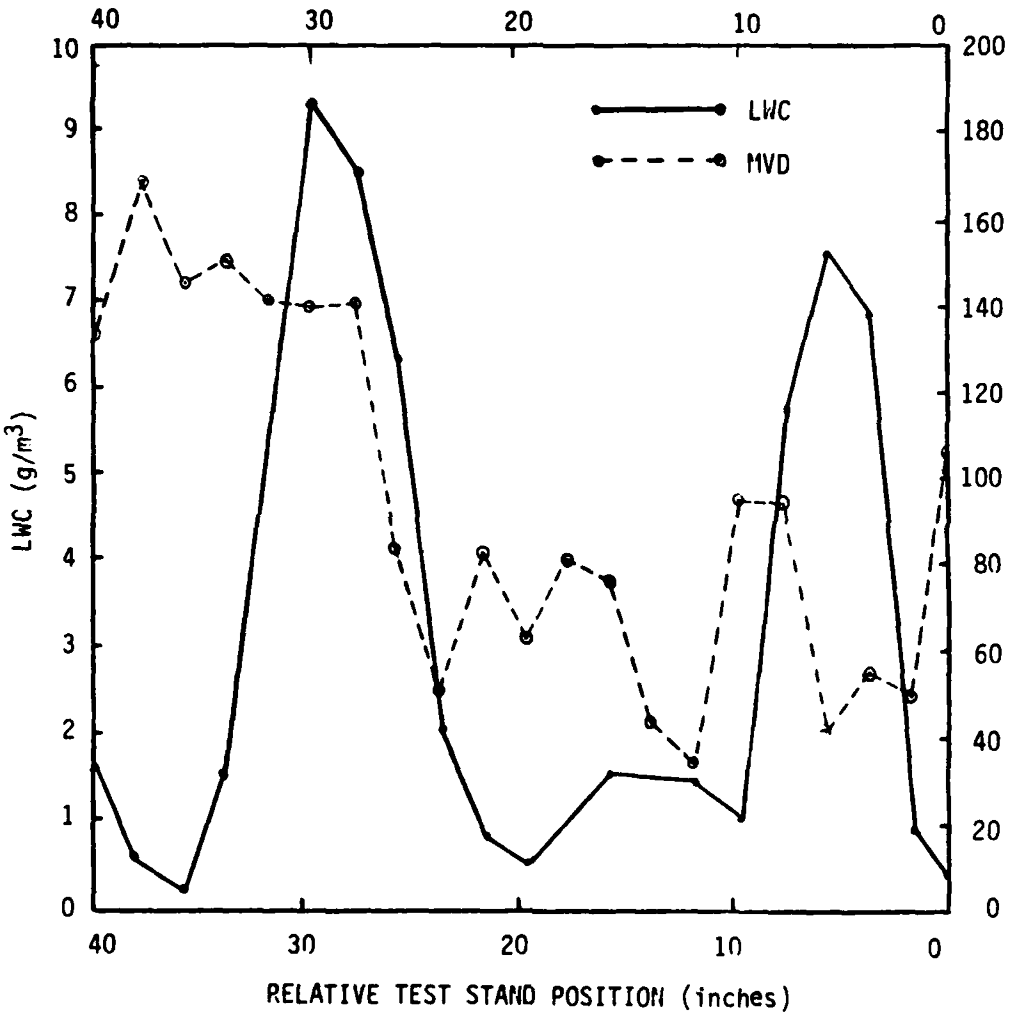


Figure 3 - LWC AND MVD VERSUS RELATIVE TEST STAND POSITION (USAF)

Liquid Water Content meter did not corroborate at all. In essence the data thus obtained were virtually useless for determining the MVD and the LWC of the spray cloud. Also at such close distances from the nozzle exit plane it is quite likely that the optical probes and the Johnson-Williams meter could become saturated, resulting in a rapid drop off in performance. One useful fact which can be gleaned from the KC-135 test is that at the distance of 3 feet, the effects of individual nozzles is still noticeable.

Unlike the results from the KC-135 wind tunnel test, the results from the HISS wind tunnel test are easier to evaluate. This is due principally to the fact that at the measurement distance of 21.5 feet the effect of individual nozzles is dissipated. From the tests it was determined that the Sonicore nozzle was the best nozzle in terms of simulating natural icing clouds. Spray MVD values were close to those of natural icing clouds and ranged from 15-50 microns and the LWC varied from 0.5-5 gm/m**3. The Spray Systems 1/4J nozzle was also found to perform well; however its main drawback was that it tended to freeze at low operating temperatures. It must be noted that similar problems occurred during the KC-135 wind tunnel test. Table 2 listing the basic performance of the nozzles is presented below.

The positioning of the nozzles in the airstream was found to have a strong impact on the spray characteristics. For example, a single Baseline nozzle oriented upwards produced a spray with a MVD of 200-300 microns. However, when the nozzle was oriented

Table 2: NOZZLE PERFORMANCE FROM HISS/BOEING PROGRAM

NOZZLE	MVD(MICRONS)	LWC(gm/m**3)	REMARKS
All American (Baseline) (1 Nozzle)	200-300	0.1 - 0.5	Some evidence of rooster tailing
Sprayco 2627A (Air Force) (1 Nozzle)	300-500	0.5 - 5.0	
Spraying Systems+ (1/4 J #29)	15-50	0.5 - 5.0	Some freezing problems at temp. below freezing
Spraying Systems (1/4 J #22) (3 Nozzles)	20-50	0.25 - 1.0	Narrow spray pattern
Spraying Systems (1/4 J #42) (2 Nozzles)	20-50	0.25 - 1.0	Very poor spray pattern distinct rooster tail
Sonicore 125 HS+ (9 Nozzles)	15-50	0.25 - 5.0	Good spray pattern, no freezing problem

*

#29 Nozzles has 6 holes and is designed for larger spray pattern.
#22 Nozzles has a single hole.
#42 Nozzles has a larger single hole for greater flow rate.

\+ It has about 1/3 flow rate capacity of baseline nozzles.

downstream with the flow the MVD was determined to be 300-450 microns. Hence proper orientation of the nozzles appears to have an important bearing on the droplet size characteristics. In addition visual observations indicated that the aft mounted nozzles produced a less steady spray pattern. There seemed to be some evidence that turbulent mixing enhances droplet coalescence.

The tunnel air temperature was observed to have an impact on the LWC. For example, when the Sonicore nozzle was operated at a temperature of $-9.4^{\circ}C$ to $-26^{\circ}C$, the LWC was 0.5-5 gm/m**3; while the LWC determined from the ambient air temperature runs was found to be less than 1 gm/m**3. A possible explanation was proposed by considering the buoyancy effect. It has been suggested that due to buoyancy forces there would be a vertical sorting or stratification of the spray plume due to the fact that at lower temperatures the buoyancy forces acting on the smaller droplets would be more significant (5). This seems somewhat convincing; however a note of caution should be interjected at this point. At a flow velocity of around 100 MPH, it takes a 100 micron droplet approximately 0.19 seconds to travel 25 ft., and at this point the droplet velocity of the 100 micron droplet is about 99% of the ambient velocity. Hence it can be seen that any changes in the flow conditions at the nozzle exit plane can have an important bearing on the results because in the short time period involved it is quite unlikely that mechanical forces such as these due to buoyancy could be important. It is, however, quite possible that droplet evaporation due to high shear forces during the initial acceleration could be sufficient to reduce the number of the small droplets. If this is true, then the low LWC at ambient test temperatures would be a result of a lack of small water droplets.

The effect of humidity was not determined in these wind tunnel tests as the test plan was not designed to make any such determination. Figures 4 & 5 give some important HISS wind tunnel results and Table 3 summarizes experimental parameters.

2.3.1 Summary:

Because of the short standoff distance of 3 feet, the spray data from the USAF wind tunnel tests were of little value. However, the tests did help to establish the overall performance of the nozzle spray rig and the instrumentation which is of considerable value as a preliminary to inflight testing. The HISS wind tunnel test program found that the Sonicore 125 nozzle and the Spraying Systems 1/4J nozzle were capable of generating a spray cloud representative of natural icing conditions although the Sonicore nozzle performed better at low temperatures. In addition it was found that the nozzles should be mounted upward and downward on the spray boom rather than aft.

2.4 INFLIGHT TEST:

Both the USAF and the U.S. Army have conducted inflight tests. However, the USAF KC-135 test program is presently underway and the data have not yet been reported. On the other hand, the U.S. Army has been conducting inflight simulation tests since 1973 using a modified CH-47C helicopter. These early tests

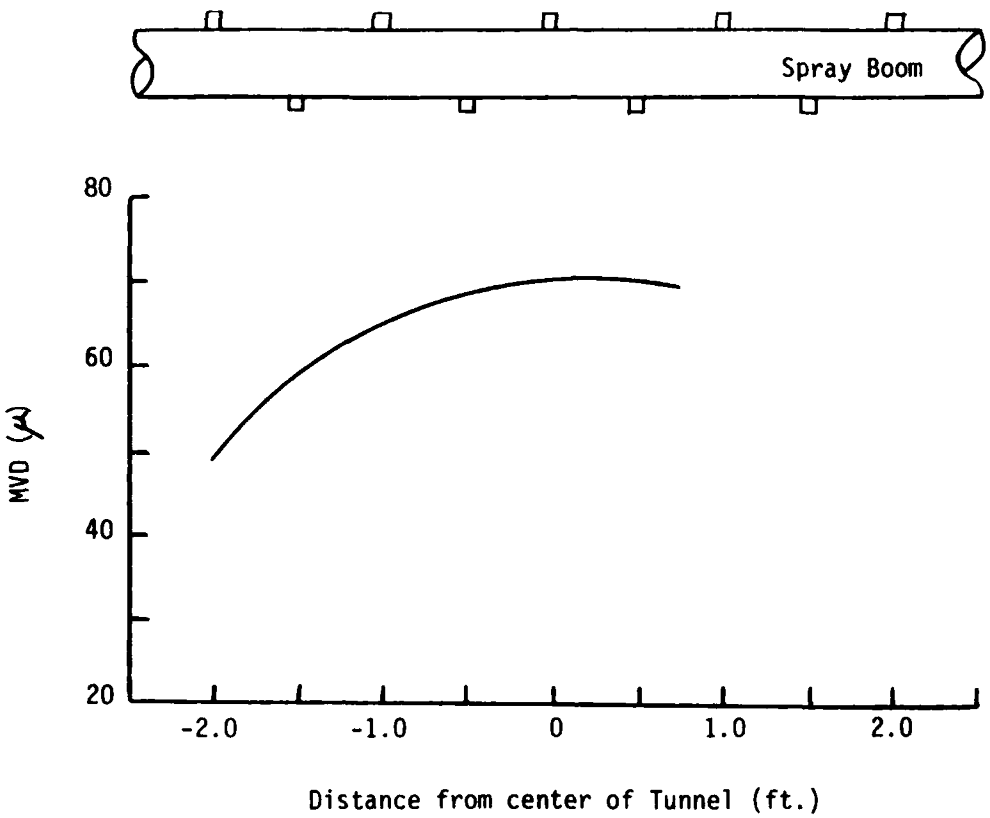


Figure 4 - HORIZONTAL TRAVERSE OF MVD (1)

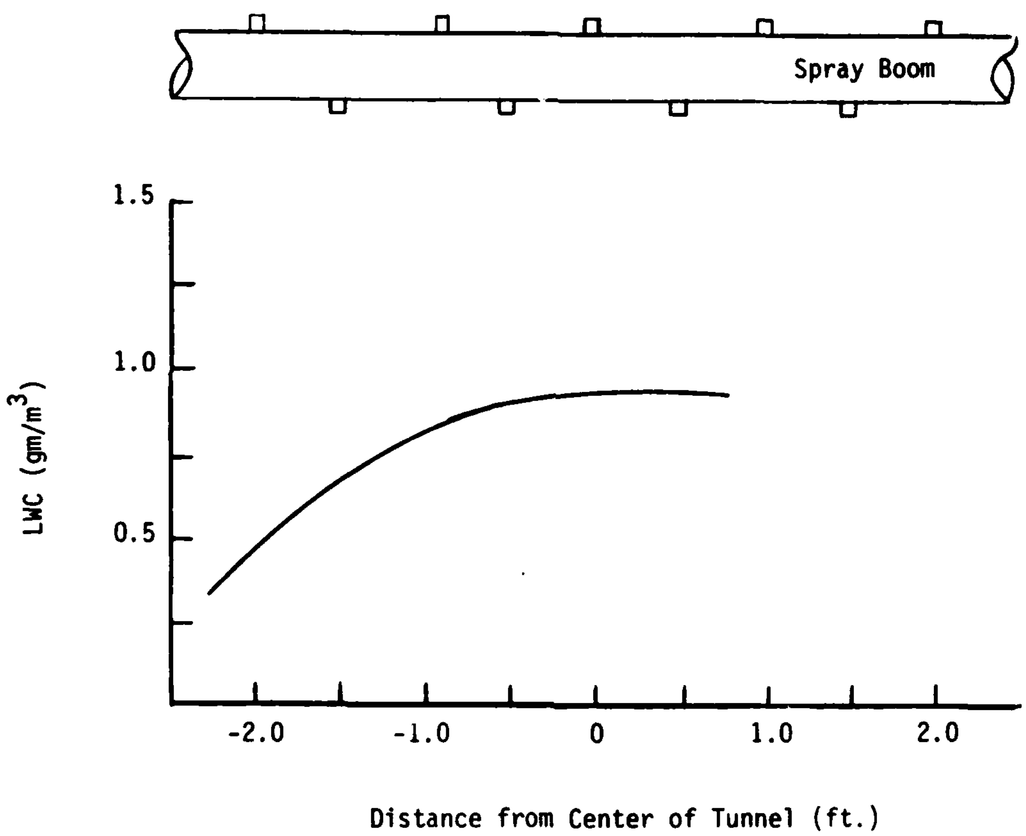


Figure 5 - HORIZONTAL TRAVERSE OF LWC (1)

Table 3: LIST OF WIND TUNNEL EXPERIMENT PARAMETERS:

TEST PARAMETERS		BOEING/HISS ICING TUNNEL	AIRFORCE/KC-135 ICING TUNNEL
Sample Time		1 Sec.	1 Sec.
Water Pressure	- Boom		60 PSI Max.
	- Tank		
Water Flow Rate	- Total	5.4 GPM (Max).	5-15 GPM
	- Per Noz.	1.3 GPM (Max).	-
Bleed Air Pres.	- Engine	10 - 90 PSI	
	- Boom		10 - 50 PSI
Bleed Air Flow Rate Per Nozzle		1.5 LBM	-
Bleed Air Air Temp. (Boom)		9^{0} TO 77^{0}C	-
Amb. Air Velocity		60-120 Knots.	100-200 MPH
Amb. Air Temp.		-26^{0}C to 30^{0}C	-
Water Chemistry		Distilled Water	-
Relative Humidity		40-100%	-
Probe Location		21.5 ft Downstream	2-3 Feet Downstream
Measurement Sweep		Horizontal	Horizontal

indicated that the artificial cloud produced was not an adequate simulation of the natural icing environment. As a result, a program was initiated by the U.S. Army to improve their icing simulation of the natural icing environment in 1979.

2.4.1 Description of Apparatus:

The USAF test set-up is based on a modified KC-135 aircraft which carries a spray rig and the auxiliary equipment required. Figure 6 illustrates the general method in which the two aircraft are positioned during the inflight tests.

The spray helicopter in the HISS Program carried 1,400 gallons of spray water which was sprayed through 97 nozzles located on the center boom. Originally, the boom was designed to use 172 nozzles; however, due to insufficient air pressures, only the central boom was used. The central boom consisted of two 27 feet sections separated by 5 feet. On the boom the spray nozzles were spaced 1 foot apart and were pointed up and down in an alternating fashion, reflecting on the favorable results obtained in the wind tunnel tests.

2.4.2 Instrumentation:

Both the USAF and the army have essentially used the same instrumentation for drop measurements. At the present time the USAF flight information is not available and cannot be discussed further.

MRI particle measuring probes were used to determine the cloud simulation characteristics in the HISS program. All

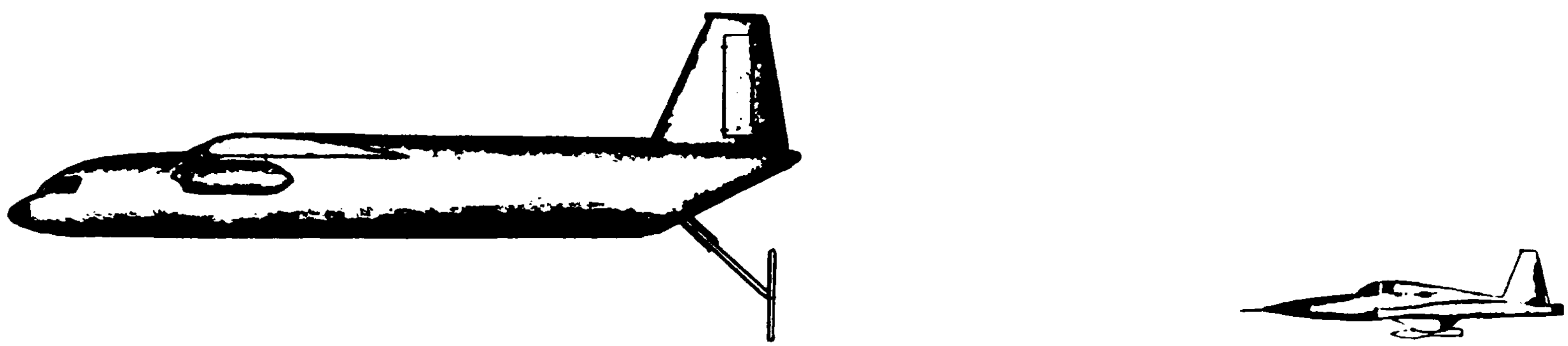


Figure 6 - SCHEMATIC OF KC-135 TEST FLIGHT ARRANGEMENT

measured cloud parameters were derived from the droplet number count, diameter classification, and the size of the air volume sampled. The LWC was determined by summing the volumes of water contained in each drop and relating it to the total volume of air sampled.

Section 2.2.3 lists the instrumentation used in the wind tunnel tests. This same description applies to the drop measuring equipment used in the flight measurements.

A chase helicopter equipped with a dew point hydrometer, thermocouple, and pressure transducer was used to measure the temperature and pressure of the air. The laser probes were identical to those used in the wind tunnel tests. The flight speed of the helicopters was approximately 90 Kts., and the chase helicopter took measurements at distances of 150-300 feet away from the spray point. It took measurements at various locations in the cloud; notably vertical sweeps in the cloud. As a side note the chase helicopter also took data in actual icing clouds.

2.4.3 Test Results:

2.4.3.1 U.S. Army:

The HISS flight test results are basically related to the liquid water content, the cloud median volumetric diameter and the cloud droplet distribution. Measurement sweeps were made in both the vertical and horizontal directions. Table 4 lists the inflight test parameters.

2.4.3.2 MVD:

The MVD generated by the recent tests was found to be more representative of the natural icing clouds than the prior HISS icing tests which used the Baseline nozzles. Hence the inflight tests validated the selection of new nozzles and nozzle configurations based on the wind tunnel tests. The prior HISS inflight tests, which used the Baseline nozzles, resulted in MVD values near 250 microns. The recent flight tests produced MVD in the range of 20-40 microns, while the LWC was found to be variable vertically throughout the cloud which averaged 36 feet in width and 8 feet in height.

2.4.3.3 LWC:

When one examines the vertical variation of the LWC (Figure 7) it can be seen that there is a bias of the LWC towards the bottom of the cloud. This may be attributed to gravitational sorting by size (5). A somewhat similar argument was presented in interpreting the HISS wind tunnel test. Another factor may have been the manner in which the HISS spray boom was operating. It was also found that horizontal variations across the cloud were less than the vertical, see Figure 8.

It was observed that the sprays emanating from the lower horizontal boom were thicker than the spray coming from the top boom. This uneven spray may have been caused by hydraulic losses in the lower section of the spray boom. This points to the care which must be taken in properly designing the spray booms to obtain equal pressures and flow rates at all locations along the

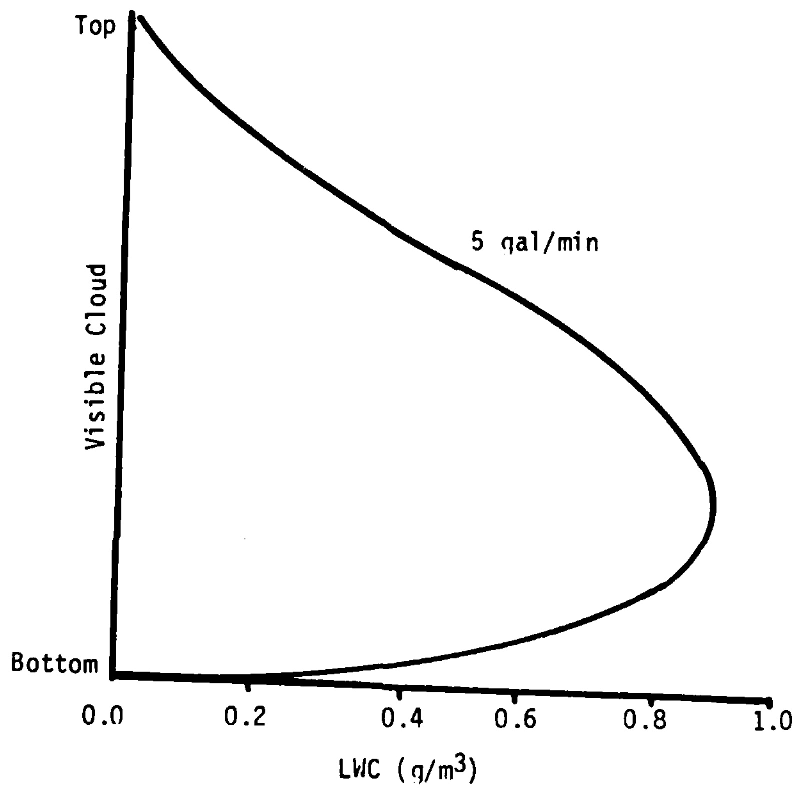


Figure 7 - VERTICAL VARIATION OF LWC
HISS - 1979-1980 (4)

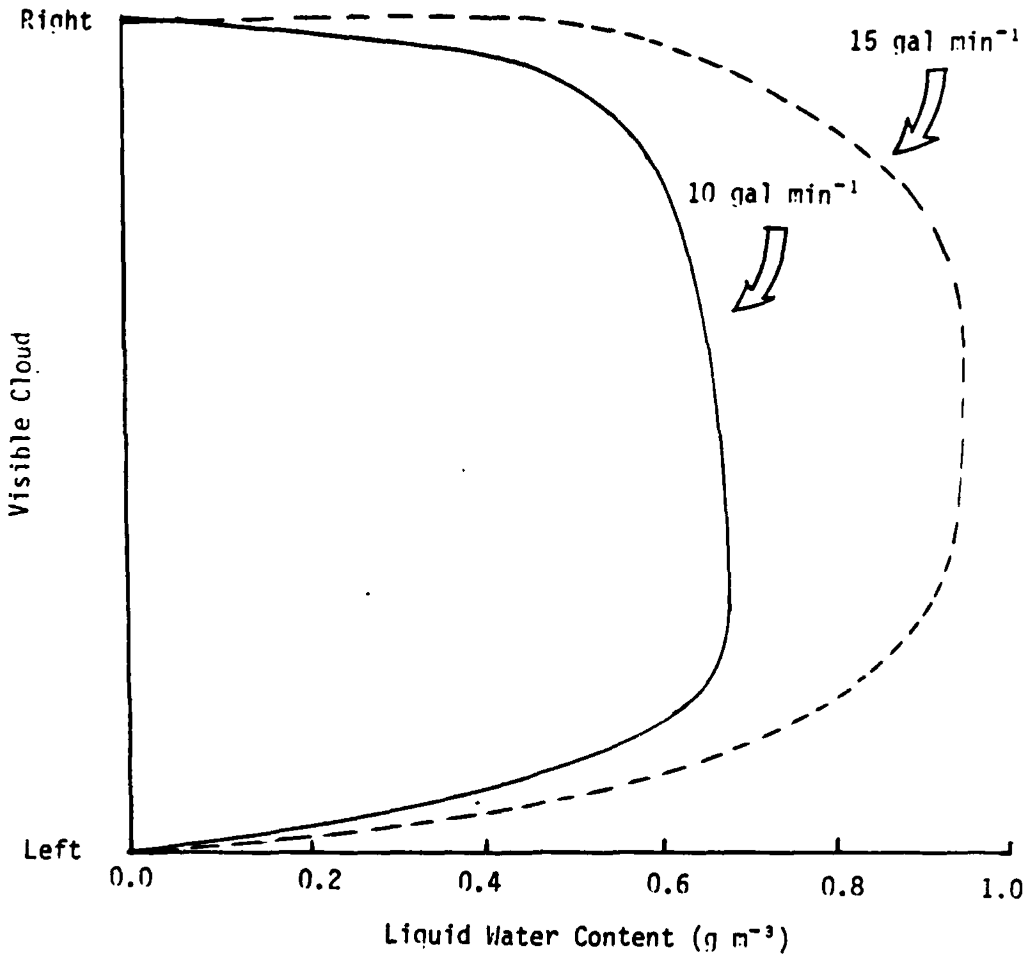


Figure 8 - HORIZONTAL VARIATION OF LWC IN THE 1979-1980 HISS CLOUD (4)

Table 4: COMPARISON OF HISS WIND TUNNEL AND INFLIGHT TEST PARAMETERS

TEST PARAMETERS		ACTUAL HISS	ICING TUNNEL
Water Pressure:	Boom	60 psi (max)	60 psi (max)
	Tank	60 psi (max)	
Water Flow Rate:	Total	5 - 150 gpm	5.4 gpm (max)
	Per Nozzle	0.1 - 3.0 gpm	1.3 gpm (max)
Bleed Air Pressure:	Engine	60 psi (max)	10 - 90 psi
	Boom	30 psi (max)	
Bleed Air Flow Rate: (Per Nozzle)		1.5 lbm	1.5 lbm
Bleed Air Temperature (Boom)		27^{0} C	9^{0} - 77^{0} C
Ambient Air Velocity		60 - 120 knots	60 - 120 knots
Ambient Air Temperature		0^{0} C to (-20^{0}) C	30^{0} C to (-26^{0}) C
Water Chemistry		Tap Water & Dye	Distilled Water
Relative Humidity		Ambient (50-100%)	40-100%
Spectrometer Probe Location		150, 200, & 250 feet	21.6 ft. downstream

boom.

The effect of humidity mainly results in variability of the concentration of small droplets. For the case of low humidity, there is a much smaller concentration of droplets less than 20 microns. This seems reasonable in view of the fact there is a higher rate of evaporation for lower humidities.

2.4.4 BASIC CONCLUSION:

By proper selection of nozzles and their orientations the HISS cloud was able to reasonably simulate the natural icing cloud. However, some minor differences exists; there is still a considerable mass at droplet sizes greater than 45 microns which are generally not present in the natural cloud. Also, in the natural cloud, the mass and number concentration peaks steeply around the MVD, while in the artificial cloud the concentrations peaks around the MVD, and is less steep.

It seems that in some ways that the artificial cloud generated by the HISS inflight tests closely approximate the so called natural cloud. At this point, it is important to expand on the idea of natural icing clouds, and the question, how closely must the icing cloud be simulated. One must note that it is quite difficult to define the so called natural icing cloud due to the fact that there are different types of clouds, and within the cloud there may be large variations of MVD and LWC. Also the exposure time is an important factor in determining the extent of ice accretion. Thus with many different icing conditions the question of how closely should the MVD and the LWC be simulated must be posed. In the following section, this specific issue will be investigated.

3.0 DROP IMPACTION/ICE ACCRETION

3.1 INTRODUCTION:

Although a comparison of the ice accretion obtained with the HISS artificial clouds was judged to be similiar to that experienced with natural clouds, this judgement was of a qualitative nature as no measurements were made of the rate of ice growth. In fact a large part of the assessment as to the degree of simulation of natural clouds in the HISS program was based on the similarity of the liquid droplet parameters such as MVD, LWC, and the drop size distributions. It is realized that this method of establishing similarity achieved with an artificial cloud may be considered adequate for qualifying the operation of the de-icing system. At the same time it should be noted that such a judgement of similarity does leave room for uncertainty. Hence it is anticipated that quantitative comparisons between artificial clouds and natural clouds with respect to the ice accretion problem may be a desirable goal. However even if one were to quantify the discrepancies in the droplet parameters, this alone would not provide a good measure of the rate and geometric location of the ice formed. As a result this section attempts to focus on the problem of developing criteria for judging the degree of simulation of ice accretion. The basis for the following discussion lies in trying to quantitatively relate any deviations in droplet parameters to the subsequent deviations in the rate of ice accretion. In order to do this it is necessary to consider the impaction problem between the droplets and the airfoil. This is particularly important since the probability of larger droplets striking the surface is greater than that for smaller ones. Hence deviations in the droplet size distribution in the larger drop size region between the HISS and the natural cloud can cause appreciable differences in the mass flow rate of water drops which actually strike an airfoil and subsequently freeze.

The following discussion covers the characteristics of the natural clouds and reviews the simulated drop distributions with respect to those for natural clouds. The overall impaction problem is briefly covered. Finally two size distributions; one for a natural cloud and one for a HISS cloud are used to find the mass flow rate of water that actually impacts a surface. This is done for both a cylinder and an airfoil.

3.2 INTRODUCTION TO CHARACTERISTICS OF ICING CLOUDS:

In order to determine just how close the liquid water content, and the median volumetric diameter are simulated with artificial clouds, a basic understanding of the physical structure of icing clouds is required. There are principally two types of icing clouds; they are the stratiform and cumuliform clouds. They differ as to the physical shape, range and variation of LWC and MVD, altitude, etc. In the following discussion the basic characteristics of the two types of the clouds will be presented.

The stratiform clouds are characteristically flat and elongated; the maximum probable cloud depth is 6500 feet above the cloud base; the horizontal range is from 20 - 200 miles. The cloud base altitudes may range from 3,000 ft. to 22,000 ft., with temperatures of $0^{o}C$ to $-30^{o}C$. Stratiform clouds existing at temperatures below O C generally contains light to moderate liquid water content (LWC: 0.1 - 1.0 gm/m**3), and the median volumetric diameter ranges from 10 - 30 microns. It has been observed that the LWC increases with an increase in altitude; however the overall trend is the reduction of the LWC as the temperature increases. It has also been observed that icing encounters with the stratiform clouds are most likely in altitudes ranging from 3,000 - 6,000 ft. while icing encounters above 22,000 ft. are rare.

Typical cumuliform clouds may vary from two to six miles in horizontal extent at altitudes from 4,000 to 24,000 ft., with moderate to heavy liquid water contents of 0.2 - 2.5 gm/m**3 or more. The median volumetric diameter of the clouds are found to range from 15 - 50 microns or larger. The cumuliform clouds are considerably more turbulent than the stratiform clouds and the LWC is not found to be uniform as with the stratiform clouds. The icing in the cumuliform clouds are typically two or three times more severe than the stratiform clouds and the icing encounters are most likely to occur at altitudes from 8,000 to 12,000 ft. In the table below, the basic characteristics of the two types of clouds can be seen.

Table 5: ICING CLOUD CHARACTERISTICS

Features	Stratiform cloud	Cumuliform cloud
Typical LWC	0.1 - 1.0 gm/m**3 (Light - Moderate)	0.2 - 2.5 gm/m**3 (Moderate - Heavy)
Typical MVD	10 - 30 microns	15 - 50 microns +
Cloud depth	6500 ft. Max.	
Horizontal extent	20 - 200 Miles	2.6 N miles
Vertical extent	6500 ft.	4,000 - 24,000 ft.
Altitude	3,000 - 22,000 ft. (base altitude)	8,000 - 12,000 ft.
Temperature	-30^{0}C to 0^{0}C	
Variance of LWC	- LWC increases with altitude (reduced as T decreases) - Icing above 22,000 ft. is rare - Minimum icing temperature is about -30^{0}C	- LWC less uniform Icing above 22,000 ft. are rare - Minimum icing temperature is about -30^{0}C - Icing is about 2-3 times severe as stratiform clouds

At this point it should be noted that there are other sources of aircraft icing. Additional icing could occur due to snow or the freezing rain. The freezing rain is characterized by some large droplets of up to 1000 microns, temperatures of 0^{o}C to -4^{o}C, altitudes from 0 - 5,000 ft., and a liquid water content of about 0.15gm/m**3. The horizontal extent may range as much as 100 miles.

As it can be seen from Table 5, the liquid water content for either cloud can vary by at least an order of magnitude. This range of change can also be found within a given cloud, usually due to changes in altitude. Furthermore this same range of change within a given cloud can occur over a period of less than 24 hours. It is felt that this perspective is important in considering the problem of artificial cloud production. It would appear that the first issue that must be resolved is whether to qualify de-icing systems in artificial clouds that somehow are judged to be typical or in clouds that are considered to be the worst case. In either case it would appear that the phrase "simulated cloud" is at present defined in the loosest sense. That is the MVD and the drop size distribution for a simulated cloud only have to possess the same general values as those of a natural cloud.

3.3 ARTIFICIAL - NATURAL CLOUD SIMULATION:

As reported in section 2.4.3 the HISS inflight tests have produced artificial clouds with drop parameters in the range found for natural clouds. This brief section reviews these results with respect to natural clouds. At present this is the only basis for comparison available. The approach taken in this study is that a comparison of cloud droplet parameters alone is inadequate to judge the degree of simulation and that drop impaction must be considered too. In examining the drop impaction problem the drop size distribution curves discussed here will be used.

Figure 9 shows the drop size distribution for both a natural cloud and artificial HISS cloud. There is nothing unique about the natural cloud shown which for the present can only be interpreted as being perhaps typical. Nonetheless, as noted in the figure, there is some deviation in the two curves in the larger droplet radii portion of the distribution curve. From a qualitative viewpoint the two curves appear to be quite similar. Nevertheless these two distribution curves will be used later to arrive at a quantitative measure of the difference in the resulting ice accretion because the two curves are not identical.

3.4 IMPACTION

3.4.1 Physical Description of Impaction

Up to this point the artificially generated cloud was compared against the natural icing cloud by comparing the respective median volumetric diameters and liquid water contents. This basis of judgement provides a first cut approximation as to the quality of the icing cloud simulation. It is rather difficult to quantify the difference in ice accretion due to flights through the natural cloud and the artificial cloud. In

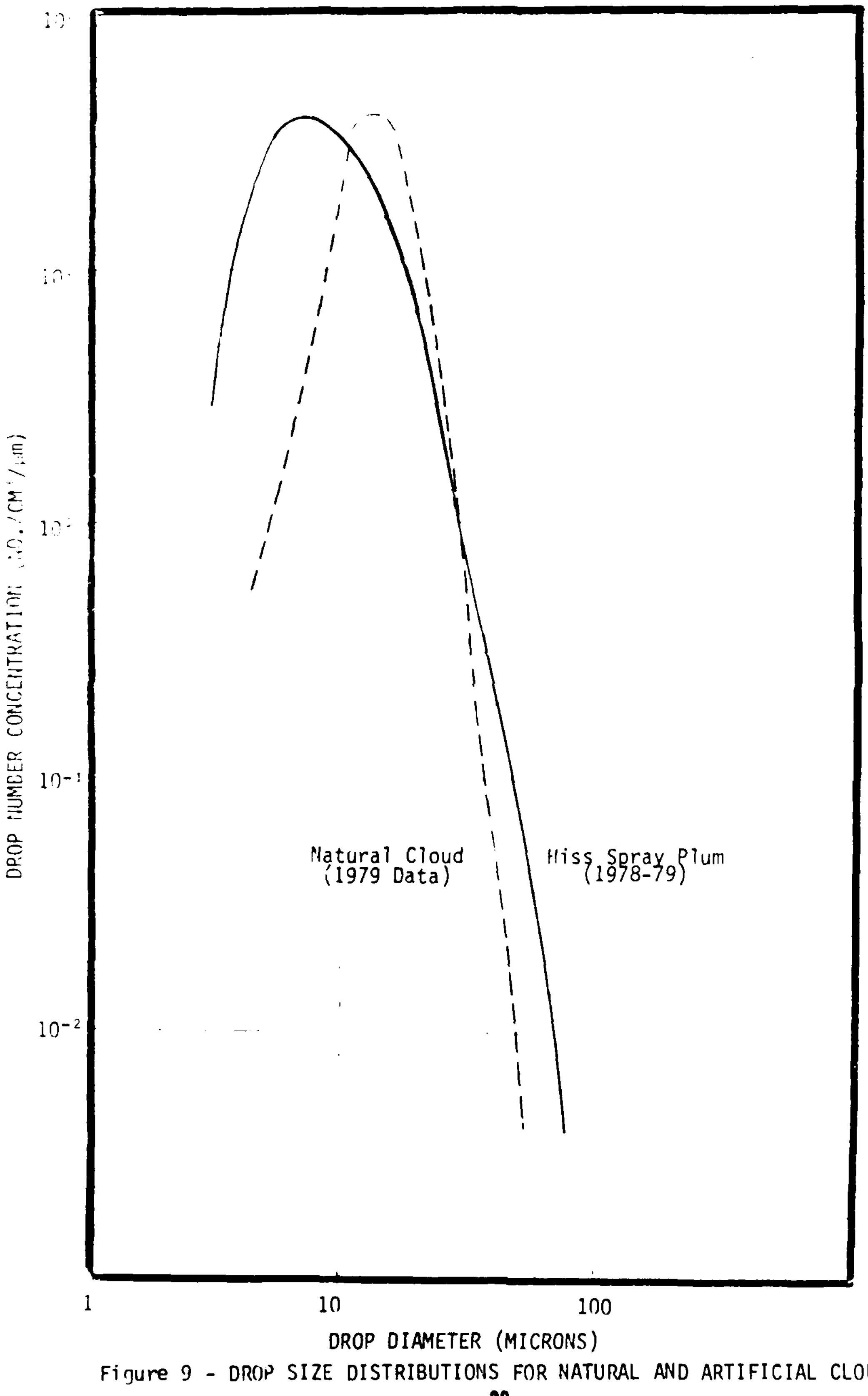


Figure 9 - DROP SIZE DISTRIBUTIONS FOR NATURAL AND ARTIFICIAL CLOUDS (5)

the following section a simple analysis is made for both a cylinder and an airfoil moving through both an artificial cloud and a natural cloud. A drop impact analysis is performed first on a cylinder rather than on an airfoil due to its simplicity of analysis and due to the fact that the angle of attack is not important. The analysis consists of trajectory calculations of the droplets as they are swept with the flow stream into the cylinder.

In actual icing conditions the ice accretion depends on many variables; however for a fixed flight condition the ice accretion is a function of the droplet distribution. Typically larger droplets have a higher probability of impinging on an airfoil than smaller ones traveling at the same speed. Therefore the larger droplets have a larger role in dictating the rate of mass flux impinging on the surface. It would therefore be preferable to match the droplet distribution as close as possible. In the following section the problem of mass flux impinging on a surface as related to the droplet distribution is investigated. In particular the sensitivity of the mass flux impingement to the distribution is covered.

3.4.2 Effective Liquid Water Content

In this section the sensitivity of the droplet impingement to the droplet distribution is investigated. The curves of the number concentration of the droplet particles vs. the droplet diameter as shown in Figure 9 were used to define the droplet distribution. In this section the droplet distribution for the

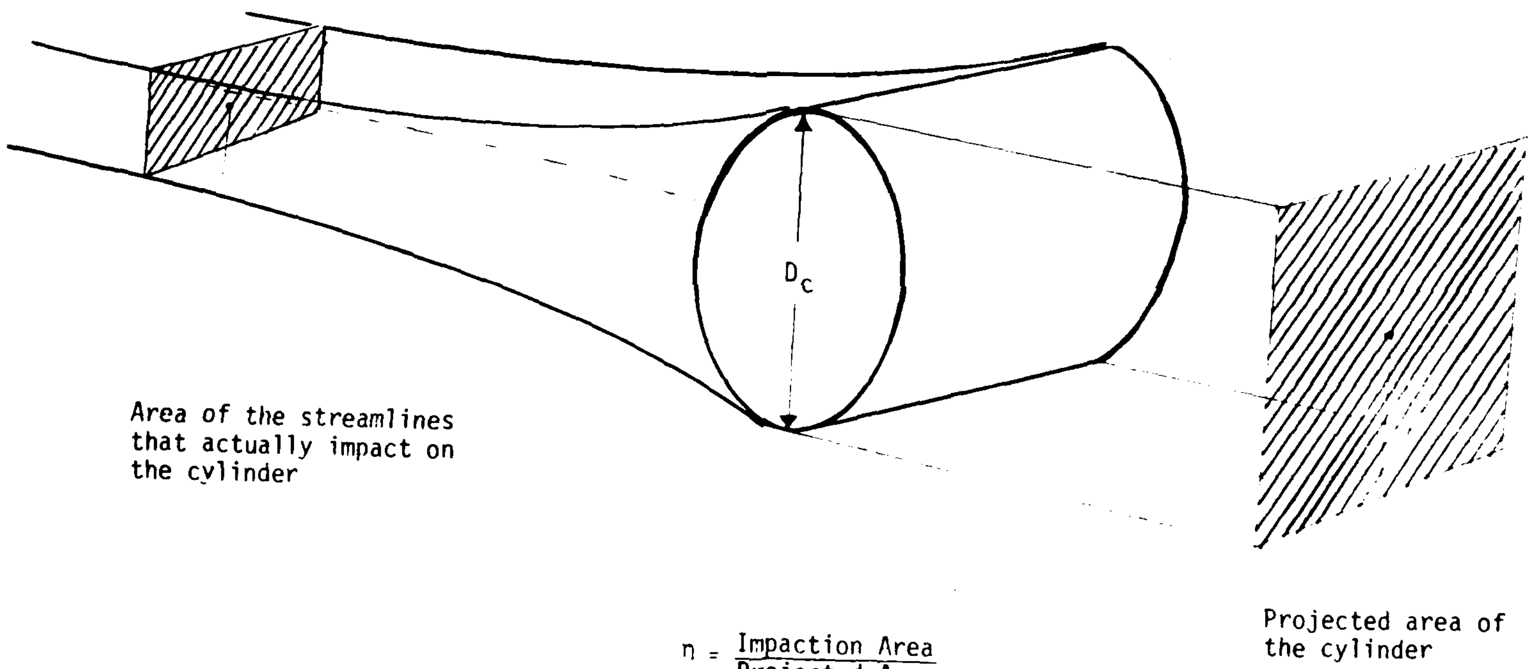
Hiss Spray Plume (1979-80) and the natural cloud (1979) was tabulated by reading points from the graph. From the tabulated data the LWC was calculated by converting the number distribution into mass distribution followed by a numerical integration. The MVD was obtained in a similiar fashion except that the numerical integration was obtained by selecting a trial value for the MVD and calculating the LWC for the droplets larger and smaller than this value. If the LWC on the right and left sides were nearly equal, then the guessed value of the droplet diameter was deemed to be the median volumetric diameter.

After the LWC and the MVD of the HISS and the natural cloud were determined, the effective LWC impinging on a object was determined. The effective LWC, here, is defined as the fraction of the actual liquid water content that actually impinges on an object in the cloud.

3.4.3 Impaction Efficiency

Cylinder

The impaction efficiency is defined as the ratio of an effective area to the actual projected area of the cylinder, see Figure 10. This impaction efficiency represents the percentage of the droplets in the frontal projected area of the cylinder through which droplets flow and actually impact the cylinder. This parameter is determined by droplet trajectory calculations for the flow field around the cylinder. This flow field can be represented by a set of ordinary differential equations, where the viscous force acting on the droplet can be approximated by



$$\eta = \frac{\text{Impaction Area}}{\text{Projected Area}}$$

Figure 10 - CYLINDER IMPACTION EFFICIENCY

the Stokes Law for low Reynolds numbers. When these differential equations are coupled and solved, one can obtain the actual trajectory of the droplet. The trajectory depends on the initial starting position relative to the center of the cylinder. The chances for collision increases for droplets closer to the center streamline. There is a dividing streamline away from the centerline of the cylinder where the droplets no longer hit the cylinder. Droplets flowing along this streamline will skim the cylinder. The collision efficiency is therefore defined as twice this length divided by the diameter of the cylinder.

Airfoil

For airfoils the upper and lower tangent streamlines are considered to form the envelope in which particles may strike the airfoil. It is assumed that particles moving in streamlines outside of this envelope will not impact the airfoil, see Figure 11.

3.4.4 Impaction Equations

In performing the ice accretion calculation it is assumed, for the purpose of discussion, that all droplets hitting the surface of the cylinder or an airfoil freeze on contact. It is also assumed that the cloud is a homogenous mix of droplets of different sizes. The analysis basically involves calculating the trajectory of the droplets in the vicinity of the object. This is done by determining the flow field around the object, and calculating the interaction of an approaching droplets with the

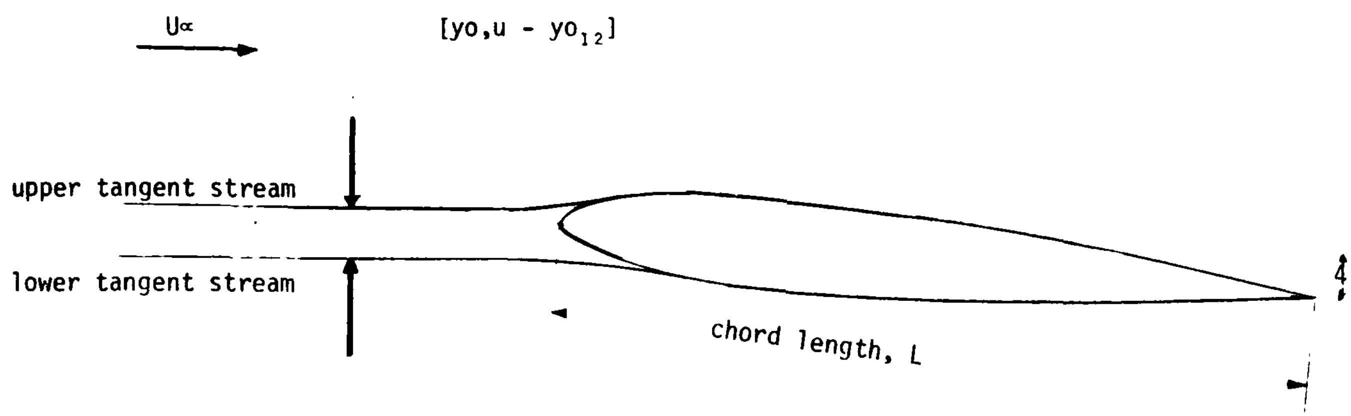


Figure 11 - AIRFOIL IMPACTION EFFICIENCY

flow field. This is typically modeled by means of coupled first order differential equations describing the flow field and the interaction of the droplet with it.

Brun and Mergler (2) solved the equation of motion of a water droplet written in the dimensionless form as:

$$\frac{dv_x}{dt} = \frac{C_D R_e}{24} \frac{1}{K} \left(u_x - v_x \right)$$

and

$$\frac{dv_y}{dt} = \frac{C_D R_e}{24} \frac{1}{K} \left(u_y - v_y \right)$$

Also the impaction parameters K & ϕ are defined as:

$$K = \frac{2}{9} \frac{\rho_w a^2 U}{\mu R_c} \qquad \phi = \frac{18 \rho_a^2 R_c U}{\mu \rho_w}$$

The air velocity components for a cylinder in a uniform, potential, and incompressible flow in two dimensions and without circulation are:

$$u_x = 1 + \frac{y^2 - x^2}{(x^2+y^2)^2}$$

$$u_y = -\frac{2xy}{(x^2+y^2)^2}$$

The equations are solved in terms of the dimensionless parameter K. The output results from the computation are often presented in terms of non-dimensional groups of ϕ and K. The parameter K is an indication of the ratio of the inertial forces to the viscous forces. It is representative of the ratio of the inertia forces tending to keep the droplet heading in its original direction, and the viscous forces which tend to force the droplet to follow the streamlines and thus deflect in the vincinity of the object. The parameter is useful because it is not dependent on the droplet size. It gives an indication as to the test altitude for a given object and flow velocity.

During the droplet trajectory calculations the droplets are assumed to approach the object parallel to the flow stream as a homogeneous mix. All droplets except those on the centerline of the object are deflected to some extent. Hence the droplets away from the centerline are more likely to deflect and miss the object. For a given flow condition, droplets at a particular distance away from the centerline will just miss the object by skimming along the surface. In the analysis the droplets bounded by the region between the centerline and the this streamline are assumed to collide with the object. The droplets outside this region are considered to miss the object. This region of collision is defined as $Y_{\theta,u} - Y_{\theta,L}$ in Figure 11 where the size of this region is a function of the droplet diameter.

In terms of the analysis the impaction of the homogeneous mix of the clouds can be broken down into the sum of the impaction of several constant droplet size clouds. During the calculations the LWC contribution due to different droplet size ranges was multipled by the collision efficiency to determine the fraction of the LWC impacting the surface. Summing up the effective LWC for each droplet size hitting the object, the overall effective LWC impacting the surface is calculated, which then can be used to determine the mass flux of droplets hitting the object.

From Table 6 it can be seen that the deviation of the LWC and the MVD of the HISS cloud from the natural cloud was in order of 12 - 30% for cylinders. For the 0.6 meter cylinder the rate of impaction for the natural cloud was less than that for the HISS cloud, while for the cylinder 0.2 meters in diameter the reverse was true. The error for the former case is 24.7% while for the latter case it is 11%. It is interesting to note that the droplet impaction due to the natural cloud was greater for the smaller cylinder, while it was smaller for the larger cylinder. The reason for this behavior is that even though the LWC is higher for the natural cloud, its MVD value was lower than that of the HISS cloud which implies that a large portion of the mass was clustered around droplets of small diameters. A larger cylinder tends to affect the flow field further away from the it; hence the droplets start deflecting further away from the cylinder and thus decrease the collection efficiency. Small droplets are more prone to the deviating streamlines and thus a large percentage of the mass contained in the small droplets for the natural cloud could miss the cylinder. However for the smaller cylinder the deflecting forces are not as pronounced as those for the larger cylinder, and thus a larger portion of the smaller droplets will hit the cylinder.

Airfoil

Calculations similar to those for a cylinder were made for a NACA 65A004 airfoil to serve as a rough check on the sensitivity of the calculated impingement of water droplets to the surface

Table 6: CYLINDER IMPACTION CALCULATIONS

Object: Cylinder
Free Stream Velocity: 200 MPH
Free Stream Temperature: $0^{o}C$

HISS Cloud: LWC = 0.534 gm/m**3, Mvd = 22 microns.
Natural Cloud: LWC = 0.725 gm/m**3, MVD = 17 microns.

Cylinder Diameter: 0.6 meters

Cloud Type	Effective LWC	Droplet Accretion Flux
HISS	0.136 / 25%	12.1 gm/(m**2)(s)
Natural	0.109 / 15%	9.7 gm/(m**2)(s)

Cylinder Diameter: 0.2 meters

Cloud Type	Effective LWC	Droplet Accretion Flux
HISS	0.281 / 53%	25.1 gm/(m**2)(s)
Natural	0.316 / 44%	28.2 gm/(m**2)(s)

geometry. This approach is also accomplished by breaking the drop size distribution curves into segments where for any given size range the inertia parameters, K and the Reynolds number of the free stream are found:

$$K = \frac{2}{9}\,\frac{\rho_w d^2 U}{\mu L} \qquad\qquad Re = \frac{d\,\rho_a U}{\mu}$$

Then the spacing between the upper and lower tangents to the air stream, $[Y_{o,u} - Y_{o,L}]$, is found using Figure 12. After $[Y_{o,u} - Y_{o,L}]$ is found the rate at which water strikes the airfoil per unit span is calculated using:

$$\frac{dW_{ice}}{dt} = (y_{o,u} - y_{o,L}) \cdot U \cdot LWC$$

For the HISS artificial and the natural cloud drop size distributions shown in Figure 9, a 34 percent difference in the mass flow rate of water impinging on the airfoil surface was found assuming the same LWC, see Table 7. This difference is about twice that found for the cylindrical case discussed earlier and emphasizes the importance of droplet distribution. Appendix A gives the calculations for the airfoil analysis.

From this limited comparison it appears reasonable to assume that ice accretion differences may be appreciable for artificial and natural clouds even though the apparent differences in LWC and drop size distributions for the two clouds are not large. It should also be noted that the size of the surface exposed to the flow affects this difference as noted for the results for two

Table 7: TOTAL CALCULATED RATE/(LWC-SPAN)-Airfoil

HISS SPRAY PLUME (1979-80)	2.084
NATURAL CLOUD (1979 DATA)	3.165

$$\% \text{ DIFFERENCE} = \frac{\frac{3.165}{LWC_{N.C}} - \frac{2.084}{LWC_{HISS}}}{\frac{3.165}{LWC_{N.C}}}$$

FOR EQUAL LIQUID WATER CONTENTS:

% DIFFERENCE = 34.15

different sized cylinders. It is also important to note that it is not realistic to assume that all droplets that actually strike the surface will produce accretion since this will depend on the drop velocity, surface condition and the angle of impact (6).

4.0 CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

Wind tunnel tests were principally useful because they furnished the basic information as to which nozzles are preferable and the way they should be mounted on the spray boom. It was determined that the Sonicore nozzles produced the most desireable spray droplet distribution. In the HISS inflight test program it was found that the droplet distribution produced was a reasonable simulation to that found in a representative natural cloud. The LWC and the MVD were found to be fairly close to that found in the natural cloud.

A quantitative evaluation of the artificially generated clouds was never attempted except in calculating the LWC and the MVD. The LWC and the MVD give a general indication of the closeness of the simulation. However, these parameters do not tell how the differences between the artificial and the natural cloud affect the overall rate of ice accretion. The calculation of the rate of droplet inpingement could be used as a basis in evaluating artificially generated clouds. For a given cloud the rate of impingement on a surface depends principally on the geometry of the surface and its velocity relative to the cloud. It must be noted that it is difficult to define a typical natural icing cloud because there are many types of icing clouds, icing conditions, and by the fact that the cloud properties change with the altitude and temperature.

It is necessary to find a way of quantitatively evaluating the artificially generated cloud. With the set of guidelines, the icing simulation tests could be readily evaluated. In the following section, a set of recommendations is presented.

4.2 RECOMMENDATIONS

This section summarizes the recommendations obtained from the body of this report and from the observations made during the review of the past work. Although the working group found that much progress had been made in recent years in all aspects of the icing problem, there are definite requirements for better instrumentation and methodology for analyzing various techniques. The following recommendations are listed below:

1. Establish criteria for simulation: Considering the possible range of drop size distributions as well as MVD and LWC values found in natural clouds, criteria for selecting a worst case or some type of typical case for qualifying deicing systems are needed.
2. Standardize data acquisition procedures for cloud measurements including required list of measured parameters.
3. Develop a data bank of icing test results containing all important droplet and cloud parameters.
4. Establish extrapolating or scaling technique between small size and larger size airfoils for ice accretion.
5. Individually determine the sensitivity of ice accretion to MVD, LWC, and drop size distribution in an experimental program.
6. Develop a better understanding of the drop impaction/ice

accretion phenomenon with regards to the following variables:

droplet impact velocity

surface geometry and material

surface temperature

droplet temperature

humidity

free stream turbulence, intensity and scale

7. Determine the effect, if any, of the size of artificial cloud on the ice accretion.

8. Develop correlation equation to relate the rate of ice accretion to the relevant parameters, in a dimensionless form.

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APPENDIX A

Appendix : SAMPLE CALCULATION FOR AIRFOIL

Specifications:

Droplet Diameter = 20

Flight Speed = 100 miles/hour = 4.7 m/sec

Altitude = 20,000 feet

Chord Length = 4 meters

Flow Conditions at Sea Level:

ρ_a = 1.169 kg/m**3

μ = 1.6 x 10^{-5}

ρ_w = 1000 kg/m**3

Conversion of Flow Conditions from Sea Level to 20,000 feet

ρ_a = (1.169)(5.32 x 10) = 0.6228

μ = (1.6 x 10)(0.8894) = 1.423 x 10^{-5}

$\rho_w \simeq$ 1000 kg/m**3

$$Re = \frac{d \rho U}{\mu}$$

$$= \frac{(20 \times 10^{-6})(0.6228)(44.7)}{1.423 \times 10^{-5}}$$

$$= 39.127$$

$$K = \frac{2}{9} \frac{\rho_w d^2 u}{\mu L}$$

$$= \frac{(2)(1000)(20 \times 10^{-6})^2 (44.7)}{(9)(1.423 \times 10^{-5})(4)}$$

$$= 0.0698$$

$$1/K = 14.325$$

From Figure 12 it is found that:

$$\frac{y_{o,u} - y_{o,L}}{L} \simeq 0.025$$

$$y_{o,u} - y_{o,L} = (0.025)(4) = 0.100$$

$$\frac{W'_{ice,20\mu}}{LWC} = (y_{o,u} - y_{o,L}) \cdot u = (0.100)(44.7) = 4.47$$

Rate of icing corresponding to 25 droplets per LWC per unit span.

Table A gives the results for all ranges of droplet diameters.

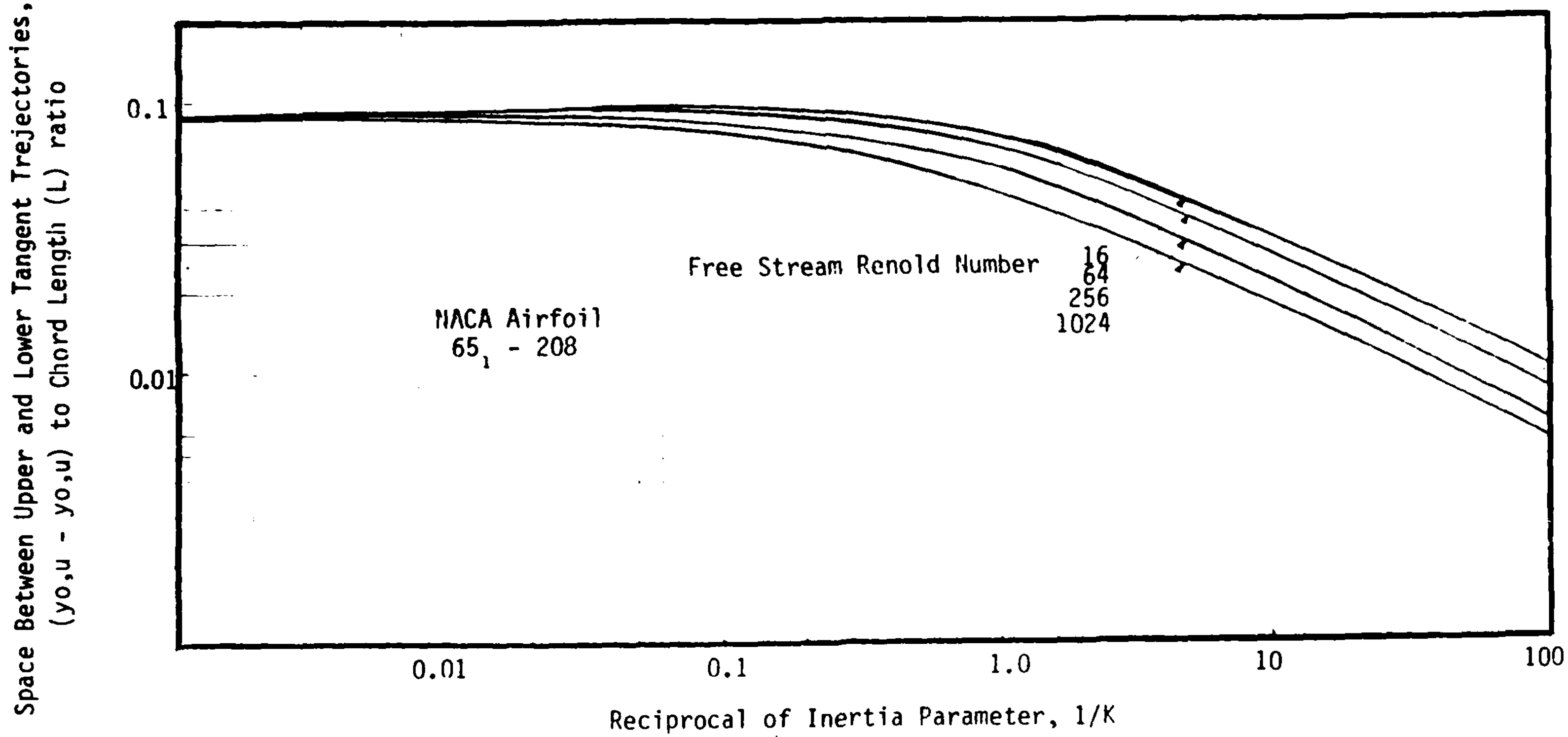

Figure 12 - IMPACTION/INERTIA CURVES FOR NACA AIRFOIL

SENSITIVITY RESULTS FOR VARIATION IN DROP SIZE DISTRIBUTION

(Airfoil)

For HISS Cloud

$\Sigma x.y$ = 522.738

Σy = 250.857

$$\frac{\Sigma x.y}{\Sigma y} = 2.084$$

Total Icing Rate Per LWC Per Unit Span For Hiss Cloud

For Natural Cloud

$\Sigma x.y$ = 420.682

Σy = 132.898

$$\frac{\Sigma x.y}{\Sigma y} = 3.165$$

Total Icing Rate Per LWC Per Unit Span For HISS Cloud

$$\% \text{ Difference} = \frac{\frac{3.165}{LWC_{N.C}} - \frac{2.084}{LWC_{HISS}}}{\frac{3.165}{LWC_{N.C}}}$$

If both LWC values are assumed to be 1, the above equation shows that the percent difference is 34.15%. This relatively large difference is due to differences in the number densities of the two clouds.

TABLE A

DIA.	RE	1/K	$\frac{y_{o,u} - y_{o,L}}{L}$	$\frac{W'_{KE}}{LWC}$	No. Density HISS	No. Density Nat. Cloud
1	1.96	5730	0			
2	3.91	1432.55	0			
3	5.87	636.69	0.0025	0.45	3.5	0.2
4	7.83	358.14	0.003	0.54	15	0.54
5	9.78	229.21	0.006	1.07	35	1.3
6	11.74	159.17	0.008	1.43	40	3.6
7	13.69	116.94	0.01	1.79	40	7.0
8	15.65	89.53	0.013	2.32	37	13
9	17.61	70.74	0.015	2.68	33	23
10	19.56	57.30	0.018	3.22	28	33

TABLE B

MVD	Re	1/K	$\frac{y_{max} - y_{min}}{L}$	$\frac{W_{ice}}{LWC}$	Guassian & HISS	Guassian & Nat. Cloud
5	9.78	229.21	0.006	1.07	35.0	1.3
10	19.56	57.30	0.018	3.22	28.0	33.0
15	29.35	25.47	0.021	3.75	12.0	40.0
20	39.13	14.33	0.025	4.47	4.5	9.0
25	48.91	9.17	0.030	5.36	1.5	1.5
30	58.69	6.37	0.035	6.25	0.7	0.5
35	68.47	4.68	0.037	6.62	0.3	0.16
40	78.25	3.58	0.039	6.97	0.16	0.07
45	88.04	2.83	0.044	7.87	0.07	0.016
50	97.82	2.29	0.048	8.58	0.047	0.008
55	107.60	1.89	0.051	9.12	0.037	0.0038
60	117.38	1.59	0.055	9.83	0.016	
65	127.16	1.36	0.059	10.55	0.010	
70	136.95	1.17	0.061	10.91	0.008	
75	146.73	1.02	0.063	11.26	0.005	
80	156.51	0.90	0.065	11.62	0.0038	
85	166.29	0.79	0.066	11.80		
90	176.07	0.71	0.068	12.16		
95	185.86	0.63	0.070	12.52		
100	195.64	0.57	0.072	12.87		
105	205.42	0.52	0.075	13.41		
110	215.20	0.47	0.077	13.77		
115	224.98	0.43	0.079	14.13		
120	234.76	0.40	0.081	14.48		

LIST OF SYMBOLS

a - droplet radius

d - droplet diameter

C_D - drag coefficient for droplet in air

D_c - cylinder diameter

K - inertia parameter

L - airfoil chord length

R_c - cylinder radius

Re - Reynolds number

t - time

U - free stream velocity

u - local air velocity, ratio of the local air velocity to the free stream velocity

v - local droplet velocity, ratio of the actual droplet velocity to the free stream velocity

$Y_{o,L}$ - lower tangent stream

$Y_{o,u}$ - upper tangent stream

x,y - rectangular coordinates, ratio of the actual distance to cylinder radius, R_c

μ - viscosity of air

ρ_a - density of air

ρ_w - density of water

τ - time scale

ϕ - dimensionless parameter

η - collision efficiency