AIRCRAFT ICE PROTECTION

Report of Symposium

This report has been approved for general availability

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by

ENGINEERING AND MANUFACTURING DIVISION
FLIGHT STANDARDS SERVICE

DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
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SUMMARY

The subject of aircraft ice protection has provoked much controversy and discourse among theorists, designers, laboratory and test engineers, and flight operations people. In view of this diversity of opinion and variety of approach, some difficulty has been experienced in applying current standards and in maintaining uniformity in the substantiation of aircraft ice protection.

This symposium recognized the need to exchange ideas and it provided a general review of icing criteria, ice protection standards, methods of compliance, and service experience. It also served as a general refresher for Federal Aviation Administration personnel involved in the evaluation of aircraft ice protection.

Technical papers were presented by government research and test organizations, aircraft engine and aircraft manufacturers, military services, and airline operators. The symposium presentations were given by government and industry representatives with particular expertise in the development, testing, operation, and maintenance of aircraft ice protection systems.

This report is intended to serve as a reference document to supplement other information on the subject since it contains current information on the icing environment and aircraft ice protection.

INTRODUCTORY REMARKS

Mr. Stephen H. Rolle, Chief, Propulsion Branch, Engineering and
Manufacturing Division, in his capacity as symposium chairman,
extended a welcome to all industry, airline, military and
government representatives participating in the Federal Aviation
Administration symposium on aircraft ice protection. He then
introduced Mr. Sliff, Deputy Director, Flight Standards Service.

Mr. Sliff advised the participants in the symposium that they
face a challenge in providing protection for the aircraft so that
it can be operated safely in any icing environment that may be
encountered. He also recommended that this should be accomplished
through the inherent capability of the aircraft design rather than
to rely upon operational restrictions to assure crew and passenger
safety. It was also stated by Mr. Sliff, that development aircraft,
such as the jumbo jets and supersonic transport, also pose a
challenge when it is realized that, in addition to the technical
problems associated with this advance in the state-of-the-art,
they must also have the capability to cope safely with such
adverse weather conditions as freezing rain, hail, icing, and
lightning. Mr. Sliff then emphasized the need for a review of
current design criteria and standards for aircraft ice protection,
and he expressed the hope that the symposium would be productive.
He also extended the support of his office in the accomplishment
of this objective.

Mr. Slaughter, Chief, Engineering and Manufacturing Division,
agreed that the participants in the symposium should accept the
challenge presented to them. He also remarked that this symposium
recognized the need to develop aircraft ice protection criteria
on a sound and technical basis. He briefly reviewed the topics
listed in the planned technical program and expressed the
appreciation of the Federal Aviation Administration for the
presentations. It was noted that the technical papers for this
symposium were prepared by experts in icing phenomena and aircraft
ice protection from industry, the airlines, the military services,
and various government organizations.

Mr. Rolle explained that a document will be published containing
all of the symposium technical papers and the discussions following
each presentation. These publications will be made available to
all of the attendees and to all interested parties who did not
have an opportunity to attend.

REVIEW OF ICING CRITERIA

William Lewis
NASA Lewis Research Center

Rational design of ice-protection equipment requires a definition of
the atmospheric conditions in which the system is expected to operate.
The primary parameters are liquid water content, effective drop diameter
and temperature. Also of interest are altitude and the horizontal and
vertical extent of the conditions.

The correspondence between an optimum envelope of design conditions and
the actual statistical distributions of the parameters as found in the
atmosphere is complex. Actual conditions in the atmosphere are highly
variable, and the most extreme conditions are of brief duration and small
extent. The probability of encountering severe conditions is also a
function of flight operating procedures and climatological factors. The
selection of design conditions also require consideration of the tolerance
of the system to temporary overloading and especially the ability to
recover after short periods in extreme conditions.

The investigation of icing-cloud parameters began with the development
of heated wings. Early tests conducted by NACA Langley had established
that if sufficient heat was supplied to produce a surface-temperature
rise of 100°F in dry air from the leading edge to 10 percent chord, the
wing would remain clean in icing conditions. This empirical criteria was
used to design experimental systems for military aircraft during the war,
but it was recognized that a rational design procedure required a know-
ledge of the range of liquid water content and drop size. Flight inves-
tigation of the meteorological parameters was undertaken in 1944 by the
Army and NACA.

Most of the flight measurements of liquid water content and effective
drop diameter were made by means of the rotating-cylinder technique.
This method consisted of exposing a set of four rotating cylindrical
collectors of different diameter with axis normal to the air stream for
a measured time interval. The apparatus was then disassembled and the
samples stored and weighed separately. Theoretical relations involving
drop diameter, cylinder diameter, collection efficiency and airspeed were
used to derive average liquid water content and effective drop diameter.
Values of drop size obtained in this way are believed to represent the
volume median; half the water is in larger drops, half in smaller. The
method also yields a rough measure of the spread in the size distribution.
More dependable information on the distribution is obtained from actual
counts of drops captured in oil, but few such determinations have been
made. My own opinion, based on both cylinder data and sample counts is
that in a typical cloud about 50 percent of the water is in drops

between 80 percent and 130 percent of the effective diameter.

Measurements in icing clouds were made in the upper Mississippi Valley
by the Air Force, AIRL, in the Great Lakes area by NACA Lewis; and in
western U.S. by NACA Ames.

By 1948, these investigations had led to an accumulation of about 1000
individual measurements of water content and effective drop size
obtained in 240 encounters with icing conditions. At the request of
the NACA subcommittee on icing problems, the Ames Laboratory prepared
a tentative table of design conditions for presentation to the sub-
committee in October 1948. After review and discussion, the subcommittee
directed publication of this table of recommended design conditions as
a technical note (ref. 1). The aim was to provide the industry with
tentative standards to fill an immediate need. It was expected that
revisions would be required as more data became available and operating
experience was accumulated.

The recommended design conditions included envelopes of maximum-severity
conditions applicable to cumulus clouds and stratiform clouds in winter.
These envelopes, called "maximum intermittent" and "maximum continuous"
icing conditions were adopted by the Civil Aeronautics Administration
and became the basis of standards for certification. These same standards,
with only minor additions, are in effect today.

These design envelopes are shown in figure (1) in the form of curves
showing combinations of liquid water content and temperature for selected
values of drop diameter. Separate envelopes were proposed for cumulus and
layer-type clouds because it was recognized that cumulus clouds were limited
in horizontal extent but could extend over a large range of altitude,
whereas supercooled stratiform clouds were extensive in a horizontal
direction but definitely limited in vertical thickness.

I want to make it prefectly clear that these curves do not represent
physical relations among the variables. Instead, they represent combina-
tions of the three variables believed to have a sufficient frequency of
occurrence to warrant consideration in design. Although physical models
were useful in defining the variation of water content with temperature,
the relation with drop size was primarily statistical. Drop size was
found to be only weakly correlated with either water content or temperature.
Lower values of liquid water content were recommended in combination with
larger drops simply because the larger values of effective diameter occur
less frequently. In layer clouds (continuous icing) the occurrence of an
effective diameter exceeding 40 microns is already a rare event and,
therefore, should be considered in combination with a typical, rather than an
unusually high, value of water content.

The basic difference between the two envelopes is the horizontal extent of
the conditions. Meteorologically, they represent different cloud types.
Cumulus clouds give rise to intermittent icing whereas continuous icing
is ex ienced in stratiform cloud types.

The selection of design conditions for each category was based on the concept that the anti-icing system should provide full protection in roughly 99 percent of icing encounters and that slight, temporary impairment of performance could be accepted. It was realized that on rare occasions icing of exceptional severity might require evasive action. In defining the envelope of combinations of W, d and T, we tried to select combinations having an equal probability of occurrence. By an examination of statistical distributions of the parameters, singly and in combination, it was determined that the condition that 95 percent of cases lie within the envelope was roughly equivalent to a probability of 1/1000 that all three variables represented by a single point would be exceeded simultaneously. Considering the fact that we had data from 167 encounters in layer clouds and 73 in cumulus, statistical extrapolation to a probability of 1/1000 was more than daring, it was downright foolhardy. We also relied on a physical understanding of the meteorological processes of cloud formation and on engineering experience with existing thermal systems.

On reviewing these design requirements after twenty years, two questions arise:

    (1) Do the specified envelopes actually represent the 99th percentile?, and,

    (2) So what? (Is it really necessary to know the probability level?)

It is suggested that operating experience with systems designed to current specifications provides the best and most pertinent source of information as to whether these specifications are marginal or overconservative. Therefore, changes should be based on experience rather than on meteorological data.

Nevertheless, it is of interest to reexamine the original design envelope in the light of additional data. Only a small number of measurements of cloud-drop size have come to my attention in the last 20 years and these are consistent with frequency distributions from the earlier data. In the case of liquid water content, three rather extensive collections of data have been completed.

    (1) NACA Lewis Laboratory collected icing-rate data using automatic instruments installed on commercial and military transport aircraft in scheduled service on domestic and overseas routes. Data were collected in a total of 1800 icing encounters during five years of operation. (ref. 2, 3, 4)

    (2) The National Research Council of Canada used a rotating-disk meter on a research airplane on ice-seeking flights to collect data on liquid water content in 1182 encounters with icing. (ref. 5)

    (3) The Russian Meteorological Service measured liquid-water content of scheduled meteorological sounding flights at several stations. A total of 4800 measurements of liquid water content were obtained at temperatures below $0^{\circ}C$. (ref. 6)

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I have been able to locate only rather brief summaries of the Canadian and Russian programs and so cannot comment on them in detail. Also, I was not personally involved in the Lewis Lab program but have some knowledge of its history.

Anticipating a need for more extensive and representative statistical icing data, both Ames and Lewis Laboratories in 1949 undertook to develop automatic instruments suitable for routine use on transport airplanes. Unfortunately, the difficulties involved in the measurement of cloud parameters proved so formidable that neither attempt was completely successful. The Ames Laboratory developed a heated-wire instrument for measuring liquid water content that provided excellent in flight, in the hands of research personnel. However, it was to complicated for automatic operation; and reduction of data was a complex and difficult procedure, therefore, it was never used extensively. The net result was an excellent research instrument and a very meager amount of data. Meanwhile, the Lewis Laboratory began with the development of a very simple cyclic icing rate meter. Problems were encountered with the calibration, but since the device was so well adapted to automatic operation, arrangements were made with the airlines to begin an extensive program of data collection. As the program progressed, difficulties with the calibration proved to be more serious than had been anticipated, but data collection continued to expand. The net result was a large amount of data providing useful information on such factors as horizontal and vertical extent of icing conditions, but considerable uncertainty remains as to the meaning of indications of icing rate and liquid water content. The data from this program was published in thre reports (ref. 2, 3, 4)each containing tabulations of liquid water content and a description of calibrations in use at that time. Apparently, as the data were worked up the calibration was changed from time to time as a result of further studies. I see no other possible explanation for the striking differences among the three reports.

One convenient statistic that may be used for an overall comparison of data from various sources is the 99th percentile of liquid water content from the entire distribution without classification by either drop size or temperature. This comparison is shown in figure 2. Values from various sources are plotted on a time scale to provide historical perspective and show the apparent trend in the airline data. The airline data and the Russian data from scheduled soundings probably contain a negligible fraction of measurements in cumulus clouds, and are therefore comparable to the early research data from stratiform clouds.

U.S. research data from layer clouds is shown classified by geographical areas but the sample is so small that the differences are not significant. The overall 99th percentile value is about .8 gm per cu meter. The NACA Airline data started at an alarming 2 g/m^3 for the 1950-51 season, fell to 1.6 in 51-52, and the final report with data for three seasons had a 99th percentile of 1.13 g/m^3. Because of the apparent trend, data in the final report were separated by season (using only entries bearing dates). If it is assumed that the time trend was mainly a result of changes in calibration and that the changes were improvements, these results indicate that the most recent and presumably most dependable data are in good agreement

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with the research data.

At the right-hand side of the figure are points representing the Canadian
and Russian data. In view of the large samples the 99th percentile points
are determined with considerable precision. The difference between the two
may reflect geographical differences, but 1 think it is more likely the
result of the fact that the Canadian data were collected on ice-seeking
flights. The average of the Canadian and Russian 99th percentile values
agrees very well with the U.S. research data. These results tend to
confirm that the 1949 envelope for maximum continuous icing conditions
does, indeed, represent approximately the 99th percentile icing condition
with respect to the overall level of liquid-water content.

In addition to the overall distribution of liquid water content it is of
interest to examine also the variation with temperature. Figure 3 shows
99th percentiles grouped by temperature for U.S. research data, U.S.
airline data and Russian data. (The Canadian data were not given in terms
of temperature in ref. 5.) Higher values from U.S. airline data may be
explained in terms of the calibration difficulties mentioned previously.
Because of the large amount of data and systematic manner of collection,
the statistical dependability of the Russian curve is very good.

An interesting anomaly is the high value for layer clouds in eastern U.S.
for data in the range from -7° to -12°C. This is probably a local effect
that shows up here because the sample included a large percentage of
measurements in northern Ohio where cold air crossing Lake Erie produces
unusually thick stratocumulus in the fall and early winter. Under these
conditions the most likely temperature at 5000 feet is between -5 and -10°C.

The fact that Russian data shows higher values of liquid water content at
temperatures below -20°C may also be due to climatological effects. U.S.
measurements at low temperatures were mostly at high altitude whereas in
Russia temperatures below -20°C are not uncommon at about 5000 feet where
conditions are more favorable for the occurrence of thicker cloud layers.

Also shown in figure 3 are points representing U.S. and Russian design
conditions for 15-micron and 16-micron drops respectively. It is seen
that both sets are in reasonable agreement with the 99th percentile of
the atmospheric conditions.

Since very little additional data has been obtained in cumulus clouds,
no satisfactory basis exists for an evaluation. A few extreme cases
have been reported and these are shown in figure 4 compared with the
"maximum intermittent" and *"maximum instantaneous" conditions. The
measurements by Neel (ref.7) show that these conditions do exist but
their importance for design is a matter of judgement.

The Russian data are of interest because of the very low temperature,
water content estimated from icing rate is not precise, and visual
estimates of icing rate are usually exaggerated, but nevertheless we

(*"Maximum instantaneous" conditions are defined in TN1855 but are not
included in CAR 4b.)

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have here a documented case of rather severe icing below -40°. Also, a similar case has been reported by Boeing in which severe icing was encountered at 36,000 feet with temperature -52°C measured in clear air at the same altitude. In view of these reports it is apparently necessary to abandon the concept that liquid water can not exist at temperatures below -40°.

In addition to the envelope of W, d, and T, the horizontal and vertical extent of the conditions are of interest, as is also the variation of average liquid water content with flight distance over which the average is calculated. Curves intended to define this relation were published as part of a probability analysis of research data and have been included in the design standards. Unfortunately the data sample from which the curves was derived was too small to give a dependable representation of the distance effect. Results from the Airline project suggest a smaller variation with distance. Since the National Research Council of Canada has collected a large number of continuous records with the rotating-disk instrument, these results, if they could be obtained in suitable form, would provide an excellent basis for an improved definition of the water content-distance relation.

Data on total horizontal extent of icing encounters obtained from the airline program is shown in figure 5. This diagram is a cumulative frequency distribution of the distance in icing. In half the encounters the icing distance was less than 20 miles, 10% extended 55 miles and 2% extended 100 miles or more.

The distribution of vertical extent is shown in figure 6. The median here is 1200 feet and seven percent exceeded 3000 ft. Values beyond this point are less probable than would be expected from simple extrapolation.

This point illustrates what may be an important factor in limiting the liquid water content in stratiform clouds. A stratocumulus cloud layer forms in the upper half of a layer of air that is mixed by the action of turbulent eddies. It appears a probable hypothesis that scale effect exists, tending to limit the vertical extent of the mixed layer to less than about 6000 feet. Beyond this point the circulation tends to break up into sublayers. This hypothesis of limited cloud-layer thickness was helpful in defining the range of liquid water from a small sample of data.

The FAR icing standards also include envelopes of temperature as a function of altitude, taken from the range on research flights. This relation is of no particular physical significance as it merely reflects operating procedures and climatological factors. There exists also a rather well defined effect of altitude (or height above the ground) on the maximum values of liquid water content.

This relation is quite different for cumulus and stratiform clouds as shown in figure 7. These envelopes of the highest values of liquid water content are based on research data. In layer-type-clouds the highest

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values of liquid water content tend to occur at five to six thousand
feet above the ground, whereas in cumulus clouds the maximum liquid
water increased with the altitude at least 15 to 20 thousand feet.
Clouds of both types have higher water content and greater vertical
extent when formed of air that comes directly from the surface layers.
In the case of stratiform clouds, the vertical motion is limited by the
thickness of the surface turbulence layer, generally less than about
6000 feet, but for cumulus clouds the sky is the limit. Since most
icing in normal operations is encountered in layer-type clouds, the
relation shown here may be useful in identifying possible problem
areas.

So far I've been discussing only clouds composed of liquid drops, but
ice clouds and mixed clouds are also important (ref. 8). If a cloud is
composed entirely of ice crystals icing does not occur on external
surfaces, whether heated or not. In mixed clouds the effect on external
surfaces is not materially different from that of the liquid water alone. As
long as the air flow is such that the ice crystals are not held in place
but are blown along after impingement, the cooling effect of the ice is
almost negligible. However, interior ducting having reverse bends or
stagnation areas may be subject to icing in snow or mixed cloud.

Although ice crystals have little direct effect in icing, the indirect
effect is of greatest importance. Because of the difference in saturation
vapor pressure, the presence of ice crystals tends to dry up the liquid
drops, thus, liquid cloud droplets cannot exist for more than a few minutes
in the presence of an appreciable concentration of ice crystals. In the
upper parts of cumulus clouds the liquid water content decreases rapidly
after the onset of snow formation. In the deep and extensive alto-stratus
and nimbostratus complexes comprising the general rain and snow areas of
cyclonic-storms, liquid cloud drops are almost completely absent in the
subfreezing portions of the clouds. It is for this reason that icing
criteria can be based on the dynamically simpler stratocumulus cloud type.

The statistical significance of ice clouds is shown in the results of an
analysis of cloud and icing frequencies observed on weather reconnaissance
flights (ref. 9). At a temperature of -5°C, sixty percent of the time in
clouds was without icing, indicating that the clouds were composed entirely
of ice crystals. At -25°C the percentage of ice clouds increased to 90%.

In addition to liquid and mixed clouds there are two other forms of icing
conditions: Freezing drizzle and freezing rain.

Since rain is melted snow, the occurrence of freezing rain requires the
presence of an inversion with a melting layer above. Very little flight
data have been taken in freezing rain. Existing design standards were
calculated for a rainfall rate of .1 inch per hour with drops 1 mm in
diameter. In connection with a study of airship icing (ref.10) frequency
distributions for temperature and rainfall rates were determined and
relations among drop size, falling speed and rainfall rate were calculated.
These statistics were used to calculate a 99th percentile envelope of con-
ditions in freezing rain.

Temp (C)	diam (mm)	L.W.C. (g/m^3)
0°	1.17	.28
-5°	1.05	.18
-10°	.75	.03

These conditions are somewhat more severe than previous recommendations. Freezing drizzle is found in and under stable cloud layers in relatively calm conditions in which time is available for the processes of collision and coalescence to produce drops of 150 to 500 microns diameter. Since a melting layer is not required, freezing drizzle can occur in a wider variety of synoptic conditions can extend to the ground, effecting landing, take off and ground operations. Without data, no more can be said. Information from operators on experience in freezing rain and drizzle would be helpful.

Thus far I have talked about the probabilities of various conditions in terms of the icing encounter as a unit of experience. There remains the question of the frequency of icing encounters.

A summary of information on this subject covering flights over ocean routes at 700 and 500 millibars was obtained from an analysis of observations by the Air Weather Service on weather reconnaissance flights (ref. 9). For the various tracks and seasons summarized, the fraction of flight time in icing varied between 0 and about 7 percent with a median of 2.3%. The fraction in clouds was from 1.5 percent to 28 percent with a median of 13 percent. The distance flown per icing encounter varied from more than 10,000 miles to about 1000 miles with an overall average of about 3000 miles per encounter.

In conclusion, we have reviewed the icing criteria used in the design and certification of transport aircraft. Although these standards are now twenty years old, they are generally consistent with data that have become available since their adoption. Since these criteria have stood the test of use, and since the total of experience with existing aircraft is more comprehensive than any data collecting program, it is suggested that future changes in criteria be based primarily on operating experiences rather than on meteorological data.

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RECOMMENDED ICING ENVELOPES

FIG. 1

CS-50096

11
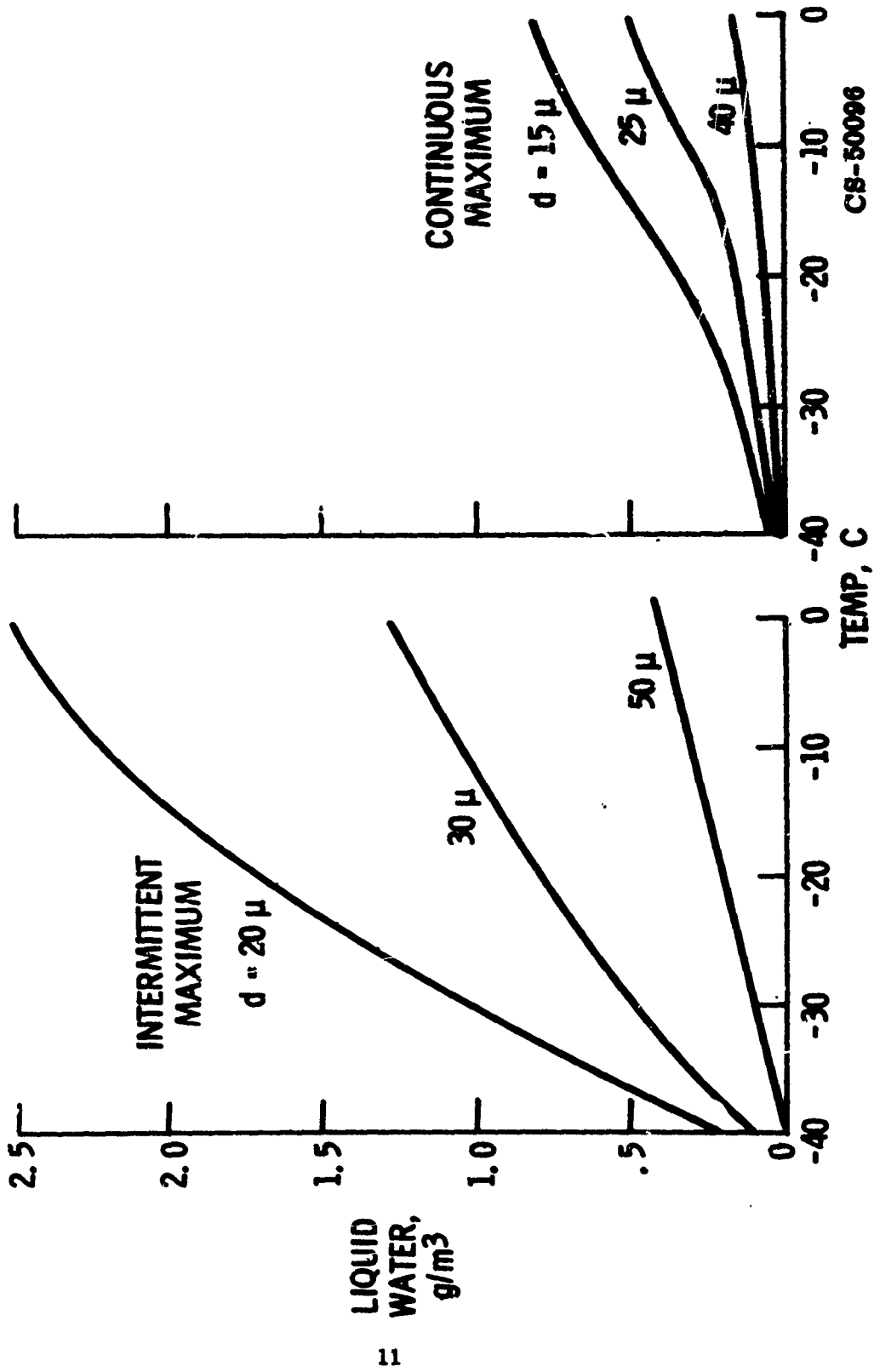
HISTORICAL COMPARISON OF DATA ON LIQUID WATER

NUMBER OF ENCOUNTERS IN PARENTHESES
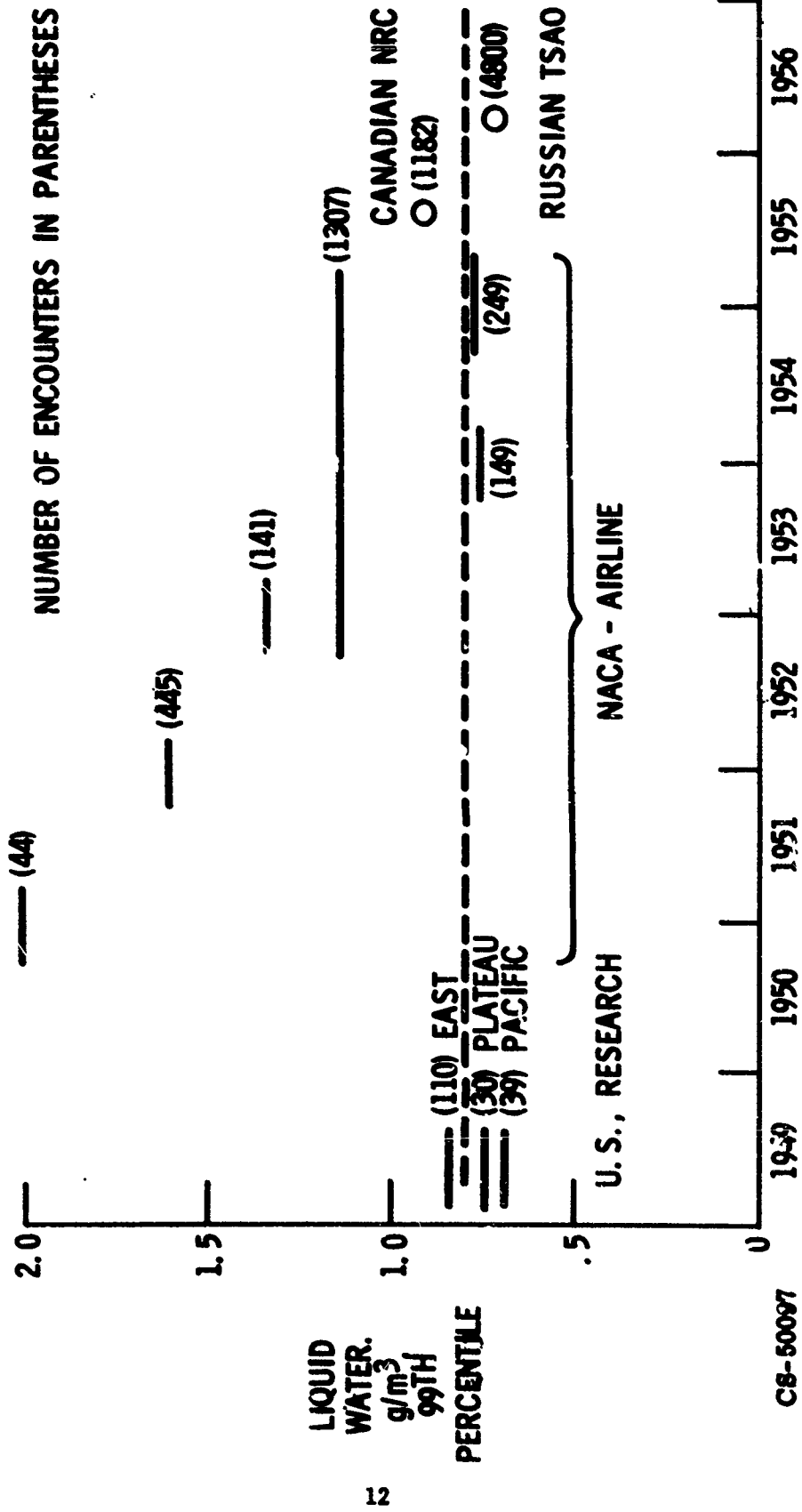
FIG. 2

CS-50097

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VARIATION OF LIQUID WATER WITH TEMPERATURE-LAYER CLOUDS

EAST ⎫ U.S. RESEARCH
WEST ⎭ U.S. RESEARCH
RUSSIAN STANDARD, 16 μ
U.S. STANDARD, 15 μ

NACA - AIRLINE

RUSSIAN TSAO

1.4
1.2
1.0
.8
.6
.4
.2
0

LIQUID WATER, g/m³, 99TH PERCENTILE

-30   -20   -10   0

TEMP, °C
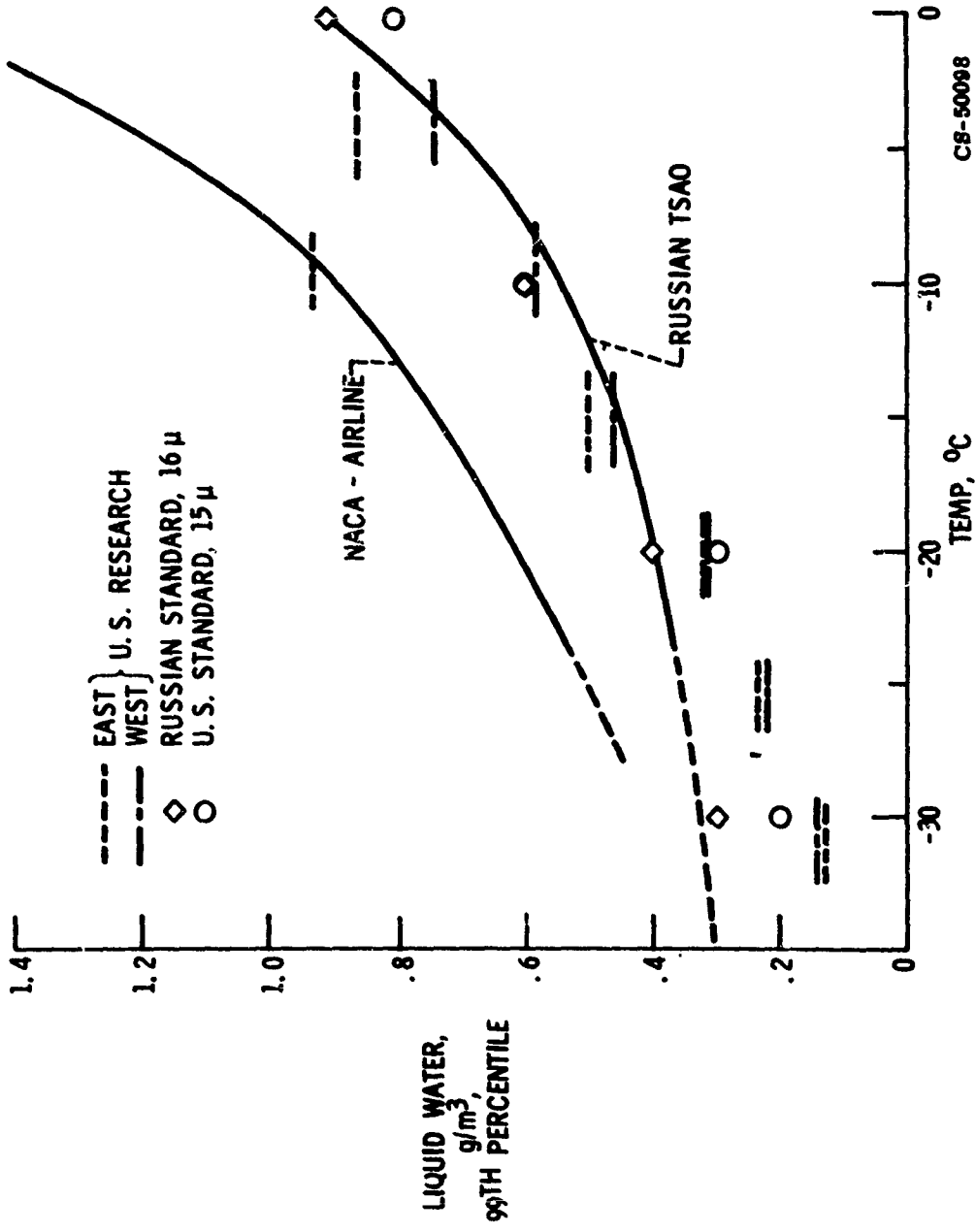
CS-50098

FIG. 3

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EXTREME VALUES OF LIQUID WATER

FIG. 4

NACA - HOT WIRE

RUSSION - ICING RATE

1/2 MILE

2 MILES

NACA "INST MAX," 1/2 MILE

NACA "INTMT MAX," 3 MILES

LIQUID WATER, g/m³

TEMP, °C

CS-50100

14
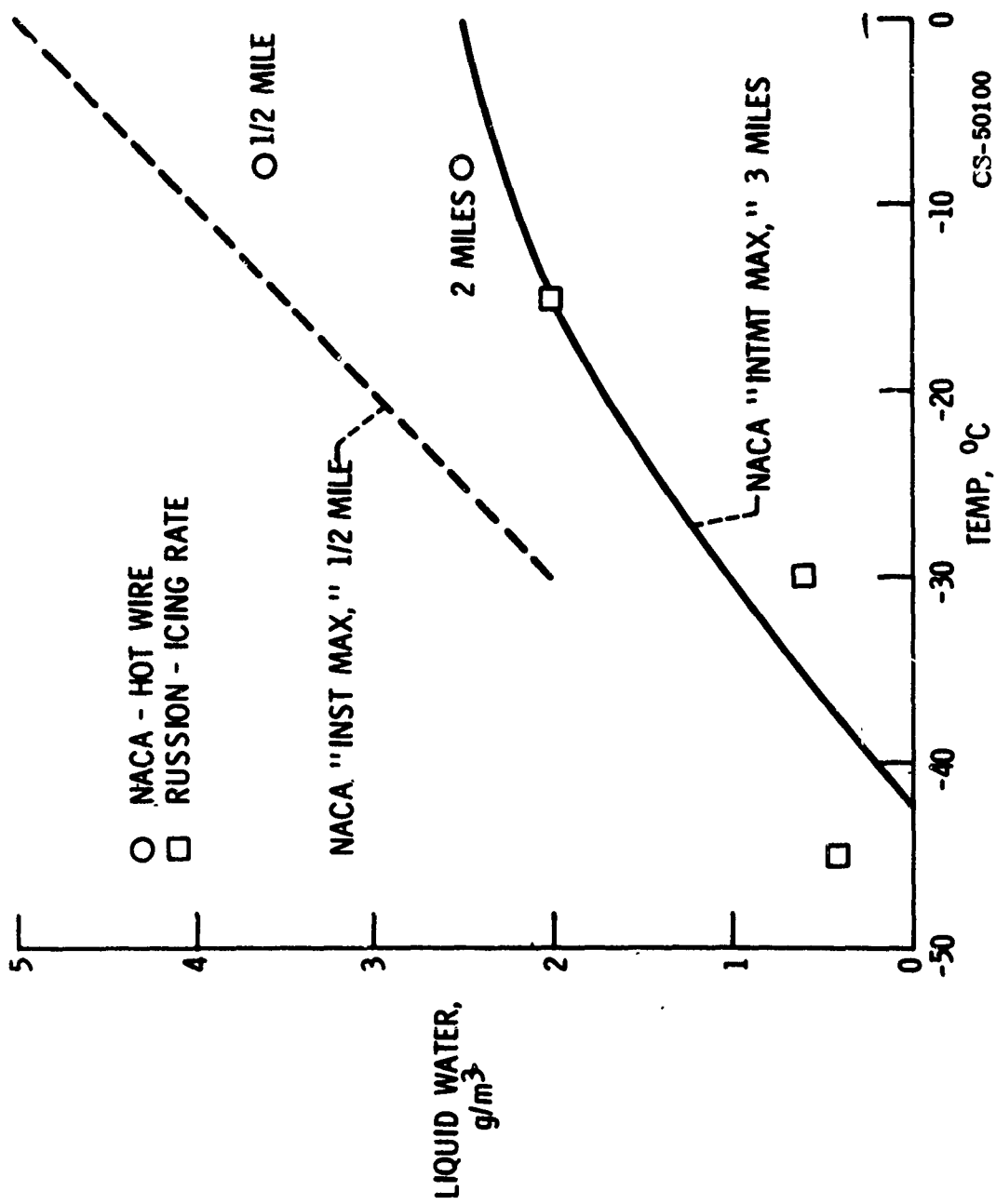
FREQUENCY DISTRIBUTION OF DISTANCE IN ICING-AIRLINE DATA
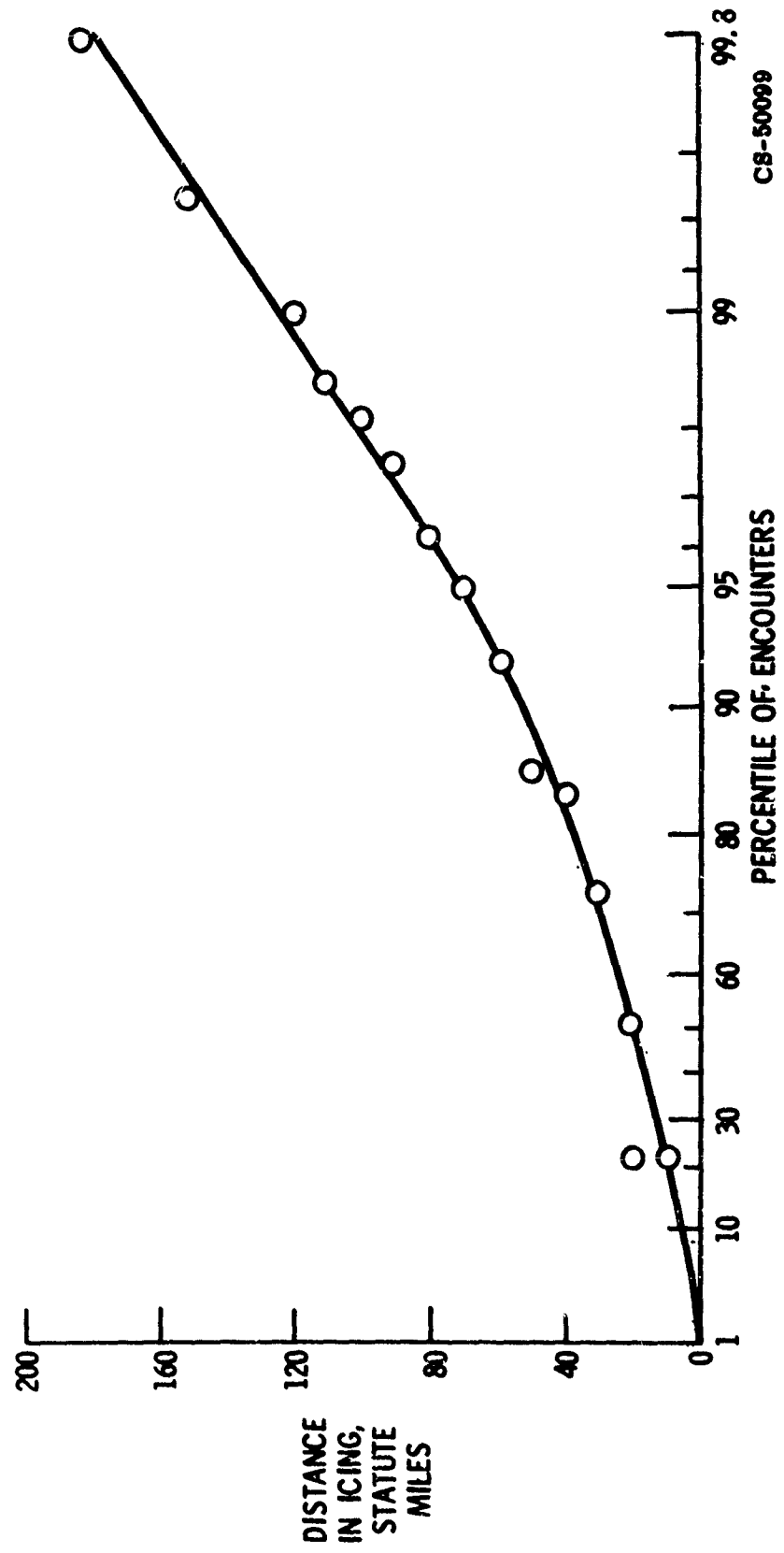
FIG. 5

CS-50099

FREQUENCY DISTRIBUTION OF VERTICAL EXTENT OF ICING

VERTICAL
EXTENT,
FT

PERCENTILE OF ENCOUNTERS

CS-50101

FIG. 6

16
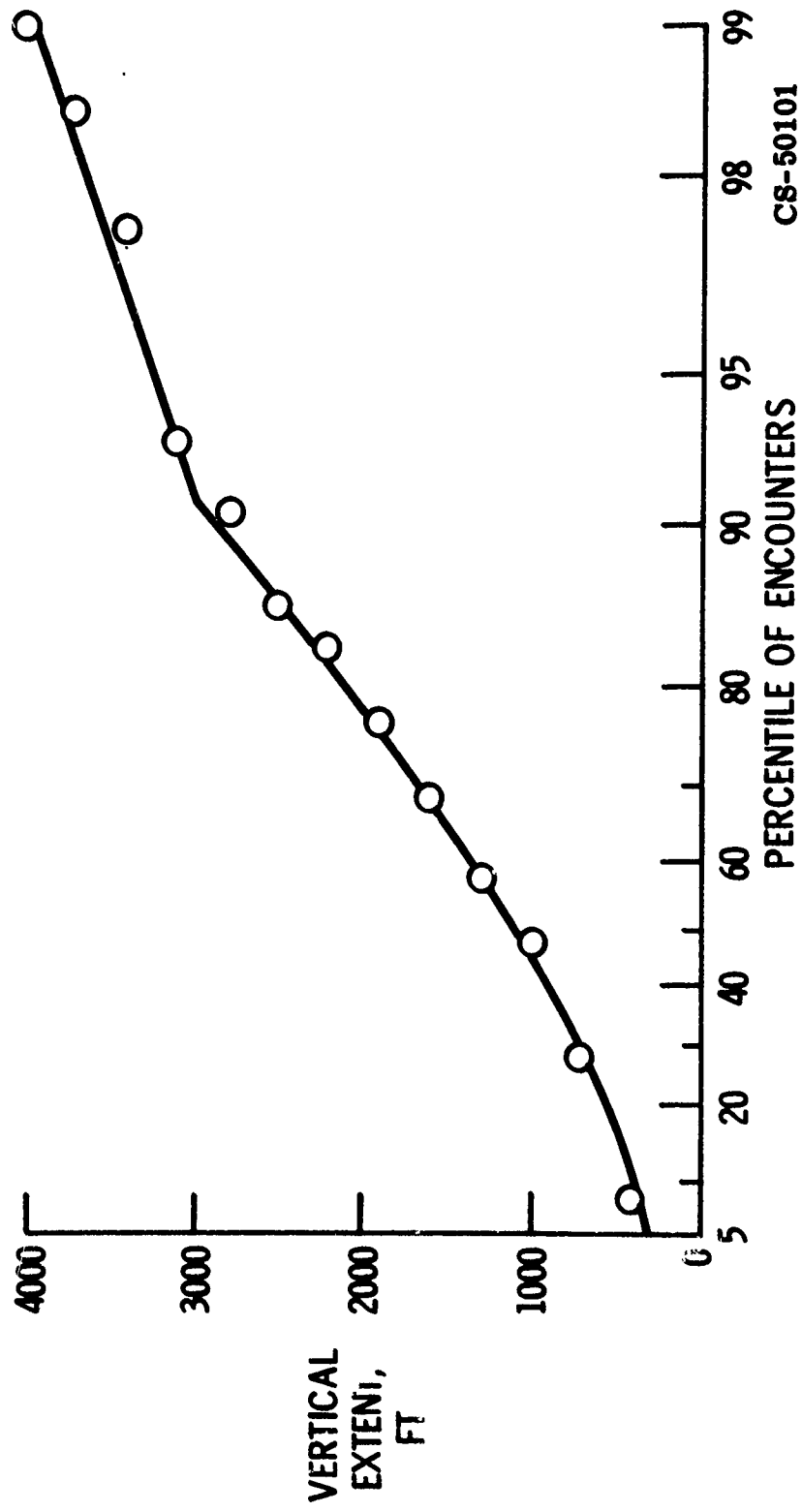
ENVELOPES OF LIQUID WATER VS ALTITUDE

U.S. RESEARCH DATA

CUMULUS CLOUDS

STRATIFORM CLOUDS

OVER WYOMING

LIQUID WATER, g/m3

2.0

1.5

1.0

.5

0

5000

10 000

15 000

20 000

PRESSURE ALTITUDE, FT

FIG. 7

CS-50102

17
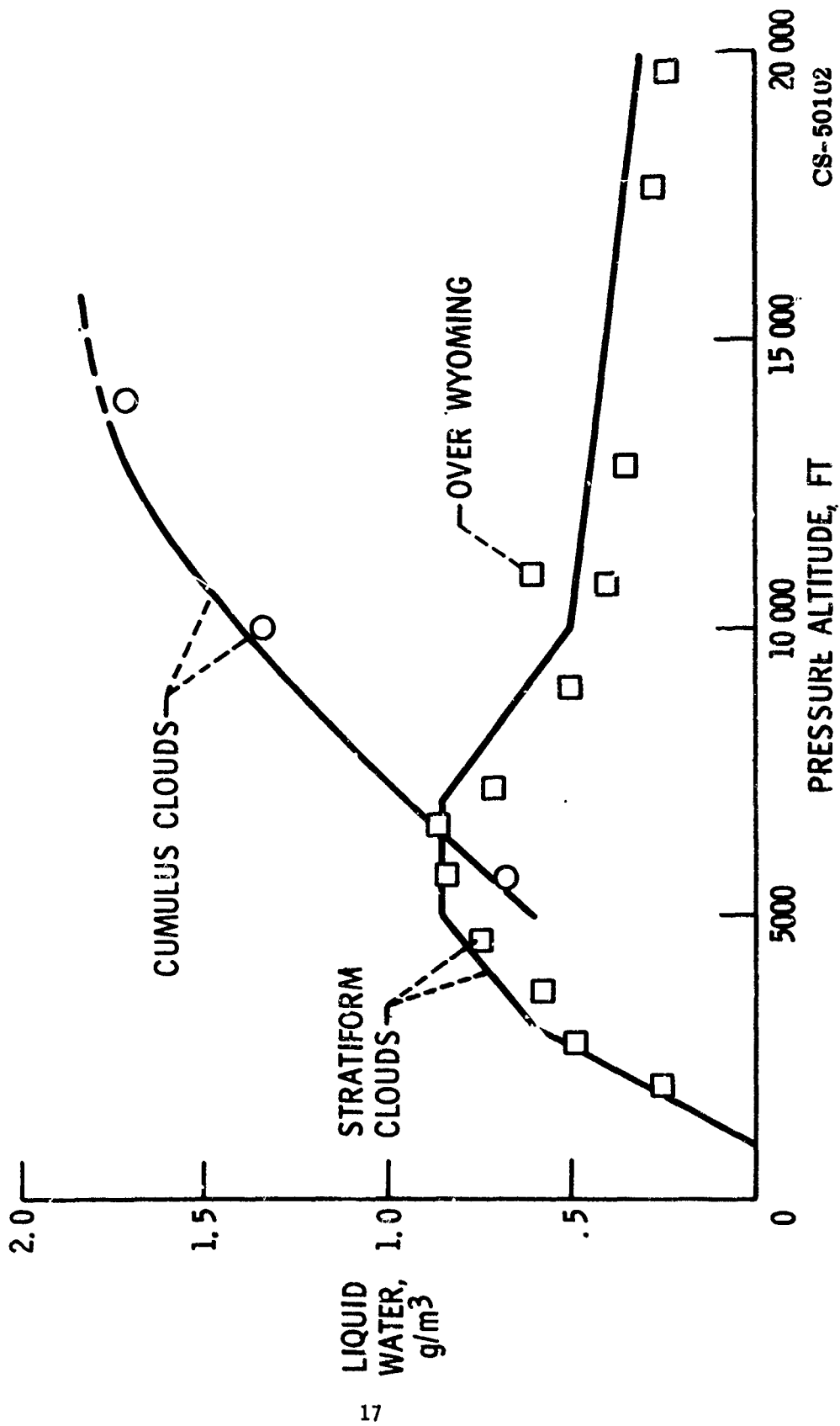
DISCUSSIONS FOLLOWING MR. LEWIS'S PRESENTATION ON

"REVIEW OF ICING CRITERIA"

Question: If investigations were initiated today, what
              instruments would you use for measuring drop size
              and liquid water content?

Answer: (NASA) - Still a problem, have no recommendation.
              (Boeing) - We have been using a "photographic oil
              slide" obtained from the airstream with success.
              (Canadian Pratt & Whitney) - In this regard, I'd
              like to point out a British Publication by R. F.
              Jones, which covers the "Determination of Ice
              Crystals," and can be found in "Aeronautical Society,"
              Vol. 63, 1959.

Question: What is the current value for ice fog and freezing
              rain, and what information is there available?

Answer: .3 gm/m^3 at 0° C. to .03 gm/m^3 at -10° C. Ice fog
              occurs at low temperatures (low as -40° C.).
              However, didn't realize there was an accretion
              problem with ground operation. United Airlines
              has used "seeding" with success in this area.

Question: What current values are there for snow?

Answer: 0 to 10-15 gm/m^3.

Question: What are the qualifying characteristics for situation
              of icing encountered where points lay outside curves,
              say 15,000-20,000 ft. altitude?

Answer: Curves only describe data taken and, consequently,
              points outside should not be taken critical.

Question: Have there been or are there any official definitions
              describing flight in heavy icing?

Answer: The FAA at one time used some general descriptions;
              however, they were eliminated because they varied
              from aircraft to aircraft.

Question: In a Russian Report, there was evidence of ice
             crystal and subcooled liquid below -40° C., true?

Answer: Yes; we also have reported information based on
             Air Force/Boeing report, as outlined in ADS-4. For
             all practical purposes, however, design, etc., it
             appears incidental.

Question: Could you define ice shape at 45 minutes in 20-mile
             clouds?

Answer: Difficult to predict because of variance.

Question: Do you differentiate between ice crystals and snow
             flakes?

Answer: Small ones are usually snow flakes; however, no basis
             of differentiation exists.

DESCRIPTION, HISTORY AND STATUS OF
NASA-LEWIS ICING RESEARCH TUNNEL

by Vernon H. Gray

The NASA icing research tunnel, at the Lewis Reseach Center, Cleveland, Ohio, is shown in plan view in figure 1. The tunnel is a closed-return, atmospheric type with rectangular cross-sections except at the 25-foot diameter drive fan in the return leg. The four corners of the tunnel have turning vanes, and the contraction section has a 14 to 1 area ratio. The test section is 6-feet high, 9-feet wide and 20-feet long. Maximum speed for the test section (empty) is 300 miles per hour, creating a test section pressure equivalent to about 3000 feet altitude. The large test chamber surrounding the test section is also at the reduced pressure, so that leads from models may come through open holes in the test section floor or walls with no seal problem. Figure 2 is a view looking downstream in the test section, showing some velocity-survey struts. The side walls and ceiling have several windows for viewing purposes, the ceiling has a removable top-hatch (measuring nearly 4 by 12 feet) for insertion of models, and the floor contains the model mounting plate located within a turn-table, which is nearly 9-feet in diameter.

The tunnel airflow may be refrigerated to -20° F, or lower if necessary. Atmospheric icing clouds are simulated in the tunnel by spraying water droplets into the cold airstream slightly upstream of the contraction section. The six horizontal spray struts contain a total of 77 air-atomizing, heated, water-spray nozzles. Calibrated

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clouds may be generated here with liquid-water contents varying inversely with airspeed over a range from about 1/2 to over 2 grams/meter^3, and with median droplet diameters from roughly 10 to 20 microns. The drop size distribution is approximately a Langmuir "D", with maximum drop diameters from two to four times the median. The icing cloud is uniform in intensity in the center of the test section over a region about 3 feet high by 5 feet wide. Figure 3 shows ice formations on unheated struts crossing the test section. The formations are uniform to within 18-inches of the floor and ceiling, and to within about 2-feet of the side-walls, where the formations start to taper off to zero at the walls.

The icing tunnel in operation is shown in the following short motion picture, with film and narration dating from 1955.

History

The icing tunnel was first operated in 1944. Prior to that, NACA flight icing research was conducted at the Ames laboratory in California, and some earlier work was done at Langley Field, Virginia. In the period from 1944 to 1957, icing research progressed steadily at the Lewis icing research tunnel, while the staff decreased from over 30 people to less than 10 (Parkinson's Law?). Over 100 NACA-Lewis icing reports were published during that period. A bibliography of these and other NACA/NASA icing reports is available, broken down into 16 subject categories such as meteorology, impingement, aircraft component protection systems, performance penalties and heat transfer. The best single-volume summary of

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this work, including other work as well, is the FAA Technical Report ADs-4, by D. T. Bowden, et. al., 1964.

In 1957, the Icing Sub-Committee of the NACA Operating Problems Committee dissolved itself, after concurring that no further major icing research areas remained for NACA to engage in. Thereafter, the Lewis icing personnel quickly phased out of icing research and into space research. Since then, the icing tunnel has been made available to the aircraft industry and other government agencies mainly for evaluation and certification tests of ice-protection systems and equipment.

In the 12 years since 1957, 44 separate icing programs have been conducted in the tunnel, by 20 different companies. Over this period, the tunnel was operated about 25 percent of the total time, while during the year just passed, it operated nearly 75 percent of the time. For 11 of the past 12 years, the breakdown of icing tests according to aircraft types is as follows:

Helicopters	38 percent
Large Commercial Aircraft	26 percent
General Aviation	21 percent
Military and Other	15 percent

According to components, the breakdown is:

Engine Inlets	52 percent
Airfoils	35 percent
Instruments	6 percent
Radomes and Others	7 percent

With rare exceptions, these tests have been unclassified and non-proprietary.

Present Status

The present operating policy of the tunnel is unchanged since 1957. In general, if an aircraft company has a problem amenable to the icing tunnel, and obtains sponsorship for the tests by a Federal agency (e.g., DOD, FAA), the Lewis Research Center will accommodate the testing on a non-cost basis, subject to scheduling and safety limitations. NASA reserves the right to accept or reject proposed icing tests based on the needs and merits of each case. Icing tunnel tests are not sanctioned if they can be accommodated in other existing facilities. The tunnel is operated by NASA personnel, but the company must build the model and supply a test crew to install it, run the tests, record the data and remove the test equipment. NASA requires a copy of the test data and final company report.

Present interest in icing and in the icing tunnel is at a high level. In addition, the icing tunnel may be used occasionally in the near future for NASA in-house aerodynamic research. Thus, the tunnel utilization factor may become higher than desired under the present operating policy.

NASA at present has no formal plans for resuming active research work in icing. Of the icing problems that need attention now and in the near future, many are isolated equipment development and instrumentation problems related to the variety of new aircraft configurations forthcoming. Two larger problem areas exist, and will doubtless be discussed further in this Symposium. One of these is the problem of determining probable ice shapes on large jet transports, evaluating their effects on

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performance and establishing the criteria for required ice protection. Most of the "jumbo jet" airfoils and components are too large for adequate testing in the icing tunnel, and may need to be flight tested in natural icing conditions. The other problem area is general aviation and V/STOL aircraft. Here, the experience level in icing problems, both in the design and in the operational and regulatory phases, is low. Making it worse, ice protection for the small aircraft is more difficult than for the large airplanes, because of the lower speeds, lower altitudes, greater ice-collection efficiencies, larger performance penalties and lower power margins. However, the knowledge required to combat these problems is largely available in the literature, and an important need now is for general aviation to obtain a better icing education.
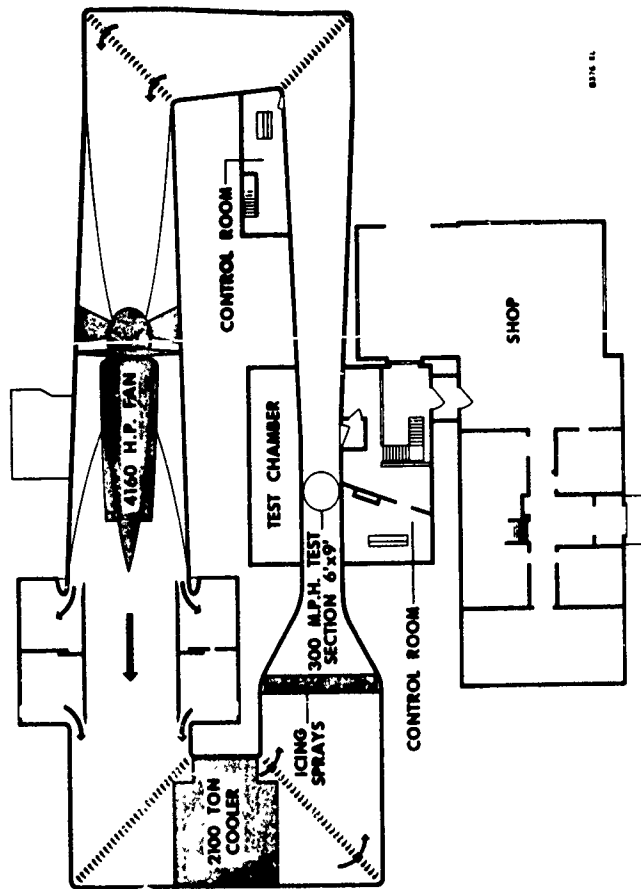
Figure 1. Plan view of NASA-Lewis Icing Research Tunnel.
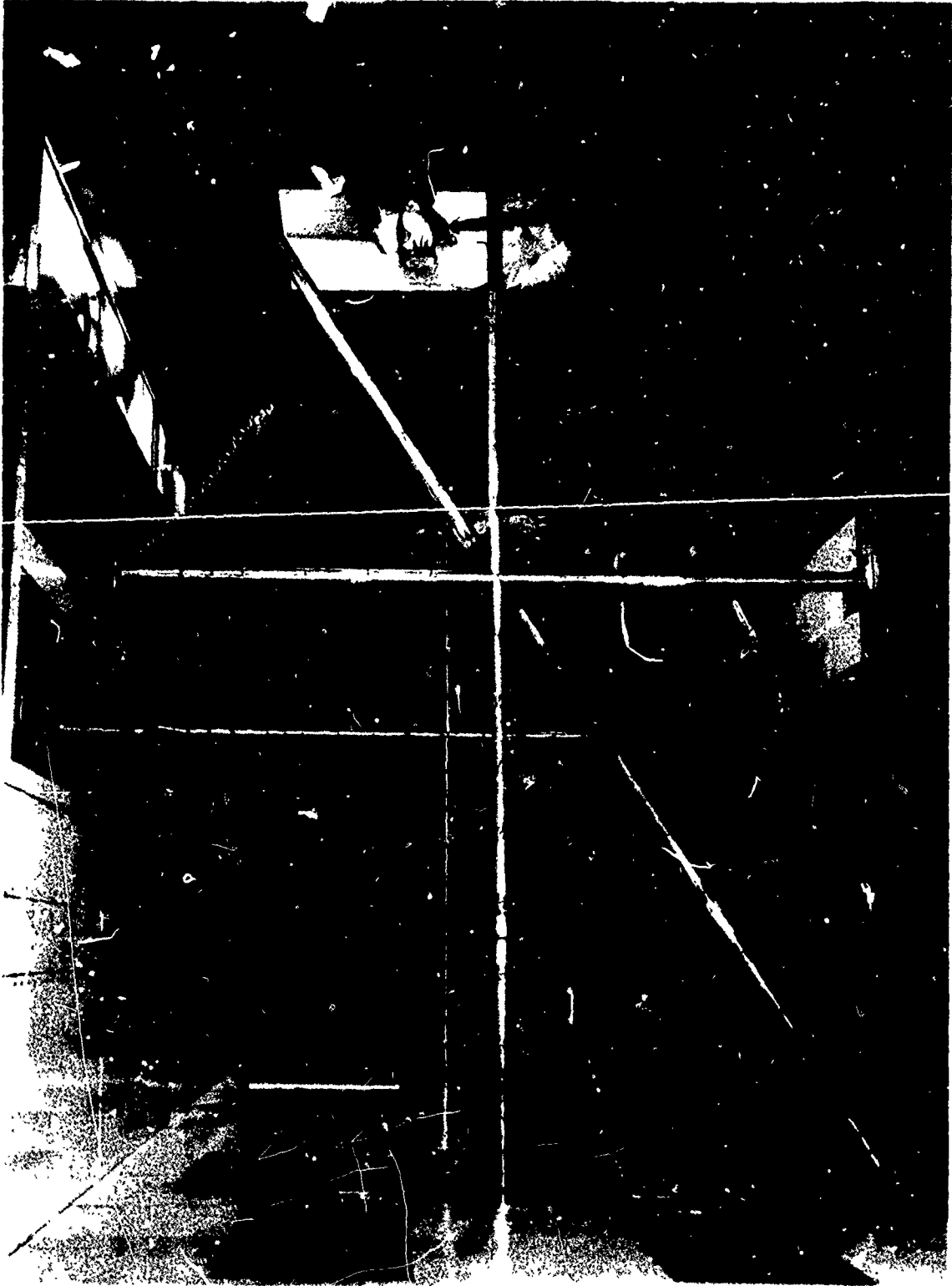
Figure 2. Test Section of Icing Research Tunnel.
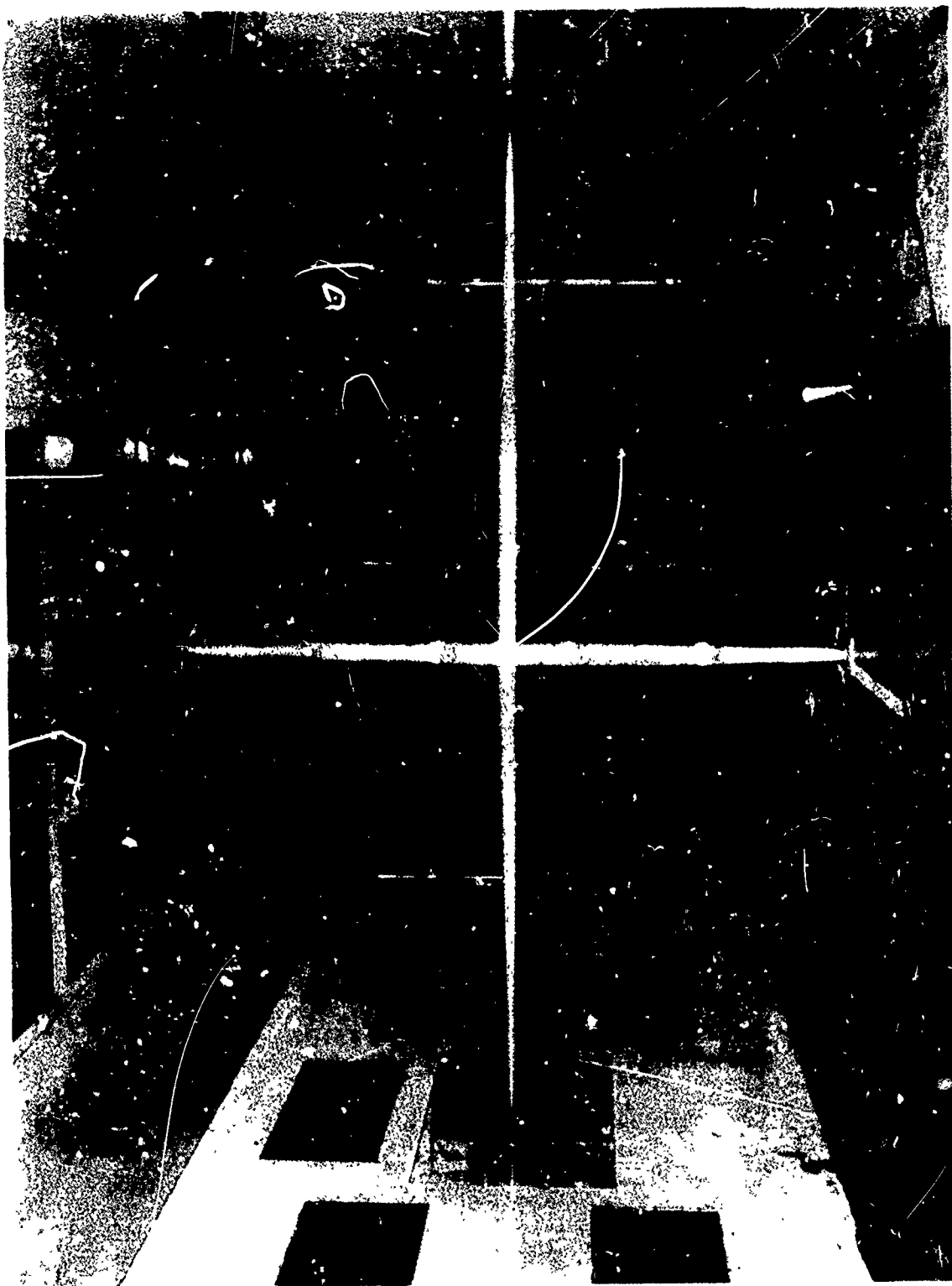
Figure 3. Icing on Struts Crossing the IRT Test Section.

AERODYNAMIC CHANGES CAUSED BY INCREASING
ANGLE OF ATTACK WITH ICE ON AIRFOIL

ICE ACC. $\frac{1}{4}$ LB/FT-SPAN

ANGLE OF ATTACK
AT WHICH ICE
WAS FORMED

CLEAN AIRFOIL

ICED AIRFOIL

$4.6°$

$2.5°$

NACA 0011
CH., $87\frac{1}{2}$ IN.
$25°F$, 175 MPH, 17 MIN.

LIFT
COEFFICIENT,
C_L

1.0

.8

.6

.4

.2

0

0   4   8   12
ANGLE OF ATTACK, DEG.
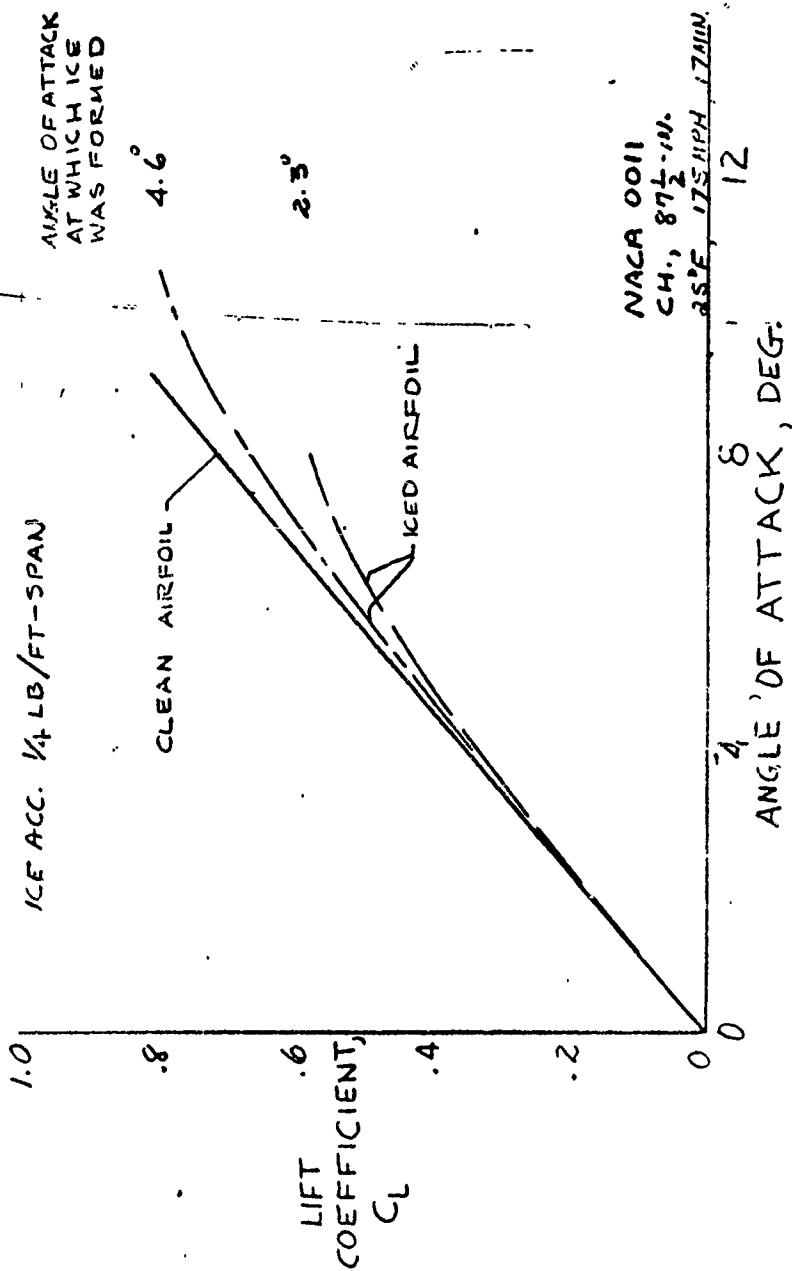
EFFECT OF SPOILER LOCATION AND SIZE
ON LIFT COEFFICIENT

SPOILER
LOCATION, %CHORD

$2.5\left.\right\}\frac{1}{4}"$ SPOILER

$1.0\left.\atop 1.0\right\}-\frac{1}{2}"$ SPOILER

→| |← 0.01c

SPOILER

CHORDLINE

CLEAN AIRFOIL

NACA 0011

LIFT
COEFFICIENT,
C_L

1.0
.8
.6
.4
.2
0

0   4   8   12

ANGLE OF ATTACK, DEG.
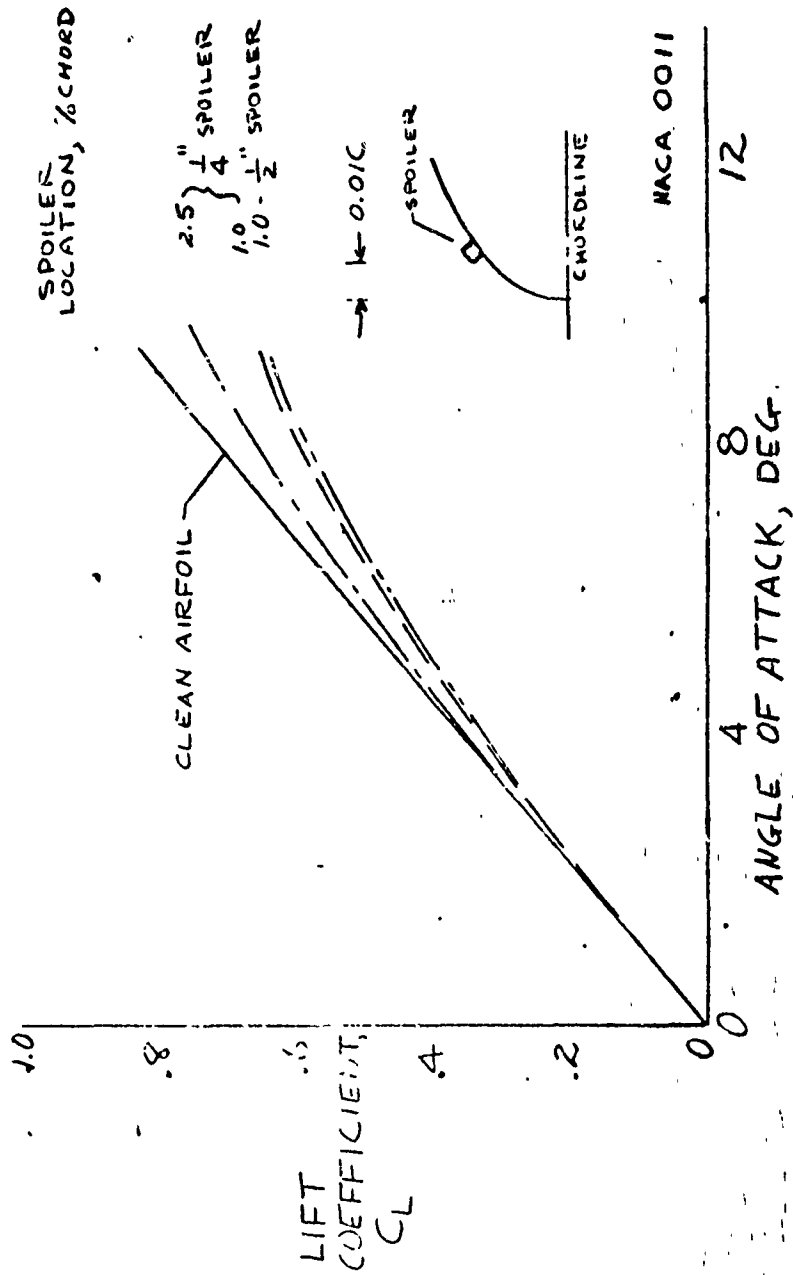
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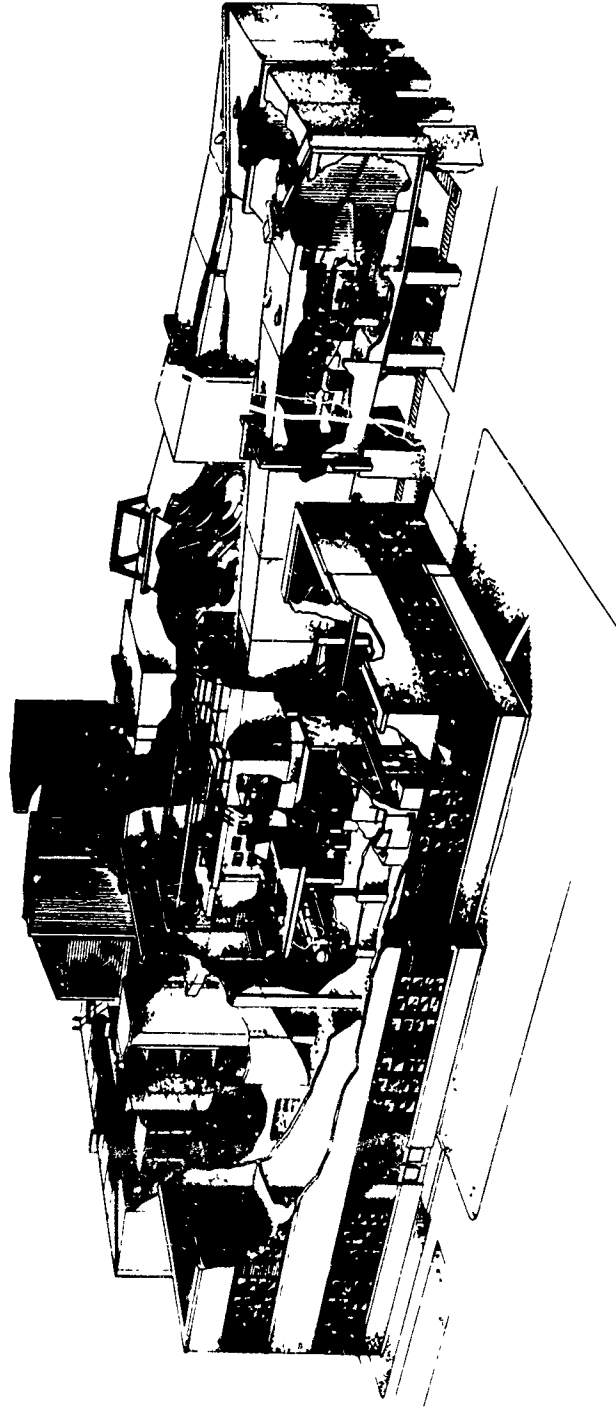
Miscellaneous

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These reports may be ordered from

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ICING RESEARCH TUNNEL, SHOP AND OFFICE

4160 H.P. FAN

2100 TON COOLER

ICING SPRAYS

TEST CHAMBER

300 M.P.H. TEST SECTION 6'x9'

14'x14'

CONTROL ROOM

SHOP

8376-8L

44
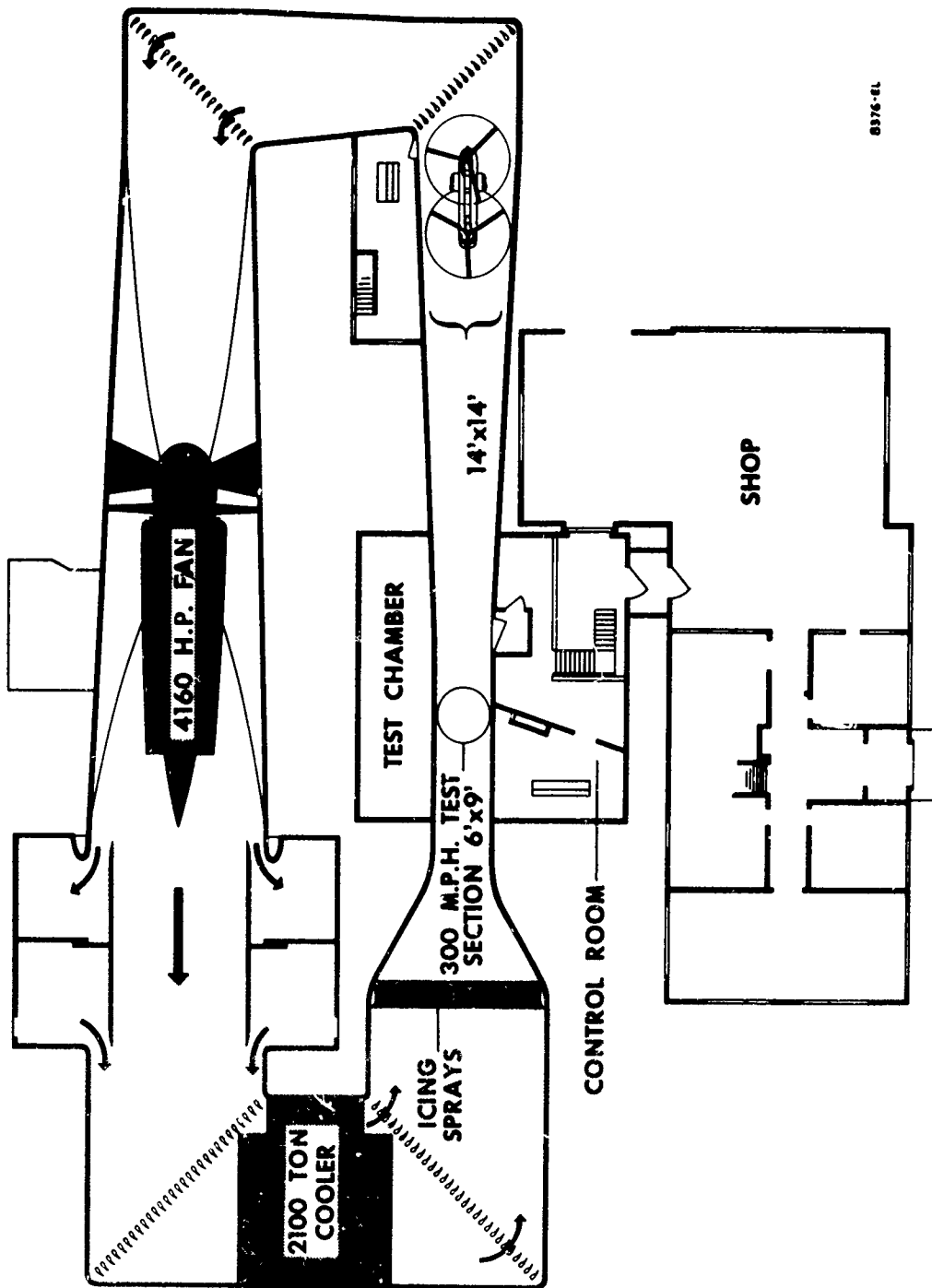
SERVICES AVAILABLE

Heated air

Primary line - 2" pipe
Up to 500 degrees F.

Secondary line - 1½" pipe
Up to 300 degrees F.

3000 pounds per hour - 75 psig.

Steam

5 pounds pressure - 2" pipe

ELECTRICAL

28 Volts DC
110 Volts AC 60 Cy.
208 Volts AC 60 Cy.

MOUNTING PLATE & TURNTABLE
ICING RESEARCH TUNNEL

46
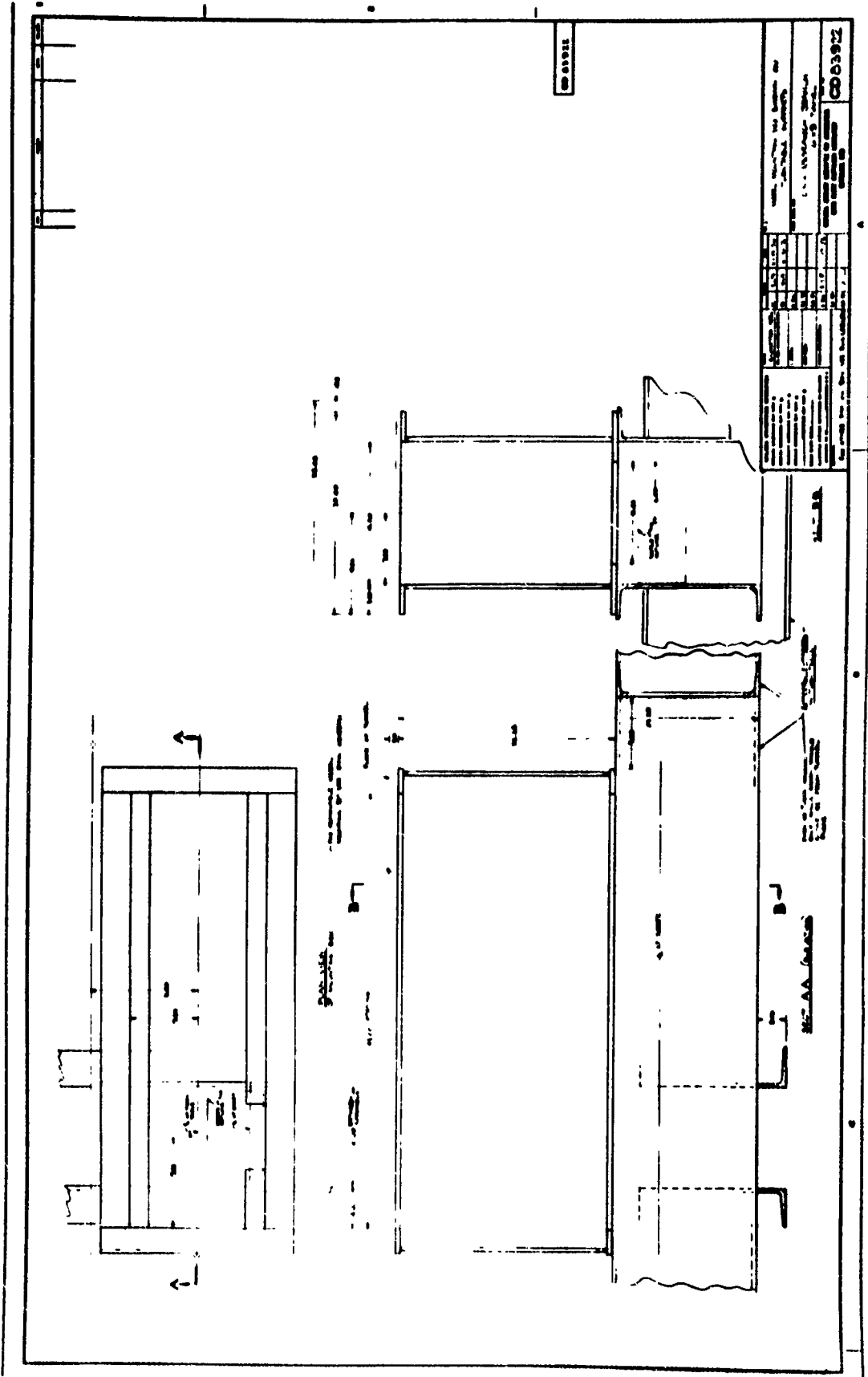
Sample determination of main spray system air & water pressure

Desired: liquid water content, 1.2 gr/m³

volume median drop diam, d_{med} = 15 microns
(tunnel spray cloud droplet size distribution
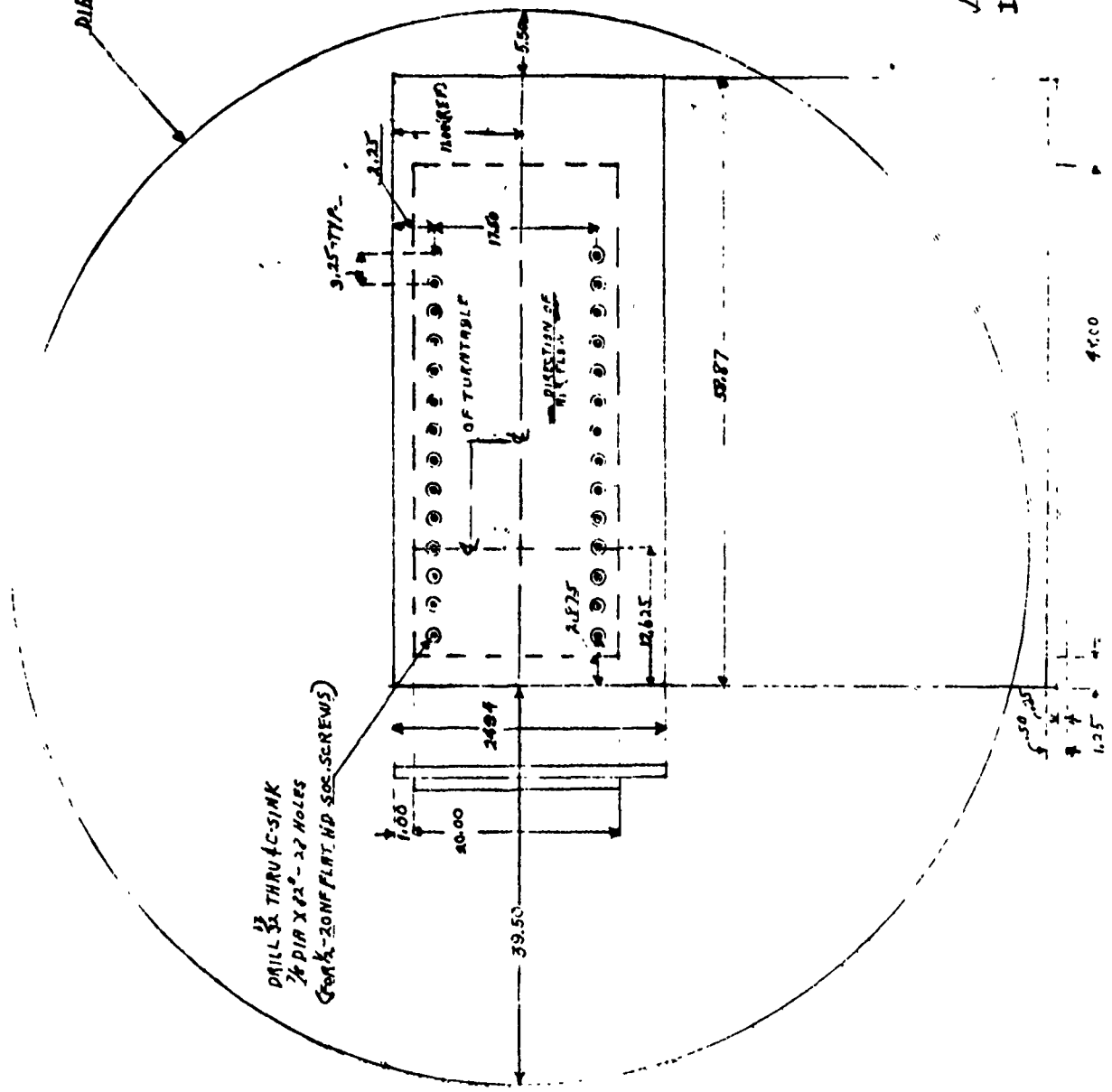approximates a Langmuir "D" size distribution)

true airspeed, 180 mph   (156 Kns)

(a) LWC (TAS) = 1.2 × 180 = 216 $\frac{gr}{m^3}$ × mph

(b) From attached figure 1, total water flow = 2530 lb_m/hr

(c) From total water flow equation (see figure 1): $\frac{2530}{77} = \sqrt{38.7 (p_{H_2O} - p_{air})}$

(d) $(p_{H_2O} - p_{air})$ = 27.9 psi

(e) From d_{med} equation (see figure 1)

$$d_{med} = \left[43.9 - 25.0 \right] \left[\frac{\sqrt{38.7(27.9)}}{\left(\frac{p_{air}}{1.13} + 10 \right) / \sqrt{\frac{640}{536}}} \right] + .006(156) + 4 = 15$$

(f) Thus p_{air} = 64.3 psig   ; p_{H_2O} = 64.3 + 27.9 = 92.2 psig

In general: capability of spray system is as follows

40 psig < p_{air} < 75 psig

50 psig < p_{H_2O} < 110 psig

$(p_{H_2O} - p_{air})$ < 10 psi not recommended

Determination of maximum droplet diameter, d_{max}

(g) From figure 2 and d_{med} of 15 microns, $d_{max} \cong$ 37 microns
  p_{air} of 64.3 psig
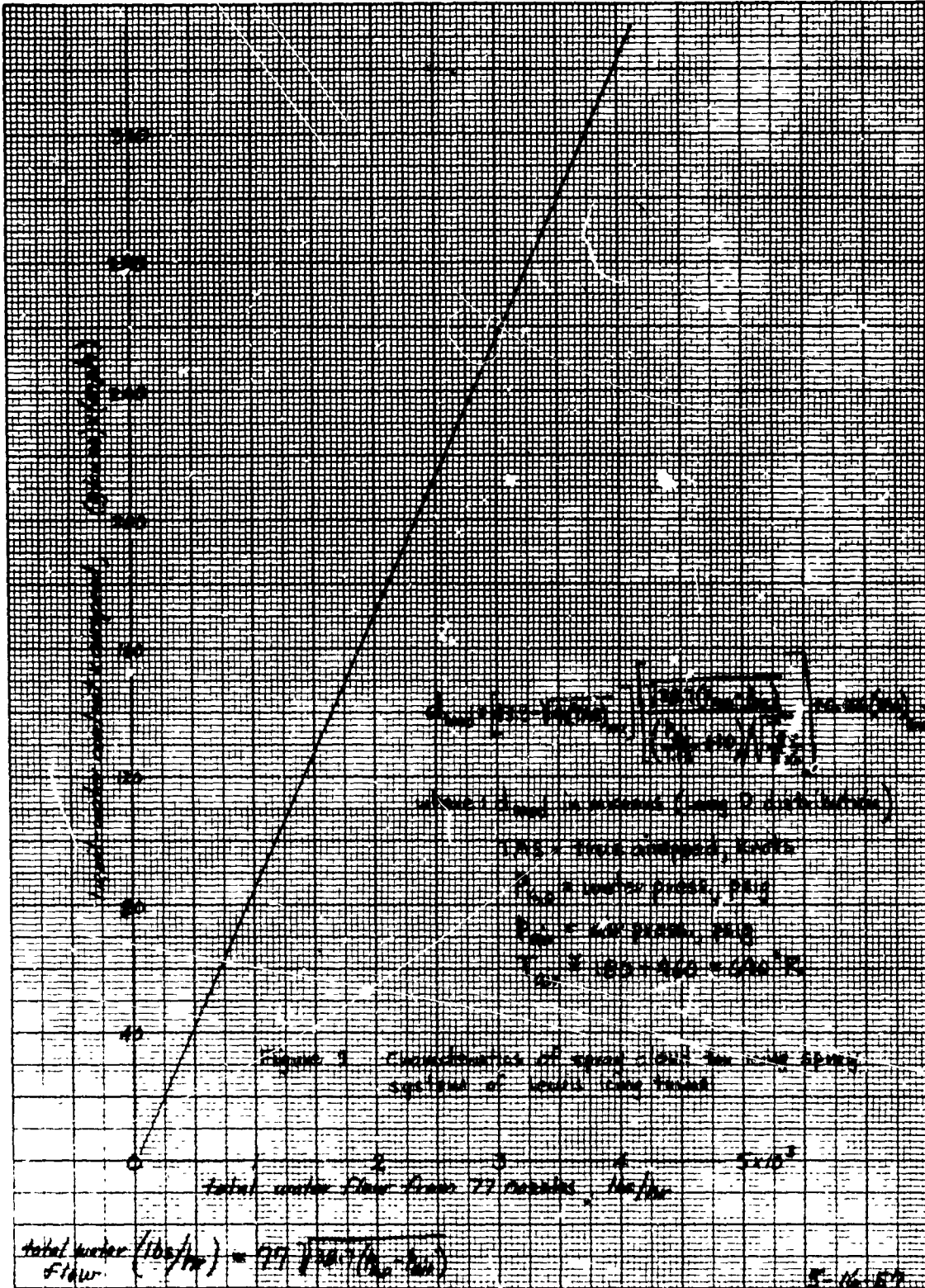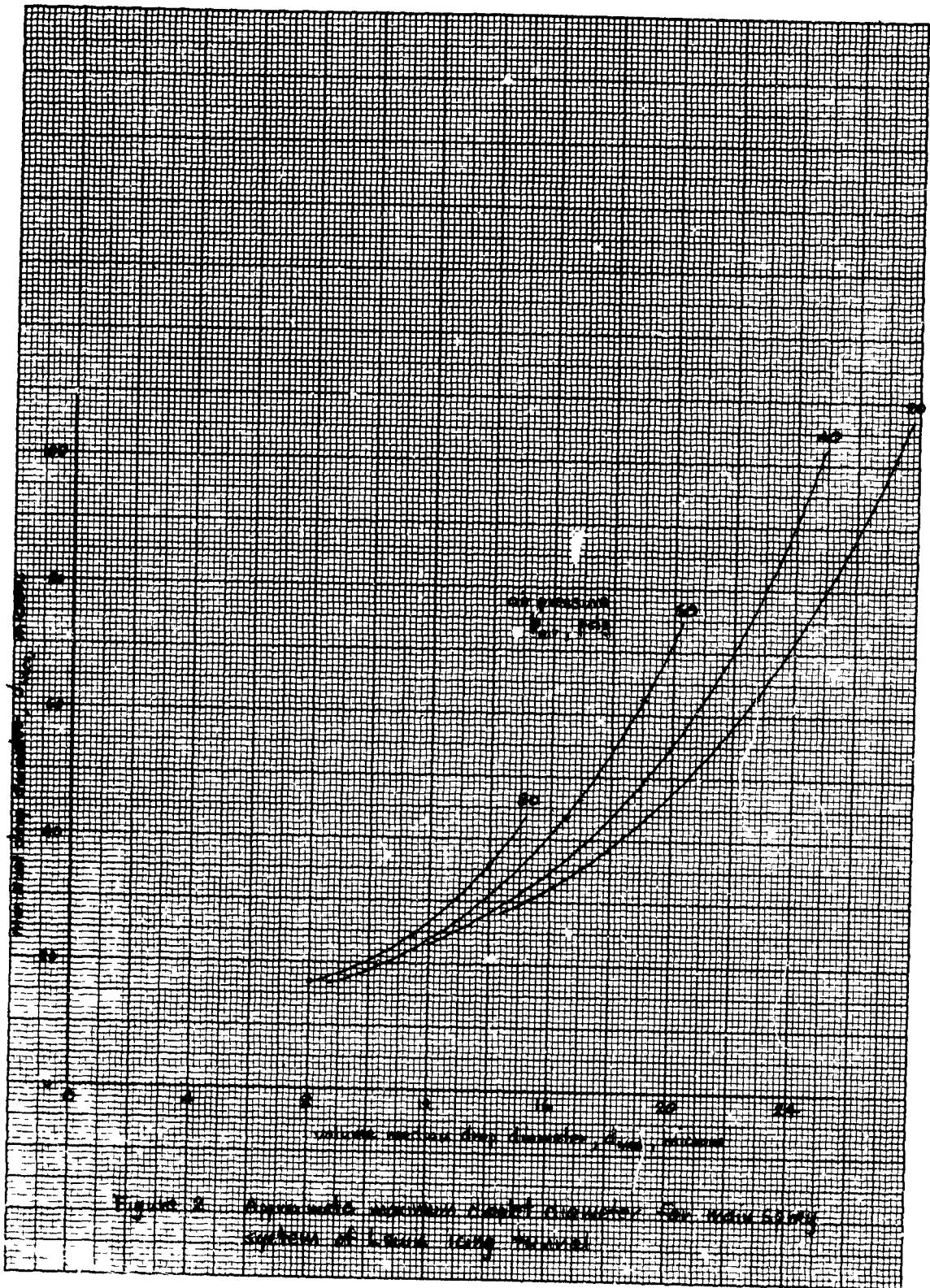
Figure 2. Approximate maximum rainfall frequency San Marcos City system of basin (Long Section)

Figure 17. - Volume median droplet diameters for various spray system of Lewis icing tunnel. ($T_{spray} \cong 440°R$)
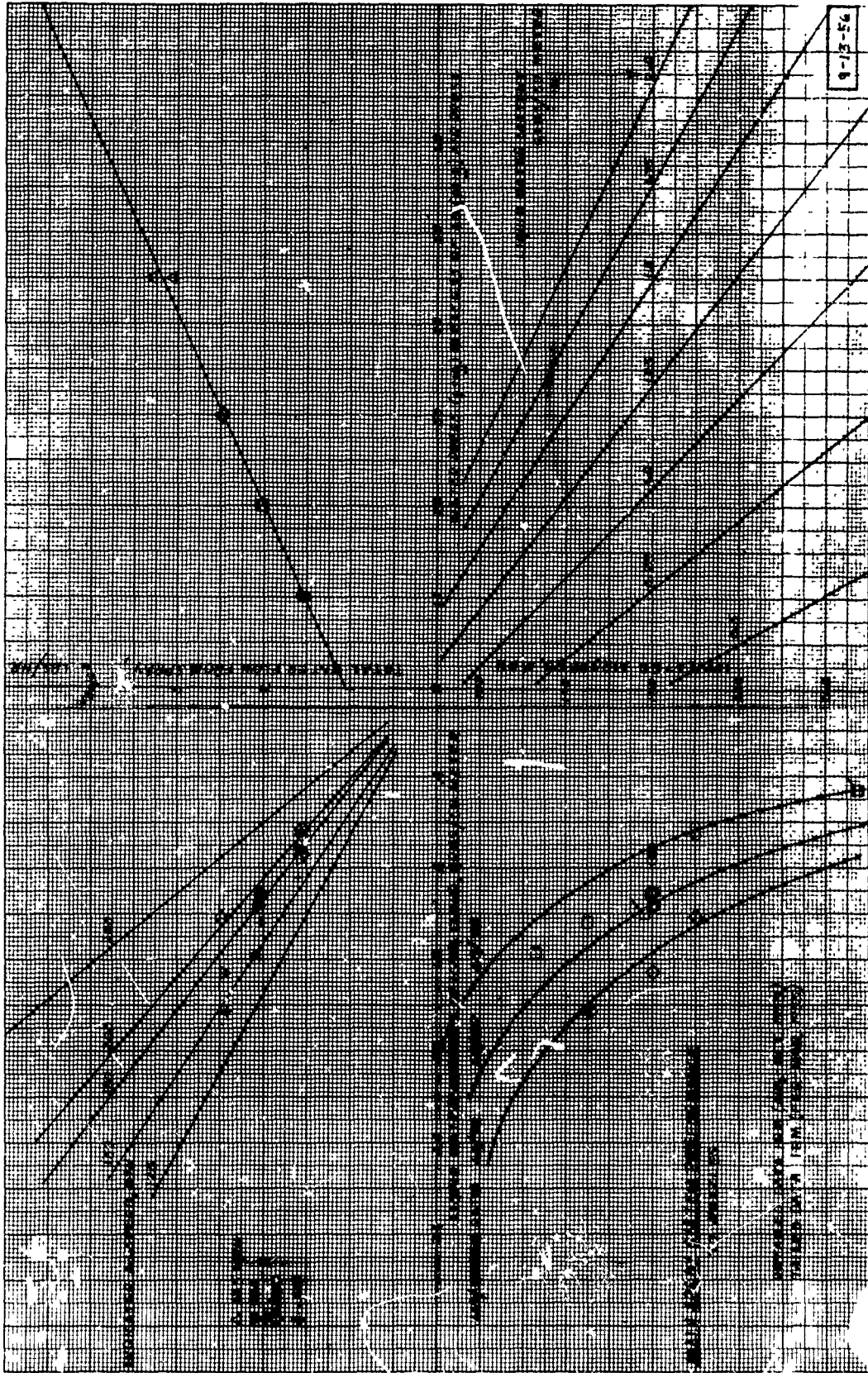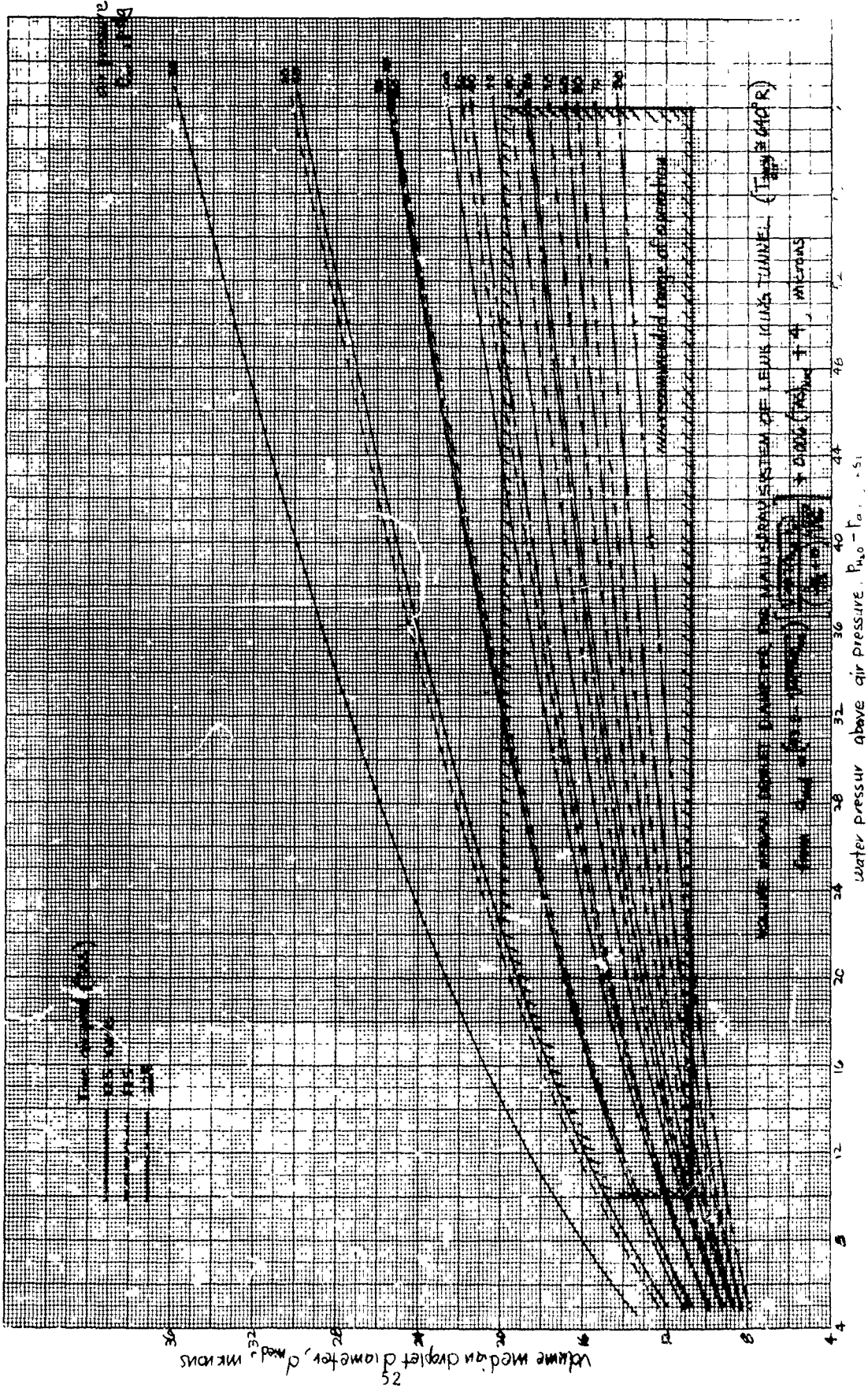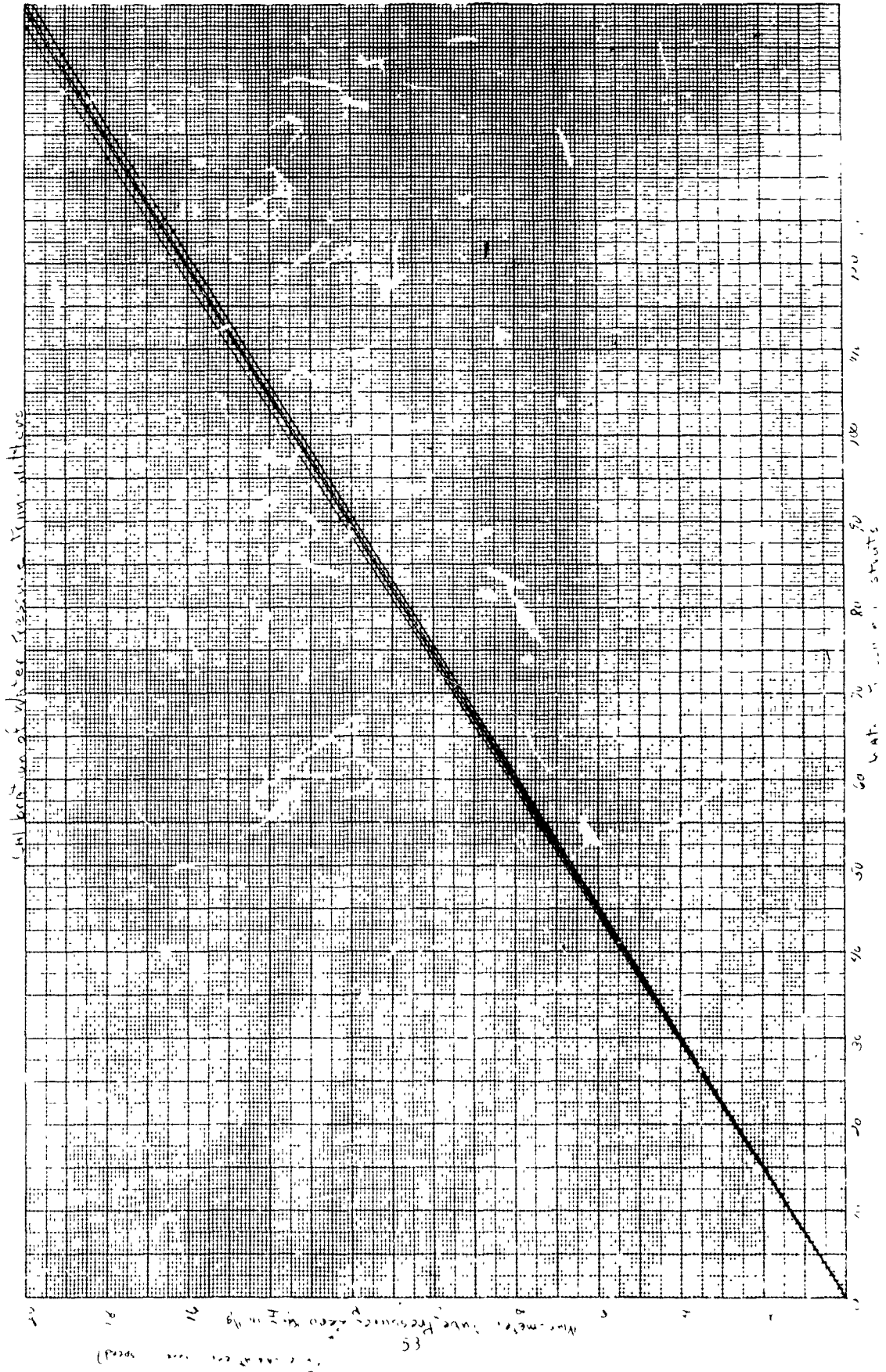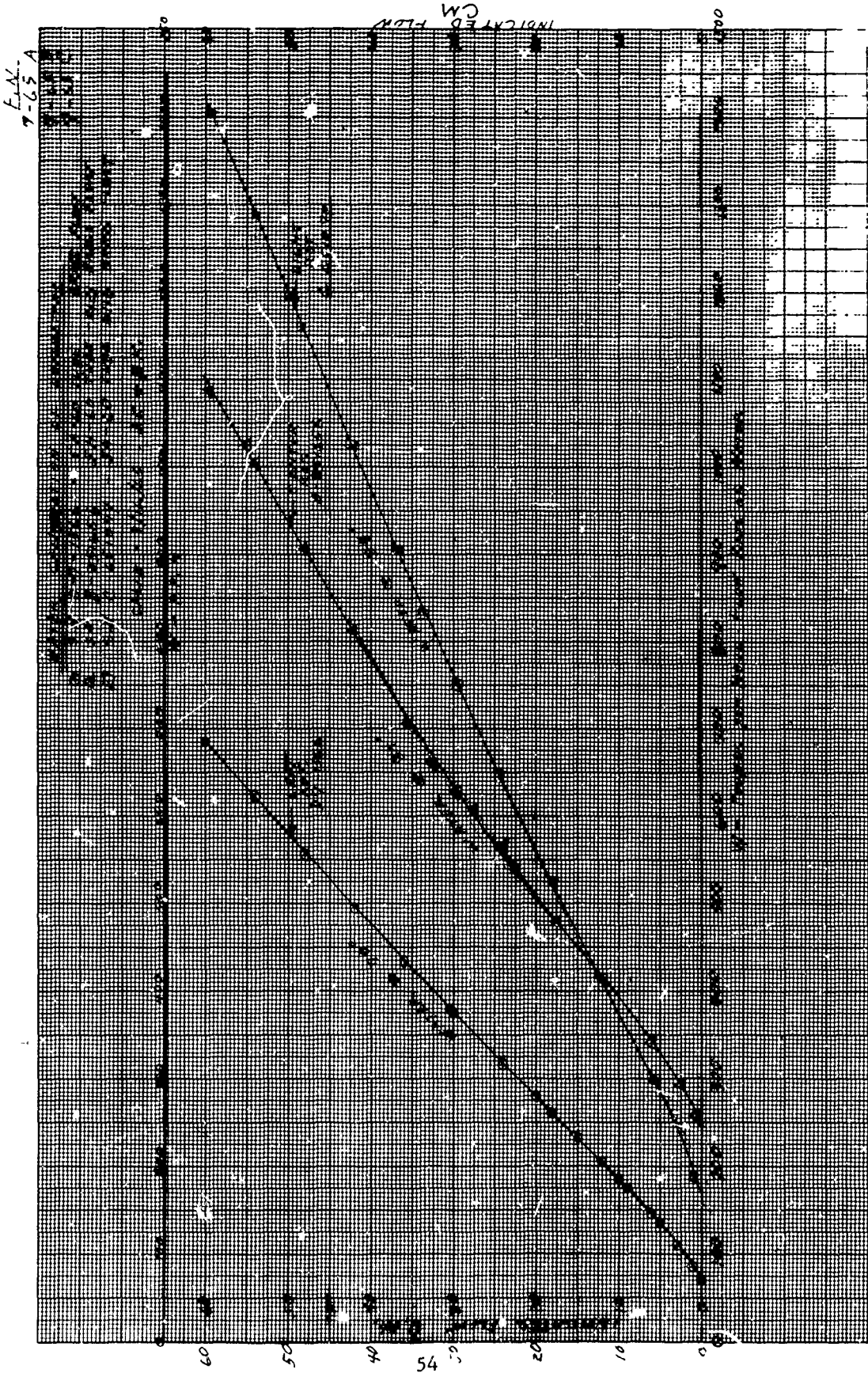
DISCUSSIONS FOLLOWING MR. GRAY'S PRESENTATION ON

"DESCRIPTION, HISTORY, AND STATUS OF NASA LEWIS ICING RESEARCH TUNNEL"

Question: Based on small tunnel tests at Lockheed, we calibrated for cloud conditions and measured liquid water distribution by rotating cylinder but got large variation of .5 - 1.22 gram/m^3. We feel a uniform cloud condition is needed, and yet understand that the Lewis system has high turbulence that prevent uniformity. Is that true?

Answer: Since 1957, no work has been done regarding calibration, etc., Conditions are still the same. From top to bottom it is good and falls off to the south. Conditions improve above 150 knots. The tunnel has 3 percent turbulence. However, models do affect cloud conditions in the tunnel.

Question: What is the tendency or difference between "upper" and "down" sections of tunnel?

Answer: We do not test in the "down" section, as conditions are no good. We only use the "up" section.

Question: When industry comes and runs tests, do they use your charts and calibration data and is there any doubt as to accuracy?

Answer: Yes, they use available calibration information and as for accuracy, tunnel centerline has a ± 15 percent error.

Question: Should the FAA rely on this calibration?

Answer: It is better than nothing.

Question: How well is the tunnel maintained?

Answer: Very good, mechanical system, etc. Technical refinement, however, is lacking.

Question: Is it true that the spray nozzles at Lewis tunnel are nonuniformly located?

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Answer: Yes, they are located by trial and error, as it is
             very hard to get clouds near walls otherwise.

Question: Would you agree that the tunnel is more adapted to
             development work rather than certification?

Answer: Yes.

Question: What is the temperature of the droplets when they
             hit the tunnel model?

Answer: In natural icing, the droplets are supercooled
             and stick to the model. In the tunnel, droplets
             are at 32° F., which results in the same effect on
             the model as in natural icing.

ICE PROTECTION FOR TURBINE ENGINES

by
Edmund E Striebel
Project Engineer, Systems Technology Group
Pratt & Whitney Aircraft
Division of United Aircraft Corporation
East Hartford, Connecticut

ABSTRACT

This paper reviews the design criteria and analytical procedures that have been applied to the design of the ice protection systems used in Pratt & Whitney Aircraft engines. A comparison of analytical calculations with experimental rig and engine test data is presented for both current and advanced engine icing problems. It is pointed out that practical design considerations, coupled with empirical substantiation, are often the deciding factors in choosing the final configuration.

INTRODUCTION

In the last few decades, considerable attention has been directed toward the definition of the meteorological icing environment and the development of analytical tools to predict ice accumulation rates on various aerodynamic shapes. The literature also contains several solutions to the problem of heat and mass transfer from a wetted surface which permit calculating the thermal energy required to provide anti-icing protection for a particular set of conditions. With this information in hand, the problem of providing ice protection for a gas turbine engine is reduced to the selection of a design point criterion, identification of those components that require protection, application of engineering judgement to achieve a practical design, and finally experimental substantiation to certify the engine for military or commercial service

This paper outlines the approach that is taken at Pratt & Whitney Aircraft toward achieving these objectives. It is pointed out that the basic engine configuration is a prime factor in determining which components require icing protection and which design approach is best in each case.

Practical design considerations also weigh heavily in configuring the ice protection system and compromises are accepted which favor the aerodynamic and structural integrity of the engine. It is shown that anti-icing protection is provided for all critical in-flight conditions, but that simple operational deicing procedures are acceptable for ground idle operation in severe icing conditions.

Finally, it is recognized that gas turbine ice protection is not an exact science by any measure, and that experimental verification correlated with field experience is essential to assure a dependable engine.

DESIGN POINT SELECTION

Meteorological Design Parameters

Basically, operation in three distinct meterorological environments must be considered for the design of a gas turbine ice protection system:

a. flight through continuous icing conditions characterized by stratiform clouds with relatively low liquid water contents,

b. flight through intermittent icing conditions characterized by cumuliform clouds with very high liquid water contents, and

c. extended ground operation in freezing rain or ice fog.

The environmental parameters that influence icing are altitude, temperature, liquid water content, droplet size, and horizontal and/or vertical extent of the cloud formation. The extensive research conducted by the Lewis Flight Propulsion Laboratory has led to quantitative correlations of these parameters which are presented in the NACA statistical icing reports. This information, which includes icing encounters by commercial, military, and icing research aircraft, is the basis for the commercial (FAR - Part 25) and military (MIL-E-5007C) standards that are used as guide lines at Pratt & Whitney Aircraft for the design and testing of ice protection systems (see References 1 and 2 respectively).

Figure 1 shows the atmospheric icing conditions as presented in Appendix C of the FAR-Part 25 specification for the intermittent maximum icing condition (3 mile cloud) with the continuous maximum condition (20 mile cloud) superimposed. The data is presented as liquid water content versus mean effective drop diameter for ambient air temperatures ranging from -40°F to +32°F. Note the significant difference between the continuous and intermittent liquid water contents and the fact that the continuous icing envelope does not extend below -22°F. The continuous icing values are used to determine the probable ice accumulation on an unheated surface during extended icing encounters, but they are never employed to calculate the heating rates necessary to provide anti-icing protection for an engine component. The intermittent maximum values are used for this purpose.
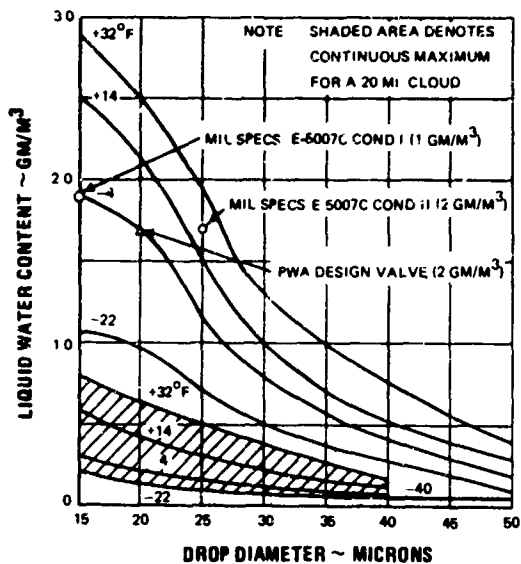
Figure 1 *Atmospheric Icing Conditions Showing the Intermittent Maximum Icing Condition (3 Mile Cloud) From FAR Part 25 with the Continuous Maximum Icing Condition (20 Mile Cloud) Superimposed*

The circular points shown on the figure indicate the two specific conditions called out in MIL-E-5007C for the sea level and static testing of running wet anti-icing systems on military engines as shown in Table I below:

TABLE I

MIL-E-5007C SEA LEVEL ANTI-ICING CONDITIONS

Condition	Liquid H$_2$O Content gm/m^3	Air Temp. °F	Mean Eff. Drop Size Microns
I	1.0	-4	15
II	2.0	+23	25

Condition II calls for about 25% higher liquid water content than the comparable point on the FAR-Part 25 specification, whereas Condition I calls for almost 50% less liquid water content than the similar FAR-Part 25 point. The triangular point indicates the environmental values that are used by Pratt & Whitney for the design of running wet, anti-icing systems (i.e. -4°F ambient air temperature, 20 micron mean effective drop diameters, and 2 gm/m^3 liquid water content). This point was conservatively chosen as the average drop size but the worst combination of temperature and liquid water content from the two MIL-E-5007C points, coupled with the fact that it agrees quite well with the comparable FAR-Part 25 intermittent maximum requirement (about 17% higher liquid water content).

Flight Cycle Analysis

To converge on a design criterion, we must now turn our attention to a study of engine operation in the icing environment. Figure 2 shows the continuous and intermittent maximum icing envelopes,

taken from the FAR Part 25, superimposed on a common plot of ambient air temperature versus altitude. Because of the much higher liquid water contents and greater extent of the intermittent maximum icing envelope in the high altitude, low temperature region, an operating line along the lower end of the intermittent icing envelope was chosen as the limiting criterion to identify those components that may require ice protection. For altitudes of 10,000 ft. and above, this operating line is almost coincident with the M-STD-210A cold day specification. Also, the straight line extrapolation back to sea level altitude yields an ambient temperature of about 27°F which is typical for severe freezing rain encounters
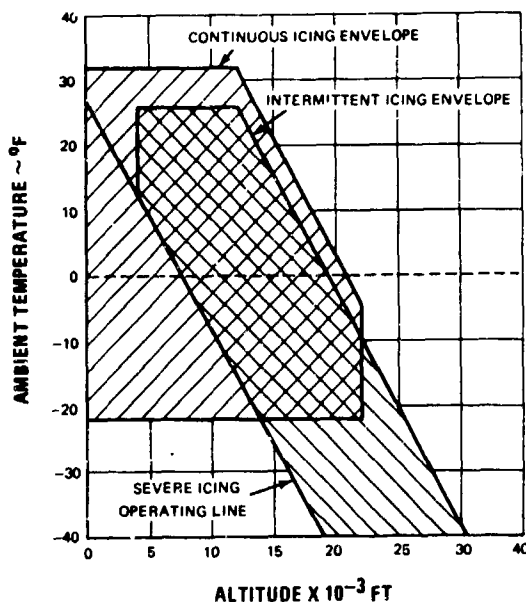
Figure 2   Atmospheric Icing Envelope From FAR Part 25

At ambient air temperatures below -22°F or altitudes above 22,000 ft, there is no continuous icing environment and only very rare encounters with intermittent icing conditions that do not pose a serious threat to flight safety. The real in-flight icing problem occurs at ambient temperatures above -4°F and altitudes from perhaps 5000 to 20,000 feet which excludes the typical cruise altitudes but encompasses the full range of holding patterns (see References 3 and 4). Note that a -4°F ambient temperature corresponds to an altitude of 9000 feet on the selected operating line. Therefore, applying the selected environmental design values (-4°F, 20μ, 2 gm/m^3) to flight altitudes below 9000 feet would represent an ultraconservative approach.

A typical flight profile for a JT8D powered Boeing 727 is shown in Figure 3 for operation along the selected icing criterion line. Also shown are the calculated equilibrium wet surface temperatures for unheated inlet case and first stator components corresponding to the reference ambient air temperature profile. Throughout the entire flight cycle, the inlet surfaces are below 32°F and therefore the inlet guide vanes and nose cone will obviously require ice protection systems. The first stators on the other hand, are either above 32°F or outside the icing envelope

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except for ground idle operation and the last 5 or 6 minutes of the descent path where the airplane could enter a continuous cloud formation and maintain flight idle power until a typical holding altitude is reached (5000 feet was assumed in Figure 3). Calculations based on exposure to either intermittent or continuous maximum cloud extents, indicate that less than 0.2 inches of ice will build up on the leading edge of the first stators during this interval. This ice accumulation will generally not interfere with normal acceleration of the engine and will be readily shed when the engines are advanced to holding power. As a result, first stator ice protection systems have not been necessary on current engines.

altitude hold with a minimum gross weight airplane is assumed for design purposes Table II is a summary of the typical design point parameters that have been used for the design of hot air, running wet, inlet guide vane anti icing systems on current Pratt & Whitney Aircraft engines

TABLE II
ANTI-ICING DESIGN POINT PARAMETERS

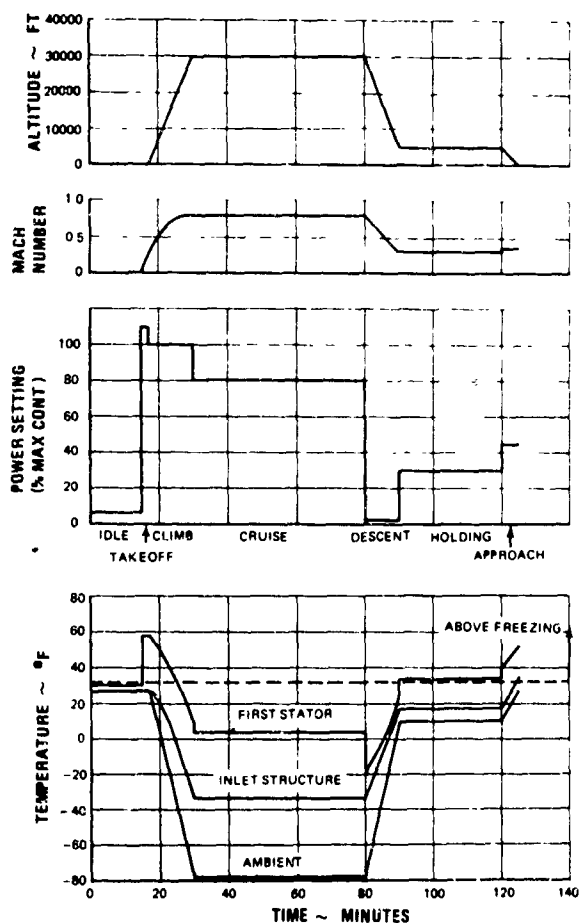| Mach Number	0.3
Altitude	5000 feet
Power Setting	Minimum Holding (Typ. 30% Max Cont)
Ambient Air Temperature	$-4^{\circ}F$
Liquid Water Content	$2 \, gm/m^3$
Mean Effective Drop Diameter	20 microns
Minimum Metal Temperature	$35^{\circ}F$

Figure 3 Typical Flight Profile for a JT8D Powered Boeing 727 Aircraft
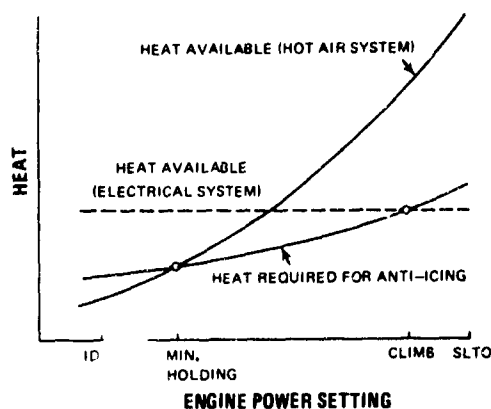
Figure 4 Heat Required for Anti Icing Versus Heat Available

If, on the other hand, an electrical anti-icing system was being considered, then just the reverse design philosophy would apply, i e., the heaters would have to be sized to prevent ice formation under high power operation as shown in Figure 4. In this case, maximum climb power at the minimum cumulous cloud altitude (4000 feet) would be a suspect condition, or possibly even take off power in an ice fog environment might be the design point criterion. In any event, a compromise design which might occasionally allow ice to accumulate on the engine inlet during the critical take-off and climb period would not be considered acceptable design practice

If we now limit our consideration to the conventional hot air anti-icing system, it can be seen from Figure 4 that the hold portion of the flight cycle constitutes the design point for in flight protection of the inlet case structure. At this condition, the engines can be exposed to a severe icing environment for extended periods of time while operating at relatively low power where the heat source available for anti-icing is minimal. Since the required engine power, and therefore the heat available for anti icing, increase with airplane gross weight and holding altitude, a low

It should be noted that preliminary testing of the advanced high bypass ratio JT9D engine indicated that the rate of ice accumulation on the first stage stators, when subjected to very high liquid water contents at simulated idle descent rotor speeds, was greater than that experienced on current production engines A comparison of the JT9D inlet geometry with a typical current engine, as shown in Figure 5, suggests the reasons for these results. The sheer size and rotation of the JT9D spinner produces a much lower catch efficiency than the much smaller JT8D nose cone As a result, about 97% of the approaching water droplets are deflected around the JT9D spinner compared to 88% for the JT8D nose cone This difference, plus the fact that the deflected water is concentrated toward the I.D. of the gaspath, causes a greater

increase in the effective water content on the JT9D first stage engine stator than the JT8D first stage fan stator which has a much lower hub tip ratio (0.41 versus 0 76).
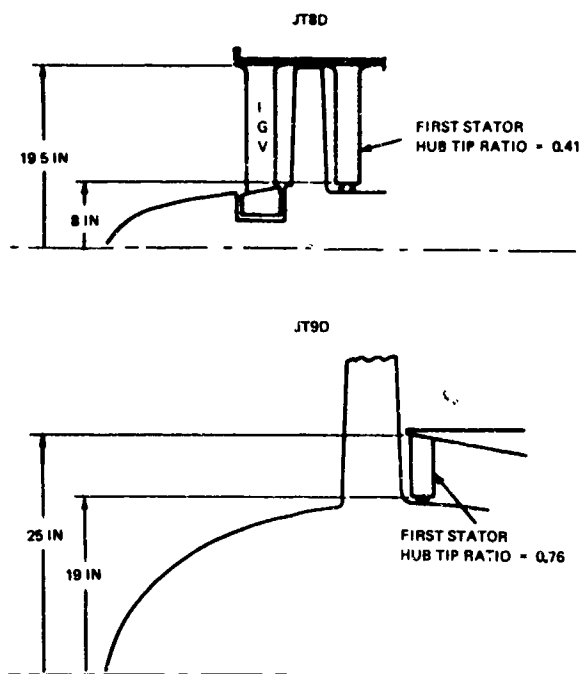
Figure 5   Comparison of JT8D and JT9D Inlet Geometry

Subsequent testing indicated that the engine could readily tolerate the more realistic icing conditions that were prescribed by the Boeing Company and, therefore, the prototype engines were cleared for use in the flight test aircraft without anti-icing systems. However, a decision was made by Pratt & Whitney Aircraft to incorporate first stage stator anti-icing in the initial production engines until sufficient flight time has been accumulated to absolutely establish that it is not required. On the other hand, spinner icing does not appear to be a problem based on the testing to date. Although so ie ice did form, the accumulation was very limited and continually shed throughout the test program.

Ground Idle Operations

The presence of freezing rain or ice fog during ground idle operation is a fairly common occurrence that presents a unique engine icing problem. Although the liquid water contents are surprisingly low (Reference 6 states typically 0.15 gm/m^3), extended periods of idle operation in these environments can produce substantial ice accumulations on nose cones, inlet guide vanes, first stators, root portions of the first stage blades, and sometimes second stage blades as well. It would obviously be impractical to provide ice protection for all of these components, and therefore this condition was also ruled out when the design point for the inlet guide vane anti-icing system was selected. Instead, periodically accelerating the engines during extended ground delays was accepted as a simple operational procedure that would efficiently de-ice the engine components.

Figure 6 shows the % N_1 required on a JT8D engine to develop sufficient bleed air temperature and fan temperature rise, as a function of ambient air temperature, to deice the inlet guide vanes and first stators respectively. For a 27°F day, increasing N_1 from 31% (ground idle) to about 42% of take-off RPM will clear off any accumulated ice from these static components.

Figure 7 is a similar plot that shows the % N_1 required to shed various ice thicknesses from the root section of the fan blades. The curves were based on the average ice removal force for titanium shown in Figure 8 which was taken from Reference 7. Other references indicate substantial disagreement with these data depending upon the surface cleanliness of the test specimen and other nebulous factors. However, flight operation reports tend to support the results shown on Figure 7, in that substantial fan blade ice accumulations (1/2 inch or more) have only been reported under relatively cold ice fog conditions Freezing rain reports usually refer only to relatively thin glaze ice formation on the fan blades.
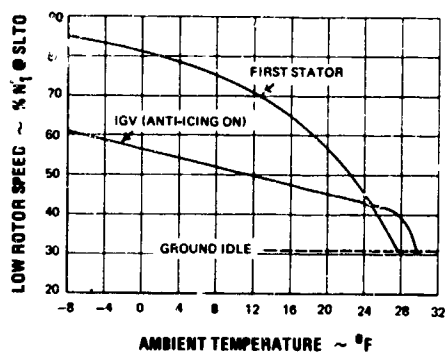

Figure 6   Percent N_1 Required to Deice the Inlet Guide Vanes and First Stator Vanes of the JT8D Engine
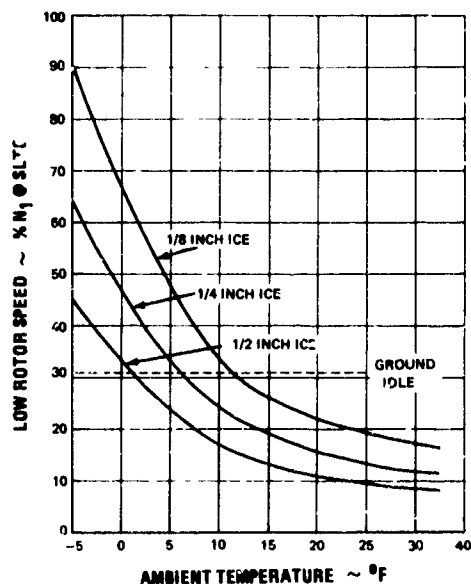

Figure 7   Percent N_1 Required to Shed Ice From Fan Blade Root of the JT8D Engine
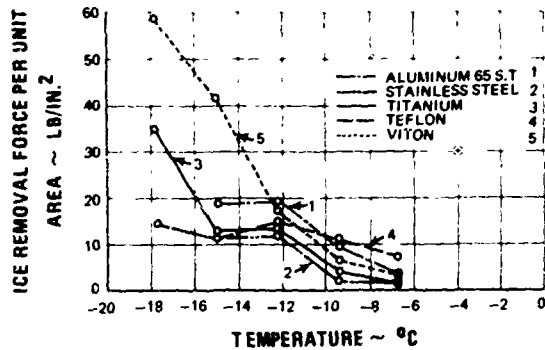
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Figure 8 Ice Removal Force for Various Materials

DESIGN CONSIDERATIONS

From the foregoing discussions, it is apparent that anti-icing and not deicing protection is desired for in-flight operation to avoid the possibility of dislodging large ice accumulations that could result in compressor damage. All Pratt & Whitney Aircraft gas turbine engines are equipped with convective type anti-icing systems that rely on compressor bleed air as the heat source. The following section discusses some of the practical considerations that have led to this design philosophy.

Type of Systems

It has long been hoped that ice-phobic coatings (coatings to which ice does not adhere) could be developed to prevent ice formation on aircraft components. Various materials which exhibit a decreased affinity for ice adhesion under static conditions have been developed However, in high speed impingement tests, these materials offered no significant improvement over standard structural materials This is apparently caused by the impinging water droplets penetrating the pores of the coatings. Figure 8 shows the impact ice adhesion properties of various materials based on tests by Stallabrass and Price (Reference 7). Testing at P&WA on JT9D spinners would tend to support these findings in that spinners made of titanium, aluminum, and teflon coated aluminum all demonstrated very similar ice shedding characteristics.

The concept of relying solely on coatings for turbine engine inlet ice protection has not been accepted for several reasons. A satisfactory ice-phobic material has not yet been developed, and therefore some degree of in-flight ice accumulation and shedding would have to be accepted as routine during any phase of the flight cycle. Also, inlet surfaces are subject to abrasive particles which would cause deterioration of the coating and pose an additional maintenance headache.

Electrical heating systems have been extensively used on piston engines to deice propellers and spinners by means of airframe supplied power delivered through a slipring assembly. However, for gas turbine applications where anti-icing protection is required for relatively large surfaces, the electrical power requirements are so severe that a substantial increase in the size of the airframe supplied generator is required to meet this demand. In addition, failure of the generator accessory would cause loss of anti-icing

protection for an otherwise operable engine. Greater complexity, particularly where slip rings may be required to transmit power to a rotating component, and generally lower reliability are also reasons for rejecting electrical systems in favor of self-contained hot air systems.

On the other hand, in some applications electrical systems offer greater flexibility regarding the distribution and control of heat. For example, in very thin airfoils with sharp leading edges, it is possible to imbed a heating element very close to the leading edge without altering the aerodynamic shape. However, to incorporate an airflow passage sufficiently close to the stagnation point to provide adequate anti-icing, it is often necessary to increase the leading edge radius and accept the associated aerodynamic penalty. The JT9D first stator is an example where an aerodynamic compromise was accepted to implement a hot air anti-icing system.

Bleed Air Location

The selection of the anti-icing bleed air location involves several interesting considerations. The first is availability. Gas turbine engines generally require bleed ports for aerodynamic stability during starting or rapid transient conditions, for airframe services such as cabin pressurization and ice protection, for internal engine services such as seal pressurization, turbine cooling, rotor thrust balancing, fuel deicing, and finally for inlet anti-icing. Priority for bleed port locations is given to the aerodynamic and airframe requirements which usually results in bleed ports at the low compressor discharge, at one or more high compressor interstage locations, and at the high compressor discharge location. The remaining services, including anti-icing, are then limited to one of these predetermined locations. The bleed air temperature from the low compressor is too low for anti-icing purposes so that the choice is usually between high compressor interstage and high compressor discharge air.

The second consideration is bleed system capacity. The high compressor discharge is usually a midstream or ID bleed system to insure cleanliness during ground idle operation, which requires that the bleed air be extracted via the restrictive diffuser struts. The capacity of such systems is fully utilized for maintaining cabin pressurization during idle descent operation and, therefore, discourages the selection of this system for anti-icing purposes.

Surprisingly, performance penalties are not a major factor in selecting the bleed location since the reduced flow requirements for the compressor discharge system tend to offset the higher "cost" of this air. However, structural considerations clearly favor the interstage bleed location since all of the components subjected to the anti-icing flow must be able to withstand the pressure and temperature associated with a "failed" condition, i.e., the control valve inadvertently left open during a maximum temperature or pressure condition. For an advanced commercial engine or supersonic military application, compressor discharge temperatures can exceed 1000°F which would jeopardize the use of titanium inlet cases and rule out all of the vibration damping materials that are commonly used in these areas. The cost and reliability of control valves are also compromised at the higher operating temperatures, and the use of a thermostatic modulating valve, which is often not used with an interstage bleed system, is considered mandatory with a high compressor discharge system. For these reasons, the JT8D, TF30, and JT9D engines all use high compressor interstage bleed air for anti-icing

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Figure 9 shows the mechanical arrangement of the anti-icing system on a JT8D engine. The air is extracted from two ports located on the 8th stage bleed manifold and piped forward via 1 3/4 inch diameter lines. Each is fitted with a motor operated on-off butterfly valve in series with a thermostatic modulating valve (the latter have been replaced on all installations by fixed orifice plates). The air is dumped into a manifold that is integral with the outer titanium fan case and then flows radially inward through the inlet guide vanes. The center section of the bottom-most vane contains the oil service lines, imbedded in a vibration damping material, which serves to force most of the air down the forward and aft passages. The other vanes have center section baffles to promote a similar flow distribution. Finally, the air discharges into the inner box where it is made available for anti-icing the airframe supplied nose-cone.
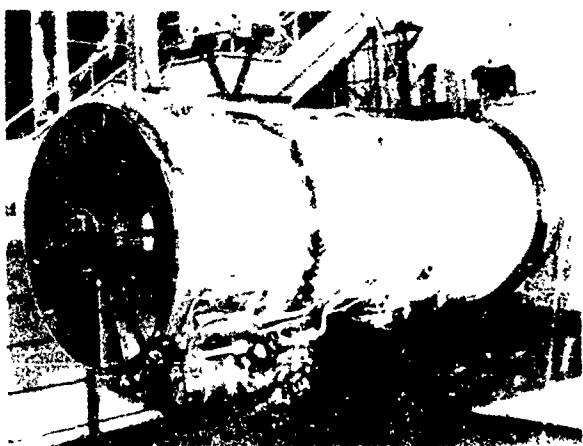

Figure 9   Typical Anti-Icing System on a JT8D Engine

ANALYTICAL TECHNIQUE

Catch Efficiency

A significant parameter which enters into engine inlet icing analysis is impingement catch efficiency. As air flows around a body, relatively small entrained water droplets tend to follow the streamlines thus avoiding impingement, while large droplets will tend to follow straighter trajectories. Figure 10 depicts typical droplet trajectories for flow past a cylinder with uniform droplet size. Catch efficiency is defined as the ratio of the actual water impingement rate on a body to that which would occur with straight line trajectories. Under this definition, the catch efficiency for the cylinder in Figure 10 would be h/D. There are numer .s references on experimental and theoretical determinations of catch efficiencies of various geometrical shapes. References 8 and 9 are used at Pratt & Whitney Aircraft for calculating the ice accumulation on nose cones and spinners. These have shown that catch efficiency increases with free stream airspeed and water droplet diameter, and decreases with air viscosity and density.
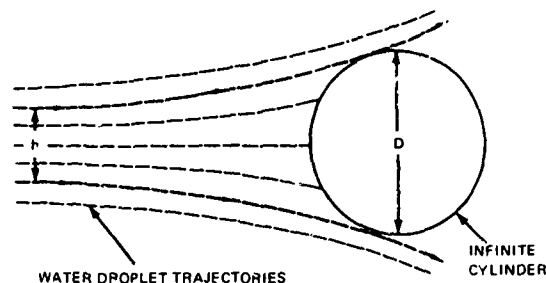
Figure 10   Illustration of Catch Efficiency

Geometrical shape and size markedly affect catch efficiencies. Very small objects at normal flight conditions approach catch efficiencies of 100% while catch efficiencies of large objects are very low. As an example, at normal idle descent icing conditions, the total catch efficiency of a JT9D fan blade is approximately 80%, while that of the spinner is only about 3%. For objects of the same size, increasing slenderness will decrease catch efficiency.

Figure 11 compares the calculated effects of ice buildup on a P&WA JT8D engine nose cone and a P&WA JT9D engine inlet spinner exposed to the same icing conditions. The large amount of ice buildup on the JT8D nose cone (approximately 3 inches at the stagnation point) suggests the need for anti-icing of this component, while the relatively thin layer (approximately 1 inch) on the JT9D spinner may be acceptable.

In this case, even though the JT8D bullet is slightly more slender than the JT9D spinner, it is the much greater size of the spinner that is the overriding factor affecting catch efficiency.

Relative to blunt objects, slender objects exhibit lower overall catch efficiencies but higher local stagnation point catch rates. To add to this effect, the impingement limit, which is the farthest point from the stagnation point at which water impinges, decreases with slenderness. This means that slender objects tend to form long projections of ice out from the stagnation point as shown on the JT8D nose cone in Figure 11. This type of formation breaks off in large chunks which can cause compressor blade damage. Blunter objects, on the other hand, such as the JT9D spinner, tend to form more uniform accretions of ice which shed off in thinner sheets.

The preceding discussion, and the analysis used to produce Figure 11, ignores the effects of water run-off as it freezes, but the basic geometric considerations are still true that object size (as reflected in projected area) is the overriding factor affecting catch efficiency, while object shape is dominant in determining the type of ice formation that will occur.

Calculated catch efficiencies of inlet guide vanes and first stage stators under normal icing conditions typically range from 80% to 90%. Due to the uncertainity of analysis, especially since droplet size distribution affects the catch efficiency of an airfoil, catch efficiencies of 100% are usually assumed for these components in anti-icing analyses.

As previously discussed, inlet guide vanes and stators are subject to an increase in effective liquid water content caused by the low

catch efficiencies of nose cones and spinners. This is, of course, the primary reason why inlet icing encounters invariably show a concentration of ice at the ID of the inlet guide vanes and stators.

ALTITUDE	5000 FT.	
MACH NO'	0.3	
AMBIENT TEMP	10°F	
LIQ H$_2$O CONTENT	0.37 gm/m^3	
MEAN DROP DIA	20 microns	

IMPINGEMENT LIMIT

JT8D NOSE CONE

OVERALL CATCH EFF = 12%

3"

IMPINGEMENT LIMIT

JT9D SPINNER

OVERALL CATCH EFF = 3%

1"

Figure 11 Comparison of Ice Accumulation on JT8D Nose Cone Versus JT9D Spinner for a Typical One Hour Hold Period
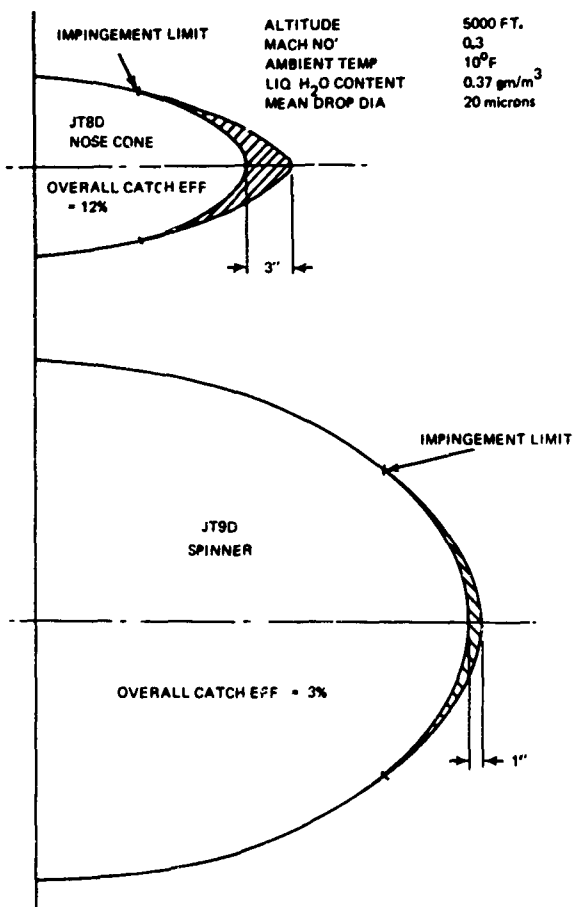
Another catch efficiency phenonmenon called "scoop factor" is shown in Figure 12. Under high speed, reduced power flight conditions, the engine is unable to swallow all the air contained in the engine inlet projected area. The solid lines in Figure 12 represent the dividing streamlines for the air, while the dotted lines represent the dividing streamlines for the water droplets which tend to follow straighter trajectories. Thus, the effective liquid water content at the inlet is increased by $(D/h)^2$, defined as a scoop factor. This factor is at a maximum (approximately 1 1/3) under conditions of idle descent.

One final note should be added here. Although the geometry of nose cones, inlet guide vanes, and stators materially affect icing rates, their design is predicated on aerodynamic and structural considerations. The anti-icing system designer can seldom influence the gaspath geometry.

WATER DROPLET TRAJECTORIES

STREAMLINES

ENGINE

INLET
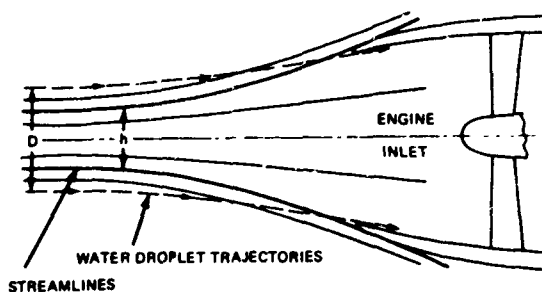
Figure 12 Illustration of Scoop Factor

Thermal Analysis

The basis for the analytical solution of the heat required for anti-icing is contained in Reference 10. This technical note rearranges the conventional equations for heat transfer and evaporation to permit a simple graphical solution. Figure 13 depicts the basic equation for the solution of heat transfer and evaporation from a surface heated to prevent icing. The equation includes the convective heat transfer to the air, the sensible heat change of the impinging water, and the heat transferred by evaporation from the surface. The evaporative heat transfer term assumes that the process is so rapid that there is no change in the state of entrained moisture; that is, the absolute humidity of the air does not change. Substituting MwL for the evaporation term would represent the amount of heat that would be required to completely evaporate all of the impinging water. Evaluation of this term would show that a prohibitive amount of heat would be necessary to maintain a dry surface for high water impingement rates. The design philosophy is, therefore, to provide enough heat to maintain the entire surface above 35°F in a "running wet" condition. This assumes that there will be negligible ice accretion due to water run back aft of the anti-iced object. This of course must be borne out by testing.

$$q \quad h_a (T_{surface} - T_{adiabatic\ wall}) \quad \text{Convective Term}$$

$$+ M_w C_w (T_{surface} - T_{water}) \quad \begin{array}{l}\text{Sensible Heat}\\ \text{Change of Water}\end{array}$$

$$+0.622 \frac{h_a K L}{C_p} \left[\frac{e_{surface}}{P_{local}} - \frac{e_{ambient}}{P_{ambient}} \right] \quad \begin{array}{l}\text{Evaporative}\\ \text{Cooling}\end{array}$$

q — Heat Rate Per Unit Area
h_a — Convective Heat Transfer Coefficient
M_w — Rate of Water Catch Per Unit Area
C_w — Spec Heat of Water
K — Degree of Surface Wetness
L — Latent Heat of Vaporization of Water
C_p — Specific Heat of Air
e — Partial Pressure of Water Vapor in Saturated Air
P — Static Air Pressure

Figure 13 Heat Transfer Equation

Computer Program

The amount of heat required for anti-icing can be found once the foll · ing are established: the amount of water impingement, the loca. heat transfer coefficient, the ambient temperature, the ambient pressure, the local pressure, the approach velocity, and the surface temperature. It is seldom possible, however, to set a constant surface temperature with a hot air anti-icing system since the hot air temperature will drop as the anti-icing air flows through the component.

However, since the evaporative cooling term is dependent upon surface temperature, a step by step solution is required based on iterations with surface temperature.

In order to expedite the iterations required for a solution, a computer program has been developed. Figure 14 indicates the required input terms to solve a given problem. As in conventional heat transfer programs, the component should be broken up into elements. The surface temperature of the first element mid-section is assumed. Once the iterated surface temperature agrees with the calculated value, the exit air temperature is calculated and used as the inlet to the next element. The exit surface temperature is used as the first approximation for the next element and the process is repeated for the complete component. Numerous combinations of anti-icing airflows and temperatures can be easily run to obtain the optimum solution for a particular problem.

EXPERIMENTAL VERIFICATION

Pratt & Whitney Aircraft uses both spray rig and icing tunnels for experimental investigations of icing problems. Spray rig assemblies, simulating natural icing conditions, are used to investigate full scale engine anti-icing capability. Icing tunnels, on the other hand, are used primarily to study the icing characteristics of individual components and obtain fundamental data useful in the design of anti-icing systems.

Vane Cascade Icing Rig

An icing cascade rig was used to evaluate the icing characteristics of the JT9D first stator. Various hot air schemes were evaluated on this rig for anti-icing this very thin airfoil. The air passage through the vane was initially located 0.70 inch from the leading and trailing edges of the vane. Testing indicated that this design was unsatisfactory and the leading edges of the vanes were then reoperated, compromising to some degree the vane aerodynamics, in order to position the hot air passage within 0.20 inch of the leading edge. Figure 15 indicates the predicted mid-span temperature distribution for the stator subjected to 2.5 GM/M^3 liquid water content at 20°F inlet air temperature. Temperature distributions are shown for the unheated vane and both heated vane configurations. It can be seen that both the leading and trailing edges of the heated vane are below 32°F. However, by relocating the hot air passage, the amount of unprotected leading edge surface is reduced from 0.5 inch to less than 0.10 inch.

Figure 14   Anti-Icing Computer Program Input and Output Quantities
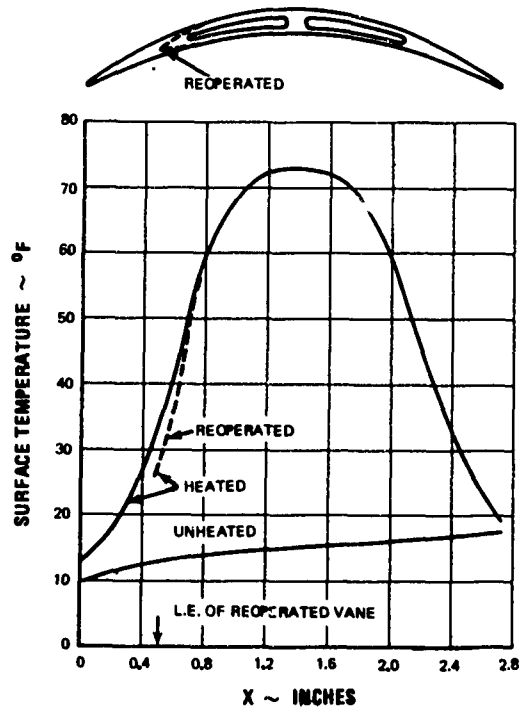
Figure 15   Predicted Mid-Span Temperature Distribution for the JT9D First Stator Subjected to 2.5 GM/M^3 Liquid Water Content at 20°F Inlet Temperature

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Figure 16 shows photographs of the unheated vane, and both heated vane configurations after 100 seconds exposure to the stated icing conditions. The first picture shows the unheated vane cascade with ice over much of the vane surface. The second picture shows the heated vane with the hot air passages 0.7 inch for the leading and trailing edges. Ice can be seen on both the leading and trailing edges but the mid-chord section is clear of any accumulation. The last picture is the heated vane with the hot air passage 0.2 inch from the leading edge. A slight ice build up can be seen on the leading edge and some on the trailing edge. Experience with the latter configuration, however, indicated that any ice that was formed would rapidly shed thereby preventing any significant accumulation.

No Anti-Icing.

Hot Air Anti-Icing One Percent 9th Stage Air.

Cut Back Vane. One Percent 9th Stage Air.

Figure 16 JT9D First Stator after 100 Seconds Exposure to Simulated 1800 N_1 at 20°F Inlet Air Temperature and 2.5 GM/M³ LWC.

As a point of interest, this particular rig demonstrated the effect of low static pressures on icing. During one run, the rig was operated with very low humidity inlet air at 70°F and 5 psia static pressure. Figure 17 shows the psychrometric chart representation for this inlet condition, which indicates that the corresponding wet bulb temperature is only 29°F. This suggests that the potential for icing exists as a result of the strong evaporative cooling effect. Figure 18 is a photograph of the rig at this extreme condition showing some ice on the vane leading edge.
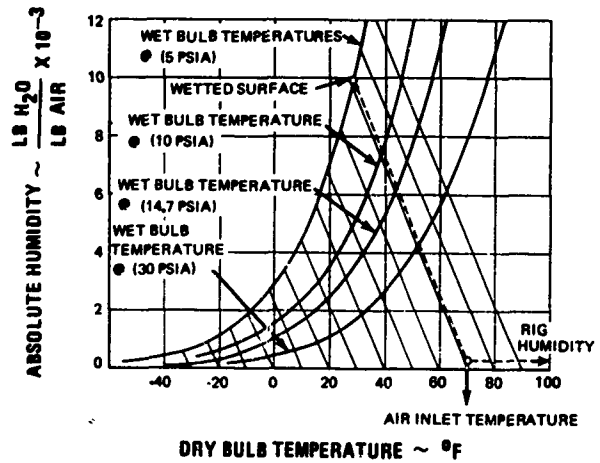
Figure 17 Psychrometric Chart Representation of Vane Icing at High Temperature and Low Pressure

Figure 18 JT9D First Stator After 5 Minutes Exposure to Simulated 2400 N_1 at 70°F Inlet Air Temperature 2.0 GM/M³ LWC. No Anti-Icing.

Engine Icing Tests

Anti-icing tests are conducted on an engine by employing a rake with pneumatic water spray nozzles. The nozzle spray rig is placed in a chamber in which the water and air mix before reaching the engine inlet. The inlet air temperature and water discharge temperature can be controlled to obtain the desired icing conditions. The water spray rig is pre-calibrated to flow 20 micron

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mean effective droplets. Figure 19, a photograph of the X208 test stand, is a typical icing installation showing the inlet duct, the water spray system, and camera equipment. Figure 20 is an inlet view showing the water spray bars.
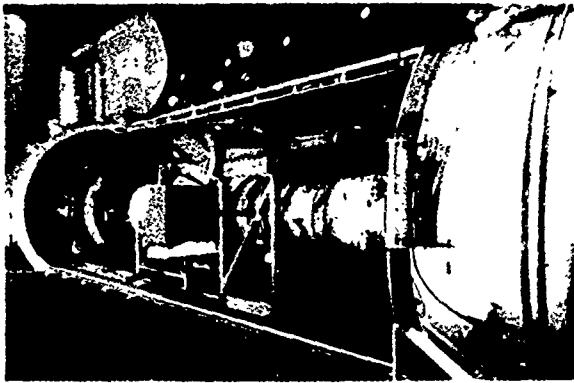
Figure 19 Installation for JT8D-1 Anti-Icing Test in the X208 Test Stand
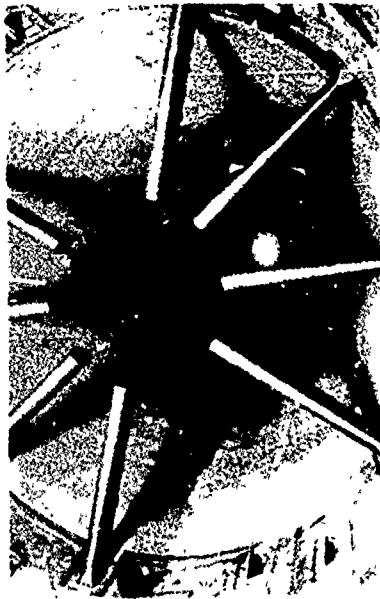
Figure 20 Inlet View of JT8D-1 Engine mounted in X208 Test Stand for Anti-Icing Test Showing Water Spray Bars, Duct and Engine Inlet

Table III shows the current capacity of the new X217 test stand, located in the Willgoos laboratory, that is being used to conduct anti-icing certification tests on the JT9D-3.

After the JT8D engine went into service, it was decided to study the feasibility of replacing the anti-icing modulating valve with a fixed orifice. Analytical studies were initiated, using the computer program previously discussed, to predict the inlet guide vane temperatures for various flow rates and icing conditions. Figure 21 shows the predicted surface temperatures for the conditions noted and the minimum flow rate corresponding to the smallest orifice size that was considered. The calculations were intended for the three vanes on either side of bottom dead center which received the lowest anti-icing airflow due to probe bosses located in the manifold. Note that freezing temperatures are predicted only at the stagnation point, from the midspan to the root of the vane.
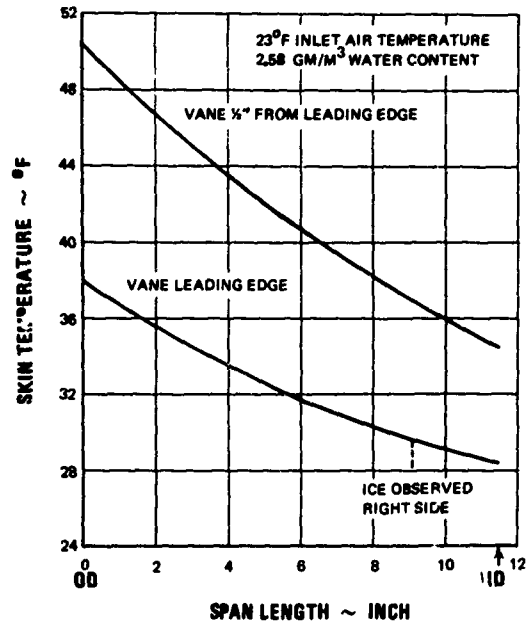
Figure 21 Predicted JT8D Inlet Guide Vane Temperatures With Minimum Anti-Icing Flow. Inlet Temperature 23°F. LWC 2.58 GM/M³. Anti-Icing Bleed Temperature 315°F.

Figure 22 is a photograph showing the vanes to be ice free at this condition except for the third vane to the right of bottom dead center. Some ice can be seen on the leading edge about one fifth of the span length from the vane root. This is in good agreement with the predictions.

Qualitative substantiation of the JT8D nose cone catch efficiency was also obtained from this same test run as shown in Figure 23. The orifice that was used in this test resulted in insufficient flow to anti-ice the nose cone, and ice formed on the stagnation point with the approximate shape as predicted in Figure 11. Consequently, a larger orifice was subsequently incorporated in the bill of material.

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Figure 22 JT8D Inlet Guide Vanes ice Free Except for Number 4 at the 15 Minute Calibration Point. Inlet Air Temperature 23°F. LWC 2.58 GM/M³. Anti-Icing Bleed Temperature 315°F.

Figure 23 JT8D Nose Cone Ice Accumulation at 15 Minute Calibration Point, Inlet Temperature 23°F. LWC 2.58 GM/M³. Anti-Icing Bleed Temperature 315°F.

FAA Certification Program

The selection of the parameters necessary to design an anti-icing system is, to a large extent, a matter of judgement. As indicated previously, conservatism is applied in the selection of water content, catch efficiency, temperature and so forth. In like manner, the anti-icing certification test program is very conservative. The Pratt & Whitney anti-icing test program exceeds the requirements of FAR-Part 25 with respect to liquid water content and ice duration time.

All test conditions are run at simulated low ambient temperatures with liquid water contents corresponding to the maximum liquid water content of a cloud existing at the total ram temperature. This combination is intended as the upper limit of the whole range of inlet ambient temperatures, Mach numbers, and liquid water contents that are possible in flight. In addition, a "scoop factor", as previously discussed, is applied to the liquid water content for the simulated idle descent flight conditions.

The icing conditions are run for a period of time at least twice that required to pass through a typical cloud extent as defined in FAR - Part 25. Also, due to the dependence of hot air inlet anti-icing systems on power, tests are run at simulated idle descent and minimum power holding conditions where the systems are most critical.

Figure 24 shows a photograph of the JT8D-1 engine inlet after being subjected to a severe test simulating a 5 minute idle descent through an intermittent maximum cloud, which is about five times that typically required. This particular test was run at an equivalent ambient of -18°F with a liquid water content of 2.65 GM/M³, which includes a scoop factor of 1.33. This picture shows ice formed on the nose cone and leading edges of the inlet guide vanes. However, the engine was then successfully accelerated to a holding power setting where the ice broke loose and was ingested with no detrimental effect on the engine. Figure 25 is a photo showing the engine inlet after the acceleration.
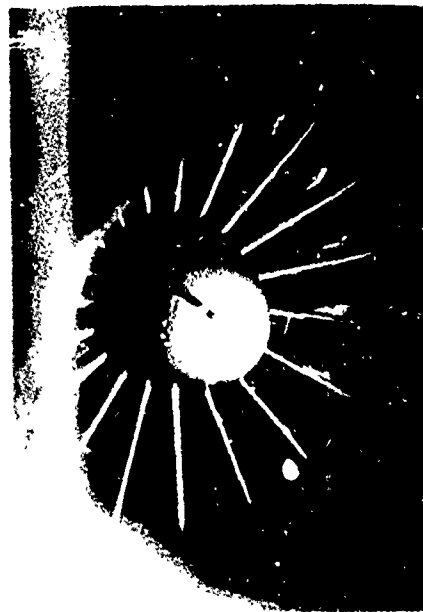
Figure 24 JT8D-1 Engine Inlet After Being Subjected to a Severe Test Simulating a 5 Minute Idle Descent Through an Intermittent Maximum Cloud. Inlet Temperature 5°F. LWC 2.65 GM/M³.

67
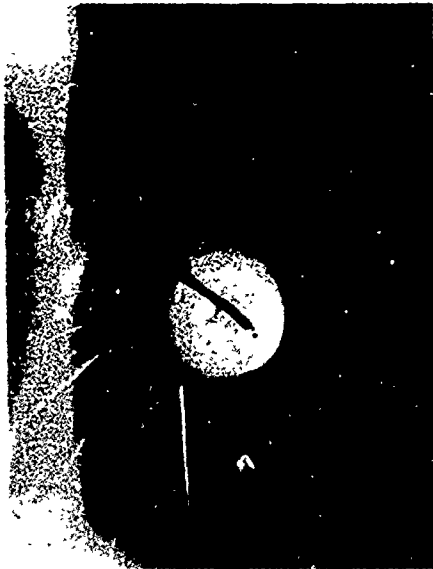
Figure 25 JT8D-1 Engine Inlet After Acceleration Following A Severe Simulated 5 Minute Idle Descent Test Through an Intermittent Maximum Cloud. Inlet Temperature 5°F. LWC 2.65 GM/M³.

The whole icing program is then not only conservative with respect to the icing conditions the engine is subjected to, but also with respect to the low engine power setting investigated. These low power descent and minimum power holding conditions investigated are not considered typical of normal flights.

In addition to investigating descent conditions, holding conditions are also simulated. A long time minimum power hold condition in a continuous maximum cloud is simulated followed by an idle descent through a continuous maximum cloud and an intermittent maximum cloud. The engine is then accelerated to an approach power setting.

CONCLUDING REMARKS

Pratt & Whitney Aircraft engines have logged an unprecedented amount of commercial flight time with no recorded loss of aircraft due to icing encounters. This record clearly establishes the adequacy of the ice protection systems and undoubtedly reflects the conservative design and certification procedures that have been used.

However, in the last year or so, there have been an increasing number of complaints regarding engine icing under extended ground idle operation in freezing rain or ice fog conditions. Several operators involved in the delays managed to avoid difficulty by periodically accelerating their engines, but most hesitated to do so for fear of skidding on the ice coated ramps. The delays were typically one hour, but ranged from a minimum of 1/2 hour to over 1 1/2 hours.

These incidents suggest that the ground traffic procedures be reviewed to hopefully avoid delays on the idle ramp during icing conditions, or at least insure that engine deicing procedures can be safely administered.

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DISCUSSIONS FOLLOWING MR. STRIEBEL'S PRESENTATION ON

"ICE PROTECTION FOR TURBINE ENGINES"

Question: In the P&WA JT9D engine, to what operating condition was the ice protection designed for the anti-iced stators?

Answer: Idle descent engine operation.

Question: How far into engines does condensation icing occur?

Answer: This is not known exactly.

Question: How thick is the Leading Edge of the JT9D fan blade?

Answer: .140"

Question: In descent would there be an icing problem on an SST engine?

Answer: Not believed to be a problem in supersonic descents, nor any different problem than present engines when in subsonic flight.

Question: Was hail tested in the JT9D engine?

Answer: Yes, along with ice ingestion. A two-hour simulated ice fog test run for two hours at idle with LWC of .5 grams/m.^{3}.

Question: How was ground ice fog testing accomplished?

Answer: The engine was run at 800 r.p.m. (fan) with small L.W. droplets and .2 to .5 LWC. The engine was easily accelerated at any time without engine damage.

Question: What engine conditions prevailed in these icing tests in idle?

Answer: The engine was held at a constant idle setting (no short bursts) covering -4°F. and 23°F. temperatures.

Question: What acceleration handling procedures will be given
           as instructions for operating on the ground under
           icing conditions?

Answer: Have heat "on" and increase r.p.m. to clear engine.
           It may stall briefly if ice is being shed.

Question: Does P&W favor ice detectors in the air inlet duct?

Answer: Yes, to enable detection of ice in virtually clear
           air conditions.

Question: In the JT9D icing test how much ice buildup was seen
           on the spinner cone?

Answer: 3/8 inch all over spinner which shed completely
           without damage.

Question: How long did the JT9D require to accelerate in
           the icing tests?

Answer: The normal time was demonstrated--4 to 5 seconds.

Question: What size ice chunks were ingestion tested in
           the JT9D?

Answer: Slabs 1" X 4" X about 2 feet. It was commented that
           in addition, a rubber boot, 9 ft. X 4 in. X ½ in.
           was inadvertently ingested without damage.

Question: Will P&W test engines at other than the one design
           point for icing design?

Answer: Perhaps so.

Question: As an icing design point, can lower temperature
           points be limiting?

Answer: Not really, as lower water content is involved.

LABORATORY TESTING OF

ENGINE ICE SYSTEMS

April 24, 1969

S.H. Davison - Manager
CF6 Mechanical Systems Design
Aircraft Engine Technical Division
General Electric Company

SUMMARY

1. General Electric has facilities which are capable of testing components and engines in simulated icing clouds. These facilities have proven to be successful in the development and qualification of turbofan engines for Military and Commercial applications. The Peebles facility has demonstrated the versatility required to simulate icing clouds for Commercial and Military applications of high by-pass turbofans.

2. The CF6-6 engine with the Douglas flight inlet installed completed icing tests designed to comply with FAR Part 25 regulations. In addition testing was conducted beyond the current definition of icing conditions to explore engine operating characteristics. These tests were also completed and all engine parameters remained within specified limits. Steady state and transient engine operations were carried out to simulate actual conditions in service icing conditions. No unacceptable characteristics were encountered.

3. General Electric has found that each engine and airframe application must be examined to determine the optimum icing protection system. Engine testing at the higher ambient temperatures and associated liquid water content has proven to be a more severe icing condition than at lower temperatures and liquid water content.

4. The Military and Commercial Specifications for engine icing systems are generally compatible from a design and engine test standpoint. The higher values of liquid water content and the temperatures associated with these LWC's have been used to design and test engines for compliance with icing requirements. FAA Advisory Circular Material defining typical flight paths and representative power settings to be used in the evaluation of turbofan engines in simulated icing conditions would be helpful.

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G.E. ICING TEST FACILITIES AND TEST PROCEDURES

G.E. ICING TEST FACILITIES

General Electric has two major facilities for testing jet engines and components in simulated Icing Conditions. The facilities at Evendale consist of two conventional cells where conditioned air is supplied through a tunnel to the test vehicle. Water spray bars are installed in front of the vehicle to provide the desired Liquid Water Content and control of droplet size. One cell is capable of supplying conditioned air as shown in Figure 1.

This facility is used for testing components of engines where icing protection systems are under consideration and early design information is desired. In addition, complete engines with airflow requirements within the levels shown in Figure 1, are capable of being tested in this facility.

A similar test cell is also available with augmented airflow capacity to 500 pounds per second using the same refrigeration system as the above cell, which necessitates use during colder ambient air temperatures to supply the desired air temperature at the inlet to the test vehicle. General Electric has found that these facilities have proven to be extremely useful during the development phase of an engine program.

The development of the large high by-pass turbofan engines lead to new requirements for simulating icing clouds. General Electric designed and built an outdoor test facility capable of testing these engines at Peebles, Ohio.

The facility was designed to include the capability of creating natural environmental conditions required for the development of a high by-pass ratio turbofan.

Figure 2 is a photograph of the installation showing the wind tunnel with 13 electrically driven fans which have the capability of producing 3280 pounds per second airflow at 60 knots. The water and air manifolds with the spray nozzles can be observed. These are used to create the simulated ice clouds.

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EVENDALE CELL REFRIGERATION CAPACITY

FIGURE 1

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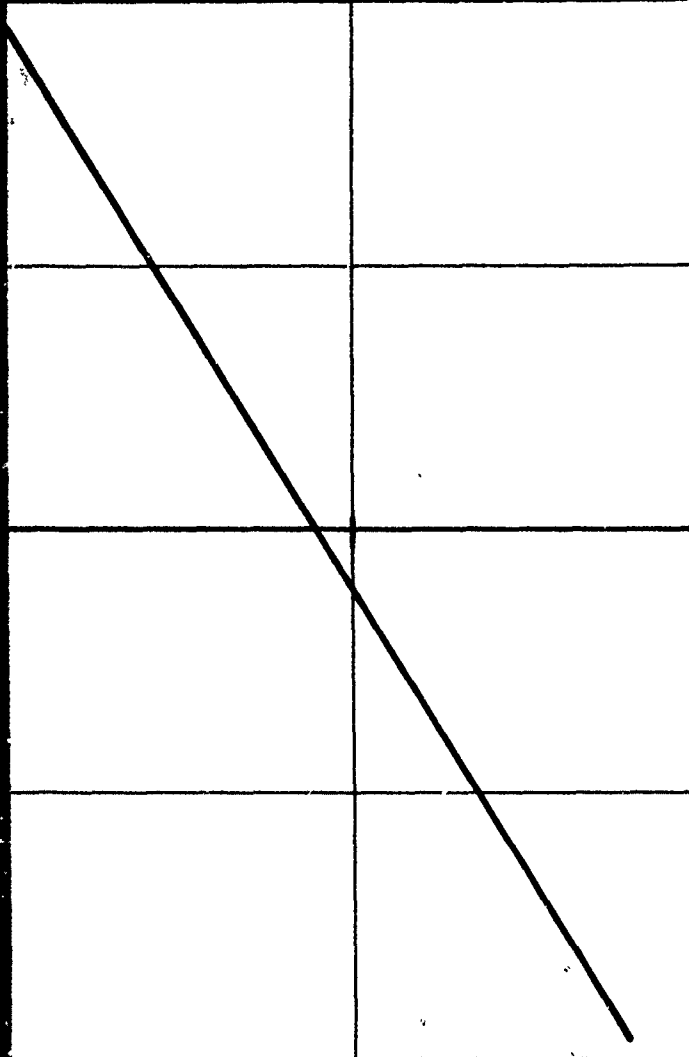
GE ICING TEST FACILITY-PEEBLES

FIGURE 2

75
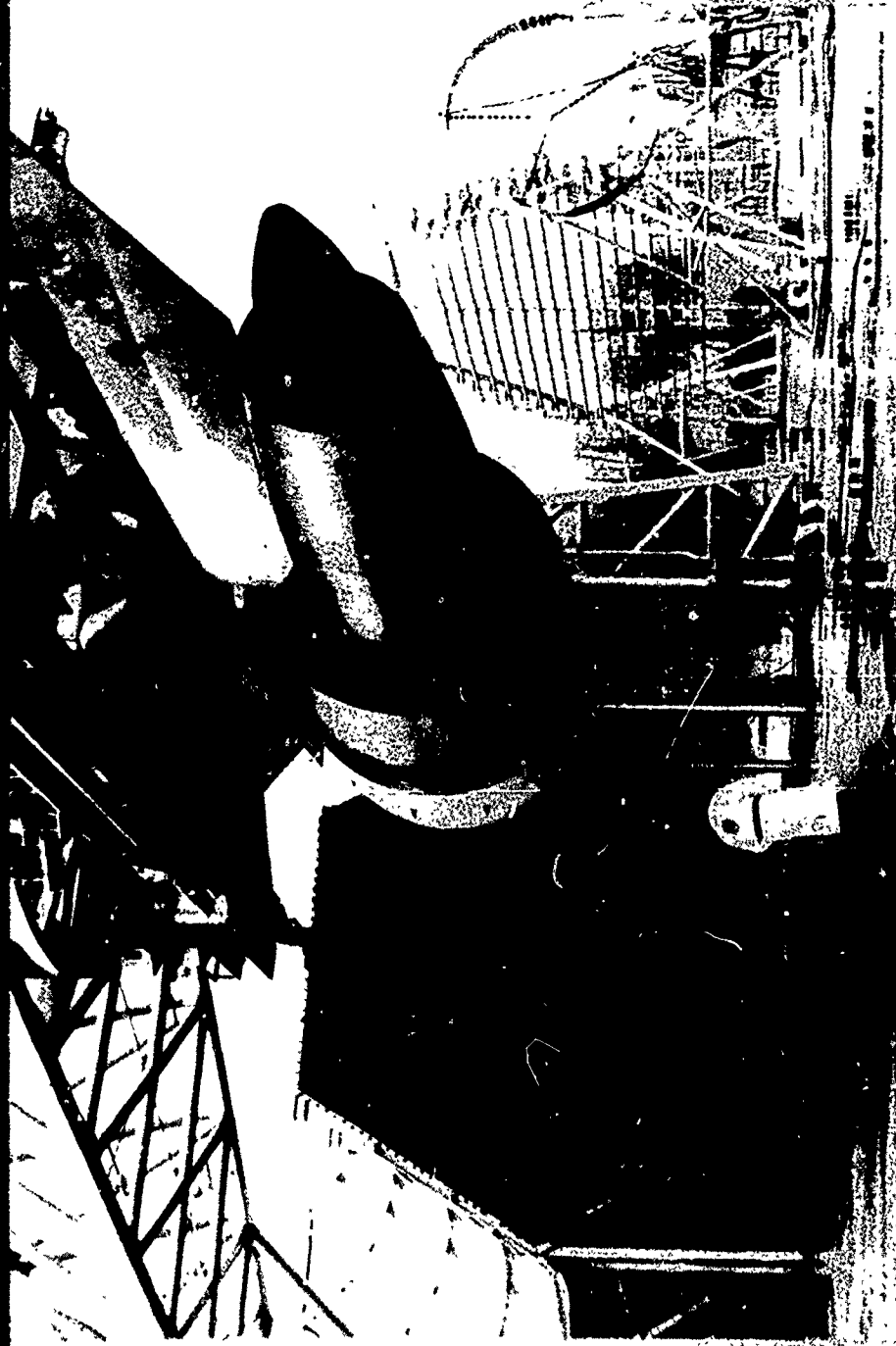
The facility was designed to provide simulated ice clouds with Liquid Water content from .5 grams/meter^3 to 4.0 grams/meter^3 and water droplets from 15 to 40 microns. The outdoor facility is limited by natural environmental temperatures and therefore testing for icing conditions is normally limited to the months of November through March. The prevailing weather conditions provide the desired temperature range of -4°F to 32°F for testing over the required range of Military and Commercial engine requirements.

PROCEDURE FOR SETTING TEST POINT IN A SIMULATED ICE CLOUD

The simulated ice cloud is established by setting the tunnel air flow for the required test point (based on liquid water content and droplet diameter for the ambient temperature) at the conditions being simulated.

The facility has been calibrated for air and water flow rates which will produce the desired test conditions. Figure 3 shows the facility capability for producing liquid water content versus tunnel airflow and water flow.

The procedure for setting a test point is to measure relative humidity and calculate the quantity of water required to saturate the air at this temperature based on the tunnel airflow. Additional water is then supplied to achieve the desired liquid water content. The facility has the capability of heating the water before entering the spray manifold where atomizing air nozzles are used to provide control of droplet diameter.

Water temperature is established to provide the required heat loss from the droplet while traveling from the spray manifold to obtain an ice cloud at the engine inlet. Water droplet diameter is controlled by setting air pressure for the water flow rate being used at the test point.

PROCEDURE FOR DETERMINING THE MEDIAN VOLUMETRIC DROPLET DIAMETER

The engine being tested is set at the desired test power setting and before turning the water on a data reading is taken. The water is then turned on and flow is allowed to stabilize. At this time a device with a lucite slide having three holes coated with silicon oil is inserted into the cloud to obtain a sample of the water droplets. The device has a manual aperture trip to expose the slide to the ice cloud.
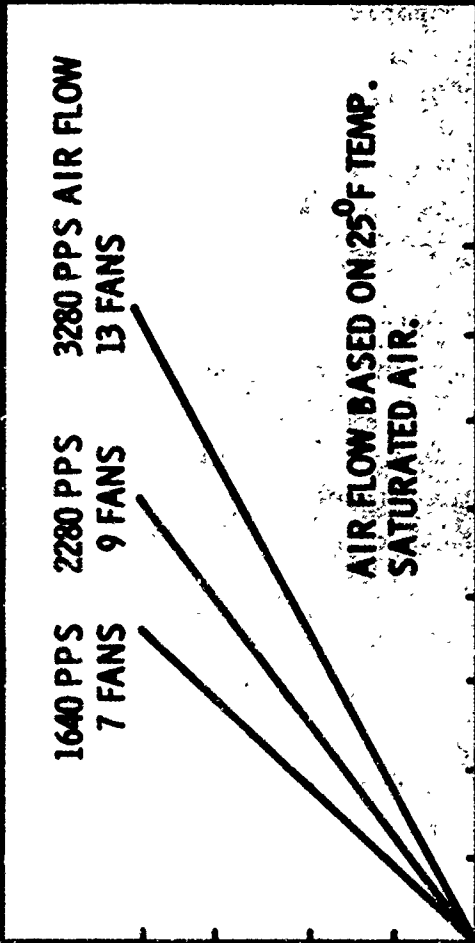
FIGURE 3

Following exposure, the slide is removed from the sampling device and placed under a calibrated microscope (Figure 4) where a series of polaroid photographs are obtained. These photographs are then studied to ascertain if the desired droplet diameter is achieved in the ice cloud. If the desired droplet diameter is not present, adjustments to the facility air supply can be made and another sample taken to establish that the desired droplet diameter is present in the icing cloud.

The median volumetric droplet diameter for the test point is established by selecting representative areas on the photograph (Figure 5) and counting the droplets and measuring their diameters.

It is assumed that all water droplets in an ice cloud are different diameters. The median volumetric diameter (D_M) is that diameter for which 50% of the mass of the water has a diameter less than D_M. It is further assumed that the water droplets captured on the oil slide remain spherical. By comparing the droplet diameter shown in the photograph to a known scale the volume can be determined and thus the mean effective droplet diameter.

The following example illustrates the procedure used:
1. Select several representative areas on the sample photograph that show droplet sizes clearly.
2. Count and categorize the droplets in the select areas and record the total number of each pre-selected diameter categories (i.e., 5, 10, 15, etc. microns).

TABLE 1

| | Diameter in Microns (μ) | | | | | | | |
	5	10	15	20	25	30	35	40
No. of Droplets - Area 1	55	--	88	--	34	--	14	2

3. Determine the volume of each pre-selected droplet diameter by:

$$V = \frac{\pi}{6} D^3$$

Since $\frac{\pi}{6}$ is constant for all diameters, it may be neglected.

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Then tabulate the total volumes of each category and determine the diameter where 50% of the total volume is greater than that diameter and 50% of the total volume is less.

TABLE 2

D	$D^3 \times 10^{-3}$	N	Vol	V_{sum}
5	.125	55	6.875	
15	3.375	88	297.000	303.875
25	15.625	34	531.250	835.125
				997.485
35	42.875	14	599.850	1434.975
40	64.000	2	128.000	1562.975
60	216.000	2	432.000	1994.975
			1994.975	

$$1994.975/2 = 997.485$$

The total volume is then 1994.975 and D_M is that diameter where 50% of this volume or 997.485 is attained. Thus D_M for this example is between 20 and 25 microns. Since 50% of the total volume is closer to the diameter of 25 microns, it would be interpreted that $D_M = 25$ microns in this case.

PROCEDURE FOR CONDUCTING AN ICING TEST POINT

The above paragraphs describe the initial set up and water droplet diameter procedure. While the engine is operated in the icing cloud automatic data readings are obtained which include performance, temperature, stress and pressures of the engine being tested. These readings are taken periodically to establish the effect of operating the engine in an ice cloud.

The Peebles facility has proven to be extremely versatile. Since the ice cloud level is set as a function of tunnel airflow (which is greater than that required by the engine) various power levels may be set on the engine with no change in the simulated ice cloud required. In addition the facility has remote control for water and air supply enabling the cell operators to interchange simulated continous maximum (stratiform clouds) and intermittent maximum (cumuliform clouds) while maintaining a test point.

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WATER DROPLET DIA. MEASUREMENT

MICROSCOPE

SLIDE

FIGURE 4

80

DROPLET SAMPLE-SIMULATED ICE CLOUD

FIGURE 5

81
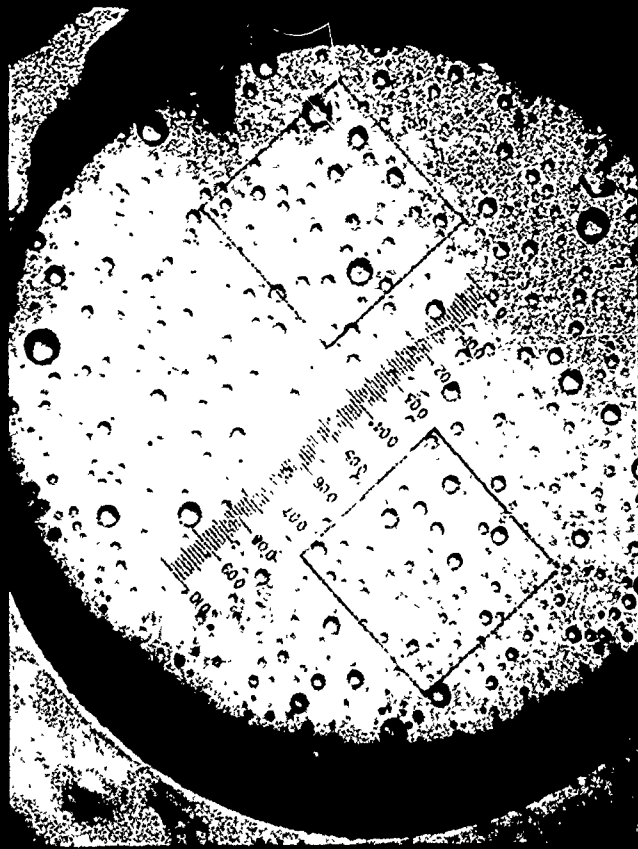
ICING TESTS CONDUCTED ON THE G.E. CF6-6 ENGINE

CF6-6 ENGINE

The general Electric CF6-6 engine is a high by-pass ratio turbofan engine and was selected by major airlines to power the McDonnell-Douglas DC-10 aircraft. Many components of the CF6-6 engine are common with the TF39 engine, the world's first high by-pass ratio turbofan engine selected to power the USAF Military Airlift Command C-5A Galaxy aircraft.

The CF6 engine recently completed a series of icing tests under conditions that complied with FAR Parts 25 and 33 requirements. In addition special testing was conducted to simulate extended holding times in ground fog icing conditions and alternate exposure to simulated cumuliform and stratiform icing clouds.

ICING TEST CONDUCTED ON THE CF6-6 ENGINE AT PEEBLES FACILITY

The CF6 engine was installed with an anti-iced Douglas inlet at the Peebles facility in February of this year. (Figure 6) A series of tests were conducted during February and March over a wide range of icing conditions. The conditions simulated included take-off and climb out, cruise, loiter, flight idle and ground idle power settings in accordance with FAR Part 25 icing cloud definitions. Also testing was conducted to simulate British-Air Registration Board requirements and engine exposure during loiter conditions of alternate intermittent and continuous maximum icing conditions.

The CF6 engine is among the first of the new family of large turbofan engines which do not incorporate an anti-icing system. Thus, it was essentail that its performance in icing conditions be thoroughly evaluated to demonstrate satisfactory operating capability under all anticipated icing conditions.

Testing was conducted with ambient temperatures of 15 to 30°F and a liquid water content range of .6 grams/meter^3 to 3.15 grams/meter^3. Mean effective droplet diameters ranged from 20 microns to 45 microns.

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CF6-6 ICING TEST SET-UP PEEBLES
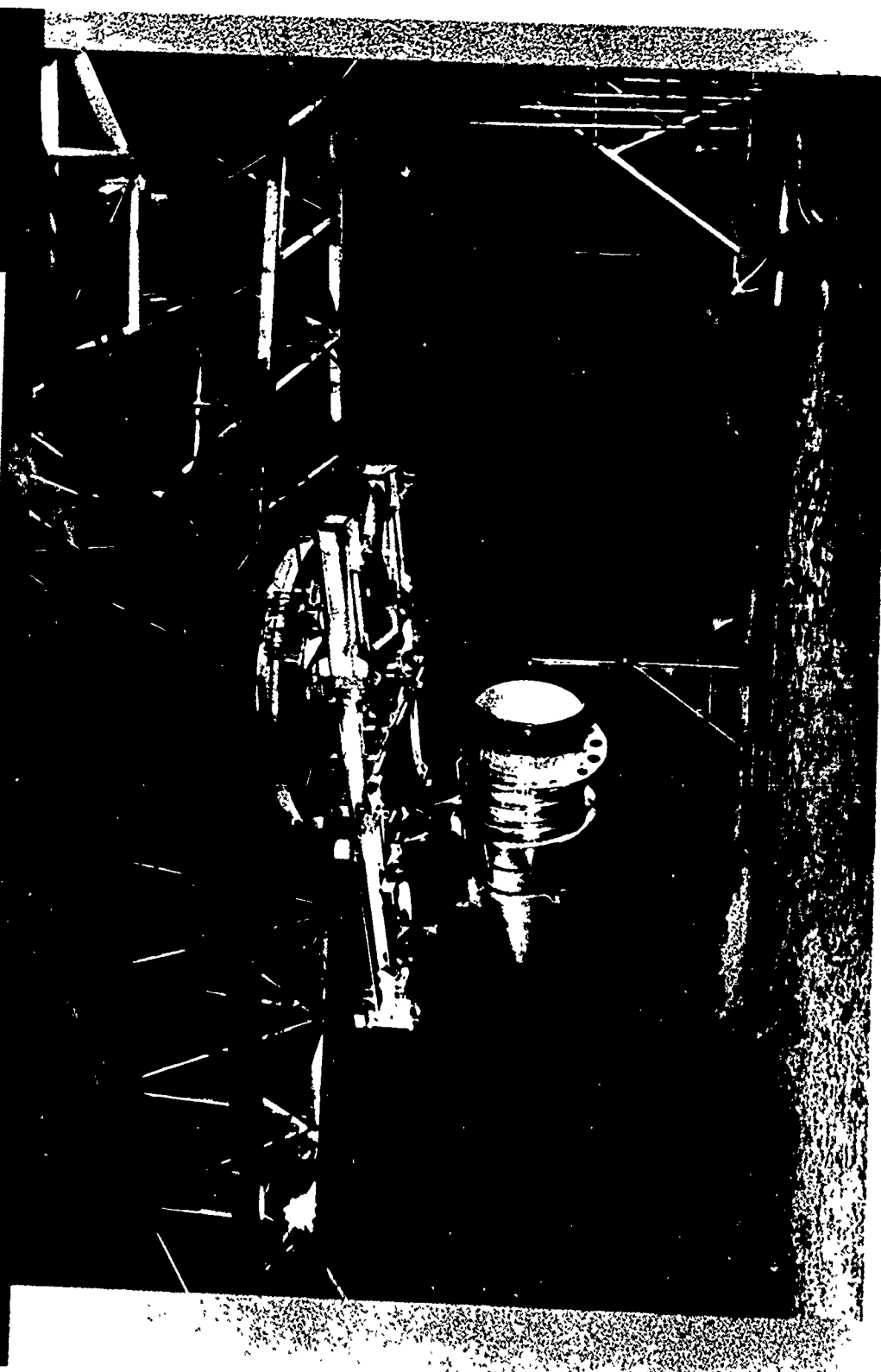
FIGURE 6

Exposure time in intermittent maximum icing conditions varied between
3.5 to 5 minutes at take-off, climb, loiter and flight idle power setting
conditions. Figure 7 is a photograph during testing under simulated maximum intermittent cloud condition.

Exposure to maximum continuous icing conditions varied between 3.5 minutes
and 45 minutes at power settings of take-off, climb, loiter and flight
idle power setting condition. Figure 8 is a photograph of a facility
pipe used to support instrumentation which is exposed to the icing cloud.
The ice accumulated is indicative of the severity of the test condition.

Ground idle power settings were tested in continuous maximum icing clouds
for one hour periods, with engine accelerations made at fifteen minute
intervals to evaluate engine response and operating techniques with ice
accumulated on airfoil surfaces. The CF6-6 engine accelerated in a normal manner and obtained desired power within specified times.

A special test was conducted where a holding pattern of a 20 mile maximum continuous cloud followed by an intercept with a 3 mile maximum intermittent cloud was simulated. The test was conducted at loiter power setting for 18 minutes simulating three exposures to each of the above clouds.

Engine thrust, fuel consumption and acceleration times remained within
limits throughout the icing tests described.

CF6-6 ICING TEST

FIGURE 7

85
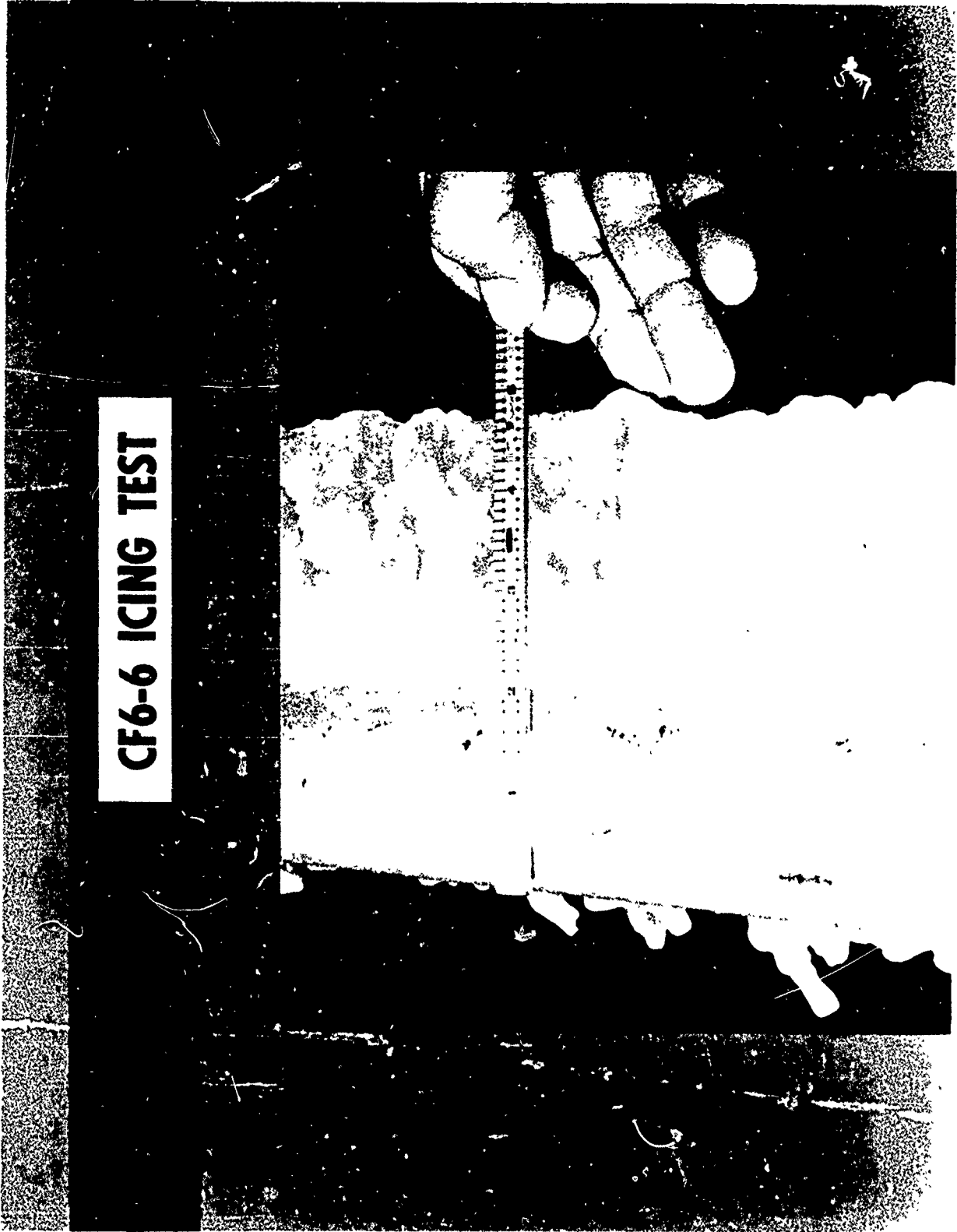
FIGURE 8

ICING TEST DATA AND OPERATIONAL EXPERIENCE
ON CURRENT LARGE G.E. JET ENGINES

ENGINE DESCRIPTION AND ICING TESTS CONDUCTED

The General Electric J79 turbojet engine family is used to power many
Air Force and Navy aircraft. The current applications include the Air
Force F-104, B-58 and F4 series aircraft. The Navy applications in-
clude the F4 and RF5 series aircraft. The CJ805-3 engine is a commer-
cial version of the J79 turbojet and is used to power the CV880 air-
craft. The CJ805-23 aft fan engine is used in the Convair 990 aircraft.

These commercial engines use the J79 gas generator and are therefore
similar to certain models of the Military engine in regard to icing
protection systems.

During the development phase of these engines a series of icing tests
were conducted at Mt. Washington, New Hampshire; Hopkins, Minnesota;
Schenectady, New York; Naval Air Test Station Trenton , New Jersey; and
with an Air Force KC-135 tanker.

This paper will summarize some of the significant factors learned from
these tests and comment on current operational experience.

J79/CJ805 TURBOJET ICE PROTECTION SYSTEM

The description provided here will refer to the current operational engine
models. Earlier engine models include a modified icing protection system
and have been retired from active Air Force service.

The J79-5, -7, -17, -19 and the CJ805-3 and -23 share a common icing
protection system which includes use of regulated compressor discharge
air to supply heat to the front frame struts, inlet guide vanes and the
engine bulletnose.

This system has proven to be satisfactory for the aircraft applications
listed in the introduction and no operational problems have been reported.
This arrangement on test did allow ice to accumulate on the Stage 1 stators
at low power settings, (and thrust loss was experienced). Figure 9 shows
the maximum thrust change while operating at the conditions specified.
Thrust recovery could easily be obtained by periodic advance of the

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throttle and return to the original power setting would result in essentially normal power level.

It may also be noted from Figure 9 that the thrust loss associated with the Military icing test point of -4°F and 1 gram/meter^3 of LWC resulted in significantly lesser thrust change than the higher temperature condition of 23°F and 2 grams/meter^3 of LWC. These results are consistent with other General Electric icing tests.

The J79-8, -10, and -15 and development CJ805 engines employed the same system described above, and in addition provided regulated compressor discharge air to the stage 1 stator vanes. This resulted in less thrust change at the higher liquid water test conditions.

Figure 10 shows these results. It is interesting to note that at the lower inlet temperature of -4°F and 1 gram/meter^3 of liquid water, the thrust difference between heated second stage stators and unheated stators is very small. (Figure 9 and 10) This can be attributed to the additional air being extracted from the engine cycle to heat the stators and the attendant loss in available energy to the primary gas stream. This system has proven to be satisfactory in service and no operational problems have been reported.

The CJ805-23 turbofan engine during the development program was tested in simulated icing conditions with the fan stators heated and with no heat. These stators (outlet guide vanes) are located aft of the fan blades. Figure 11 shows the results of thrust change for both configurations. The engine was certified without heated stators for reasons that are clear when looking at the results as shown on Figure 11.

The increased thrust loss with heated fan stators is attributed to the reduction in primary mass flow available to drive the fan and exhaust into the main gas stream. If this air remains in the cycle the additional mass flow provides more energy to drive the fan and also adds thrust when exhausted through the primary nozzle. These test results aided General Electric in determining the optimum ice protection configuration for inlet guide vane less high by-pass turbofans like the CF6-6 engine.

The CJ805-23 system has performed satisfactorily in field service and no operational problems have been reported.

CJ805 ICING CONDITIONS
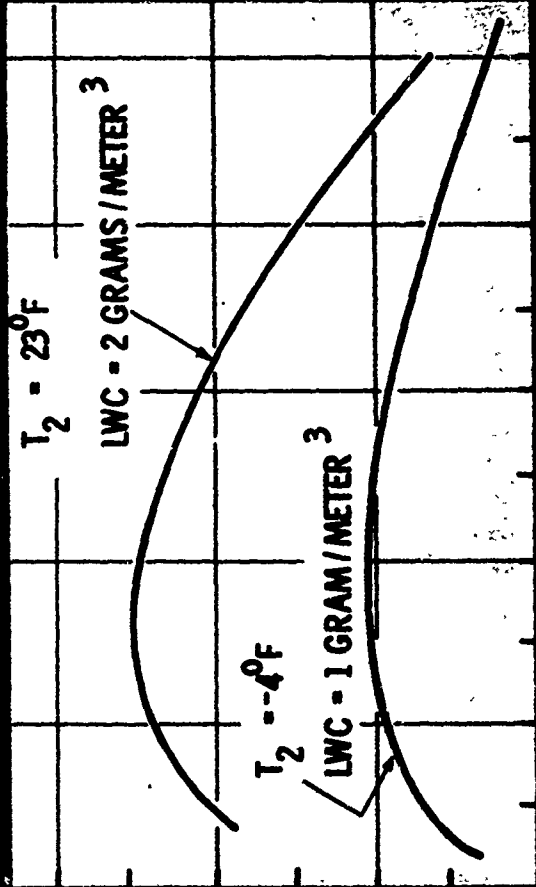
FIGURE 9

CJ805 ICING CONDITIONS
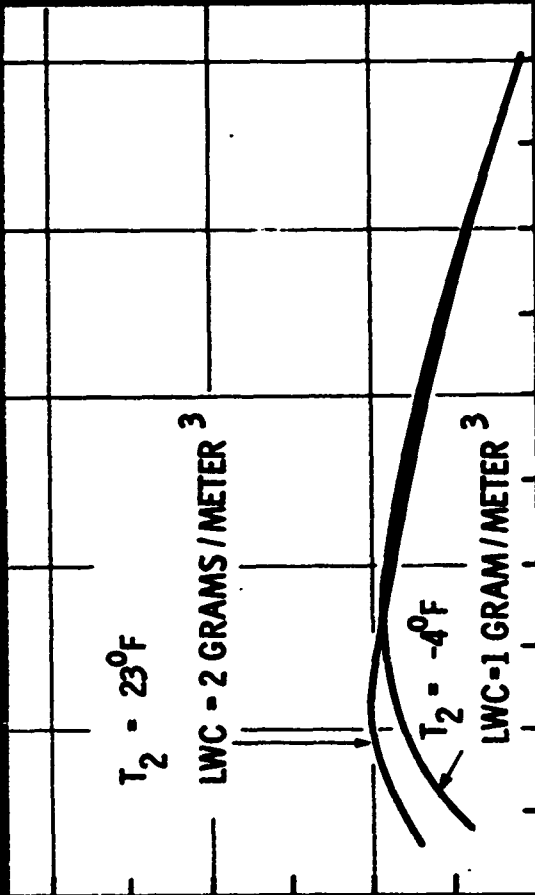
FIGURE 10

90

CJ805-23 MAX.CONT. ICING CONDITION TEST

FAN OUTLET GUIDE VANES

HEATED

NON - HEATED
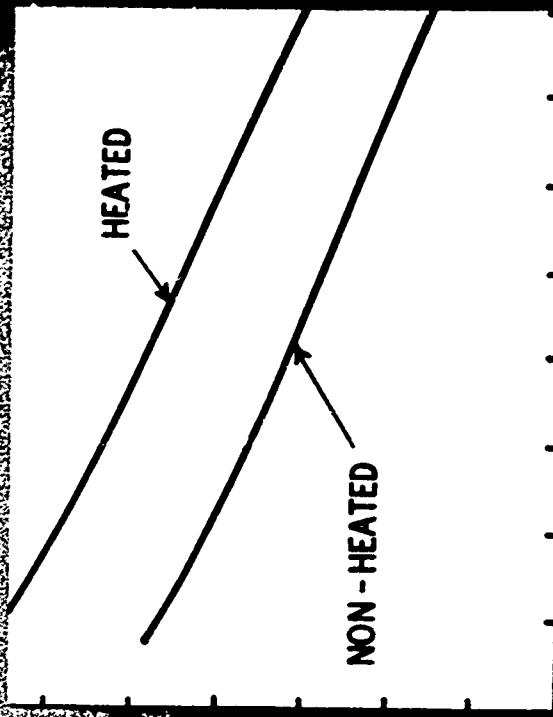
FIGURE 11

91

SELECTION OF ICING CONDITIONS FOR
ENGINE DESIGN AND TESTING

The primary specifications used in the design and evaluation of an air-craft jet engine icing systems are defined in Military Specification 500$ and Federal Air Regulation Parts 25 and 33.

The designer has to consider all of the aspects covered in these regulations and the application of the engine under consideration.

The Military Specification defines only two icing conditions, however, a quantitative level of thrust loss and SFC increase and time for engine acceleration under these icing conditions is specified. FAR Part 33, covering engine certification standards, has the general requirement that the engine be capable of operation throughout the flight power range without ice accumulation adversely effecting engine operation or causing a serious loss of power in the icing conditions defined in Appendix C of FAR Part 25. These conditions, presented in graphical form, cover a wide range of liquid water content, droplet size, ambient air temperatures, cloud extents and pressure altitude.

DESIGNING TO MILITARY SPECIFICATIONS

General Electric has found that in the design and testing of ice protection systems the selection of Condition I (SLS, 23°F, 2 grams/meter^3 and 25 microns) is the most limiting. The system is sized at this point for the lowest power setting (usually ground idle) used in operation of the engine in icing conditions. Design of an engine to meet all of these requirements however may result in additional weight and cost which is not required to provide satisfactory operational service.

DESIGNING TO FAR SPECIFICATIONS

FAR Part 25 poses some different problems to the designer in selecting the icing condition for sizing the system when heated surfaces are a part of the ice protection equipment.

Figures 12, 13, 14, 15, 16 and 17 are copies of icing curves present in Appendix C of FAR Part 25. General Electric has found that for design of a heated system the higher LWC of Figure 15 (LWC = 2.7, T = 25°F, Droplet Size 15 microns) becomes the design point for the system.

Based on test data and experience; sizing of the system for idle power setting at sea level, resulted in a satisfactorily operating system throughout the flight map.

Engine testing in simulated icing conditions in compliance with the FAR requires some judgment on the part of the test engineer. This is particularly true when establishing the test time for each condition or conditions under investigation. For example, assume that a continuous maximum condition is to be tested and the following conditions are present:

$$T_0 = 14°F \quad \text{Droplet Diameter} = 25 \text{ microns}$$
$$(\text{Figure 12})$$

This condition would then yield a cloud horizontal extent of 17.4 miles (Figure 14). Examining Figure 13 reveals that this type of cloud exists at pressure altitudes from 0 to 17,000 feet. The problem arises then as to how long the icing test should be run to demonstrate compliance with FAR requirements. Current jet transport aircraft have been assumed to travel to 3 to 6 nautical miles per minute which yields a test time of 5.8 to 2.9 minutes, assuming a linear penetration of the cloud. However, due to aircraft holding requirements, arguments have been presented that it is feasible to hold in a cloud like the example for periods exceeding 30 minutes. Further, during this holding pattern it has been proposed that there is a potential of penetrating a maximum intermittent type cloud or even holding in this high LWC type cloud.

General Electric has discussed these conditions with the FAA Regional office and arrived at mutually agreeable test conditions for specific engine tests. It would be helpful in the design and evaluation of ice protection systems and for defining engine icing tests if the regulations were supplemented with guidance material, such as an Advisory Circular, which would be more definitive with respect to typical aircraft flights and holding patterns. This information would be very useful in evaluating engine designs which do not incorporate heated ice protection systems.

FIGURE 12

94
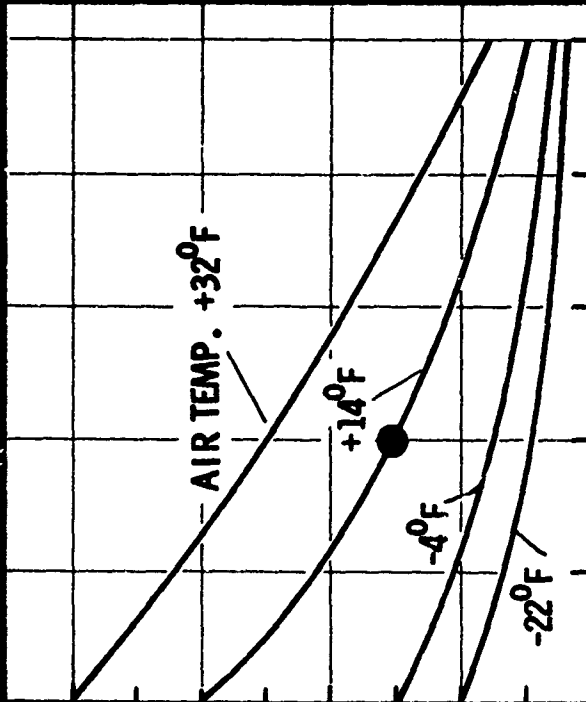
CONTINUOUS MAX. ATMOSPHERIC ICING CONDITIONS

FIGURE 13

95
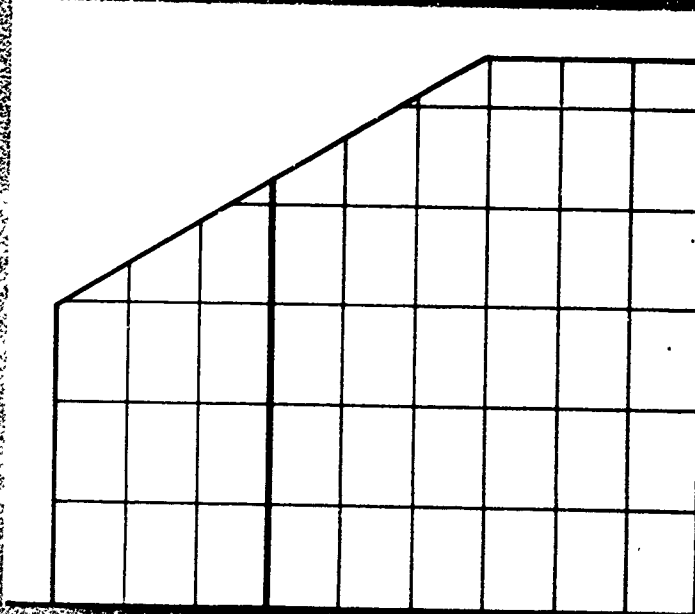
MAX. CONT. ATMOSPHERIC ICING CONDITIONS

FIGURE 14

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INTERMITTENT MAXIMUM (CUMULIFORM CLOUDS)
ATMOSPHERIC ICING CONDITIONS
LIQUID WATER CONTENT VS MEAN EFFECTIVE DROP DIAMETER

FIGURE 15

97
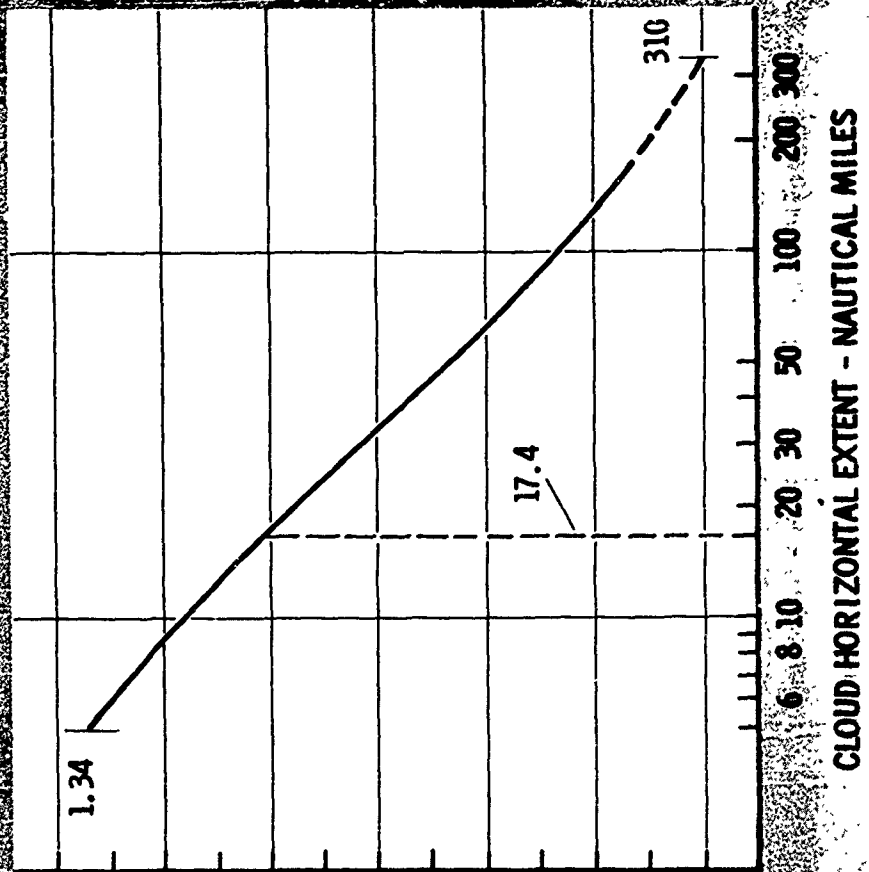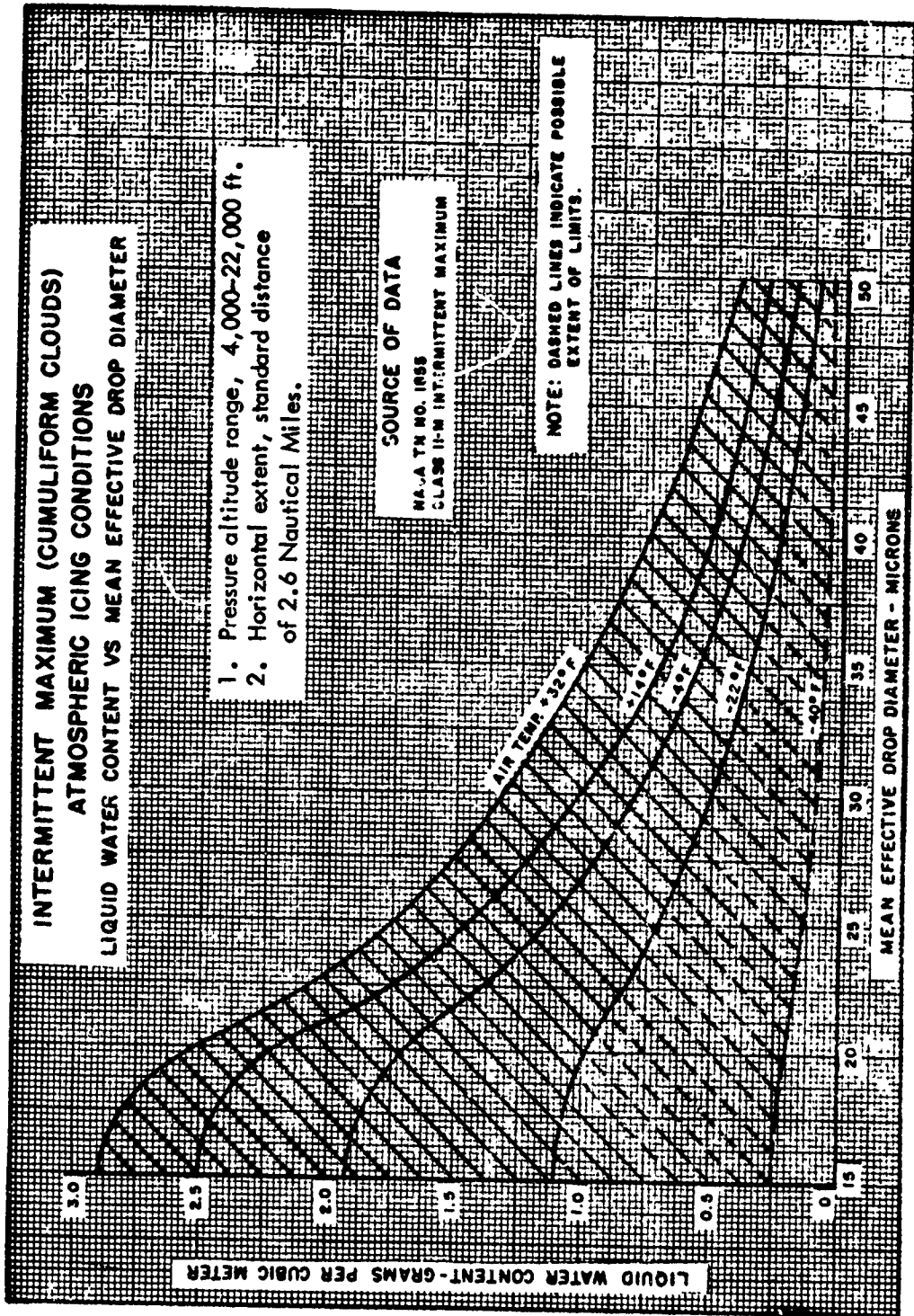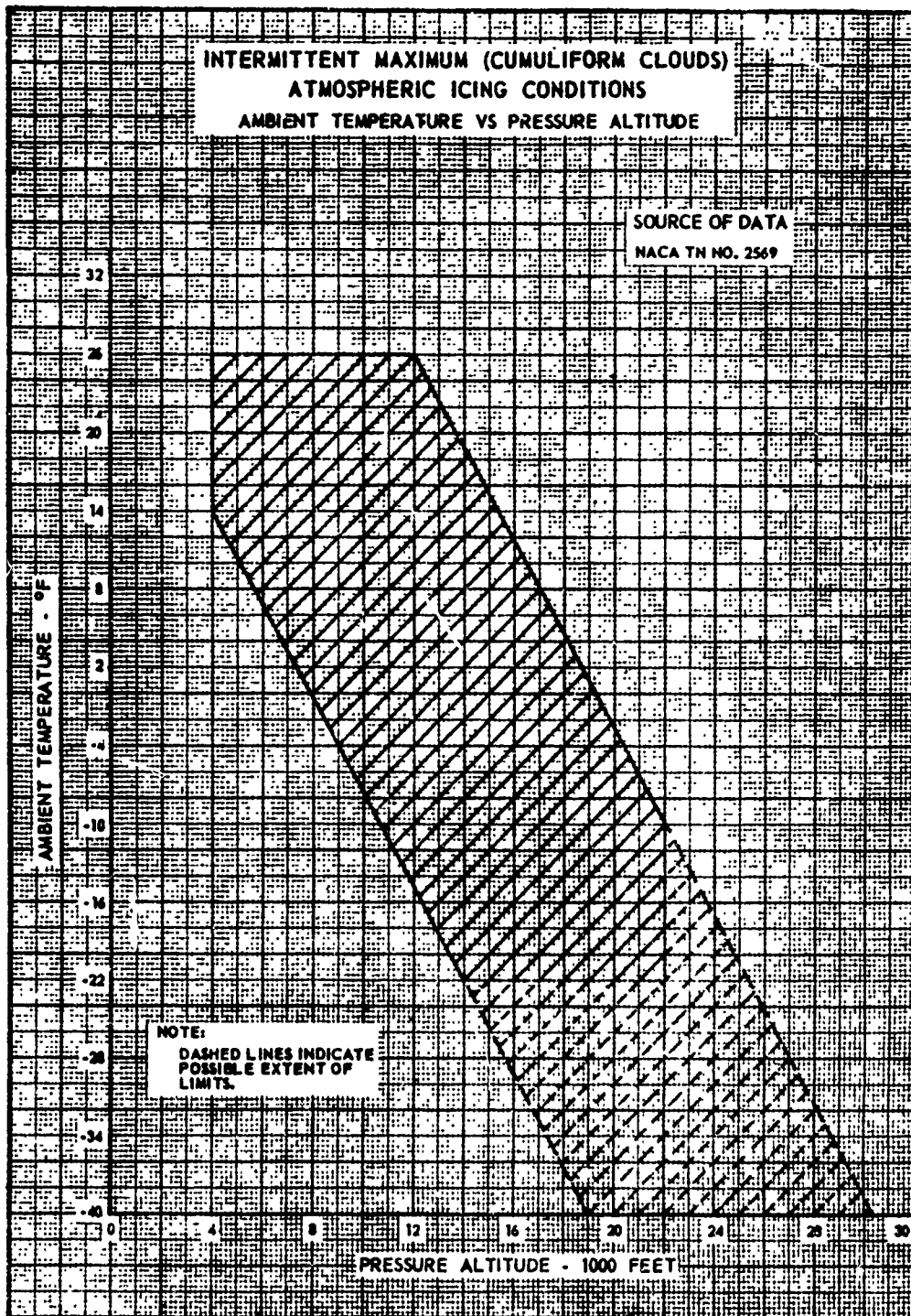
FIGURE 16

DISCUSSIONS FOLLOWING MR. DAVISON'S PRESENTATION ON

"LABORATORY TESTING OF ENGINE ICE SYSTEMS"

Question: Has the GE SST engine (GE4) been icing tested?

Answer: It is too early in the program; I am not aware of
             any test data at this time.

Question: For GE tests of the CF6 and TF 39 fan engines, what
             test conditions were used?

Answer: Maximum Intermittent: Up to 2.6 LWC for 5 minutes
             with 20 to 30 micron drops.

             Continuous: .7 to .8 LWC for 45 minutes at 18° F.
             to 20° F. temperature.

Question: Were TV or cameras used?

Answer: High-speed movies were taken to evaluate icing and
             shedding. Repeated shedding was anticipated
             and demonstrated. The need for the 45-minute test
             duration was questioned by the speaker.

Question: Was the engine repeatedly accelerated in the ice fog
             testing?

Answer: Yes, every 15 minutes.

Question: What times or what intercepts were tested in the
             CF6 tests?

Answer: Maximum Intermittent: 3 miles.

             Continuous: 20 miles.

             An 18-minute cycle was run, 5 minutes @ continuous,
             1 minute @ intermittent, and repeated three times.

Question: What power losses were indicated in the icing runs?

Answer: Only the loss incurred from the use of bleed air.

Question: Should engine and airframe icing limits' requirements
             differ?

Answer: FAA Western Regional Office indicated they want
            the engine to be better protected than the airframe.

            NASA indicated that full engine power is needed at
            all times to cope with airframe icing, which may
            occur from high intermittent icing conditions. The
            airframe protection is generally designed for
            continuous icing level.

Question: On the TF39 ground idle tests, how much ice was
            accumulated?

Answer: Just before engine accelerations the spinner was
            iced all over, and ½ inch of ice built up on
            the inner radius leading edges and outer surfaces
            of the fan blades. ¼ inch of ice on IGV's; fan
            OGV's had ¼ to ½ inch of ice. There was ice on
            the flow splitter and core IGV's.

SMALL GAS TURBINE ENGINES
AND INLET ICING PROTECTION

PREPARED FOR

FEDERAL AVIATION ADMINISTRATION ICING SYMPOSIUM

FAA HEADQUARTERS
WASHINGTON, D.C.
APRIL 28-30, 1969

BY
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SECTION CHIEF
ENVIRONMENTAL PROJECTS
ALLISON DIVISION OF GENERAL MOTORS

SMALL GAS TURBINE ENGINES AND INLET ICING PROTECTION

G. V. Bianchini

GENERAL

This paper presents Allison model 501 and 250 turboprop/
turboshaft engine anti-icing system design, test, and
service experience. The intent of the paper is to provide
an insight to: (1) small engine icing protection require-
ments and design criteria, (2) icing protection system
development techniques in dry air and icing atmospheres,
and (3) methods used to demonstrate icing protection com-
pliance with Civil Airworthiness Requirements.

The two engines upon which the paper is based span the
extremes in what is considered the small engine field. The
501 series is nominally a 32.5 lb/sec air flow engine with
models ranging in power from 3750 to in excess of 5000
equivalent shaft horsepower. The 250 series is nominally
a 3.2 lb/sec air flow engine with models ranging in power
from 250 to in excess of 400 shaft horsepower. Relative
sizes of these two basic power plants are shown in Figure
1.

Models of both engine series are currently in service in
military as well as commercial applications.

Figure 1

104
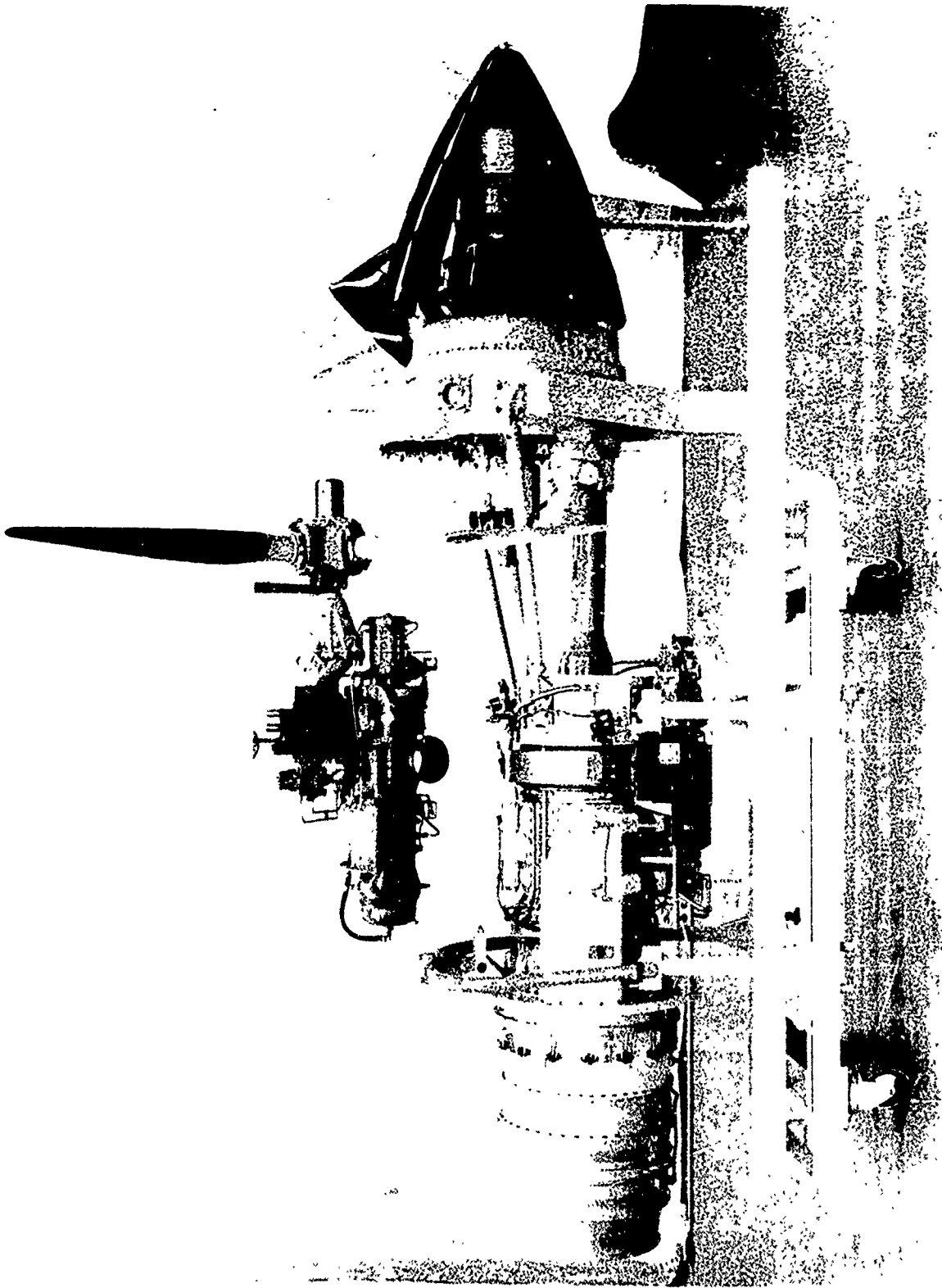
ICING PROTECTION REQUIREMENTS

Because the smaller engines power aircraft which generally
fly in the altitude ranges more conducive to icing, icing
protection is utilized more frequently and for greater
durations than the large engines. However, the protection
requirements for small gas turbine engines are not unlike
the protection requirements for large engines of similar
inlet configurations. Based on our general icing exper-
ience and specifically on the experience with these two
powerplants in the small engine field as compared to our
experience with turbojet engines ranging to 160 lb/sec air
flow, the effect of engine size on icing protection re-
quirements appears to be limited to acclimating the designer,
the development engineer, the airframe manufacturer, and
perhaps the user to the size.

Assuming no inherent aerothermo-mechanical problem or de-
sign weakness, there is little, if any, difference in en-
gine capability to operate with ice accretion regardless
of the engine's size. There is no question that: (1) a
given size ice accretion on the inlet components will cause
a significantly greater power loss on a small engine than
on a large engine and (2) the ingestion of a given quantity
of ice may create a greater power excursion and/or be more
conducive to flameout on a small engine than on a large

engine. On a proportional basis, however, there is no discernible difference between engine capabilities in either circumstance as will be discussed later.

DESIGN CRITERIA

Meteorological Parameters

Over the years there has been considerable discussion as to the meteorological conditions to which engine icing protection systems should be designed. A significant amount of statistical icing data has been obtained and several divergent points of view have been taken in regard to interpretation of the data. This divergence can be noted in Figures 2 and 3 which clearly show significant differences between the military, FAA, and British ARB specification requirements. These differences, of course, tend to add to the designer's confusion in his quest for and selection of specific meteorological design criteria.

Our initial icing and icing protection experience with gas turbine engines dates back prior to the onset of the 1950's when the Military were in the early process of formulating their specification requirements. Because of that experience and because we have been primarily military oriented in gas turbine engine design, we have generally used the military requirements for the design of our engine anti-icing systems.

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ENGINE ICING SPECIFICATIONS

AIR TEMPERATURE VS LIQUID WATER CONTENT

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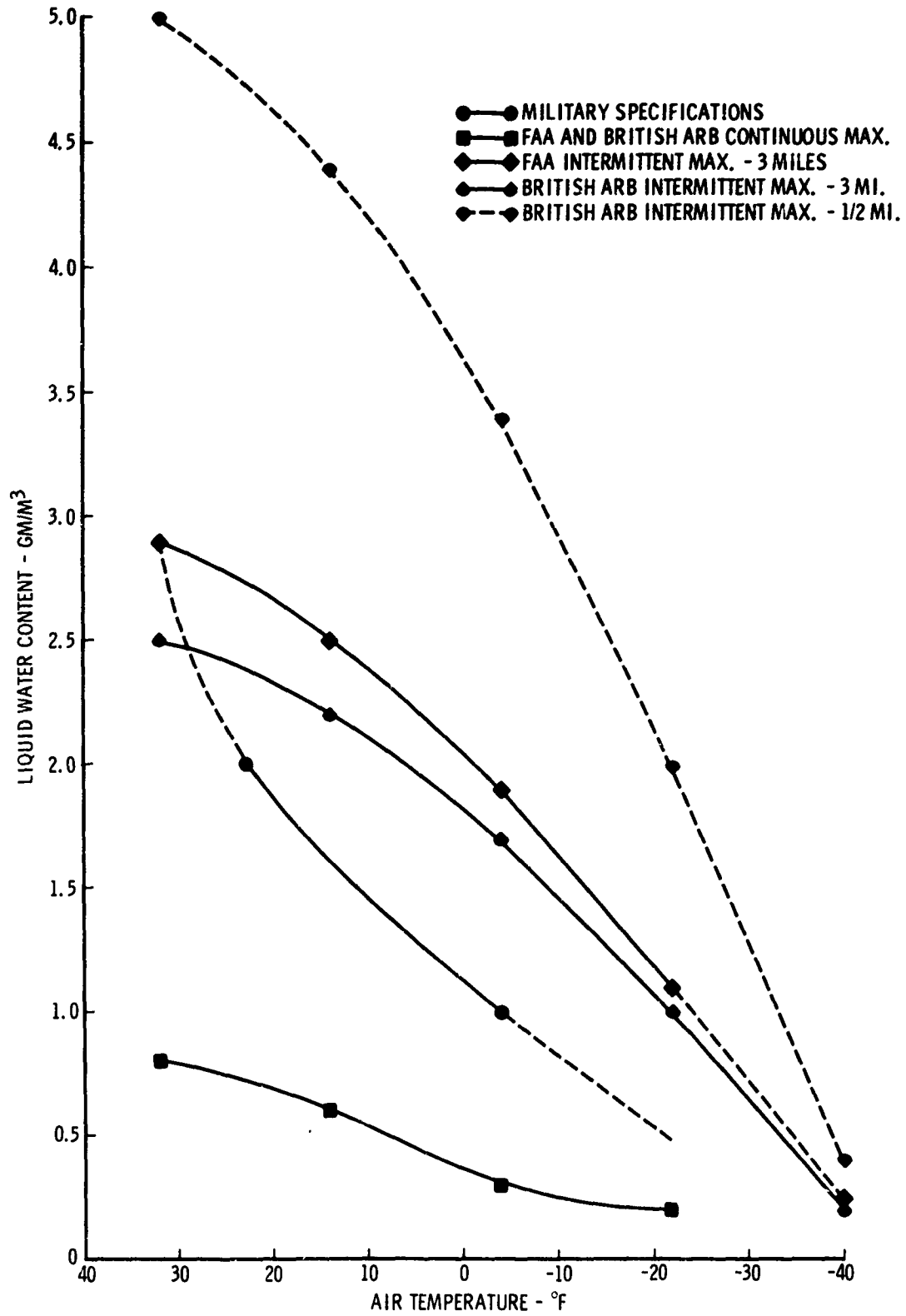
Figure 2

ENGINE ICING SPECIFICATIONS
AIR TEMPERATURE VS MEAN DROPLET DIAMETER
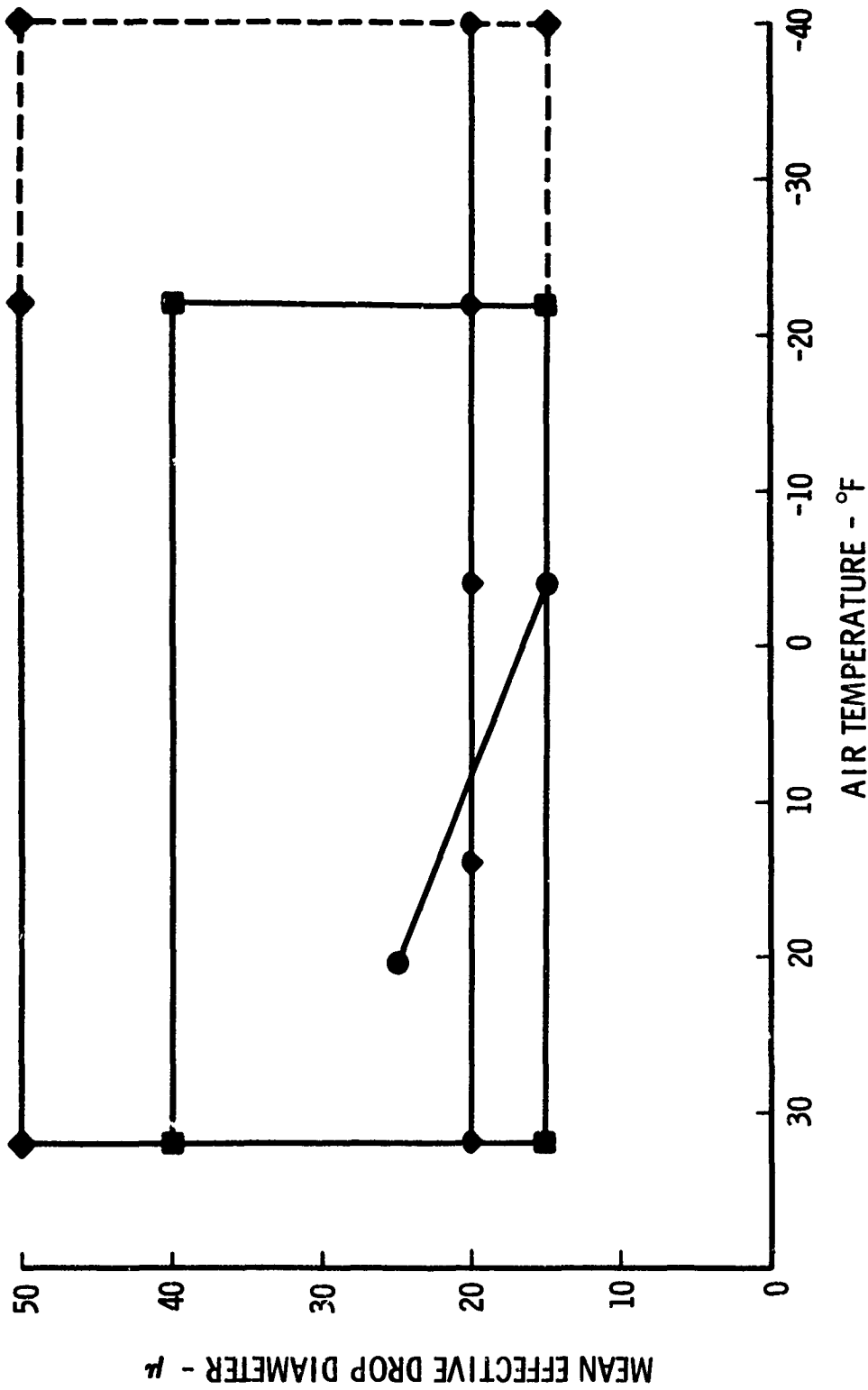
Figure 3

The military specifications were formalized about nineteen years ago and became the standard for the industry at that time. Although the conditions selected appeared to be quite arbitrary at the time, they have proven to be a well-chosen compromise between an excessively strict requirement demanding an anti-icing system which will protect the engine against every icing condition, with inherent penalties on performance and one which results in adequate icing protection and does not impose significant penalties on performance. The military specifications also define an engine test cycle under which the engine shall demonstrate its ability to operate under the specified conditions. This cycle is an important consideration since it defines the amount and sequence of low power operation, which is the critical design area. The military requirements have proven to be satisfactory in service as they have been in use since their inception without change or known indication of inadequacy.

As can be noted in Figures 2 and 3 the FAA and British ARB specifications indicate a requirement for icing protection to an ambient temperature substantially below the military specification (-20 to -40°F vs -4°F) which is believed to be wholly unnecessary and unrealistic. From experience, the wealth of available icing literature, and

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presumably from other papers that will be presented at this
symposium, it is apparent that (1) with decreasing ambient
temperature there are decreasing probabilities of encountering
significant icing, (2) the shape and quantity of ice forma-
tions at low ambient temperatures precludes the necessity
of protection at those conditions, and (3) the heat require-
ments to prevent icing are a function of ambient temperature.

While icing can theoretically occur and has been demonstrated
under carefully controlled laboratory conditions below -40°F,
the moisture which can be sustained by cold air is extremely
limited and turbulence etc. in the natural environment en-
hance the transition of free water in the atmosphere from
the supercooled condition to ice crystals, thereby minimizing
the icing which can occur at the lower temperatures. Sig-
nificant icing encounters at ambient temperatures from -10°F
to -20°F are rare and from -20°F to -40°F are practically
non-existent. Further, icing poses a threat to gas turbine
engines only if significant blockage occurs seriously de-
grading performance etc. or if large quantities of ice can
be ingested to cause mechanical damage and/or, because of
aerodynamic disturbances during the ingestion process, to
cause large performance excursions or flameout. As can be
observed in Figure 4 the type "c" - streamlined ice, which

A. Mushroom

B. Intermediate

C. Streamlined

Direction
of Airflow

Basic Forms of Ice Accretions on
Gas Turbine Vanes and on Cylinders

Figure 4

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is characteristic of icing at relatively low temperatures,
does not create a blockage and cannot significantly affect
an engine inlet. The characteristic shape and low water
content precludes large ice accretions and because the ice
is also characteristically hard and brittle it can be easily
ingested by an engine with no deleterious effect. Engines
can and have operated in this type icing for prolonged periods
without icing protection. Therefore engine anti-icing system
design directed to combat icing at these extreme ambient
temperatures requires excessive quantities of anti-icing
energy with no derived benefit. As will be shown later, an
engine anti-icing system design which provides complete
protection at the military specification points does not
incur a significant performance penalty and is more than
capable of safe, efficient operation at the other specifica-
tion requirements.

There are also significant differences in the liquid water
content of the three individual specifications. While the
liquid water content consideration is important for a de-
icing system or an evaporative ("running dry") anti-icing
system, it can be shown that it is of relatively little
importance for a "running wet" engine anti-icing system as
will be discussed under anti-icing system development.

Aerothermodynamic-Mechanical Parameters

The basic aerothermodynamic design considerations and cal-
culation techniques for icing protection system concepts
are well documented in the literature (especially so for
aircraft surfaces) and will be discussed in some detail
by the other papers concerned with protection for aircraft
and the large engines. Therefore, this discussion will
be limited to generalities of engine anti-icing system
design and the design approach at Allison.

The anti-icing systems for the 501 and 250 engines are
similar and are very conventional in nature. They both
are simple on-off "running wet" thermal anti-icing systems
which utilize compressor discharge bleed air as the heat
source. The systems are designed to maintain the engine
inlet components free of ice during flight idle power
under the meteorological conditions prescribed by the
military specification. Flight idle (or minimum flight
power) is selected as the design point because it is a
critical flight condition and, with utilization of com-
pressor bleed as a heat source, it results in a minimum
anti-icing energy available condition. A system so de-
signed provides outstanding icing protection throughout
the engine's flight operating range. In fact, unless the

system is modulated with an increase in power setting, it may be somewhat overdesigned at the high power end of the engine's operating range.

Generalizing, adequate engine inlet component icing protection, utilizing a compressor bleed system, can be accomplished with approximately 1% of the maximum compressor flow regardless of engine size. The generalization is based on protection of inlet guide vanes, bearing support struts, inlet sensing components for the control system, and an inlet bullet or, in the case of the remote reduction gear of the 501 engine, the torquemeter housing. The major portion, 60-70%, of this flow is apportioned to the inlet guide vanes. An additional 1% of compressor flow is also normally required for protection of the aircraft air inlet duct or, in the case of some turboshaft/turboprop integral reduction gear designs, the outer wall of the annular inlet.

A review of engine anti-icing system designs in industry over the years indicates that anti-icing system air flows actually range from 3/4% to in excess of 2% of compressor flow. At first consideration, this information refutes the generalization of a 1% bleed requirement. However, detailed investigation of the individual systems results in substantiation of the generalization. The flow requirement

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will vary slightly from the generalized value dependent
upon the selection of the anti-icing air flow circuits--
parallel vs series flow--and the extent to which hot lube
oil or heat from other engine services may be used in a
specific design. Heat transfer considerations indicate
that the most efficient use of hot air in the anti-icing
system is attained by the maximum number of flow circuits
in series and definitive work by NASA in the 1950's showed
that use of a series system would reduce the bleed require-
ments. The basic layout of one large thrust producing
engine design is such that it enhances the use of a complete
series system and that engine has the lowest anti-icing
flow--3/4%. Several engines do utilize flows in the 2%
range but these engines are those turboprop/turboshaft en-
gines with integral reduction gear designs or others which
have certain peculiarities and specialized areas requiring
protection. Our model 250 is one of these and utilizes
1 1/2% bleed for anti-icing. We demonstrated an ice free
inlet with the "as designed" 1% flow but had to increase
the flow during the engine development program to minimize
first stage compressor stator vane icing which hadn't been
anticipated. With these exceptions the generalized value
is well substantiated by the many other engine designs. As
a matter of interest, our 501 series utilizes 1.04%, our other

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turboprop models have required 0.9% to 1% and models and our turbojet engines have utilized flows ranging from approximately 0.85% to 1.2%.

Allison has successfully used the 1% flow generalization in preliminary design for system sizing and then depends upon heat transfer analysis to either substantiate the preliminary design values or tailor the system as required in the detailed design. The detailed systems have had flow utilization results as previously indicated. Like most other engine manufacturers, we have always ignored the effect of droplet size by assuming 100% catch efficiency of the engine inlet components in the heat transfer calculations. However, because a "running wet" anti-icing system is primarily sensitive to ambient temperature, we have in later years eliminated both droplet size and liquid water content as meteorological considerations in our analysis of "running wet" systems.

Generalization of the anti-icing flow requirements for either small or large engines without inlet guide vanes, especially high by-pass turbofan engines, cannot be made at this time because of the limited icing experience with these engine designs. However, analyses to date would indicate icing protection requirements for these engines may be more sensitive to the aerodynamic design of the

compressor or fan, the specific aircraft mission and sub-
sequently the engine operating modes. Some recent designs
have incorporated a modulated system for the fan outlet
guide vanes and an evaporative or "running dry" system
for the inlet bullet or rotating spinner. These systems
have yet to be evaluated in an icing atmosphere to confirm
the necessity of some of these features.

Performance loss due to anti-icing bleed will vary to some
extent from one engine design to another but can be en-
compassed by a generalization. A 1% diffuser (compressor
discharge) bleed results in approximately a 2% power reduc-
tion. If the anti-icing system discharges the air over-
board after use, the power loss for the anti-icing system
bleed will be similar to the standard diffuser bleed. How-
ever, in most cases much of the anti-icing system discharge
is directed into the compressor inlet and a 1% bleed for
anti-icing usually results in approximately a 3% power re-
duction because of additional heating of the inlet air, etc.

ANTI-ICING SYSTEM DEVELOPMENT

Anti-icing system development at Allison is conducted on both rigs and complete engines and both in dry air and icing atmospheres. The dry air testing permits the anti-icing system components to be heavily and reliably instrumented to obtain data which can be correlated with the calculated design data for evaluation of the system effectiveness and the validity of the design techniques. Minimal anti-icing system component instrumentation is utilized during tests in icing atmospheres because of the inherent problems with instrumentation in this environment and the potential effects some of the instrumentation may have on the icing results.

Basis for Dry Air Tests

During many observations of thermal anti-icing system tests in our early years at the Mount Washington Aeronautical Icing Research Laboratory, it was noted that the liquid water content of the icing atmosphere had little or no effect on the heat requirements of components being anti-iced. It should be noted that these observations were made for a "running wet" anti-icing system only (i.e., anti-icing which is designed to prevent the formation of ice, without complete evaporation of the water). In subsequent

icing seasons at Mount Washington definitive data was obtained to substantiate the observations by conducting tests over a wide range of liquid water contents at given ambient temperatures and manually regulating anti-icing air flow to the components on test to the minimum heat requirement condition for each icing environment. This minimum condition was attained by allowing the component to ice very lightly, increasing the heat sufficiently to begin removal of that ice and then stabilizing at a point where the heat was barely sufficient to prevent icing of the component. The anti-icing flow data was recorded after a minimum of 15 minutes of stabilized operation at each condition. It should be noted that the differences between the lowest and highest liquid water contents during test points at each ambient temperature ranged from approximately 0.3 to well in excess of 2.0 grams per cubic meter. Typical data obtained for the engine and one of the individual components are shown in Figure 5. Although there is some data scatter, the trend is quite definite and was considered to be satisfactory substantiation that "running wet" anti-icing systems are primarily sensitive to ambient temperature.

Utilizing this data as a basis, it was felt that development testing of engine anti-icing systems could be conveniently

501 Engine
Minimum Anti-Icing Flow Requirements
Mount Washington Icing Tests
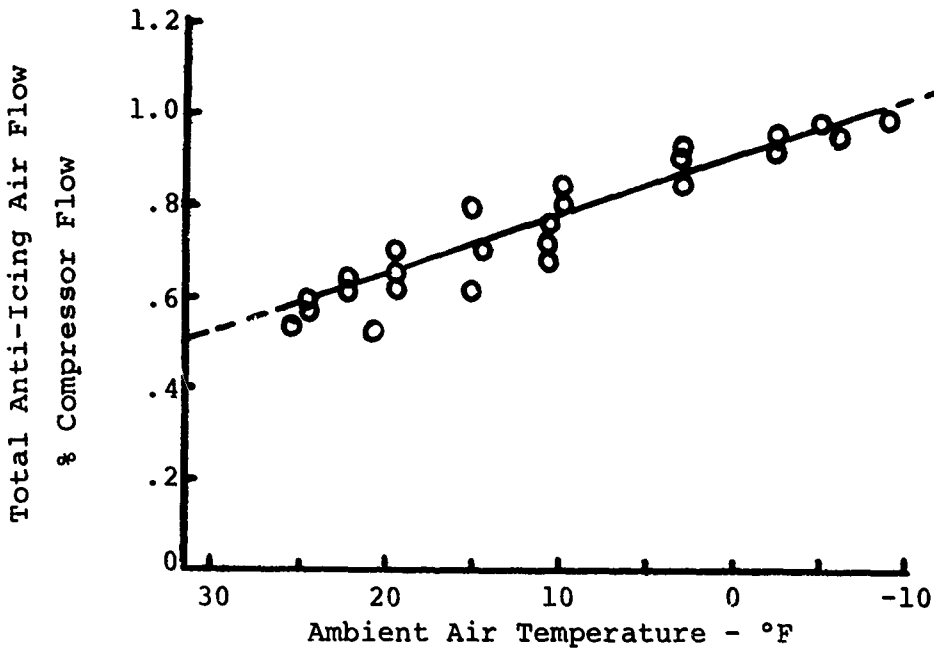
501 Engine
Torquemeter Housing Minimum Heat   Requirements
Mount Washington Icing Tests

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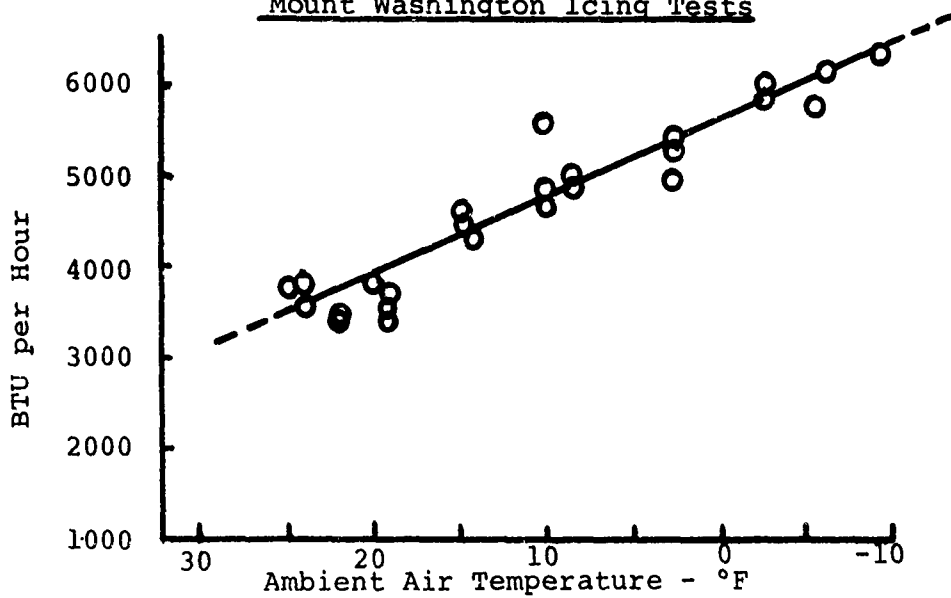
Figure 5

conducted in dry ambient air conditions by measuring anti-icing system component skin temperature rise due to anti-icing energy. As a result an Allison dry air test program was evolved to demonstrate the concept. The overall program encompassed use of two components from a turbojet engine and the entire anti-icing system for a turboprop engine. The objective of the program was to attain a minimum average component skin temperature rise (ΔT) value of 45'F on all components at flight idle in dry air tests and then subject the same components to tests in an icing environment. The minimum ΔT of 45°F was determined on the basis that a skin temperature of 32°F will prevent icing and allowing 3° for uneven heating results in a desired skin temperature (T_s) of 35°F. To ensure encompassing the military specification of anti-icing to an ambient temperature of -4°F, it was desired to provide icing protection to an ambient (T_a) of -10°F, thereby requiring a ΔT ($T_s - T_a$) of 45°F. Presentation of the detailed data resulting from this program is beyond the scope of this paper and no attempt will be made to do so. Let it suffice to say that both the dry air tests and the subsequent icing tests were successful and the data obtained correlated extremely well. Since that time Allison has ignored liquid water content in its anti-icing system heat transfer calculations during the detailed design of

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"running wet" anti icing systems. The calculations are
directed toward attaining the 45°F temperature rise at
flight idle operating conditions in dry air.

Dry Air Tests

As previously indicated, dry air tests are conducted on
both rigs and engines. The rig testing is conducted very
early in an engine development program--most times long
before sufficient hardware is available for the first en-
gine assembly. Components are evaluated individually and
eventually as a complete inlet system. Modifications are
made, if required, and all data obtained are referred back
to the design calculations for correlation.

As engines become available in the development program, dry
air tests of the complete engine anti-icing system are con-
ducted on a parasitic basis for final tailoring and evalua-
tion prior to preparing for tests in an icing atmosphere.
Icing tests are not attempted unless the components can
demonstrate the desired temperature rise in dry air and the
anti-icing system operation is considered satisfactory.

Icing Tests

In the early years of gas turbine engine anti-icing system
development, our icing tests were limited to a small eight
inch icing tunnel in house and during assigned test periods

during the winter season at the military supported Mount Washington Aeronautical Icing Research Laboratory. We were grateful for the opportunity to test at Mount Washington-- and the old facility was perhaps the birthplace of many careers in icing and icing protection technology--but the limited available test time and comparative inaccessibility led to our dry air development technique and subsequently to the development of our own icing facilities.

Current in house icing tests are conducted on full scale compressors in the compressor laboratory or on full scale engines in any one of several engine test chambers. The icing test set up utilizes a cloud chamber which encompasses a series of spray bars to support the desired number of air atomizing nozzles of NACA-Lewis design. The cloud chamber, cloud chamber control system, and associated ducting are designed to facilitate adaption to the existing test facilities. Conditioned air is supplied through the cloud chamber and ducting to the test article from our centralized special facilities building. Our early installations utilized a standard multi-rotating cylinder installation, an NACA icing rate meter, and a Johnson-Williams icing severity meter for measurement of the icing cloud. However, following a large number of cloud chamber calibrations and compressor-engine icing tests, our data correla-

tions were such that we now simply operate the spray nozzles on the desired water-air ratio in measured air flow and duct velocity conditions. Our current operation parallels that used for many years at NASA-Lewis.

These icing protection development tests are conducted over a broad range of meteorological conditions but are primarily concerned with the conditions presented by the military specification. The test runs at each power setting, from flight idle to takeoff, are for a duration ranging from a minimum of 15 minutes to in excess of 30 minutes. The objective of the extended runs is to observe for any ice accretion which may occur. While the liquid water content (LWC) or total liquid water intercepted (LWC x time) has little effect on the heat requirements of the anti-icing components, there is a large effect on the rate or size of ice build up which may occur if a component surface is deficient. Therefore, we are assured of a thorough evaluation of component and/or overall system effectiveness by conducting the extended test runs.

CIVIL AIRWORTHINESS COMPLIANCE DEMONSTRATIONS

There is no substitute for flight operation as far as final evaluation of the engine icing protection is concerned. However, demonstration on the ground in an icing facility is valid and can be accomplished much more rapidly and economically For these reasons, most engines have been qualified on the ground. Currently all of our icing protection compliance demonstrations are made in an icing facility under the meteorological conditions and test cycle required by the military specifications. An exception to a bona fide icing demonstration would be on an uprated model of a given engine series. Assuming only minor changes to the uprated model, compliance demonstration would be limited to the results of the dry air tests on the new model and submission of the results of both the dry air and icing tests of the original engine model.

We have had an opportunity to qualify one engine by a combination of dry air tests, ground icing tests, and flight tests in both natural and simulated icing atmospheres. The simulated cloud in flight was generated by use of tanker aircraft and water spray systems. The experience in this engine program provided added confidence to our dry air development test technique and, of course, provided additional

substantiation to the results of the ground icing tests.
The experience also indicated that a tanker icing facility
has a definite place in the evaluation of icing protection
systems. A word of caution, however--the tanker system
concept must be properly developed to ensure a realistic
icing cloud. Our experience with tankers, both good and
very bad, has made us a critic--a friendly one we hope--
of the tanker concept.

The WADC tanker, of which you will see more in another
paper, provided a relatively realistic cloud and subsequently
reasonable results. We have, however, been a proponent for
additional development to incorporate air atomizing nozzles,
better spray control, etc. for more precise icing simulation.
The other tanker with which we had experience was not de-
veloped even to the state of the WADC tanker at that time
and provided very unrealistic conditions from every con-
ceivable standpoint with corresponding results. Unrealistic
as they were the results were of serious concern and were
cause of many additional hours of static icing tests of the
complete power plant and the initiation of a comprehensive
natural icing flight test program. The net result was that
the additional testing, time, and dollar expenditures proved
that the tanker tests were invalid indeed--the propeller,

inlet duct, and engine icing protection systems were more than adequate and operated very effectively, a point which had previously been proven by the original static icing tests and the WADC tanker tests. It is apparent then that the tanker does have a place in the expeditious evaluation of icing protection systems but only if the tanker concept is properly developed.

MILITARY SPECIFICATION STATIC SEA LEVEL TESTING vs
STATIC ALTITUDE AND FLIGHT TESTING

Both the 501 and 250 engine icing protection systems were developed to the military specification requirements using the dry air test technique and both were subjected to static sea level icing tests to demonstrate compliance. To date both systems have proven to be completely satisfactory in service. The point here is that the design and evaluation of an anti-icing system which meets the military specifications at sea level will result in a configuration which is satisfactory at altitude and the meteorological conditions encountered in flight operations.

With exception of the tanker tests and the Electra certification flights in natural icing, the meteorological conditions under which the 501 engine has been tested are presented in

Figures 6 and 7. The Mount Washington tests (6288 ft.)
were conducted in both natural and simulated icing cloud,
the Allison icing facility tests were conducted at sea
level to 20,000 ft. pressure altitudes in simulated icing
cloud, and the "Elation"flight tests were conducted in
natural cloud at altitudes ranging from 3700 to 19,000 ft.
The "Elation" was a constellation, modified with Electra
power packages, which was the Electra propulsion system
test bed. The engine inlet components were viewed by
direct observation or via a closed circuit television
installation and engine performance was monitored through-
out the tests. The engine was capable of operating com-
pletely free of ice at each of these conditions over its
flight operating range and no discernible difference was
ever noted in its protection effectiveness.

Two points of interest in the natural icing flight tests
are the ambient air temperatures at which the icing con-
ditions were encountered and the relatively low water con-
tent of the icing cloud. Only two icing encounters were
obtained below -10°F and with exception of one encounter
the liquid water contents were at or below the FAA and ARB
continuous maximum specification. This is true even though
in excess of 100 flight hours were devoted to searching
for the most extreme conditions throughout the United States
and Canada. The vast majority of the 17 hours of total

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ALLISON 501 SERIES ENGINE TEST CONDITIONS
IN ICING ATMOSPHERES
AIR TEMPERATURE VS LIQUID WATER CONTENT

⇧ 5.6 GM/M³
⇧ 6.0 GM/M³

●——● MIL-E-8593(ASG)
■——■ C.A.A. and BRITISH A.R.B. CONTINUOUS MAX.
◆——◆ C.A.A. INTERMITTENT MAX. - 3 MILES
⬟——⬟ BRITISH A.R.B. INTERMITTENT MAX. - 3 MILES

⬟——⬟ BRITISH A.R.B. INTERMITTENT MAX. - 1/2 MILE

▲ ALLISON C-398-C CONTINUOUS
▼ ALLISON C-398-C INTERMITTENT
⊙ 1954-1955 MT. WASHINGTON TESTS
⊡ 1955-1956 MT. WASHINGTON TESTS
◇ 1956-1957 MT. WASHINGTON TESTS
✕ "ELATION" FLIGHT TESTS
⊙ 1957-1958 MT. WASHINGTON TESTS
△ ALLISON ICING FACILITY TESTS-S.L.
▽ ALLISON ICING FACILITY TESTS-ALT.

Figure 6

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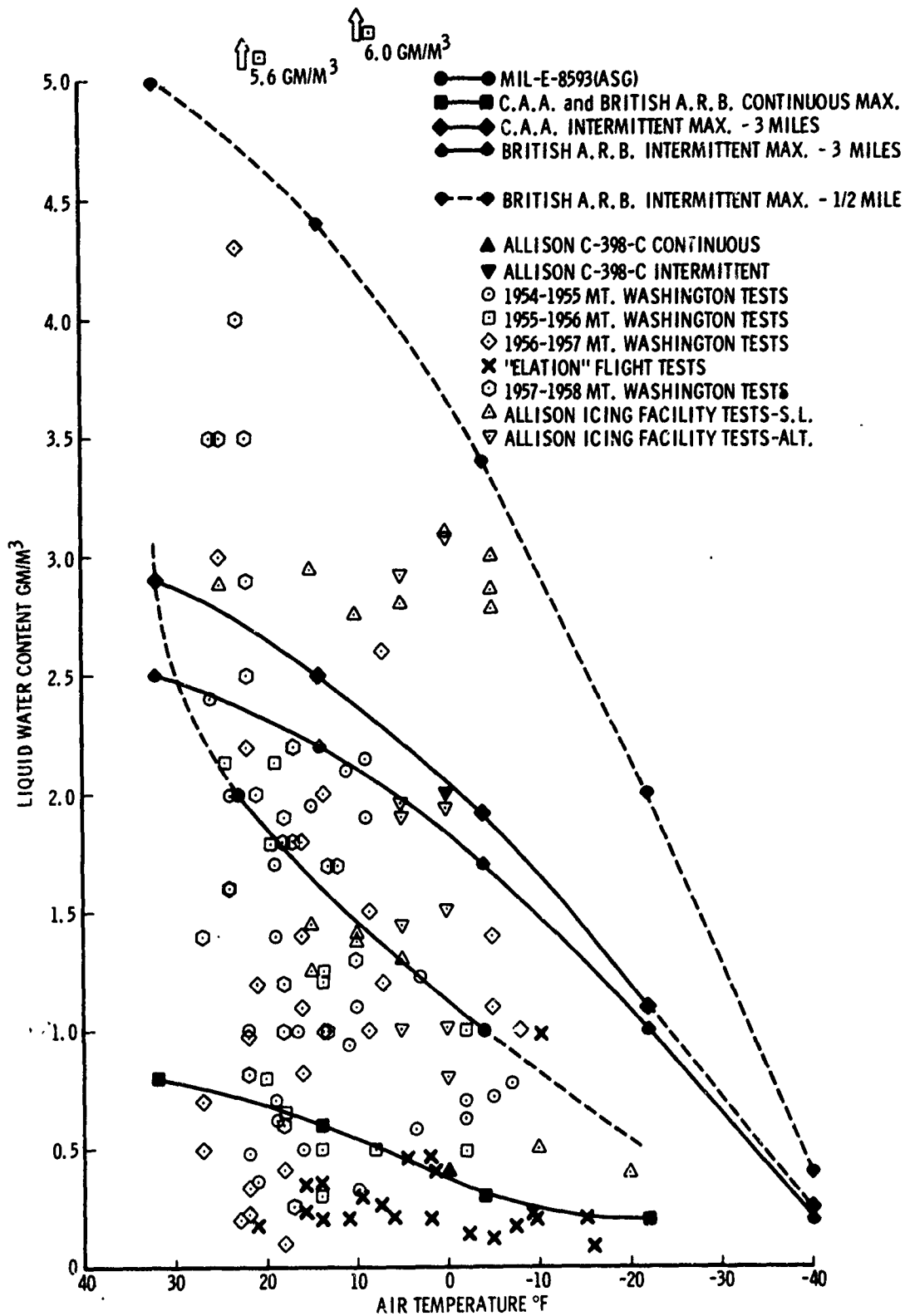
ALLISON 501 SERIES ENGINE TEST CONDITIONS
IN ICING ATMOSPHERES

AIR TEMPERATURE VS MEAN DROP DIAMETER

Figure 7

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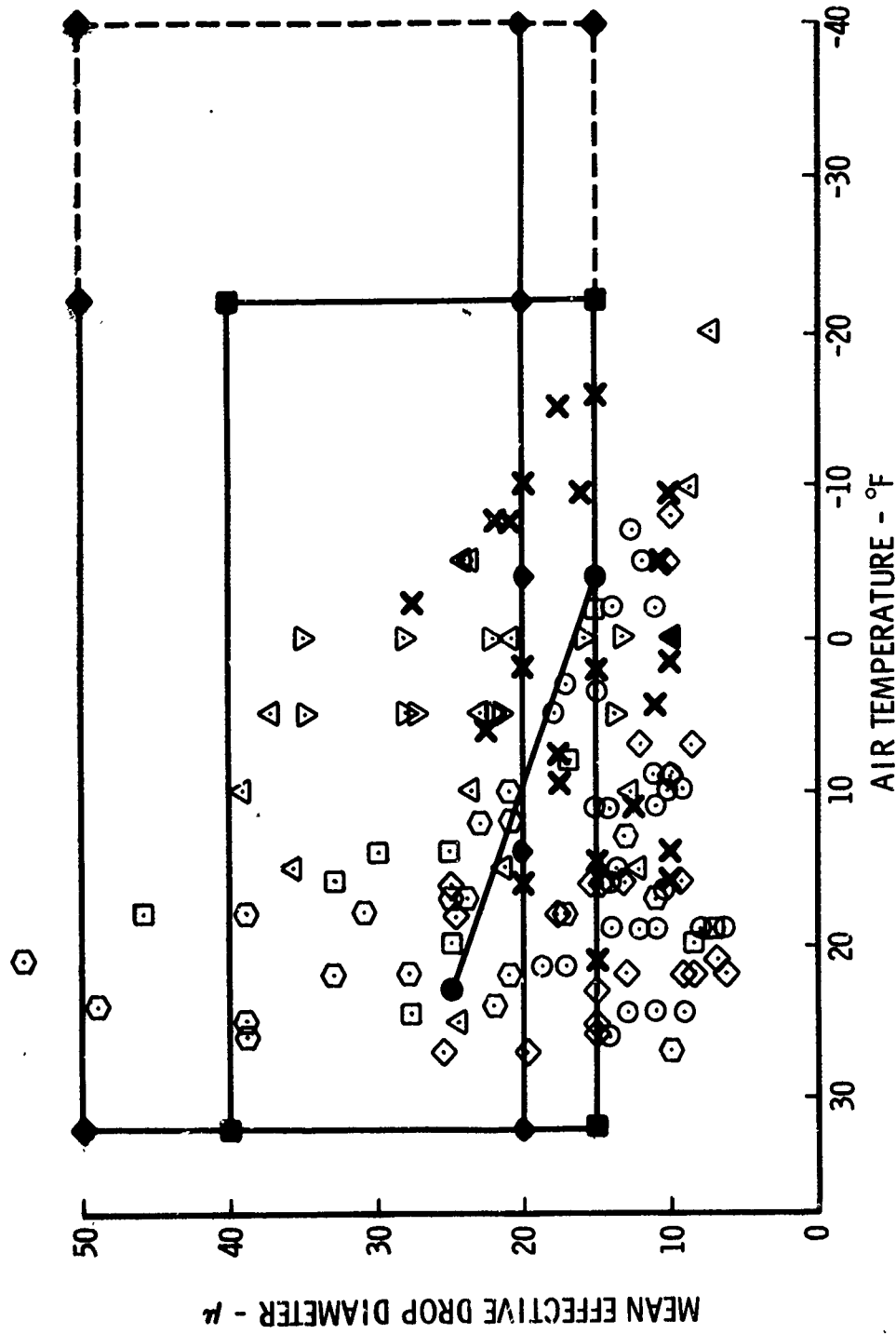
icing flight time was spent circling in huge cumulus cloud
build ups--the most severe cloud forms--to obtain even these
conditions.

Mount Washington weather has been billed as "the worst in
the world" and it boasts "only 23 clear days a year"--yet
significant icing cloud between -5° and -10°F are extremely
rare there. One would have to dig back into the archives
to find the original data to separate the natural icing
liquid water contents from those obtained by water spray
in the data presented in Figure 6. However, if memory from
years of expreience at Mount Washington serves, natural icing
liquid water contents in excess of one gram per cubic meter
are also extremely rare there except at the higher ambients
and conditions approaching a freezing rain. The conclusion
here is that, as previously stated, the military specification
points are a well selected compromise and it is recommended
that all agencies adopt that specification as standard.

ICE INGESTION

Inadvertent ice ingestion sometimes occurs during the anti-
icing system development testing and an engine is always
forced to ingest ice during the icing protection compliance
demonstration. Inadvertent ice ingestion can occur if the

inlet duct, cowl, other components upstream, or components
on the engine itself which may for some reason be deficient,
accrete ice curing the icing tests. After the accretions
reach a critical size, they are often dislodged by aero-
dynamic loading and pass into the engine. The intentional
ice ingestion occurs because the military specification calls
for a delay in actuating the anti-icing system after icing
is encountered. The engine must, therefore, ingest the ice
that accretes on its inlet during the delay period. In
addition, hail impact and ice ingestion tests are conducted
since reasonable immunity to damage from ice ingestion, etc.
is a well defined requirement for FAA certification.

There is considerable difference between engines of differ-
ent design in regard to their susceptibility to such damage.
However, the differences relate primarily to design features
and not necessarily to size although the small engine may
have an advantage because of the shorter blade and vane spans.
When ice ingestion (and other foreign object ingestion) occurs
the basic damage is usually typical because of the mechanism(s)
of ingestion. Ice ingestion in particular is usually re-
stricted to the first stage or two and results because the
tip of the rotating blade moves forward out of the plane of
rotation as it is struck by ice (or strikes ice that is

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passing through the preceding stationary vanes) and the forward movement is sufficient to cause intereference at the outer trailing edge of the upstream vane assembly. The interference manifests itself in rolled over leading edge blade tips, occasionally some blade bending, and tearing or impact damage of the vanes at the points of contact. The manifestation may involve only one or several blades but the vane damage usually involves a larger number. In general, the spacing between inlet guide vanes plays an important role in minimizing vulnerability to ingestion damage, narrow spacing minimizing the size of the ice which can enter the compressor. The axial spacing between the guide vanes and first stage rotor and the subsequent stator vane and rotor play an important part in an engine's tolerance to ingestion. Other differences in design such as blade material, the stiffness of the blades relative to their length all have a bearing on this problem. It is difficult to assess which design feature plays the major role.

Based on comparative experience with the current 501 engine models and a 501 engine which was designed with a transonic first stage (no inlet guide vanes), it would appear that the engine without guide vanes was much less tolerant to ice ingestion from a mechanical standpoint. So much so, in

fact, that part span inlet guide vanes were designed in an attempt to protect the outer span of the compressor blading. Unfortunately, development of the transonic compressor design was deleted for other reasons and additional ice ingestion tests of this design were not completed.

As ice or other foreign objects are ingested, they tend to create flow disturbances etc. which manifest themselves as momentary engine power losses. The degree and duration of the power losses are functions of total quantity of material ingested and the mechanism of that particular occurrence of ingestion. If a sufficient quantity is ingested, the flow disruptions etc. may result in a complete loss of power. Because they are designed to operate on air, engines may be overwhelmed by major flow restrictions and disturbances.

Both the 501 and 250 engines have been subjected to relatively extensive ingestion tests which have included ice, snow, hail, birds, sand and dust, water, and other foreign objects to which they may be exposed during commercial or military operations. A comparison of their ice ingestion tolerances is presented in Figure 8. There are differences in the data used in the presentation which prevent a precise comparison, but the comparison should be adequate to indicate that, on a proportional basis, there is little difference

Water Content in the Atmosphere During a Rainstorm

(References: Aero. Meteorology, W.R. Gregg; Encyclopedia Americana
Vol. 23 "Rainfall"; T56 Power Augmentation, L.W. Shutts 7/28/55)

Model 501
2.075 lbs ice/sec or 15 gals H_2O/min

Model 250
0.159 lbs ice/sec or 1.085 gals
H_2O/min

Model 250
0.124 lbs ice/sec or 0.9 gals H_2O/min

Model 501
1.49 lbs ice/sec or 10.7 gals H_2O/min

Model 501
0.97 lbs ice/sec or
6.9 gals H_2O/min

Extreme cloud burst

Plum Point, Jamaica
May 12, 1916
8 inches in 15 min.

Portabella, Panama, Nov. 29, 1911
2.48 inches in 5 min.

Record rainfall reported during the
Kansas floods, 1954. 8 inches in 1/2 hour.

Extremely hard rainfall (4 inch/hour)

Rainfall - inches/hour

80   70   60   50   40   30   20   10   0

.01   .02   .03   .04   .05   .06

$$\frac{\text{Weight of Water}}{\text{Weight of Air}} = \text{Atmospheric, Water to Air Ratio}$$

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Figure 8

in engine tolerance to ingestion from a performance stand-
point.

The 501 engine data was obtained from the hail tests in
which, following an extensive series of single and multiple
firings of ice balls ranging from 1/2 to 3 inches in diam-
eter, large charges of hailstones were projected into the
engine inlet at 380 to 415 miles per hour. The charges
were comprised of one 3-inch ice ball, breech loaded, and
a sufficient number of 2, 1 1/2, 1, and 1/2-inch ice balls
muzzle loaded onto the 3-inch ball to make up 1, 1 1/2,
and 2 lb charges. The 250 data was obtained from the sim-
ulated snow ingestion tests which were accomplished using
finely crushed ice. In this case the ice was dumped, as a
mass, down a chute directly onto the face of the compressor.
In both cases the impact and ingestion process was essentially
instantaneous. However, for purposes of this discussion
it was assumed that the process occurred over a period of
one second--a conservative assumption.

On this basis the 501 engine encountered a flameout or total
loss of power at a water-air ratio of approximately 0.064
as indicated by the shaded square symbol in Figure 8. It
should be noted that this quantity of ice in the one second
time frame is equal to 15 gallons of water per minute and

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the engine has continually demonstrated its ability to in-
gest in excess of that quantity of water on a steady state
basis with no deleterious effect. The open square symbols
designate test points in which there was little or no en-
gine reaction to the ingestion. The model 250 engine in-
gested quantities of ice up to a water-air ratio of approx-
imately 0.058 before flameout was encountered as indicated
by the shaded triangle symbol. While this quantity of ice
in the one second time frame was equal to little over one
gallon of water per minute, the 250 has demonstrated its
ability to ingest two gallons per minute (0.09 water-air
ratio) on a steady state basis. The open triangle symbol
designates test points in which there was little or no
engine reaction to the ingestion.

It is apparent from this comparison then that although the
smaller engines cannot ingest the total quantities of ice
that larger engines can, there is little difference in their
capabilities on a proportional basis.

In conclusion, it should be restated that the effect of
engine size on icing protection requirements appears to be
limited to acclimating the designer, development engineer,
airframe manufacturer and perhaps the user to size. In this
regard the airframe manufacturer and user should concern

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themselves with the prevention of ice accretions on the aircraft and the aircraft air inlet system to minimize potential problems. Inlet screens which are predominant on helicopter installations today should be eliminated or otherwise antiiced as they pose a significant hazard to the powerplant in some environments. This point was proven as long ago as 1951 with large engines when a flight of aircraft encountered serious problems with screens over Richmond, Indiana which was cause for loss of life and equipment. Look around you--large engine aircraft installations no longer have screens.

DISCUSSIONS FOLLOWING MR. BIANCHINI'S PRESENTATION ON

"SMALL TURBINE ENGINE ICE PROTECTION"

Question: Since we expect the pilot to be alerted and to turn on his anti-icing system upon penetration of an icing cloud, with unreliability of ice detectors how long can an engine be exposed to ice before the anti-icing system need be turned on?

Answer: In -250 engine development program, we ran several minutes in icing conditions, at 1 to 2 grams liquid water content, and engine power deteriorated. Therefore, the pilot would have to know ambient temperature and flip the system on as his aircraft was beginning to ice. The -501 engine ran as long as 34 minutes in icing conditions, and eventually had a 43 percent power loss before the anti-icing system was turned on. The military require a 15-minute run with anti-icing off and then to be turned on. In our development programs, we test at each point for 15 minutes (whether LWC is high or low) without the ice protection system on.

Question: Do you run an evaporative system?

Answer: No. We run "wet" but with no icing. At cruise, we are well over design and run "clean," which is "wet" but ice free. At ground idle, we do not run "clean," but have run for periods of an hour at ground idle with no detriment.

Question: At what liquid water content do you conduct your tests?

Answer: We do not emphasize LWC, but rather temperature. We are concerned with the minimum temperature rise of the metal at $45^{\circ}F$. The $45^{\circ}F$. is an average skin temperature rise. This approach was used for the -501 and -250 engines.

Question: In your approach, you are saying that LWC does not have much impact on a running wet system, but you say temperature rise is the design criteria; if you turn on a system at $-20^{\circ}F$. and it was designed for $-10^{\circ}F$., wouldn't you be aggravating the condition by turning the system on rather than leaving it off?

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Answer: In our experience, no. At -20°F. ice is so limited
           in shape and quantity, you can do without the anti-
           icing. When you turn it on, you immediately shed
           a portion of it. After a while, you shed all of the
           ice. We never run artificial icing below -10°F.

Question: Rather than a question, this is a rebuttal comment
           on screens. The objective of screens is to keep
           objects out of the engine. Problems with a screen,
           such as the one on the PT-6 engine, are few, due to
           the small size of the screen. This screen has
           demonstrated its capability to keep the engine
           intake clean and free from ice with its inertial
           separator vane in the inlet. This engine screen
           meets the military requirement of 30 minutes at
           2 grams LWC without any anti-ice protection.

Answer: There was no intent to comment adversely on engine
           screens, but rather to comment on aircraft screens.
           Even these could be made to work. Our experience
           with aircraft screens indicates that in very wet
           snow, and in a very narrow temperature band, 2° F.
           to 3° F. at most, the screen slushes. Air vapor
           trails are visible as the air goes over the screen
           at a higher velocity and a pulsation is noticeable.
           Either the air carries the slush over the screen and
           into the bellmouth, or directly through the screen
           and directly into the engine.

Question: Referring to your concept of 45° F. temperature rise
           and discounting LWC, what change in heat requirements
           would occur if LWC was considered?

Answer: Do not have the exact figures, but the change in heat
           requirements would be negligible. We agree our
           method may not be 100 percent accurate, but it is
           practical. Our approach is not applicable to an
           evaporative system, only a running wet system.

ICE TUNNEL TESTING

AT THE NAVAL AIR

PROPULSION TEST CENTER

By: J. Lawrence Palcza
Project Engineer
April 1969

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INTRODUCTION

The history of propulsion systems has clearly shown that the most important factor in the development of a new weapons system is determination of its performance characteristics in the environment to which it will operate in service. This type of testing is done for the Navy at the Naval Air Propulsion Test Center (NAPTC) and makes a major contribution to the Navy's effort to supply the highest quality engines to the fleet.

NAPTC has been conducting enviornmental icing tests since 1959. The first altitude icing test was conducted in 1962. The first turbofan icing test was conducted in 1968. Tests have been conducted on the J71, J75, J79, J52, J57, J60 and TF30 series of gas turbine engines.

DESCRIPTION OF NAPTC

The facility at Trenton is capable of supplying complete environmental simulation on experimental and production turbojet and turbofan engines. This includes the ability to simulate air speed, altitude, temperature, humidity, water ingestion, missile exhaust gas ingestion, inlet pressure distortion and icing. Engine transient operation is possible throughout the entire flight regime.

The test wing houses six major test areas. There are three altitude chambers, two sea level cells and a ten-foot diameter subsonic induction wind tunnel.

The Aeronautical Engine Department facility in Philadelphia is a recognized authority in the fields of turboprop and small turboshaft engines, aircraft engine accessories, and fuels and lubricants.

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About 95 percent of the Philadelphia facility's efforts is directed to testing of small turbine engines and their associated projects.

ICING SPRAY SYSTEM

Probably the most critical factor required for conducting icing system evaluations is the control of droplet size.

The object of the icing system is to produce a homogeneous cloud with a uniform distribution and drop size. These spray rigs are installed in a large inlet duct so as to reduce,as much as possible, the effect of air velocity on drop size and distribution. The location of this system varies somewhat between test programs; however, it is kept in the range of 30 feet from the engine inlet. Figure 1 is a typical instrumentation diagram of an engine installation indicating approximate locations of the various systems.

The heart of the spray rig is the concentric water-air nozzles which produce the cloud of varying droplet sizes depending upon the water-air ratio supplied to the nozzles. Each nozzle has a relatively low water flow rate. Because of the low nozzle flow rates, tests have been conducted with as many as 100 nozzles to meet the maximum test conditions. The nozzles are mounted in a series of air foil shaped spray bars which are installed in the inlet ducting.

The air supply for the nozzles is from a 100 PSI air system. The air pressure is modulated with remote controlled pressure regulators and heated to 135°F (to prevent nozzle freeze-up) through steam heat exchangers. The water is also heated to 100°F as an added precaution against nozzle freeze-up.

The icing systems are calibrated in the test cells prior to each

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engine evaluation. It has been found that droplet sizes vary due to variations in the cell geometry. Consequently, parameters such as nozzle water-air ratio for various droplet sizes are determined for each new installation.

DROPLET SIZE DETERMINATION

During icing system calibrations conducted at NAPTC, both the rotating multicylinder and the oil slide mechanism for measuring droplet sizes have been employed.

The rotating cylinder assembly used at NAPTC consisted of five cylinders of varying diameters. These cylinders were mounted on a common shaft and inserted perpendicular to the airstream. The cylinders were rotated with an electric motor and withdrawn from the duct after a predetermined time.

After a run, the cylinders were removed from the duct, disassembled and weighed to determine the amount of ice collected on each cylinder. By knowing the nominal diameter of each cylinder, the amount of ice on each cylinder and the ambient conditions, it is possible to calculate the volumetric median droplet size and LWC of the airstream.

The volumetric median droplet size is defined to be the droplet size "d" at which half of the total volume of sample is contained in drops of diameter greater than "d" and half of the total volume less than "d".

The oil slide assembly consists of an injector rod and a plastic slide. The plastic slide has 3 holes 0,10 inch in diameter and 0.06 inch depth. After these holes were filled with a silicone grease, the slide was placed in the rod and immersed into the airstream. A plate covering the slide was then withdrawn allowing the slide to capture

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droplets. The assembly was then removed and the slide placed under a Bausch & Lomb Photomicrograph camera. The droplets in the distribution photograph were then counted and categorized as to their diameters. Theoretically, the LWC can be determined using the oil slide mechanism or the rotating cylinders; however, this approach has proved to be inconsistent. Consequently, the LWC is calculated by knowing the total water and mass flow.

NAPTC experience has chosen the oil slide mechanism for determining droplet size over the rotating cylinder due to ease of operation and consistency of results.

Attempts were also made to use a Johnson-Williams liquid water content meter. Usage of the instrument in the test cells proved to be highly inaccurate.

METHOD OF TEST

1. Photographic Coverage

   a. A closed circuit TV system is employed upstream of the icing spray rig. This is used to view the engine inlet after an icing run and to determine when the ice cloud has completely filled the inlet duct.

   b. A 16mm high speed motion picture camera is used to photograph the engine inlet during the ice run. This camera is installed outside the ducting photogrphing through a clear plastic or pyrex section of duct.

   c. A 35mm robot camera is installed outside the duct and immersed into the airstream during engine shutdown after an icing run. These photographs are enlarged and used for the Center's formal reports.

INSTRUMFNTATION

The anti-icing bleed pipe is removed and instrumented with P_T, P_S and T_T probes for airflow measurement. The airframe supplied bulletnose is

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temperature instrumented internally, occasionally some of the IGV's are also instrumented for skin temperatures. This has proved useful in determining approximately at what power setting an engine can be tested and still have sufficient anti-icing protection. Duct airflow is measured utilizing a steam heated total pressure probe and four heated wall statics. Duct air temperature is read on an electrically heated Rosemount probe. Steady-state and transient data of various engine parameters are also available.

All icing tests are preceded by a steady-state calibration of the engine's operating line with the anti-icing system on and off. An accurate measure of thrust fuel flow, etc., are recorded for TSFC and performance loss analysis.

The anti-icing system is usually actuated 5-10 minutes before entering the icing environment. The icing cloud is kept on for 10 minutes after which time the engine is chopped and photographs fo the engine inlet are taken.

After completion of the icing tests, another calibration of the engine's operating line is performed to note if any deterioration has taken place during the test program.

ICING SPECIFICATIONS

Variations in test requirements exist between national and international icing specifications. Three of the most well known are tabulated below:

| | MILITARY | | FAA MAXIMUM | | | | BRITISH CIVIL AIRWORTHINESS REQUIREMENTS MAXIMUM | |
			Continuous		Intermittent		Continuous	Intermittent
LWC	1.0	2.0	0.5	0.3	1.9	1.6	0.8	2.5
Temp.	-4	+23	+23	-4	-4	+23	32	32
μ	15	25	25	15	15	25	20	20

Most of the icing runs performed at NAPTC are conducted with a 10 minute simulation of the specification conditions. For the LWC tested, this would appear to be a very severe condition i.e. 50 mile extent of icing for an aircraft flying at 300 mph. However, test experience has shown that engines with insufficient anti-icing protection encounter performance degradation and/or engine stall or damage within five minutes; well within the bounds of possible environmental encounters.

RESULTS OF NAPTC TESTING

J71-A-2E

In 1959 in-flight accidents involving the McDonnell F3H-2 aircraft powered by Allison J71-A-2E engines were believed to be caused by water and/or icing of the inlet and the fuel control inlet pressure sensing probe.

An evaluation to determine the cause of their in-service failures was begun at NAPTC.

It was found that ice blockage of the P_{T2} sensor affected the fuel control.

Recommendations were also made to strengthen the IGV assembly and to adopt compressor clearances to avoid rubbing.

Further testing developed methods for fleet operations when icing conditions were encountered in aircraft using the J71-A-2E engines.

J57-P-20

In 1961 testing of the Pratt and Whitney J57-P-20 engine used in the Chance-Vought F8U-2N aircraft was begun to determine the suitability of the engine for all-weather applications.

After testing at sea level and altitude conditions, it was found that the bulletnose of the F8U-2N aircraft collected ice at 15,000 ft altitude

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with an inlet temperature of 25°F and LWC of 1.6 gm/m^3 causing damage to the engine.

It was concluded that the alternator and constant speed drive located in the bulletnose did not give sufficient heat to prevent ice formation on the bulletnose and that the loss of performance due to the anti-icing air extraction would prevent the aircraft from operating satisfactorily at the higher altitudes within the engine operating envelope.

It was recommended that the F8U-2N not be considered on all-weather aircraft and that the airframe manufacturer improve the bulletnose to have a better anti-icing capability.

J79-GE-15

During testing of the J79-GE-15 it was found that a modification of the anti-icing system was necessary to provide acceptable bulletnose support strut anti-icing.

The modification consisted of blocking eight of the ten flow passages in the bulletnose "doors", thus enabling increased anti-icing air through the struts.

J60-P-3A

In the test of the J60-P-3A a thrust loss greater than the allowable 5% occurred at the lower engine speeds.

This loss was as high as 23% after 5 minutes. Upon conclusion of the test, it was recommended that the J60 engine hot be flown in icing conditions. If the pilot should inadvertently fly into icing conditions, it was recommended he use the military power setting.

After the test cell investigation of the J60, an actual inflight icing test was performed by using a North American T39 Sabreliner and a KC135 tanker as a spray source.

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Results were similar to those experienced in the test cell.

J52-P-6A

After testing a J52-P-6A in 1966, modifications were made to the A-4E and A-6A aircraft flight manuals. These flight plan alterations were to prevent the possibility of engine inlet icing at various flight conditions.

TF30-P-8

The evaluation of the TF30-P-8 engine was the first turbofan tested under icing conditions at NAPTC. These tests, conducted in 1968, revealed inadequate anti-icing protection to the inlet total pressure sensor and the inlet guide vanes.

Modification to the inlet pressure sensor is presently underway.

Figure 2 is a pictorial indicating the ice buildup on the IGV's and the first stage fan blades at the two conditions tested. At the +23°F condition, engine stalls were encountered as high as 13,540 RPM (N_2) after only three minutes in the icing environment. It is believed that the stalls were caused by the ice buildup on the fan blades. Future turbofan engine testing should substantiate this severe problem area.

FIGURE 1. TF30-P-8 ENGINE ANTI-ICING TEST
INSTRUMENTATION DIAGRAM
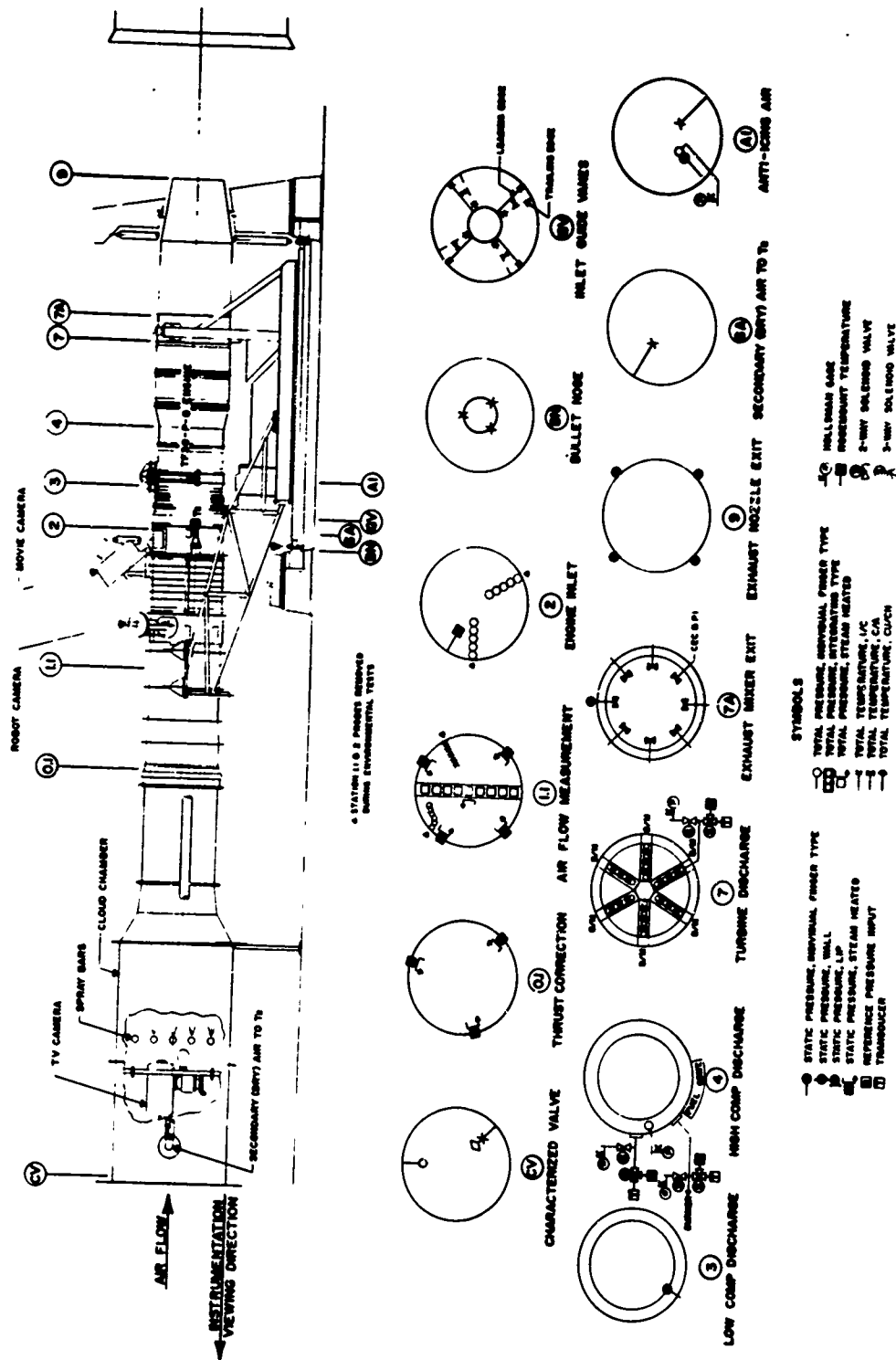
FIG. 2: SCHEMATIC DEPICTING ICE ACCUMULATION ON THE IGV'S AND FAN BLADES.

AIRFLOW ⟶

IGV'S

FAN BLADE

ICE ~ $\frac{1}{8}$" THICK

CONDITION: SLS, T_{T2} = +23°F

AIRFLOW ⟶

IGV'S

FAN BLADE

LIGHT FROST
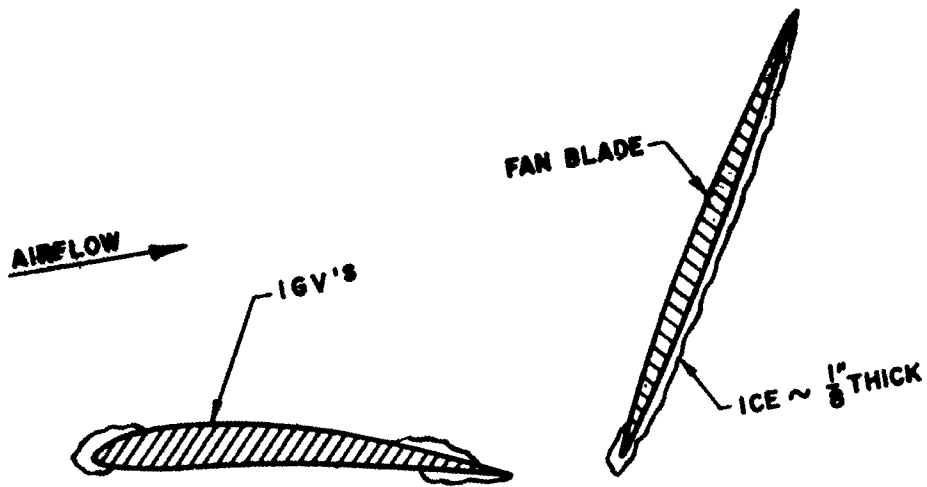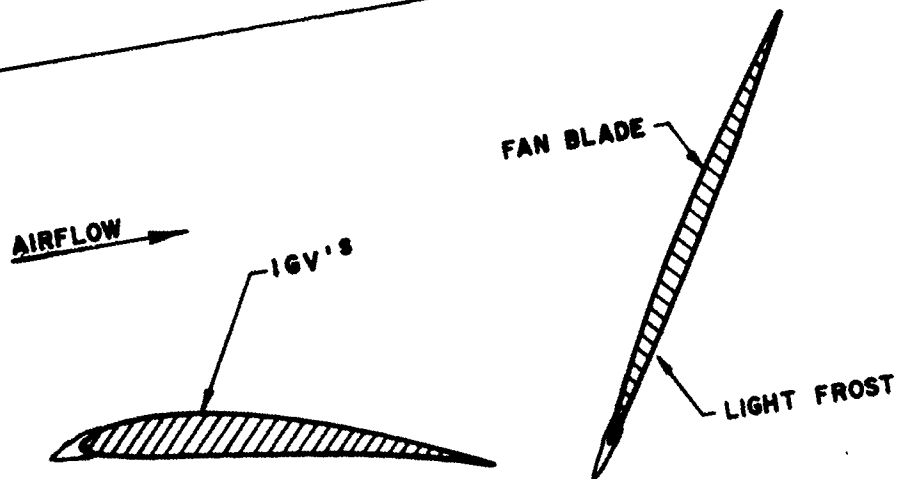
CONDITION: SLS, T_{T2} = -4°F

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DISCUSSIONS FOLLOWING MR.PALCZA'S PRESENTATION ON

"ICE TUNNEL TESTING AT THE NAVAL AIR PROPULSION TEST CENTER"

Question: If, during your test, the de-icing system is energized 5 minutes before test, how do you coordinate and anticipate this operation in service?

Answer: We feel the pilot should know when icing conditions are expected and turn on de-icing systems accordingly.

Question: What means are available to serve pilot warning?

Answer: We (Boeing) recommend that if temperature is below 10° C. and visible moisture is present, the icing system should be initiated.

Question: On MIL-SPEC., is a time given?

Answer: No, time is based on our own experience.

Question: How did you measure local distribution rates?

Answer: We used a screen to observe ice buildup.

Question: How do your tests fit into the qualification procedures for a military engine? Do the tests at Trenton constitute additional testing?

Answer: In the past, tests were based on in-flight problems encountered. No penalty was given for not meeting requirements. Now MIL-SPEC. calls out all government tests, and requirements must be met.

Question: What techniques or instruments are used to determine icing conditions?

Answer: Presently, no instrument is available that is relied upon. For detection of icing conditions, it is really up to the pilot to determine the conditions he is in.

Question: Is Trenton facility available to the non-military?

Answer: Yes, we recently tested a J3TD fire extinguishing system for FAA. Others are also welcome, depending on our schedule.

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Question: Is distilled water used in testing?

Answer: Yes.

A WATER SPRAY TANKER FOR
ICING SIMULATION

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1. For the past 20 years the Air Force has been deeply involved in water spray tanker development and utilization, for the express purpose of testing aircraft engines and anti-icing systems before they are cleared for operation in icing environments. Both the military and civilian industry have capitalized on this venture, and have found it a profitable means of assuring aircraft safety and performance, by detecting immediately inadequacies in ice protection systems. Testing in natural weather is much more time consuming than testing with tankers and sometimes does not detect these flaws as quickly. Directly involved in water tanker development has been the Adverse Weather Section, Flight Test Engineering Division, Directorate of Flight Test of the Aeronautical Systems Division at Wright-Patterson AFB, Ohio.

2. Until a few years ago ASD's B-29 and KC-135 water tankers had a monopoly on the inflight icing simulation business. Today, however, we note an increasing competition from American industry and Great Britian. Cessna and Lear Jet have built small tankers and the Ministry of Technology has outfitted a Camberra B-57 to spray water inflight. There's probably a few others we haven't heard about who have tackled the problem.

3. Today, ASD has two spray tankers at its disposal. The widely acclaimed KC-135-refueling-tanker-turned-water-carrier, and the less known but equally effective C-130 palletized water spray tanker. The C-130 rig is the one we're really proud of; developed in the last few years it has sprayed many of the slower, prop driven aircraft that couldn't meet the KC-135's speed range. The concept is similar to the "piggyback" idea introduced by the railroads, and consists of localizing all of the water spray apparatus (tanks, pumps, boom, etc) on one gigantic pallet (Figure 1), which may be installed or removed in any standard Lockheed C-130 aircraft in a matter of hours (Figures 2 & 3). When icing programs are on the wane the aircraft and water spray apparatus part company; the aircraft off to other tasks and the water spray apparatus to storage.

4. Together, the two tankers pack a powerful punch. In the speed range between 90 and 300 KIAS they provide an icing environment to please every customer. Cloud moisture contents are on the order of 0 to 1.75 grams of liquid water per cubic meter of saturated air (LWC). Mean water droplet diameters available are not variable, and are fixed by the water nozzle's constant geometry.

5. The icing cloud produced behind the tanker has been represented by several different conceptual models. Some of the models are more accurate than others, and some more widely used than others. The most accurate models are not necessarily the ones being the most widely used by our customers. The simplest and most widely used approach is the "homogeneous rate-of-catch" model. This model assumes a constant density and uniform LWC across any given lateral section of the cloud, lending itself to relatively easy mathematical representation. It also most closely approximates a small sample of common stratiform cloud deck.

6. Another model takes into consideration the evaporation around the circumference, and air entrainment along the length of the cloud. Here again, however, a relatively uniform cloud core is assumed for calculation of LWC.

7. Still closer examination of the icing cloud reveals a characteristic that may prompt us to reconsider our previous definitions of the icing cloud, and how they are equated to nature. Figure 4 points out the systematic turbulence actually present in the cloud. We think these concentrations of liquid water, which seem to alternate between the top and bottom of the cloud in a fairly regular manner are high energy vortices generated by the nozzle moving through the air mass. You see examples of this phenomenon when following a truck down the road and you observe small swirls in the dirt beside the road as vortices break off the rear of the truck.

8. But what is the significance of all this talk about "uniform density" clouds and "turbulent vortex" clouds? In a nutshell, just this: (1) Is the tanker's cloud a carbon copy of nature's cloud; the only difference being the smaller geometric scale? (2) Is nature's LWC directly convertible to the tanker's LWC? (3) If not, are we justified in testing our ice protection systems to one standard and assuming a direct relationship to yet another standard? We think there is cause for doubt in present test methodology, and room for improvement. The tanker has inherent cloud characteristics which may or may not match nature's cloud. To tie the two environments together may require altering our thinking a bit and discovering a method of measurement (besides LWC and drop size) that is amenable to both environments.

Icing Nozzle

Boom

Four Each 840 Gallon Tanks
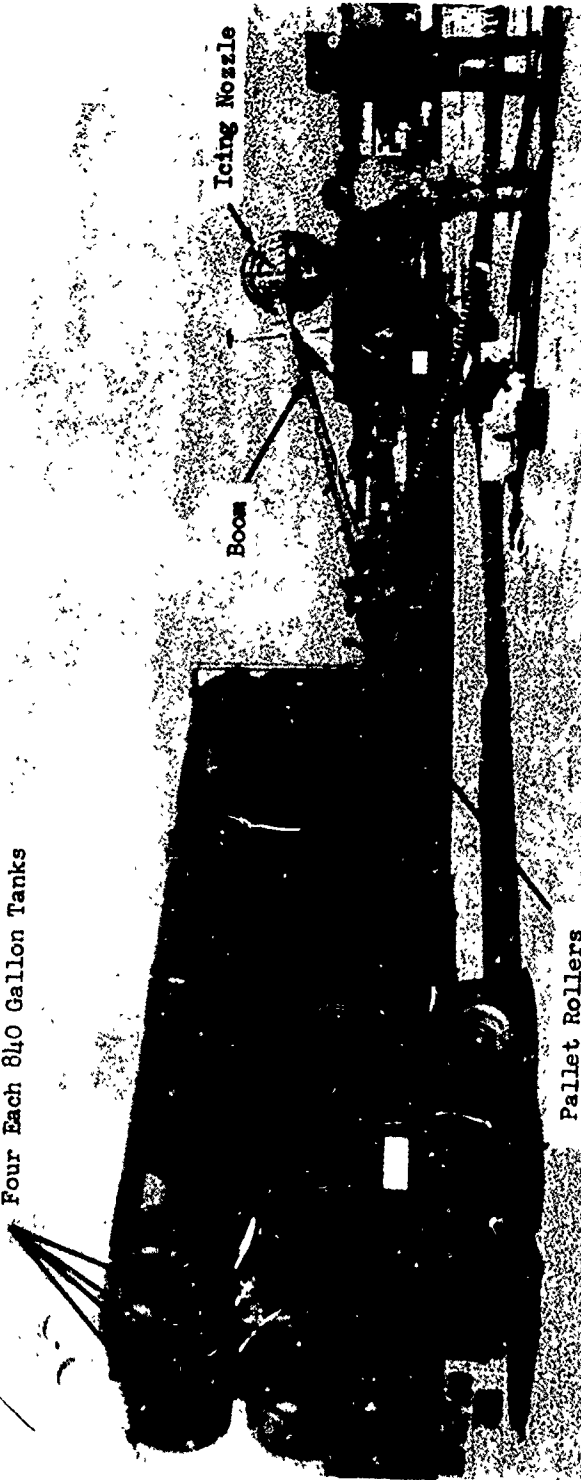
Pallet Rollers

FIGURE 1.   Complete Unit Before Installation
In The Aircraft

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FIGURE 2. Palletized Spray Rig Installed In The Cargo Deck Of A JC-130A Aircraft

WATER-LEVEL SIGHT GAGE
(Total Water Remaining, Gallons)

FLOWRATE MANOMETER   (GPM)

BLEED AIR PRESSURE   (PSIG)

WATER PRESSURE   (PSIG)

AIR TEMPERATURE   ($^\circ$C)

UHF COMMUNICATIONS

STATION 610

WATER TOTALIZER   (GALLONS)
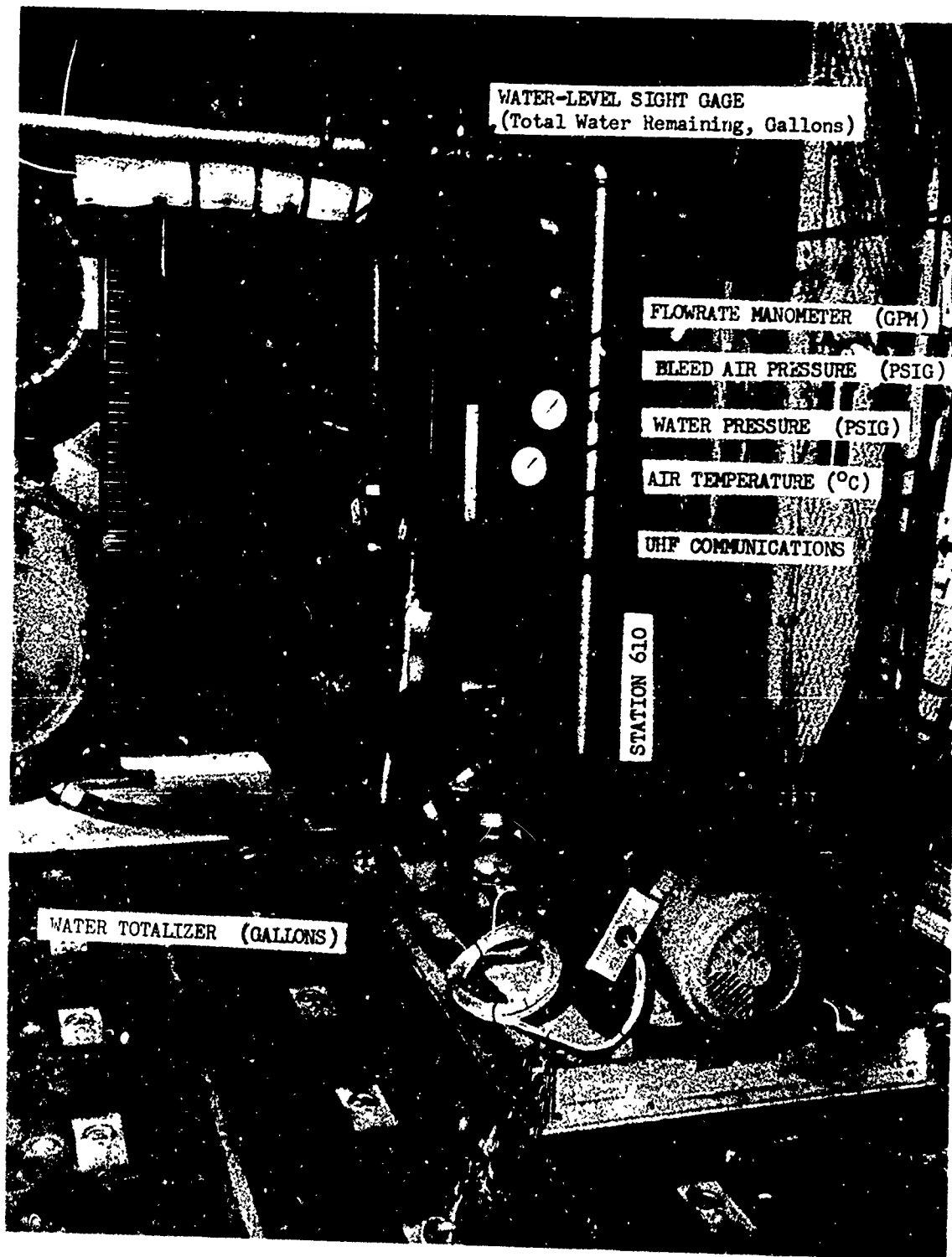
FIGURE 3.   Instrumentation Components

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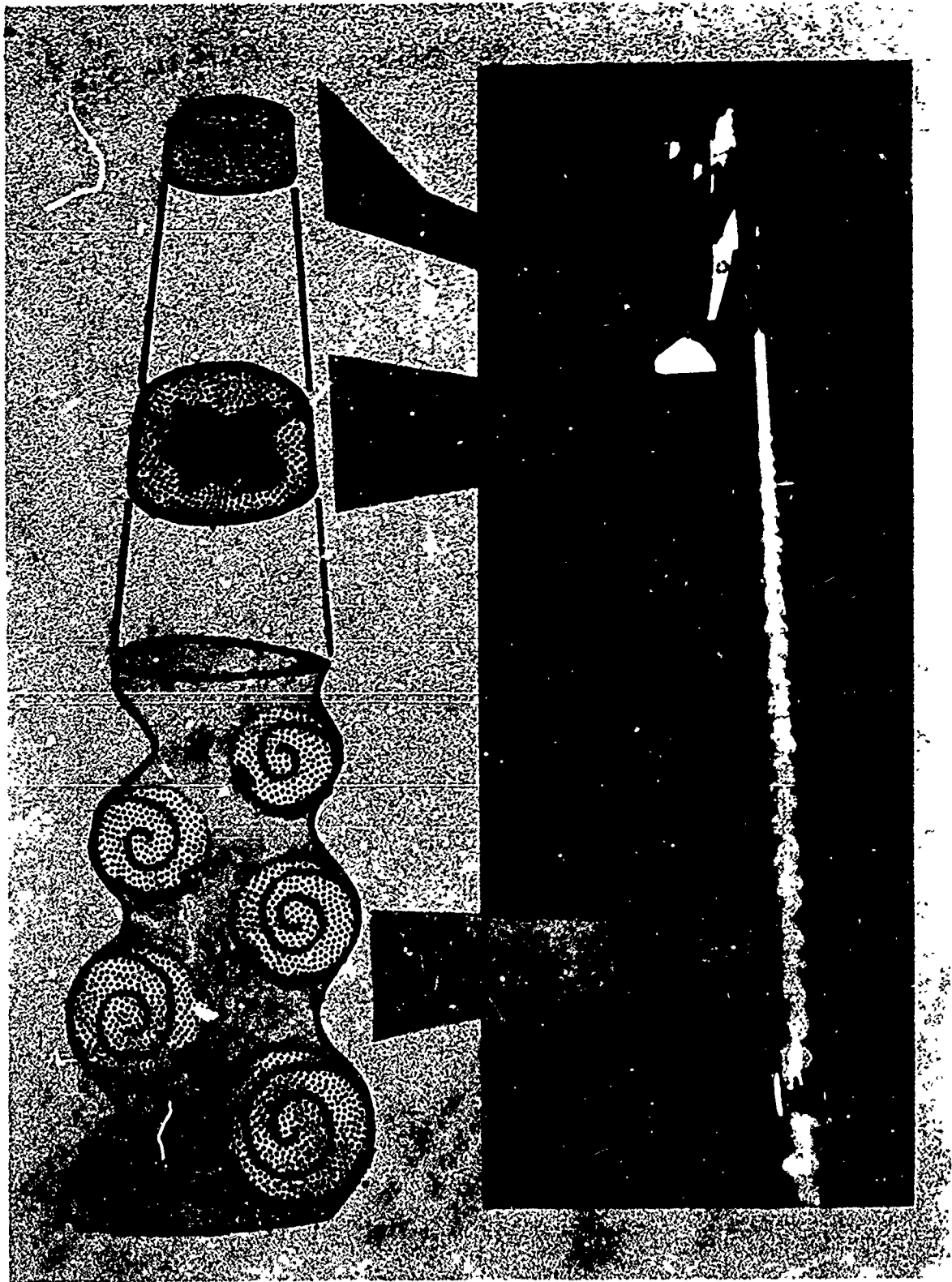
FIGURE 4. Icing Mission In Progress

ICING FACTORS, WATER SPRAY
TANKERS AND SPECIFICATIONS

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INTRODUCTION

1. Civil and military organizations in the business of flight testing
ice protection systems and devices frequently come in contact with the icing
envelopes in Federal Air Regulation Part 25, design and MIL Specifications.
Although the envelopes may be satisfactory tools for the designers, they
are unacceptable for the test people because they are near impossible to
apply and adapt effectively to atmospheric conditions. Consequently, it
is proposed that a new criteria be prepared based on factors that are more
up-to-date, realistic, possible to duplicate inflight and adaptable to variable
atmospheric conditions.

ICING HAZARD

2. Aircraft icing is one of the major weather hazards to aviation.
Ice on the aircraft decreases lift, increases weight, drag and stall speed,
spoils visibility for the flight crew and may produce false flight instru-
ment indications. In addition, an accumulation on exterior movable surfaces
may affect the control of the aircraft. In the past, airframe icing was a
hazard mainly because it tended to cause difficulty in maintaining altitude.
Today, although most aircraft have sufficient power to fly with a heavy load
of ice, airframe icing is still a serious problem because it results in
greatly increased fuel consumption and decreased range. Further, the possibility
always exists that engine-system icing may result in loss of power.

3. This description of the hazard is stated very succinctly in Ref 1
and 2, and very likely encompasses all that need be fundamentally said about
aircraft icing. However, some operational aspects of the icing hazard lead
one to reason further.

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4. Let us rearrange the description and set down, perhaps, a few words in general about factors conducive to icing and about some of the operational aspects of flight in icing conditions. Inflight icing situations that are of primary importance can be classified as:

a. Icing on the airframe and air data sensors causing problems with aircraft control and response, and produces false flight data.

b. Icing on the engine inlet lip and engine duct surface the ingestion of which seriously affects engine performance.

c. Severe fogging, frosting or icing of the windscreen critically affecting visibility.

RECKONING WITH ICING HAZARD

5. In our modern turbojet aircraft having powerful engines, excellent climb and descent characteristics, etc., structural or airframe icing does not appear to be a critical factor in any flight condition except that one involving prolonged holding procedures. Fogging and frosting of the windscreen apparently is not a problem on most aircraft with the exception of those light weight aircraft and helicopters having only defogging equipment. Consequently, we believe that icing of the jet engine is the foremost of any icing problem to the aircraft. In turbo-propeller and internal combustion engine propeller driven aircraft, icing problems still exist but they are of a different nature and magnitude.

6. ICE PROTECTION: Anti-icing systems on engines are activated anytime an aircraft is flown thru an icing cloud. Icing is most prevalent in the temperature range of 5°C to -20°C when the dewpoint spread is 3°C or less. Therefore, it is difficult to set a fixed value for "maximum extent of icing clouds". It is our opinion that a protection system should be "ON" when flight thru icing exceeds 15 nautical miles. May we cite again our argument favoring adoption of new criteria for evaluating icing factors?

7. OPERATIONAL CONSIDERATION: A combination of high engine power settings and low airspeed in icing prolongs the icing exposure and increases the hazard in holding patterns, GCA's and instrument approaches. It is a good policy to minimize the exposure to icing by avoiding the prolonged holding procedure, and by climbing and descending quickly through icing clouds. Most aircraft, even unprotected ones, have the capability to penetrate small regions of light icing with little danger of sustaining engine damage.

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8. ONE TECHNIQUE: Special instructions have been issued on all
aircraft on which USAF Category II All Weather tests have been conducted
as well as on all aircraft on which ordinary icing tests have been conducted.
Jet engine damage from ingested ice often occurs when throttles are advanced
to recover some lost rpm, airspeed or to maneuver. The technique of reducing
both airspeed and power for ingesting ice is believed to be instrumental in
reducing jet engine damage. Consequently, throttles should be advanced
cautiously while flying in icing conditions or after departing an icing cloud.

ICING PARAMETERS

9. WHAT DATA? The geometric pattern and physical property of an ice
formation depend upon four main variables shown descriptively in Figures
1, 2, 3 and 4.

    a. Content of water in the cloud;

    b. Ambient temperature;

    c. Size of the water droplets (collection efficiency); and,

    d. Size or shape of the collecting body.

Another variable, airspeed, can be added when effects of icing are evaluated
in terms of accretion, rate-of-catch or rate-of-build of an ice formation.
Say what one may about how these variables are organized to produce atmospheric
icing conditions, the operation of an aircraft or vehicle ice protection
subsystem is concerned only with rate-of-catch of water or, perhaps in
other words, the rate at which ice is being built up, or the total accumulation
of ice. Therefore, during system evaluations, all design and theoretical vari-
ables should be translated into more meaningful data on which to demonstrate
and qualify an ice protection subsystem.

10. A controversy still exists among theoreticians, designers and test
engineers over the methods used to evaluate ice protection subsystems in
operational (non-laboratory controlled) conditions. Several times in the past
it has been suggested that an icing envelope be designed that is based on
rate-of-catch (or rate-of-buildup of ice). This would certainly provide the
test and evaluation people with a more realistic tool by which to evaluate the
effectiveness of ice protection devices. There is still less agreement on:

a. What are the necessary prerequisites leading to formation of ice on aircraft; and,

b. An acceptable definition for an icing intensity standard.

However, most people use some relationship of water content, distribution of drop size, flow pattern of drops around an object, and temperature to satisfy a predetermined requirement or a specification.

11. ICE FORMATION PREREQUISITES: The total number of factors to which ice formation has been attributed exceed a score (Table 1), Ref 3. Although the factors are of interest, no attempt will be made in this paper to evaluate the amount of direct or indirect influence exerted on an ice formation by each factor. Many are likely insignificant in relative importance, contributing hardly anything measurable. Moreover, to consider all of them during a test and evaluation would appear to be an awesome task.

TABLE 1. FACTORS INFLUENCING THE FORMATION OF ICE.

1. Temperature of the air	13. Density of the clouds
	14. Relative humidity
2. Vertical temperature gradient	
	15. Humidity at the surface
3. Air temperature at the surface	
	16. Pressure system
4. Velocity of the wind	
	17. Air mass or front
5. Direction of the wind	18. Type of precipitation
6. Turbulence of the air	19. Form of the water in the cloud
7. Height of the cloud base	20. Air pressure
8. Altitude above surface	21. Time (season) of the year
9. Orography	22. Conductivity of the collecting body
10. Thickness of the clouds	23. Surface roughness of collecting body
11. Type of clouds	24. Chemical composition of the drops
12. Amount of clouds	25. Electrical charge on the drops

12. INTENSITY STANDARD (Ref 2): In November 1968, the subcommittee for Aviation Meteorological Services in the Office of the Federal Coordinator for Meteorology recommended the use of a new airframe icing reporting scale for all FAA, DOC and DOD handbooks, manuals and publications. Although the scale was intended for use primarily in the reporting of icing encountered by pilots flying C-54 and C-118 type aircraft, and Ref 2 contains a caution "not to state operational effects of icing on other types of aircraft", the scale is used anyway in test work because the terms seem to be appropriately descriptive regardless of the type of aircraft actually encountering icing conditions. The terms in the icing intensity standard are described in Table 2.

TABLE 2.   INTENSITIES OF ICING.

TRACE OF ICING.   Ice becomes perceptible. Rate of accumulation slightly greater than rate of sublimation. It is not hazardous even though deicing/anti-icing equipment is not utilized, unless encountered for an extended period of time - over one hour.

LIGHT ICING.   The rate of accumulation may create a problem if flight is prolonged in this environment (over one hour). Occasional use of deicing/anti-icing equipment removes/prevents accumulation. It does not present a problem if the deicing/anti-icing equipment is used.

MODERATE ICING.   The rate of accumulation is such that even short encounters become potentially hazardous and use of deicing/anti-icing equipment or diversion is necessary.

SEVERE ICING.   The rate of accumulation is such that deicing/anti-icing equipment fails to reduce or control the hazard. Immediate diversion is necessary.

13. Methods and facilities utilized for the conduct of icing tests have been presented during this conference. Both natural and artificially produced icing clouds have been used extensively to evaluate aircraft and engine ice protection systems, Figures 5 and 6. Operating characteristics and limitations have been determined during both short and long periods of exposure in conditions described in Figure 7. Quantitative data are sometimes gathered but most of the time the data are qualitative in nature. Icing data points can be put into a matrix, a sample is shown in Figure 8.

ICING TANKERS

14. Practical methods for using tanker aircraft to simulate all types of ice conditions outlined in FAR-25 has been the subject of considerable concern within the Aeronautical Systems Division's Directorate of Flight Test for several years. It is our opinion after observing numerous evaluations of windshield, air data sensors, engine inlet and wing leading edge ice protection subsystems that tanker, natural and wind tunnel tests conducted on similar plan forms do correlate where similarity in temperatures, airflow, average water content and drop size exists. Figure 9 shows an excellent example of mushroom icing obtained while flying in a tanker icing cloud. Consideration should always be given to the fact that the tanker tests are three dimensional where the test aircraft, in combination with the spray tanker, exercised freedom of movement that is not inherent in wind tunnel type tests and stable natural ice conditions. Skillful handling of test aircraft as pictured in Figures 5 and 6 is absolutely necessary in order to produce accurate and consistently reliable test results.

15. Tanker tests are reliable but meteorological conditions day-to-day cannot be controlled. Variations in humidity and ambient temperature, effects of cloud cover, and freezing level altitude are a few factors which have to be reckoned with each mission when conducting tests with a spray tanker. With the present pneumatic atomizing spray rig, adequate control is maintained over the flow, both in rate and volume, of air and water to produce a consistent cloud having an average water content of any chosen value between 0 and about 1.75 grams of water per cubic meter of air. Drop size is usually governed more by design of the water/air atomizing spray nozzles than by the amount and type of mixing of water with the ambient turbulent air that is behind the tanker.

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16. SHORTCOMINGS IN PRESENT ICING TANKERS: We as test people have very limited control over the droplet size distribution since nozzles are usually designed to operate most effectively over either a fixed distribution having a mean droplet size, for example, of 20 microns or a fixed flow rate. Consequently, a distribution having a mean drop diameter of 15 microns as is specified in MIL-E-5007 and FAR Part 25 or a distribution having a mean drop diameter, of say 35 microns, as is shown in the envelopes in FAR Part 25 cannot be produced without either altering the spray nozzles or completely redesigning/rebuilding the spray rig now being used by the Aeronautical Systems Division's Directorate of Flight Test at Wright-Patterson AFB, Ohio. In Figures 10 and 11, some icing cloud characteristics of the ASD water spray tankers have been superimposed on the FAR envelopes for comparison of the icing environment.

17. The cloud behind any tanker is turbulent, as opposed to the stable conditions encountered in natural weather. Evidence of three pronounced, perhaps widely different, environments are pictured artistically in Figure 12. There is a definite useful area in which to run inflight icing tests, flying too close to the nozzle produces liquid water instead of ice, and too far from the nozzle produces equally unusable ice crystals. However, rime ice thru clear ice formations may easily be simulated in that part of the cloud between the two extremes.

NATURAL ICING (?) OR TANKER ICING (?)

18. Statements have been repeatedly made that tanker icing is not realistic, it is too severe, it causes too much engine damage during ingestion, it is incapable of being compared with natural icing data, or the cloud lacks uniformity, and so on. The one outstanding, positive factor in favor of tanker icing that is consistently overlooked is that the test aircraft can be moved a few feet laterally or downward and be in perfectly safe VFR conditions, either above the home airport or a designated test/restricted area. For example, a test point can be terminated after only a few seconds of exposure, or in the other extreme, extended well over an hour. Also, a variety of water contents, temperatures and speeds can be produced for test conditions, and these can be altered in flight whenever necessary.

19. SOME TANKER ICING EXAMPLES: A few examples of special studies that have been made are shown in Figures 9, 13 and 14.

a. Figure 13. Extremely heavy icing was desired in order to test the limits of protection on the windscreens, engine inlets and air data sensors on the aircraft. No physical damage was done to the aircraft or to the engines during these tests.

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b. Figure 14. On the other hand damages have been sustained
throughout the years since 1953. If there ever exists a curse to testing;
engines bear a convincing percentage of it. In this, a typical example
out of hundreds of tests, the front face sustained peripheral damage that was
confined to the first two or three stages. The engine remained partly usable
(never completely lost power) during the recovery of the aircraft to its home
base. While testing engines in moderate to severe condition, experience has
indicated that some engine ice ingestion damage may be expected once out of
10 data runs each of whose test time equals or exceeds 5 minutes duration.
Moreover, engine damage has hardly ever been observed while testing in light
icing conditions even for periods of time approaching 30 minutes duration.

20. SOME NATURAL ICING EXAMPLES: While icing tankers are used
primarily to explore the limits of performance, to confirm design analysis,
to seek out and identify problem areas, deficiencies, characteristics
and limitations minimizing the expenditure of valuable flight and calendar
time, flight tests conducted in natural icing conditions provide us with
the operational and practical information needed to approve clearances
for the whole aircraft to perform its mission. Examples of results from
three natural icing encounters are shown in Figures 15, 16, and 17.

a. Figures 15 and 16. Here are two excellent examples,
each a different basic form of ice, picturing the appealing or exemplary
qualities of natural icing. Meteorological conditions associated with
these encounters are unknown. However, the shapes that appear in the
buildups are similar to the ones used as models for making interpolations
and correlations between qualitative natural and tanker-produced icing.

b. Figure 17. Engine damage from ingested ice can occur during
the icing encounter but is most likely to occur immediately after departing
the icing condition, particularly where the outside temperature rises to above
freezing, or where throttles are advanced to recover some lost RPM, airspeed
or to maneuver. Interested in what happens when ice is ingested by an engine?
Briefly here is the account from the record of the B-47 Aircraft Icing Tests:

On 10 April 1953, a region of moderate icing
intensity was penetrated with the anti-icing
systems inoperative. Ice entering the engine
from the nacelle cowl ring leading edges caused
complete destruction of the number 3 engine and
extensive damage to the remaining five engines.

The aircraft was landed safely at Wright-Patterson AFB following the ordeal.
The gaping hole in the engine nacelle provided observers an awesome view of
the broken compressor case and compressor blades.

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TEST AND ASSESSMENT

21. When using water spray tankers, controlled experimental conditions
are chosen which permit the influence of the various meteorological factors to
be studied one at a time, Figure 8. The complete solution is reached when the
combinations of the various factors are developed into charts, graphs or placed
on the FAR Part 25 curves, Figures 10 and 11. Data obtained by controlled
experiments can be disentangled in one of the following ways:

     a. Interpolate between charts based upon design or synoptic
charts prepared from test or experimental data.

     b. Adjust the data obtained on flights and tests to fit synoptic
or design data.

     c. Attempt to find correlations between test charts and synoptic or
design charts.

     d. Depart from the conventional dependence upon design charts,
synoptic charts and specifications.

22. None of these methods is entirely satisfactory. It is difficult to
apply the first two because no generally accepted technique has been developed
for making the interpolations. The third method receives the most attention and
by using appropriate scale factors has produced relatively good results. It
is possible from the outline shown in Figure 8 to prepare charts of meteorological
data in which some parameter other than time is held constant. In general,
little use can be made of this possibility when testing in natural icing conditions
because of the difficulty of locating so broad a spectrum of persistent icing
weather conditions in which to test. For the fourth method, some scale
modeling, simplification of design criteria, proportional analysis, qualitative
definitioning, and forecasting analysis have been undertaken; some were partially
successful, others have produced no practical solution or could not be developed
into a universally acceptable technique.

CONCLUDING REMARKS

23. The only tests that can have any value are those in which a
correlation can be established between the severity of the icing condition and
the rate at which ice protection is supplied. If this condition is met, it
should be possible to extrapolate from the results of a few icing encounters
to obtain a broad interpretation of the effectiveness or performance of the ice
protection system, aircraft or item being evaluated without the expenditure of
excessive flight time and effort in the search for extremely severe icing
conditions.

24. Intelligent conversion of the design requirements, the Airworthiness Standards and MIL specifications into a meaningful format that will simplify testing; and, provide some universally acceptable scale modeling and proportional analysis techniques covering a large spectrum of conditions (i.e., the envelopes in FAR Part 25) is of great importance.

25. A new test specification should be prepared that will be amenable to wide usage of simulation devices and at the same time provide, as many as possible, the features summarized above.

REFERENCES

1. AFM 105-5. Weather for Aircrews. USAF Manual.

2. AWSM 105-39. Forecaster's Guide on Aircraft Icing. USAF Air Weather Service Manual. 7 Jan 1969.

3. NAVAER 50-IR-106. Meteorological Conditions for Ice Formation. April 1944. Translation of work of A. D. Zamorski.

LIST OF FIGURES

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EFFECT OF LIQUID WATER CONTENT ON ICE FORMATION

(SMALL PROBE IN 10 MILES OF FLIGHT)

LIGHT ICE
.125 to .25 GM/M³

MODERATE ICE
.25 to .50 GM/M³

HEAVY ICE
.50 and UP GM/M³

Figure 1. Projected area and collection efficiency of body, distance travelled and water content yields the catch or buildup.

EFFECT OF TEMPERATURE ON ICE FORMATION

COLD

COOL

WARM

MARGINAL
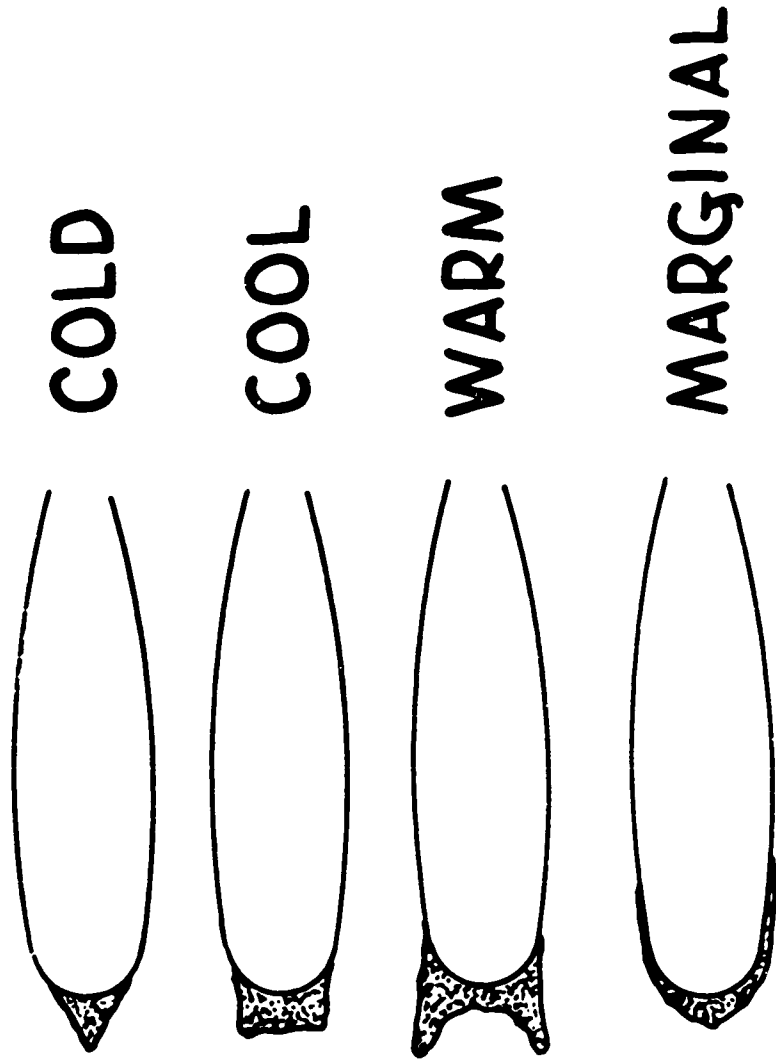
Figure 2. Cold temperature icing will always be light. Liquid water content of a cloud generally diminishes with decreasing temperature.

EFFECT OF DROPLET SIZE ON ICE FORMATION
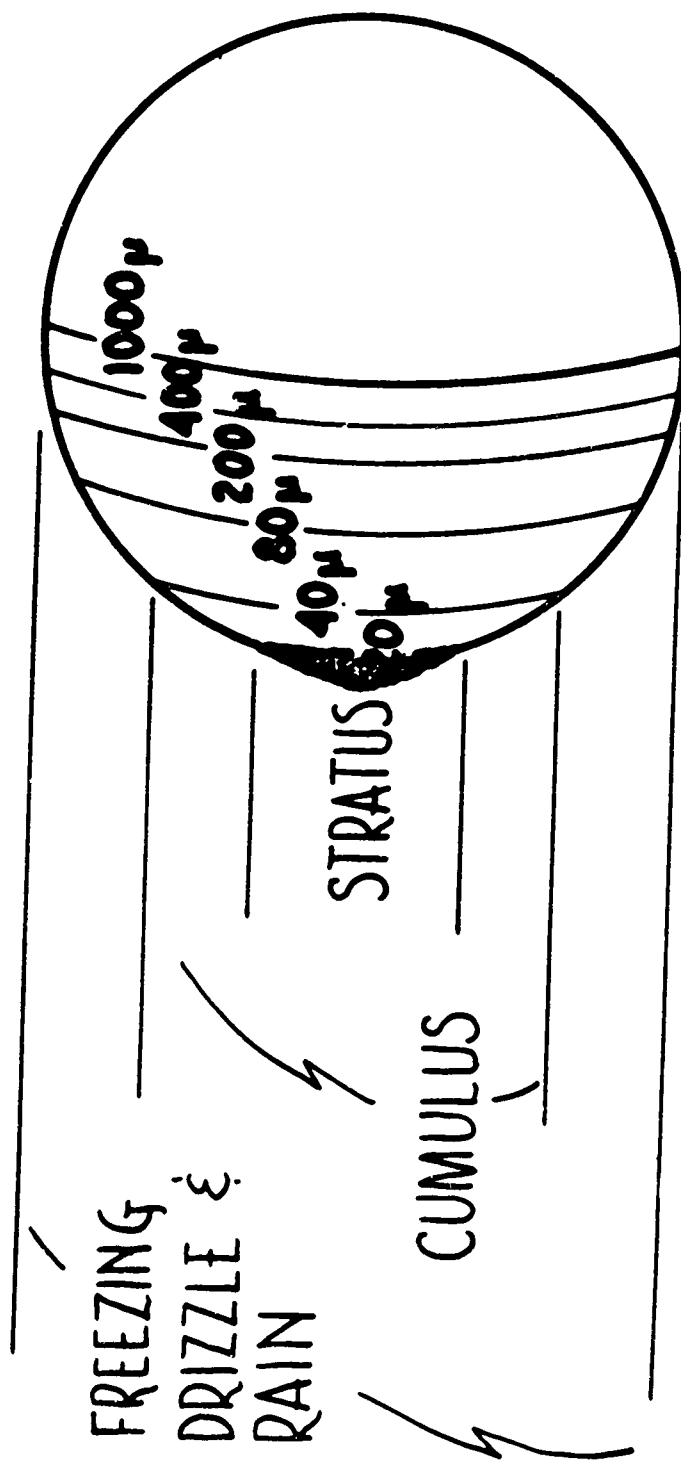
Figure 3. Streamlines and droplet trajectories, relative velocity of the droplet and collection efficiency influence the area of impingement.

EFFECT OF SIZE OF THE OBJECT COLLECTING ICE

20μ DROPS

3 FT. DIA.
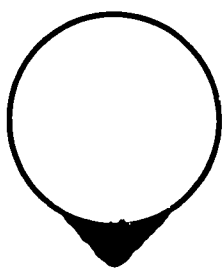
12 IN. DIA.
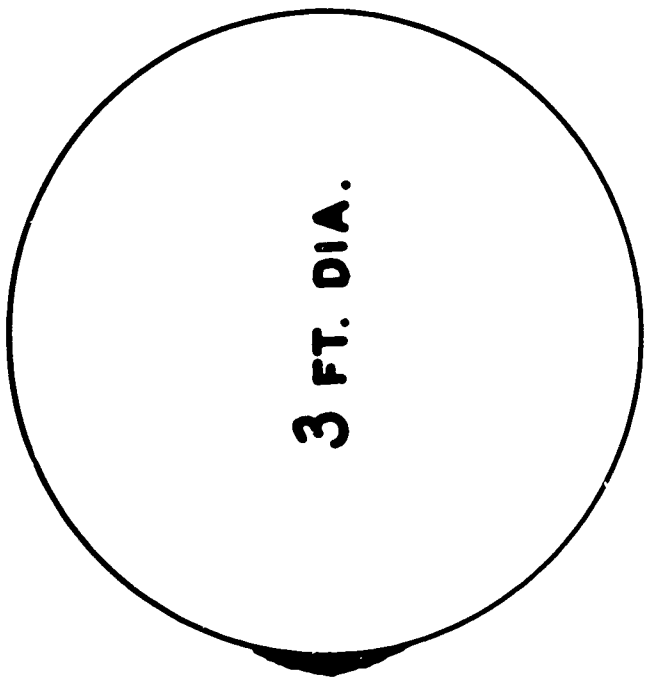
3 IN. DIA.

SAME EXPOSURE TIME
SAME ICING CONDITIONS

Figure 4. Size of object alters streamlines and droplet trajectories.

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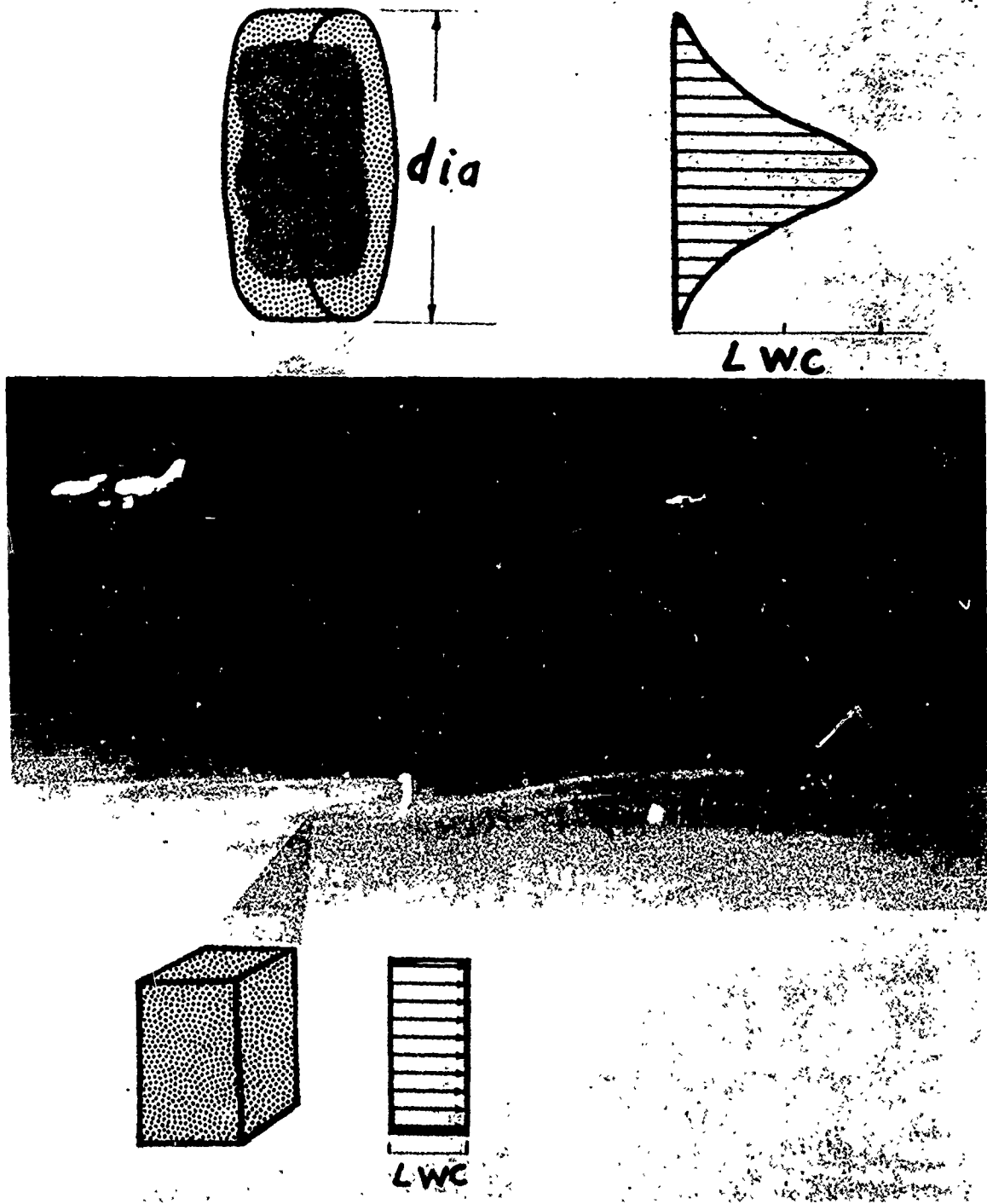
Figure 5. KC-135 tanker for testing at speeds between 150
and 300 KIAS. Inserts depict variation of
water content in section of cloud.
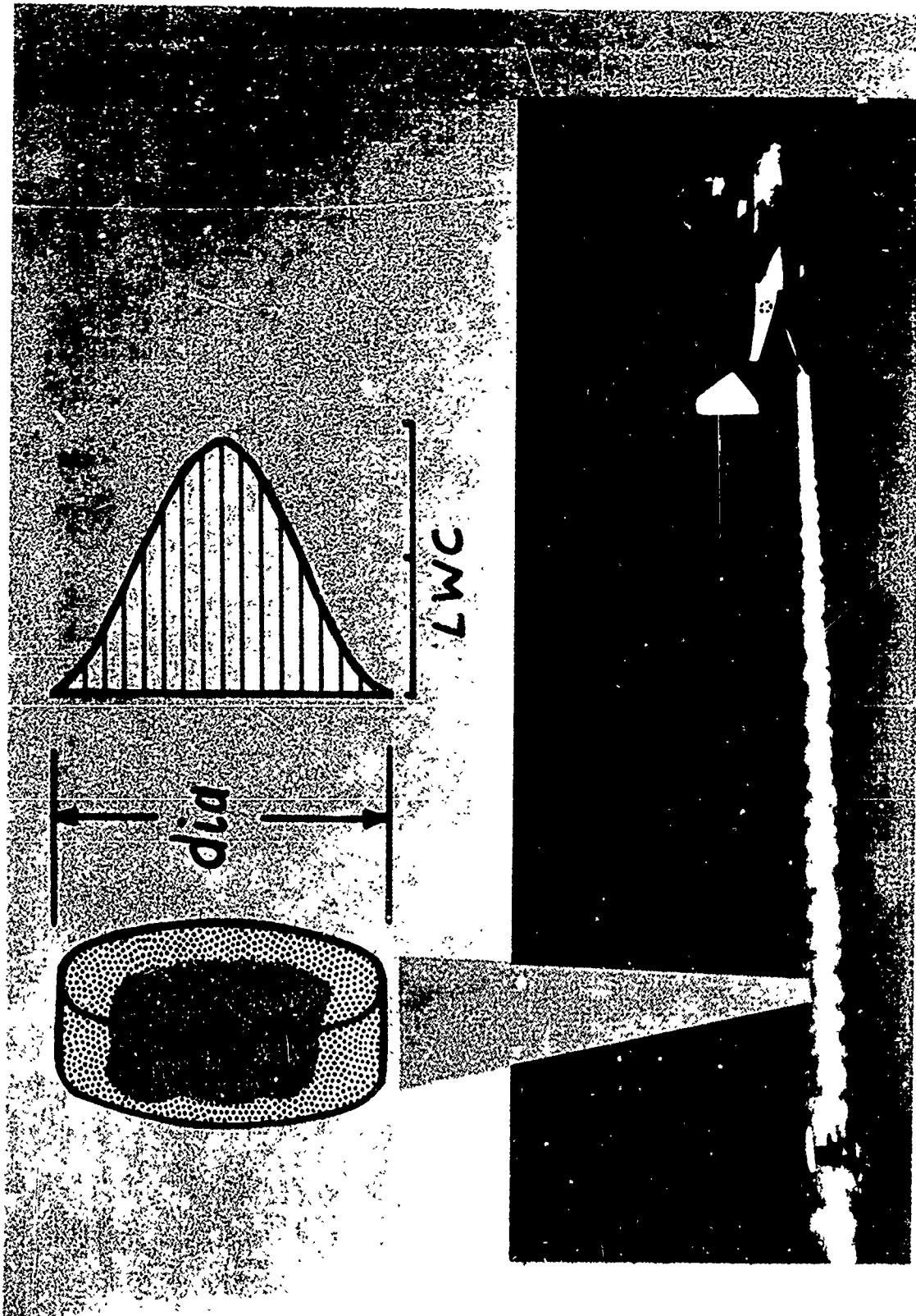
Figure 6. C-130 tanker for testing at speeds between 90 and 180 KIAS. Insert depicts variation of water content across cloud.
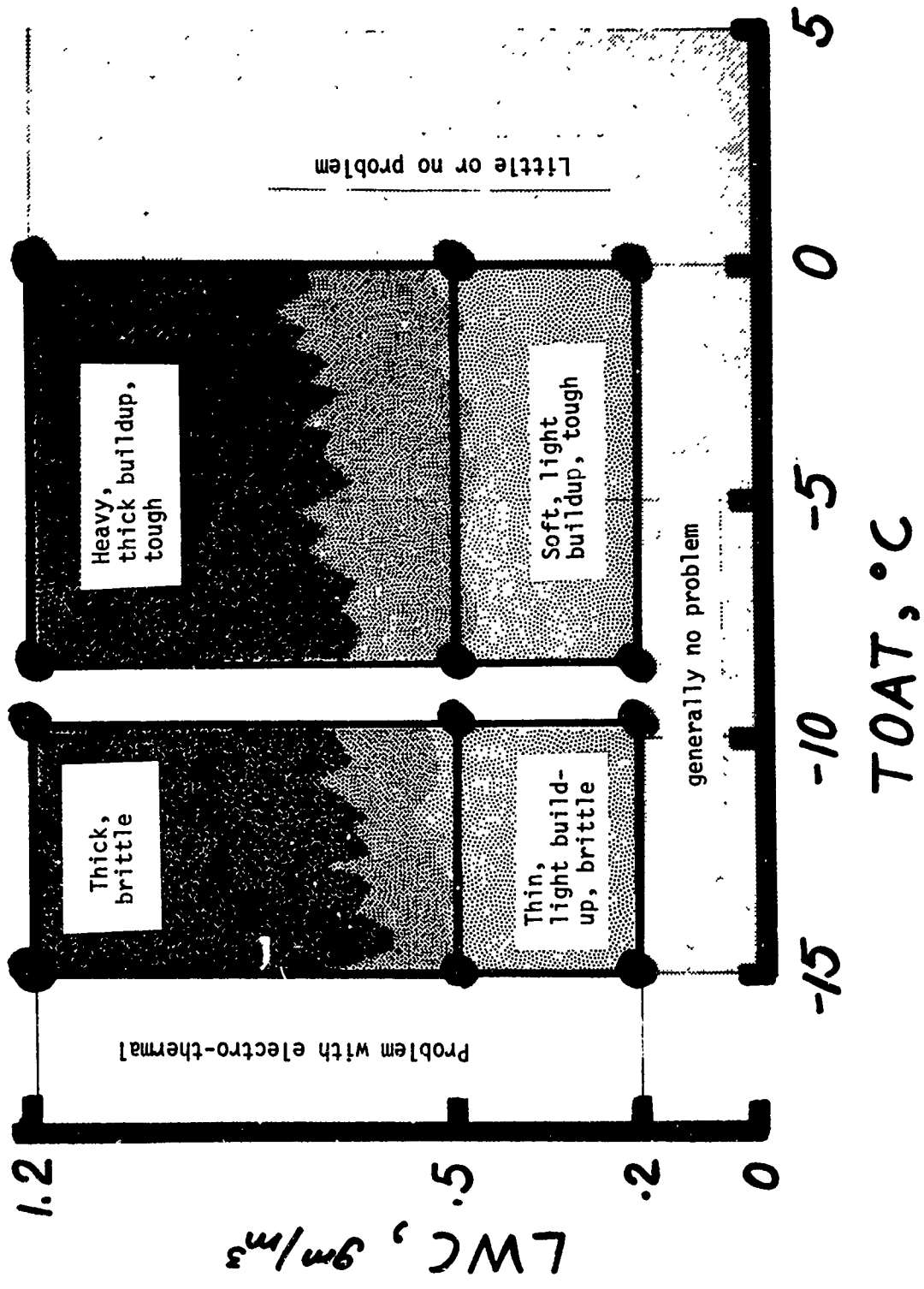
Figure 7. An icing scale, helpful in classifying qualitative data.

Figure 8. Matrix of icing factors representative of test points.

Figure 9. Mushroom type ice builtup on a wing tip. Cloud was provided by a tanker.

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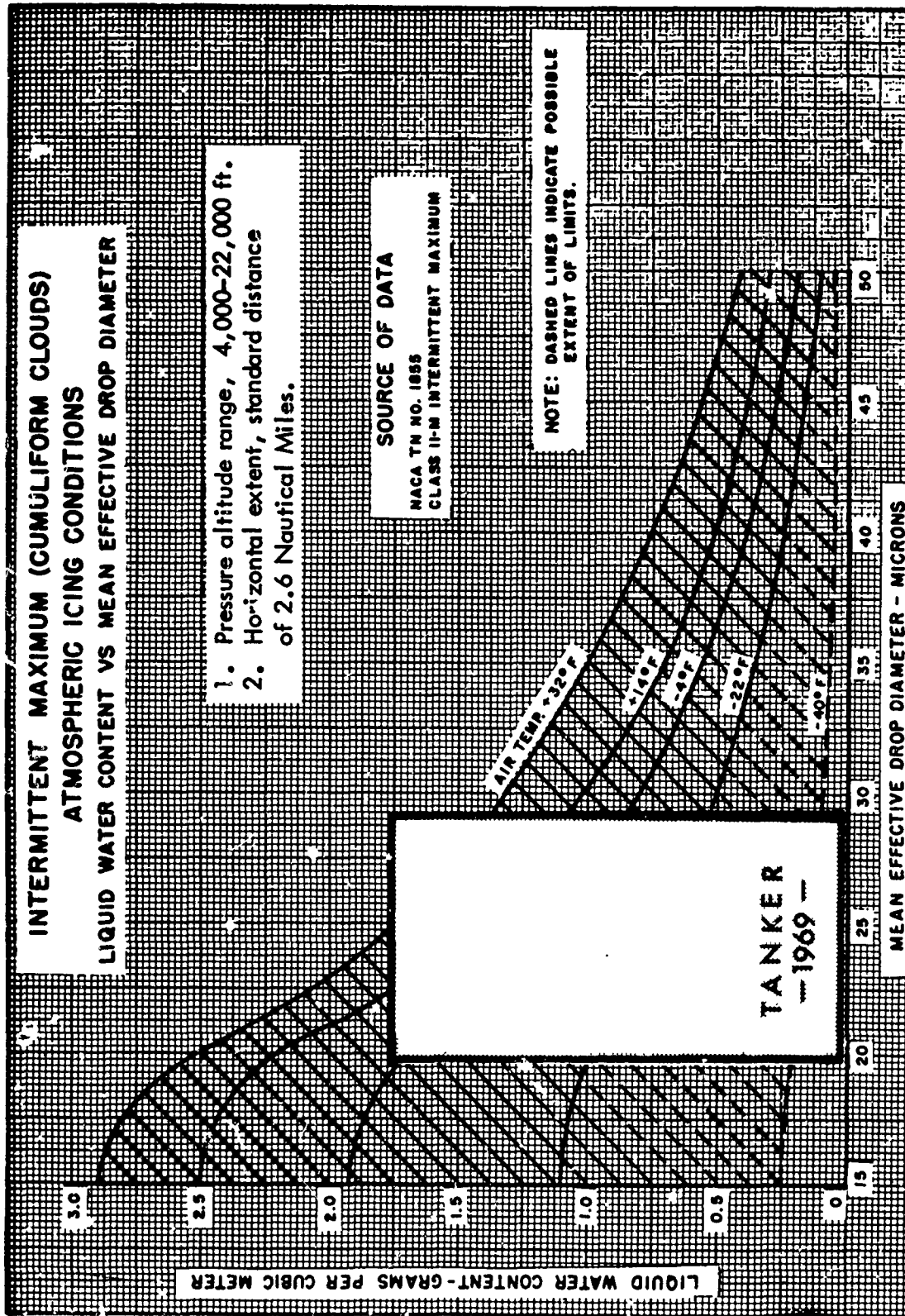
Figure 10. Icing tanker characteristics and FAA Airworthiness Standards.
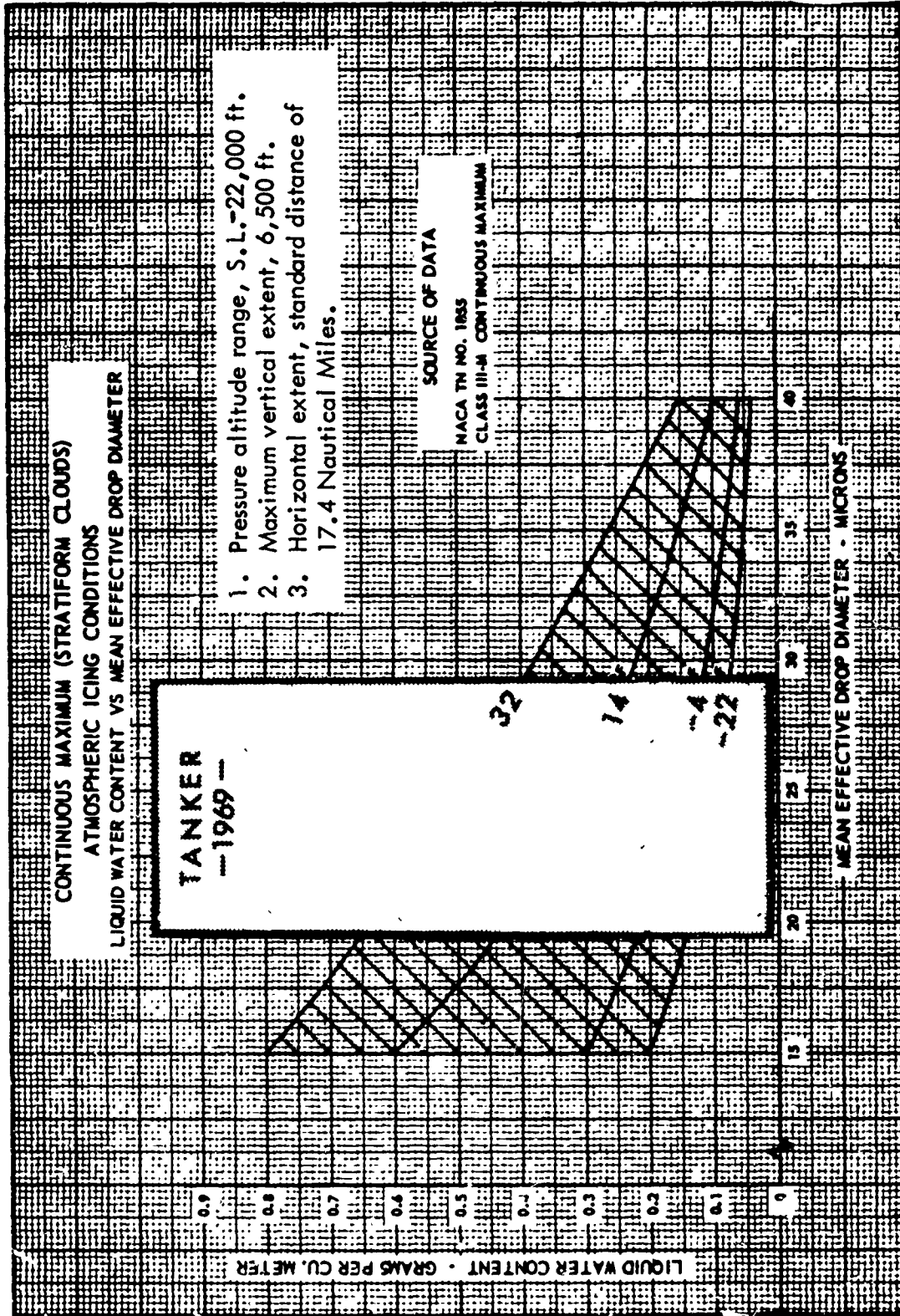
Figure 11. Icing tanker characteristics and FAA Airworthiness standards.
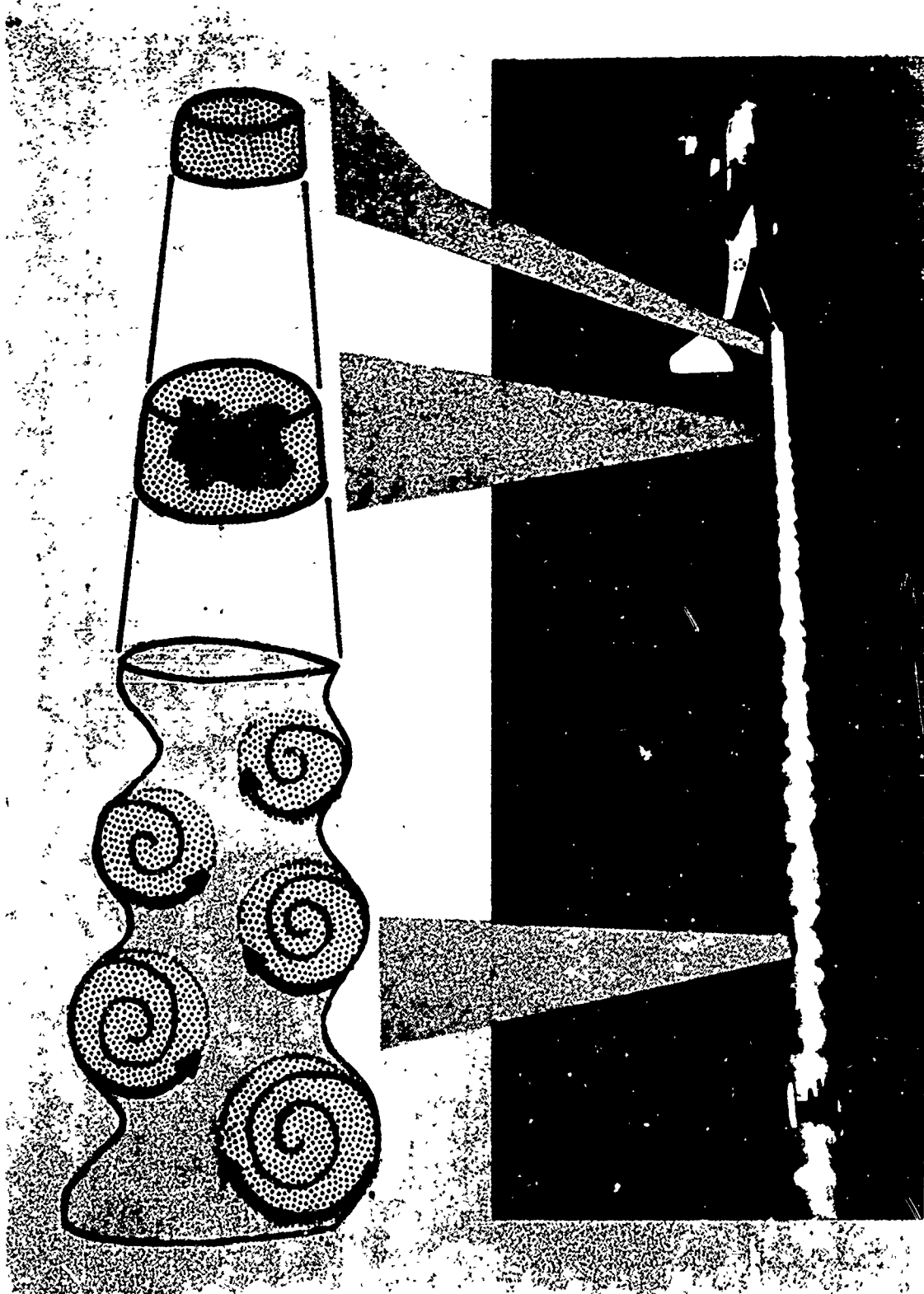
Figure 12. Environments in a tanker icing cloud.
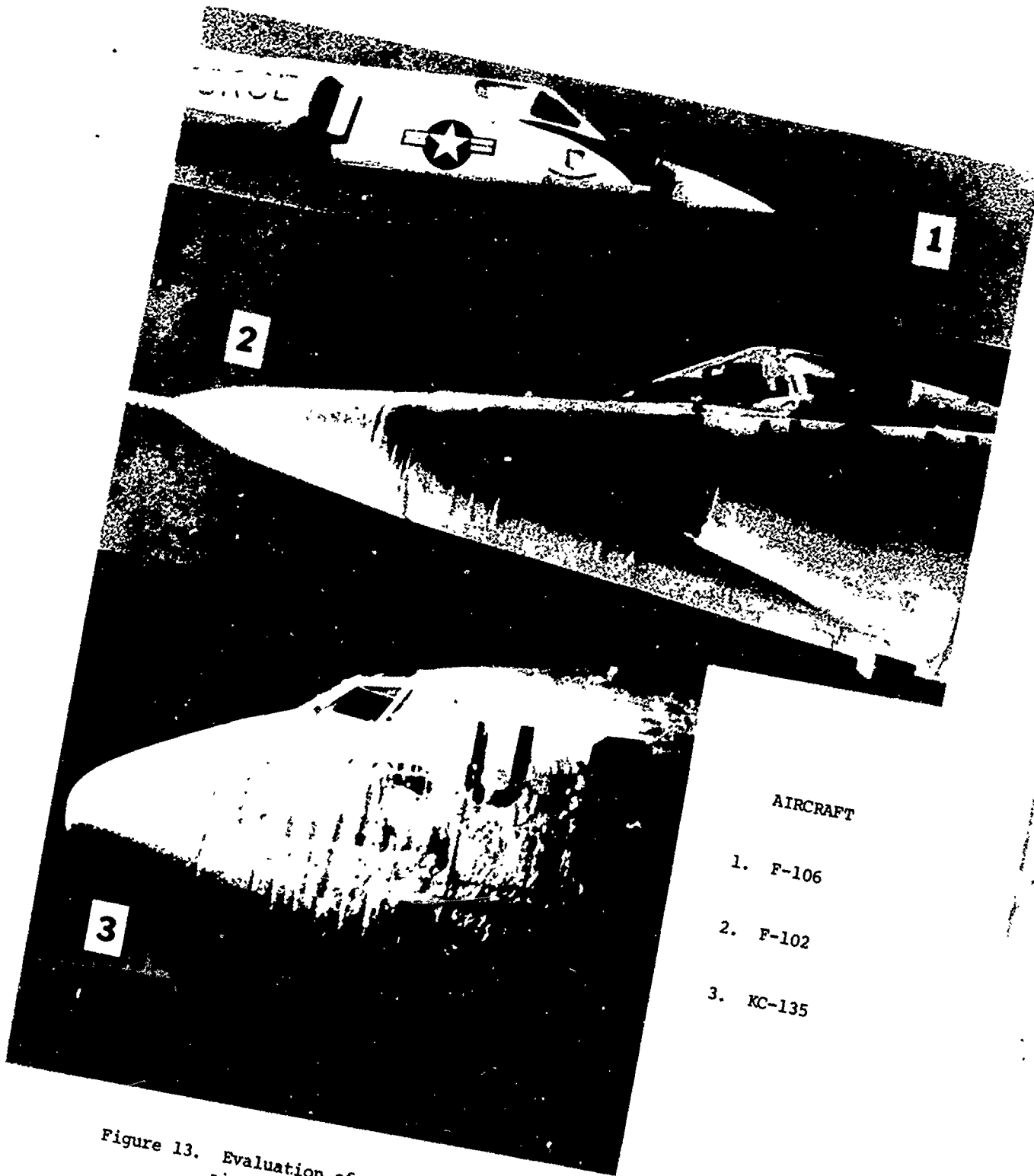
AIRCRAFT

1. F-106

2. F-102

3. KC-135

Figure 13. Evaluation of engine inlet, windscreen and
air data sensors.

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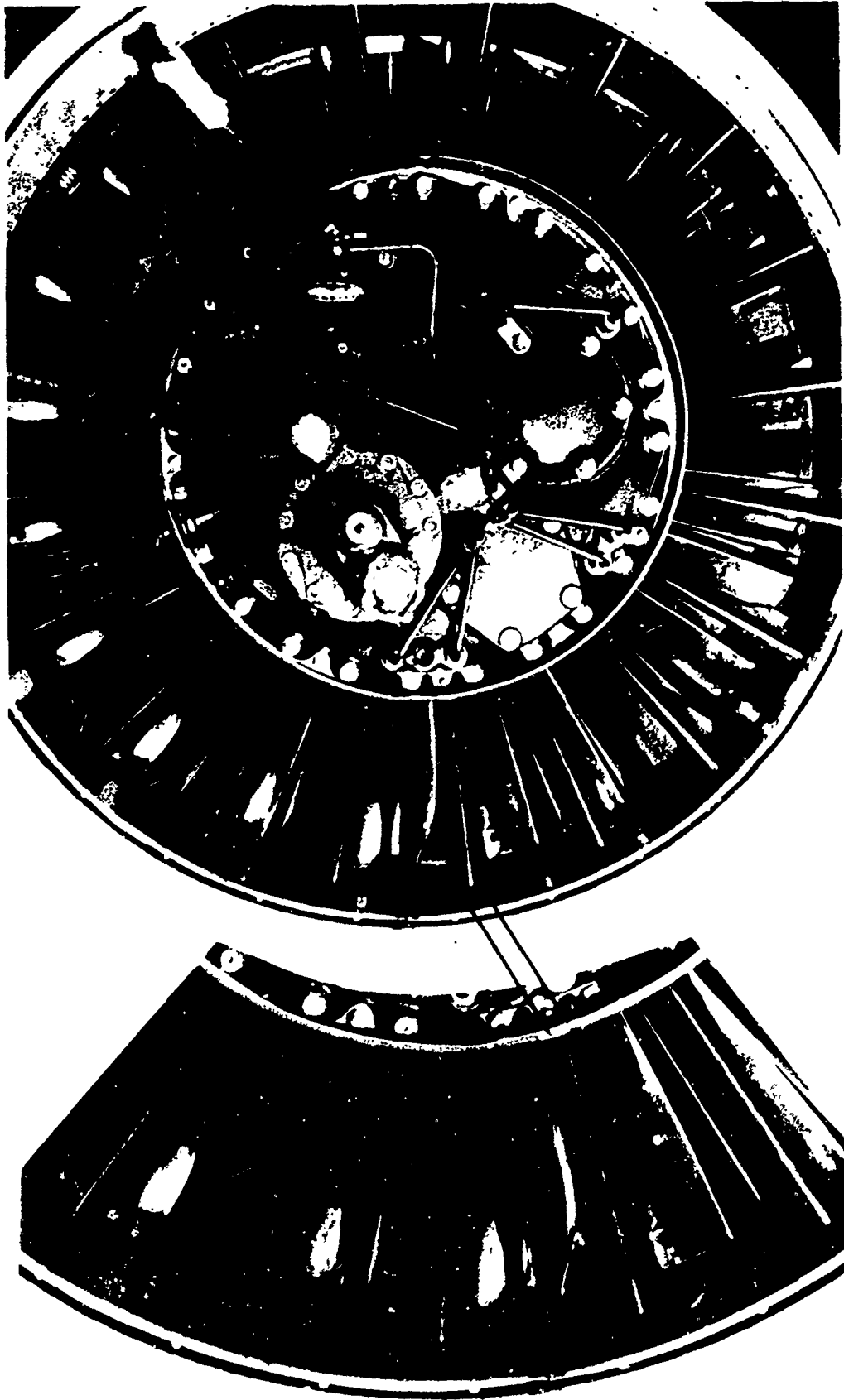
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of tanker ice.

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Figure 15. Natural Ice.
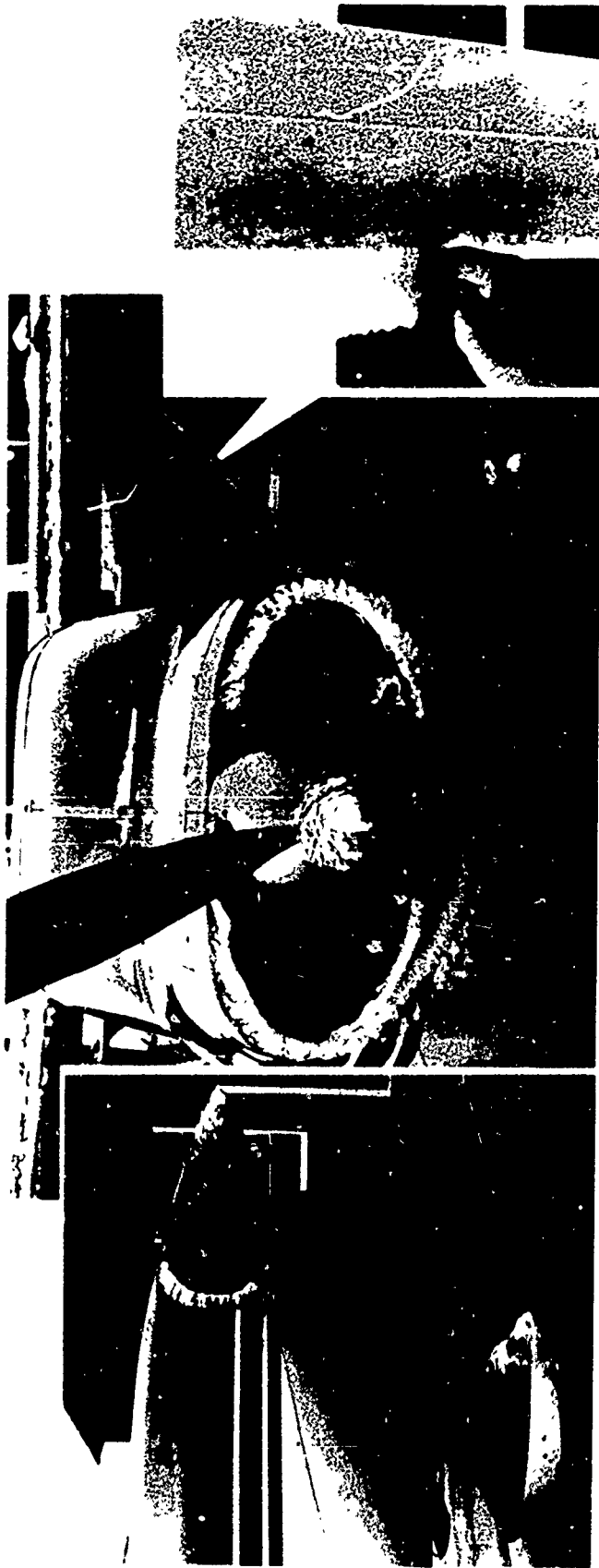
Figure 16. Natural Ice.

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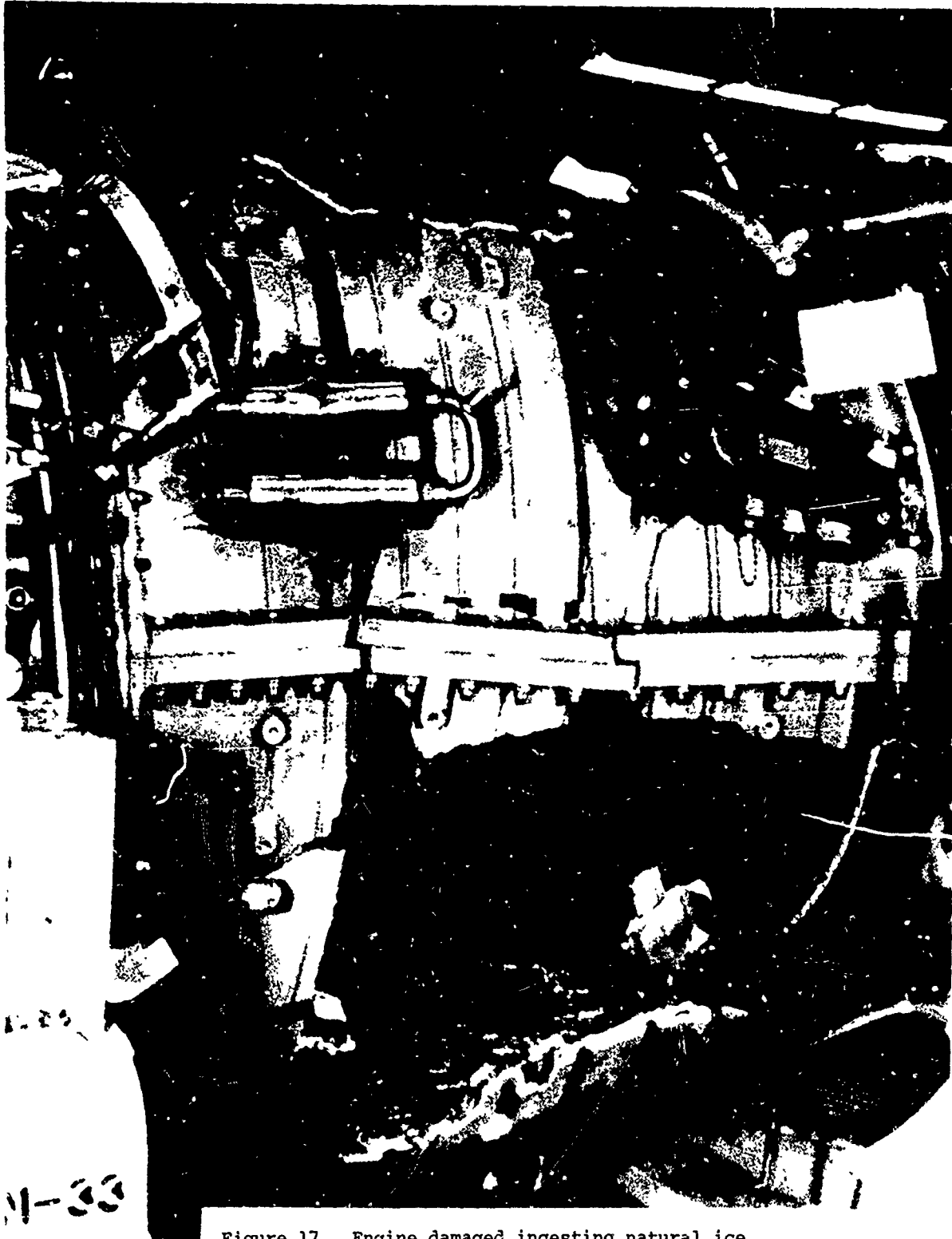
Figure 17. Engine damaged ingesting natural ice.

DISCUSSIONS FOLLOWING LT. REILLY'S PRESENTATION ON "A WATER SPRAY
TANKER FOR ICING SIMULATION" AND MR. SCHUMACHER'S PRESENTATION ON
"ICING FACTORS, WATER SPRAY TANKERS AND SPECIFICATIONS"

Question: How far back from a spray rig is it necessary to fly;
            what is the criteria for freezing; what is the
            relationship of the test aircraft from the tanker
            versus water temperature?

Answer: At -10° C. water flow is as little as possible in
            order to mix and cool the water. The water is not
            as cool as ambient conditions; one must fly 150 feet
            to 500 feet from the tanker; and at -20° C., the
            water will freeze so the flight must be made closer
            than 400 feet down to 150 feet.

Question: What extent of the nozzle development has been
            coordinated with NASA and Lockheed? Freezeout can
            occur in the nozzel if there is no heating of the
            water; how does bleed air warm it?

Answer: The temperature is not regulated but bleed air is,
            from a 150° to 200° C.

Question: Have you tried higher humidity and different
            atmospheric conditions?

Answer: You have to know the ambient conditions, such as
            temperature and humidity. We do not instrument,
            but by calibrations and charts we are within
            20 percent of the conditions. We have no data on
            the freezing factor, which depends on the distance
            from the tanker.

            In actual practice, a run is conducted and photographed
            as a check prior to each test.

Question: We dispute the diagram of the mushroom ice shape.

Answer: In icing simulation with the tanker, we may get
            different speeds, color, and density of ice. We try
            to match shapes.

Question: In the supercooled area too far back from the tanker,
            you may get ice crystals. Also, dye will effect ice
            crystallization, so that you have no liquid water
            content. You need to measure droplet size.

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Answer: One needs to know the characteristics of the impingement area and you will have a good idea about the size of droplets and liquid water content.

Question: Do you test until a problem occurs?

Answer: For engines we start low and work up. If problems are encountered, engine manufacturers are notified and asked about further tests.

Question: How do you arrive at a liquid water content calibration?

Answer: By photographing the liquid water stream with a known scale. In assuming a round cloud and that all the water is in the cloud, you may remove any effects you desire to compute this liquid water content. This is done before and after each test.

The geometric size of the cloud, speed, and flow rate, and assuming 100 percent of the water are needed for computation.

Question: Have you tried instrumentation?

Answer: We have tried rotary cylinders and liquid water content measuring, and they show that the computations are correct within 15 percent.

Question: Have you considered using the same type of equipment that is on test stands for calibration and simulation?

Answer: Because of the number of locations that can be checked within the cloud, it is difficult to test the entire volume of the cloud. This problem arises because of the three dimensional effect of the cloud and the test vehicle. We have measured drop size with glass slides.

Question: What about drop size with distribution?

Answer: A sample of 166 glass slides was made at a particular spot in the cloud. The maximum droplet size is 83 microns and the smallest is 11 microns, with a normal frequency distribution.

Will exceed 40 microns once out of a 100 times and 80 microns once out of a 1000.

We will publish the calibration of the installation shortly.

Question: Are any water droplets supercooled?

Answer: No, temperature in the cloud is 4° to 5° warmer than ambient. This is one of the greatest deficiencies of the system.

AIRFRAME DESIGN FOR PROTECTION AGAINST ICING

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29 April 1969

INTRODUCTION

It is many years since the subject of aircraft ice protection has been accorded a place on the program of a technical society meeting, let alone designated the sole topic of an entire meeting. Like the ill-fated NACA Subcommittee on Icing Problems which(was disbanded in 1957),it was at least temporarily displaced by space age technical activities and budgets before all the necessary answers to its problems had become completely evident.

One of the first things the writer/(speaker) did after being invited to make this presentation was to comb through his file of reference material, and found there a prior paper which he presented in 1952 at the S.A.E. National Aeronautics Meeting in Los Angeles. The title was "Ice Prevention as Related to Airframe Design - 1952" (Ref. 1)[*]. As the title implies, it was a progress report on the state of the art as of that specific time period. Except for certain deficiencies in the prediction of aircraft design trends, this seventeen-year old paper is reasonably applicable to most of today's problems in this field. One notable example of the fuzziness of the 1952 crystal ball was the statement: "Transport aircraft seem to have reached their maximum size, probably as the result of airport and other economic considerations". In today's presentation, I shall try to avoid such hazardous prognostications and limit myself to a presentation of the state-of-the-art as we know it from our experience to this date.

[*]See page 212 for References.

As I discuss the ice prevention technology today, I would like to avoid dwelling at length on the derivations and analytical substantiation of the important parameters that form the basis of this technology. Instead, I prefer to refer this audience to FAA's own excellent report, ADS-4: "Engineering Summary of Airframe Icing Technical Data" (Ref. 2), a manual of design information prepared under contract by Dean T. Bowden and his co-authors of G-D Convair and dated December 1963. This manual has become the "bible" of the designers of ice protection systems and represents a very useful contribution to the art. Most of the significant fundamental principles of the anti-icing technology are to be found in either this report or in its comprehensive references.

The present ice protection regulatory material in FAR 25 was originated by members of an ad hoc committee assembled in Los Angeles in 1953 by the Aircraft Industries Association at the request of the CAA. The writer (speaker) had the honor of serving on that committee and recalls that the primary guideline which became the governing criterion for the committee's proposed material was simply: <u>Achievement of safe flight in icing conditions</u>. The regulation was not intended to prescribe any specific method of protection, nor even to establish whether an active ice protection system was required at all on a particular air vehicle but, instead, it was intended to provide a rational definition of the icing environment as it was likely to occur in nature and to permit the aircraft designer to judge if, and in what form, protective measures were necessary to meet the basic criterion of safe flight. At the same time, methods of demonstration of the adequacy of protection were also defined and a step-by-step procedure was established for their use. By and large, this regulation has performed its purpose very well in the intervening years and a high degree of flight safety in ice has been demonstrated by those aircraft certificated under it. The relatively few accidents attributed to icing encounters have generally involved older aircraft designed prior to the effective date of the present regulation.

ICE FORMATION CHARACTERISTICS:

Thanks to the basic work of Dr. Irving Langmuir and his associates in the early 1940's, we came to understand the physics of the behavior of cloud particles in

the aerodynamic flow field of an airplane. Earlier studies of natural clouds showed that they generally consisted of concentrations of spherical liquid water droplets ranging in diameter from less than one micron to over 100 microns, and varying in liquid water content (L.W.C.) from less than 0.1 gram per cubic meter of cloud volume up to 2 or 3 grams per cubic meter. These clouds of liquid droplets could range in temperature from as high as the local ground level dewpoint down to sub-zero F, and even as low as -40°. Clouds below the normal freezing point of water contain either droplets of subcooled liquid, or, if sufficient nuclei are present, ice (or snow) crystals. Dr. B. Vonnegut (Ref. 3) has pointed out that one of the most important factors influencing the history of a cloud is the fact that the vapor pressure of a subcooled water droplet is appreciably higher than that of an ice crystal at the same temperature. Therefore, once an ice crystal is present in a cloud, there will be a strong tendency for subcooled liquid droplets to distill over to and enlarge the ice crystals. This was the mechanism that permitted Langmuir and Vonnegut to conduct their well known cloud-seeding and rain-making experiments.

Another similar characteristic which is believed to affect cloud behavior is the increase in vapor pressure associated with the higher free energy of very small particles compared to large particles so that without the presence of ice crystals or any other nuclei, the small droplets evaporate to condense on the larger and fewer droplets. This continual migration from small to large droplets is one evidence of the inherent instability of natural clouds. Flight test evidence of this type of instability has been repeatedly reported by pilots. Many test programs have involved two or more entries into the same cloud structure with just a few minutes of time intervening. Heavy icing would be encountered in the first pass through the cloud and none at all during the second. Frequently, snow would be encountered after the first pass.

Droplet impingement on any solid body moving through a cloud will be governed by the droplet's tendency to move in a manner different from that of an adjacent air molecule. According to Dr. Langmuir's hypothesis, only very small droplets (which have a large drag-to-inertia ratio) behave approximately like the air

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molecules and follow the flow patterns around the airfoils, bodies, struts, etc., and consequently do not impinge on these surfaces at ordinary vehicle velocities. The icing problem in operational aircraft, however, is caused by the fact that most subcooled clouds encountered do contain droplets large enough to have sufficient inertia to cross air stream lines (or flow paths) and therefore do impinge on leading edge surfaces.

The analysis of just what percentage of the cloud droplets swept by the projected area of the advancing aircraft will be intercepted by the forward facing surfaces, is mathematically predicted by examining the acceleration toward the surface imposed by the droplet inertia as opposed to the aerodynamic drag which tends to cause the droplet to move around the airfoil or body by following the air stream lines. Once this concept is understood, it is possible to develop a reasonable sense of judgment as to what parts of any typical aircraft will be most vulnerable to icing. It will also become evident why, when driving an automobile through a ground fog, the windshield having a large radius of curvature remains dry while the small diameter radio antenna mast will be wet and draining a steady water flow downward to its base.

Several years after the mechanical behavior of cloud particles was understood, we were able to relate it to the concurrent thermodynamic processes which were also involved. By this means we were better able to understand the nature of the ice formation process and to begin to correlate the shape of the formations with other measurable parameters of the process.

We can start with the general thermodynamic energy balance presented by Dr. Myron Tribus in his Ph.D thesis of 1949 (Ref. 4). The elements of this balance are graphically represented in Figure 1. The writer/(speaker) treated this balance in a systematic and more comprehensive way in an I.A.S. paper presented in 1951 (Ref. 5). In that treatment, particular attention was given to those cases in which at least part of the unheated ice deposit would be at 32°F. A new parameter, the freezing fraction, n, was defined as that proportion of the impinging liquid which froze on impact. Tom Dickey in a later paper (Ref. 6) used the freezing fraction to explain and correlate the change in shape of ice formation with variations in this parameter. Figure 2 is taken from his paper, and in it he relates three basic classes of ice formation to speed, temperature and freezing fraction.

Generally speaking, streamline or "rime" icing is a non-hazardous and often self-limiting formation of ice which is shaped, as shown in Figure 1, roughly in accordance with the distribution of the original impingement pattern. In other words, the droplets completely freeze exactly where they strike the leading edge. In this case the freezing fraction is 1.0 and generally this condition corresponds to low ambient temperature, low flight speed and small L.W.C. Because these formations are instantaneously formed, they entrap air, are porous and referred to as rime.

If, on the other hand, the freezing fraction is in the lower range, say 0.2 to 0.4, enough impinging liquid is not frozen on impact so that its subsequent flow as liquid to other locations away from the stagnation area causes it to solidify in a pattern quite different from the original impingement pattern; in the worst case it freezes in two progressively projecting horns at about 45 to 60 degrees above and below the stagnation line, as indicated in Figure 3. The operating conditions yielding low values of the freezing fraction are: high sub-freezing ambient temperature, high flight speeds and heavy L.W.C. It is significant that the rate of growth of this so-called mushroom-shaped formation is accelerated because the droplet trajectory pattern is made progressively more adverse as the original airfoil contour is distorted to the double-horned shape at an ever-increasing rate. These formations are not self-limiting except when they become structurally unstable and break off. This may occur long after they are aerodynamically intolerable. Because the delayed freezing of the redistributed liquid creates a non-porous transparent multilayer ice buildup, it is often referred to as glaze ice. Figure 4 represents a sketch of Dickey's "intermediate" or "arrowhead" ice formation in which the concavity of the "mushroom" type is filled in due to the higher value of the freezing fraction.

It should also be noted that when conditions are conducive to mushroom (glaze) type of ice formations, it does not really matter what the original contour of the leading edge is; any shape will rapidly deteriorate to the same basic two-horned pattern. An actual icing wind tunnel test of a standard safety razor blade proved to be just as susceptible as a blunt airfoil. The above comments apply to a straight, unswept leading edge. When leading edge sweep is involved,

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the adverse results of low freezing fraction are magnified as a result of the three-dimensional flow. The chordwise effect is similar to that of the straight leading edge, but the spanwise redistribution of water catch results in periodic prongs of ice rather than uniform spanwise upper and lower ridges. Figure 5 is a photo of the icing tunnel test section looking downstream at a straight leading edge model of the Electra horizontal stabilizer after exposure to a glaze ice condition. Note the dark transparent quality of the ice under liquid collected and not completely frozen in the stagnation line recess. This feature is typical of formations associated with freezing fraction values less than 1.0. Figure 6 is a photo of a similar but swept leading edge (in this case the C-141 horizontal stabilizer), and in this case the periodic peaking of the horns along the span which is typical of the swept configuration can be clearly noted.

In the present state of the art, we do not yet have an analytical means for predicting the shape of these divergent ice formations as a function of time of exposure, although in the opinion of the writer/(speaker) the essential elements of an adequate computer program for this purpose are available in the literature. A graduate student or Ph.D candidate having access to a good icing tunnel could, by careful observation, define the physical mechanism of the process we have described and presumably formulate a computer program which would permit analytical predictions of the ice shape as a function of the duration of exposure.

There is a tendency among some people working in the icing technology to discount the validity of icing-wind-tunnel-generated formations as being highly unrealistic and at least double the magnitude associated with flight in natural icing clouds. The writer/(speaker) does not entirely concur in this but believes that this skepticism relative to tunnel results stems from the non-linearity of glaze ice $(n < 1.0)$ buildup rates. There is, however, one factor that does tend to make natural icing conditions less severe than tunnel results would indicate. That factor has to do with the fluctuation of L.W.C. due to the cellular structure of most clouds. In the icing tunnels, the L.W.C. and droplet diameter are held quite constant.

Natural icing flights in which the writer participated during the mid-1950's yielded adequate evidence of the occurrence of mushroom ice formations. Figure 7 is a photo of a fixed cylinder device used to obtain data on maximum cloud droplet diameter in flight. This cylinder was 5.4 inches in diameter and 10 inches long and mounted as shown outside a cabin window normal to the airstream. The forward half of its surface incorporated an electrically powered heating element for periodic removal of accumulated ice. The cylinder was painted a dull black and was marked at 10° angular intervals to permit judging the maximum impingement line when viewed from inside the cabin, as shown in Figure 8. This cylinder had been calibrated in an icing wind tunnel and the maximum indicated droplet size agreed very well with the trajectory theory.

Figure 9 is a view from the interior of the Electra, showing a so-called "totalizer cylinder and measuring strut." This was an unheated device used only to judge the rate of ice buildup during any particular icing encounter. After a number of consecutive passes through large cumulo-nimbus clouds, the total accumulation as indicated in Figure 10 amounted to about 3½ inches. The L.W.C. varied between 0.5 to 1.5 grams per cubic meter and the average maximum droplet diameter as indicated in Figure 11 was about 25 microns. A view of the corresponding ice formation on the horizontal stabilizer is shown in Figure 12. Obviously, the totalizer device would have some significant limitations in other than rime ty; ing conditions.

A series of droplet size indicator cylinder photographs taken during icing flights of a WV-2 (RADAR CONSTELLATION) airplane are shown in Figures 13 through 20. Figure 13 shows a formation resulting from the following exposure:

Freestream temperature.	17°F
Airspeed (true):	190 knots
Altitude:	10,400 ft.
L.W.C.:	0.25 to 0.54 grams/cu. meter
Max. Droplet Diam.:	75 microns
Av. Droplet Diam.:	72 microns
Duration in icing:	24 minutes

Figures 14 and 15 were taken immediately following Figure 13 during a deicing cycle which frequently was not completely successful due to the absence of enough aerodynamic force to dislodge the ice mass. The ice usually moved very slowly outboard as shown. A variable sweep mounting would have expedited spanwise removal. Figures 14 and 15 are, incidentally, good examples of the condition which is avoided by the use of the heated parting strip in electro-thermal deicing systems.

In Figure 16 the airplane is about to enter a new icing exposure, but as can be seen, some residual ice still clings to about the outer one-third of the cylinder length. In Figure 17, the cleared inner two-thirds of the cylinder span is accumulating ice under the following conditions:

Freestream temperature:	17^0F
True airspeed:	200 knots
Altitude:	14,000 ft.
L.W.C.:	0.24 to 0.81 grams/m^3
Max. Droplet Diam.:	60 microns
Av. Droplet Diam.:	40 microns
Duration in icing:	33 minutes

Figure 18 shows the cylinder again partially cleared; in this case the outboard deposit has separated. Figure 19 shows the maximum deposit for the above cloud condition (Fig. 17). Figure 20 shows a deposit for conditions similar to those of Figure 17 except for the maximum droplet diameter which ranged between 72 and 100 microns.

For purposes of comparison, Figures 21, 22 and 23 show icing wind tunnel formations for the following conditions:

Fig. No.	Speed Knots	Temp. F	Drop Diam., Microns	L.W.C. Grams Cu.Meter	Angle of Attack	Time Minutes
21	150	C	8	0.6	0	10
22	150	0	20	1.1	0	6
23	150	15	20	1.1	0	6

Note that the character of the formation changes from rime ice to mushroom ice as the L.W.C. and temperature are increased. Note too that the size of the formation increases as the freezing fraction goes down, for the same values of L.W.C. and droplet diameter (Fig. 23 vs. Fig. 22).

The determination of these adverse ice shapes is the first step in the process of evaluating the aerodynamic effect of deletion of ice protection in any particular exposed zone of an aircraft. Simulation of these ice formations on wind tunnel aerodynamic models, as well as on flight test aircraft, is a relatively simple, straightforward procedure which is already being widely used.

EFFECT OF AIRPLANE DESIGN TRENDS

Vehicle Size

In accordance with the cloud droplet trajectory characteristics, the larger the subsonic air vehicle the smaller the ice catch efficiency will be. In fact, beyond a certain critical leading edge radius, not only does the catch _efficiency_ decrease but the _total_ ice catch also decreases. In other words, the catch efficiency decreases faster than the frontal area increases. However, not all components of an air vehicle vary dimensionally in proportion to the vehicle size. Certain protuberances such as air data probes, antennas, vents, engine inlet cowl lips, etc., remain relatively fixed in size and therefore do not avoid the ice accumulation tendency just because the major elements of large air vehicles tend to. It should 'so be noted that the low ice catch efficiency of a large vehicle may be entirely or at least partly offset by a possible increase in its operating speed. On the other hand, a turbojet or turbofan-powered transport tends to be designed for ice protection required during traffic holding conditions in which the flight speeds are not significantly affected by vehicle size or design cruising speed.

Vehicle Speed

Vehicle speed itself can provide protection against ice because of aerodynamic heating, but, generally, when sufficient speed is available for such protection during the flight profile, the corresponding operational altitudes are high enough so that they do not usually involve exposure to icing. The exception to this general

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statement could involve certain special military air vehicles with which I assume this audience is not concerned. For civil transport vehicles we must conclude that extended operation under traffic holding conditions tends to be the most critical design condition, depending, however, to some extent on the method of protection selected.

Vehicle Configuration Factors

In discussing the influence of configuration on the ice protection requirements, it will be convenient to divide vehicles into two basic categories: subsonic and supersonic cruising speed.

a) Subsonic.

Among the factors affecting the ice protection of a subsonic vehicle is the planform of the wing and empennage, in particular its sweep and aspect ratio. This can vary from that of the intermediate range turboprop transport having a straight low aspect ratio wing with relatively short spanwise exposure of leading edge to that of a long range turbo-fan transport having a sweep of 30° to 35° and a high aspect ratio wing with a high-lift leading edge device for good airport performance. The latter vehicle could present a proportionately greater demand for ice protection than the former.

The spanwise variation in leading edge radius is yet another significant subsonic configuration factor. If this variation is large enough, it frequently permits the deletion of protection in the thick inboard section of the wing since the aerodynamic consequence in this area is minimal due to the small ice formations associated with the large leading edge radius and chord length.

The leading edge high lift devices can vary considerably. The simplest would be a hinged-down (or drooped) leading edge flap. Also hinged, but less simple, would be the Krueger type of flap. The most complex, but probably most aerodynamically effective, is the leading edge slat which in extending forward and downward, creates a slot ahead of the fixed part of the leading edge. These high lift devices, if employed at all, are usually deployed only briefly during final approach and landing, and are therefore not likely to be exposed to extensive icing.

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The drooped leading edge is the easiest type to protect against ice because its geometry permits the simplest transfer of heating air or other protective fluid. Also, the available surface geometry is probably most adequate for both the normal and high-lift positions. In effect, it is a variable camber leading edge and its surfaces accommodate the local flow field in both extremes of travel.

The Krueger flap can be protected if necessary, but because it retracts into the lower surface, its protection may not be essential.

The extendable slat usually requires protection at least in the retracted position, where, in effect, it becomes the wing leading edge. Whether this protection is also designed to function while the slat is extended, will depend on the extent to which the slat's contribution is essential to the vehicle performance in the approach and landing maneuver. This can be evaluated in simulated icing tests of a low speed wind tunnel model.

The slat geometry usually permits sufficient upper surface chordwise coverage to provide adequate protection, but the limited chordwise extent of its lower surface may be marginal. However, the aerodynamic sensitivity to lower surface ice formations is not usually critical. Protection of both the movable slat as well as the adjacent fixed wing surface is also hard to justify. There could be a possible problem due to the deposit of a small amount of ice in the slot behind the slat. This might require a delay in slat retraction until the ice had been melted (after landing) or provision of a non-overload type of retraction actuator system. This latter comment is also directly applicable to trailing edge extendable flaps where ice deposits on the leading edge can also cause structural inter- ference on retraction.

Another category of subsonic configuration factor is engine location. When engines are located on forward wing pylons there is no probability of ingestion of ice shed from other parts of the airframe other than the inlet itself. When engines are located in the wake of the wing leading edges, there is the possibility of ingestion of ice shed from that area. If such ingestion can cause engine damage, the surface causing such shedding

may require protection for this reason alone. This consideration is not limited to subsonic vehicles, but is equally applicable to supersonic types. Whether ice is shed due to aerodynamic heating associated with speed acceleration or due to operation of a cyclic protection system, the same problem exists, although deliberate cyclic operation of a protective system can be scheduled to limit the size of the ice formation shed into the engine inlet and thereby avoid damage. One contemporary corporate jet transport, the DH-125, utilizes inboard wing ice protection; in this case, a fluid deicing system, primarily to avoid ingestion of hard ice formations into the inlets of its aft-mounted engines.

b) .Supersonic.

For supersonic cruise vehicles the wing planform could involve a blunt subsonic wing leading edge swept to an angle greater than the Mach angle corresponding to the cruise Mach number, or it might involve a delta planform in which the leading edge sweep was less than the cruise Mach angle, requiring a knife-sharp supersonic leading edge. Obviously, the ice impingement characteristics of these two radically different configurations would be quite dissimilar and their protection systems would be equally different. Both, however, would probably involve low speed flight as the critical design condition. Icing tunnel tests of an unswept supersonic leading edge airfoil have indicated that at high angles of attack typical of approach, the ice formations, particularly rime ice formations, tend to build downward and forward in a manner which tends to create an ice flap, and actually may improve the lift coefficient. The drag is also increased, but the lift-drag ratio tends to improve. Whether this would be true for a swept sharp leading edge is not known. However, the lift characteristics of a sharp delta planform wing at the rather high angle attitudes required for approach and landing are dependent on flow reattachment to the upper surface promoted by the leading edge vortex peculiar to that planform. This would, in the opinion of the writer, tend to make it less sensitive to a leading edge ice formation than a blunt leading edge. There would, of course, be ice deposits on the lower surface, extending far back on the chord but relatively uniform in character.

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The significant icing problem of the supersonic transport, at least for one having a fixed delta or double delta planform, seems to be on those surfaces which, when shedding ice in the course of vehicle acceleration, could release large enough formations to result in engine damage if and when ingested. Such formations would be at or near the ice melting temperature, at which the physical properties of the ice are potentially most damaging.

Sources of shed ice would be (a) the wing leading edge forward of the inlets, and (b) the inlet itself. Thus, the principal criterion for ice protection of the supersonic transport will probably be engine damage due to ice ingestion unless, of course, the engine could be made to tolerate the ingestion.

COMMENTS ON METHODS OF PROTECTION

Undoubtedly the most reliable, trouble-free and economical method is achieved in an aircraft having no protection system at all, provided that safe flight in ice can be demonstrated. While this may be achieved for the wing and empennage of some large vehicles, it is not likely to ever result in deletion of protective measures for the propulsion system, the windshield system, or certain of the air data sensors.

Mechanical Ice Removal

This, one of the oldest methods of protection in the industry, is best known in the proprietary form of inflatable leading edge boots.

Although pneumatically inflatable boots have been tremendously improved over a period of about twenty-five years, and in spite of the fact that the operational energy requirement is probably lower than that of any other method, there is a persistent reluctance to use this method extensively. That reluctance probably stems from the following factors:

a) Vulnerability of the inflatable cell to penetration and damage by accidental impact on the ground.

b) Lack of a simple and not unsightly repair for the damaged cell referred to in a) above.

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c) The ice removal effectiveness is very dependent on a sufficient and physically suitable ice accumulation to be broken off completely. The cyclic operation of the boot cannot be pre-programmed but must be dependent essentially on pilot observations of the ice buildup. Too frequent operation may result in no removal at all. Operation at night with the impaired visibility of flight in an icing cloud would make the correct timing of the operational cycling very difficult.

d) There is some finite, but hard to identify, drag penalty associated with the deflated boot surface that is invariably charged against the boot for the entire life of the vehicle. This may be a very small penalty, but it has an adverse effect on the acceptance of this system.

Thermal Anti-Icing and De-Icing

Even since this method was introduced by German designers into pre-World War II military aircraft, it has been the most widely used and satisfactory method in the industry's experience. It has also been the most extravagant of energy required. The heat sources for its use have varied from early exhaust gas waste heat recovery exchangers to fuel-burning combustion heaters warming ram air, to turbine engine compressor bleed air. Because this method has been so effective, we have tended to be willing to pay an ever-increasing penalty for the heat energy consumed. As turbojet engines of relatively low pressure ratio and high specific airflow were replaced first by turboprop and currently by high-bypass ratio turbofan engines, the penalty for bleed extraction has been increasing step by step. The reason for the increase in penalty has been the fact that to increase the performance of these modern engines, the gas generator sections (which provide the bleed air) are designed to operate at ever-decreasing specific air consumption. As the bypass ratio increases, the gas generator airflow decreases and the airplane size (and therefore bleed air demand) increases. The bleed air extraction thus becomes a greater percentage of the gas generator airflow and not only causes a severe increase in specific fuel consumption, but may even approach the operational limit of bleed air quantity available in the particular engine cycle. The compressed air pressure ratio also tends to increase with bypass ratio. This latter factor means that complex, multi-stage bleed control systems are required to accommodate the entire span of engine operating thrust conditions (i.e., taxi, takeoff and low-thrust descent). It is not surprising, therefore, that designers have been exploring ways of reducing the operating penalty of the continuously operating engine bleed air anti-icing systems. The first such method was to cycle the bleed airflow to segments of the entire system, one segment at a time.

Ice would be allowed to collect to an aerodynamically acceptable point and then removed by a brief application of bleed air which was used only long enough to remove the ice accumulation. In one version of this approach, the wing leading edge was anti-iced by continuous bleed airflow, and momentarily some of this air supply was diverted to the empennage to provide a so-called "one-shot" removal of all accumulated ice prior to final approach and landing. In other aircraft, bleed air was used for wing ice prevention and no protection provided for the empennage at all. In still others, the empennage was protected by another method not using bleed air. Most recently, in aircraft where the bleed air penalty is high, the wing anti-icing system design has been treated so as to provide "marginal" ice prevention. In the latter case, the design is premised on the prevention of ice formations on the upper forward contours of the leading edge, but not necessarily prevention of frozen runback ice beyond the leading edge nor on any of the lower surfaces of the wing. Safe flight in these cases has been demonstrated by simulation of the expected partial formations of ice and evaluation of the airplane handling qualities in flight test. All of these approaches to the conservation of bleed air point to the awareness of the operational penalty of using large quantities of compressor bleed air in a time period when the demand for higher propulsive efficiency is in itself magnifying the impact of this penalty.

Electro-Thermal De-Icing and Anti-Icing

There was a period starting in the early 1950's when it was thought that electro-thermal cyclic de-icing would be a very satisfactory answer to the question of how to reduce the penalty for ice prevention. There were numerous applications to empennage leading edges, some of which are still operational today. But the majority of these systems have either been deactivated or replaced. Two factors have contributed to the discard of this method. One is the fact that the leading edge electrical heating elements were not designed with sufficient emphasis on reliability and damage resistance. The other adverse factor was the dependence on a continuously heated parting strip which ran spanwise at the stagnation area, and also chordwise between segments of cycled areas. The power consumption of these parting strips was enough to create a very significant power load and, in effect, size the airplane's

electrical system. The cost of maintenance of the electro-thermal systems was an additional adverse factor.

Electro-thermal anti-icing is widely and successfully used for certain specialized and small applications. Two particularly good applications are: 1) air data sensors, and 2) conductive transparent windshield heating elements. These applications have stood the test of time and other methods are not likely to replace them. Figure 24 is a view looking forward through the heated windshield panels of the WV-2 after 77 minutes of total exposure to natural icing under conditions also associated with Figures 13 and 17. This figure illustrates that it may be necessary under some design conditions to provide some form of protection for windshield frames as well as the transparent panels. Figure 24 happens to correspond to an extremely high intensity exposure which was purposely prolonged as part of the test program schedule. No need was established on the WV-2 for frame ice protection.

Chemical Anti-/De-icing systems

Although the use of freezing point depressant fluids is very old, there has emerged a contemporary version of this method which can be integrated into any leading edge structure. This version is generating new interest in this method. This method is fully described in FAA's Technical Report ADS-4 (Ref. 2) on pages 3-10 through 3-14 and in Figs. 3-6 of that reference. The system is of British origin but is now licensed in the U.S. It has been applied in production to two aircraft which are certificated to operate in the U.S.; these are the Short Skyvan and the DH-125. Reports from users are quite favorable, but the system does depend on a consumable fluid. The sizing of the fluid reservoir therefore becomes the critical design problem, and it must be adequate for the most extensive icing exposure expected. The method is said to be effective in both a de-icing and anti-icing mode, so that conservation of fluid may be accomplished by cyclic operation. It is conceivable that fluid flowrate could also be regulated in accordance with the degree of freezing point depression required so that less fluid would be used at high temperatures than at low temperatures. In any case, the weight, reliability, durability and initial cost are such as to make this method potentially attractive. It has the added feature that when used as a de-icing means, the slush that is formed in the removal process is not likely to damage any part of the aircraft intercepting the shed ice. It also tends to protect the entire chordwise surface since the fluid flows aft along the surface before leaving at the trailing edge.

CONCLUSIONS

In closing this 1969 state-of-the-art review, the writer/speaker feels that the most important need in the present stage of the technology is the development of a reliable method of predicting the size and shape of glaze ice formations for both straight and swept wing leading edges so that model scale wind tunnel aerodynamic characteristics as well as full scale flying qualities of candidate aircraft can be evaluated by application(and removal) of similated ice shapes under safe and economical test conditions. By this means, the deletion of unnecessary protective systems may be accomplished whenever justified.

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3. Vonnegut, B., "Supercooled Clouds," Lecture #1, University of Michigan Airplane Icing Information Course, March 30 - April 3, 1953.

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FIG. 1

EVAPORATION OR SUBLIMATION

CONVECTION

WARMING OF DROPLETS

VISCOUS OR KINETIC AIR HEATING

KINETIC HEATING BY WATER DROPLETS

HEAT OF FUSION
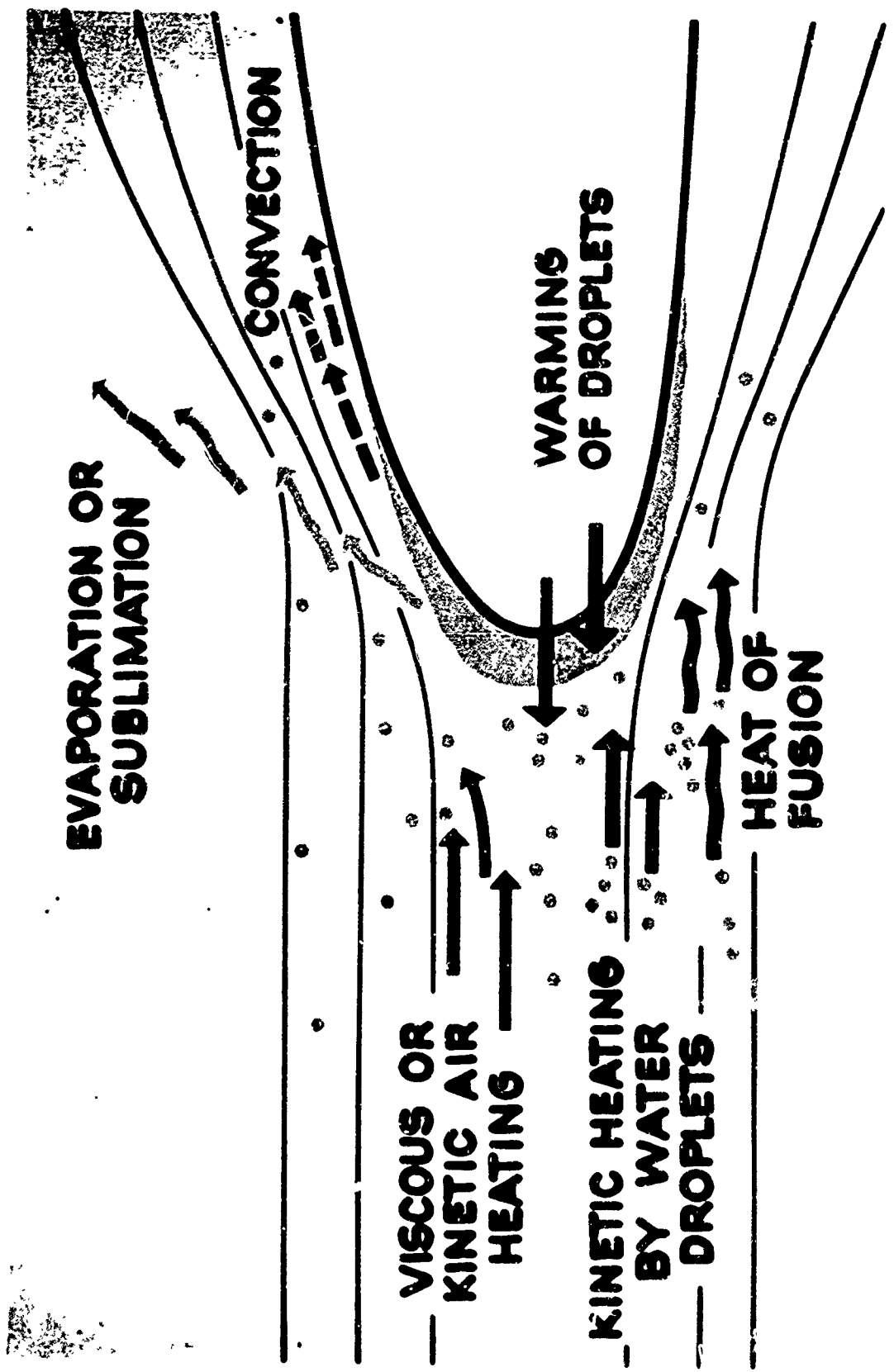
FIG. 2 VARIATION OF SHAPE OF ICE FORMATION
WITH VELOCITY AND AMBIENT TEMPERATURE

FIG. 3

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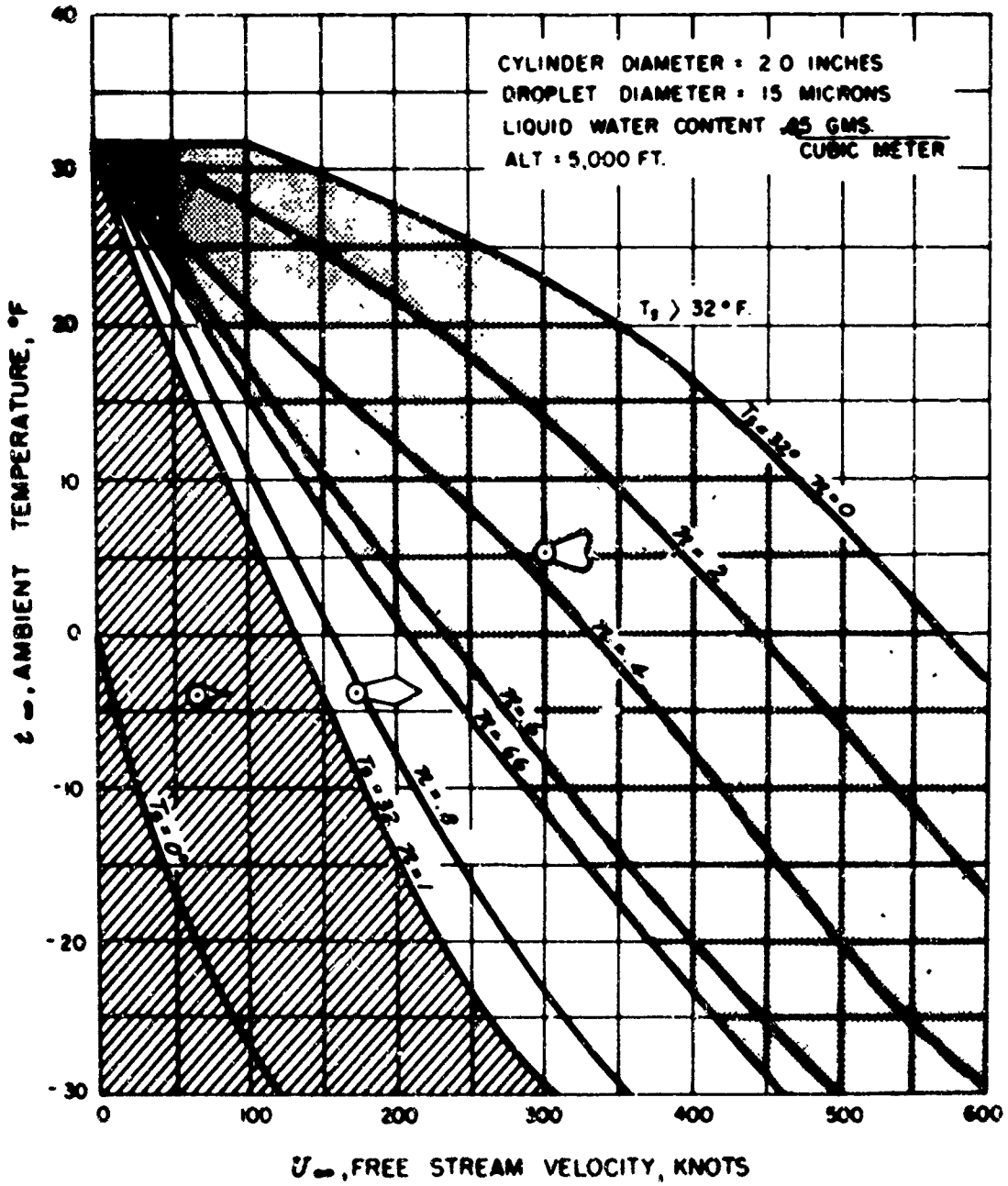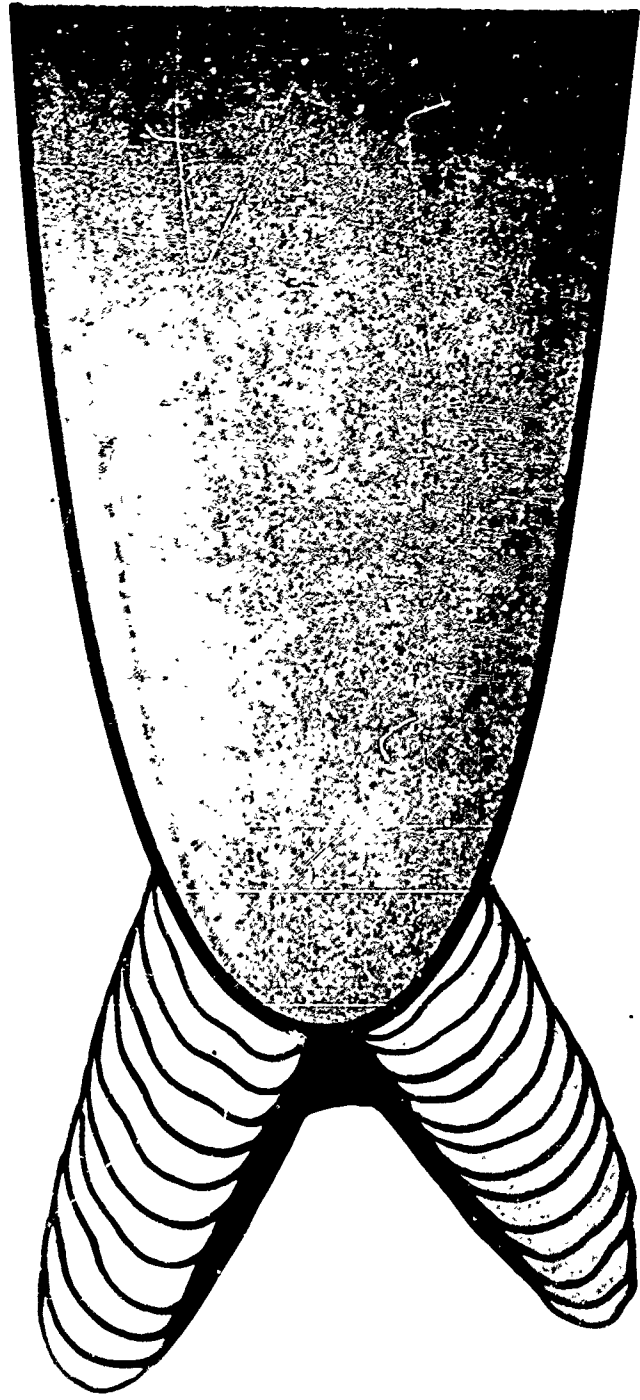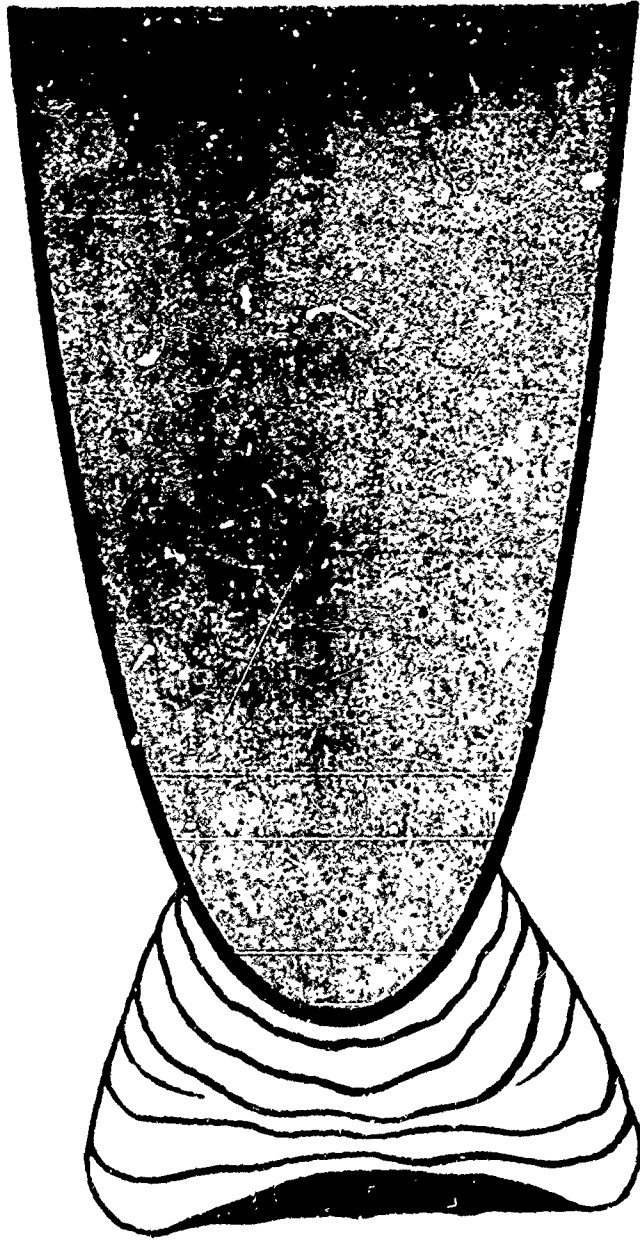
FIG. 4

FIG. 5   ELECTRA AIRFOIL MODEL IN LOCKHEED ICING WIND TUNNEL.

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FIG. 6
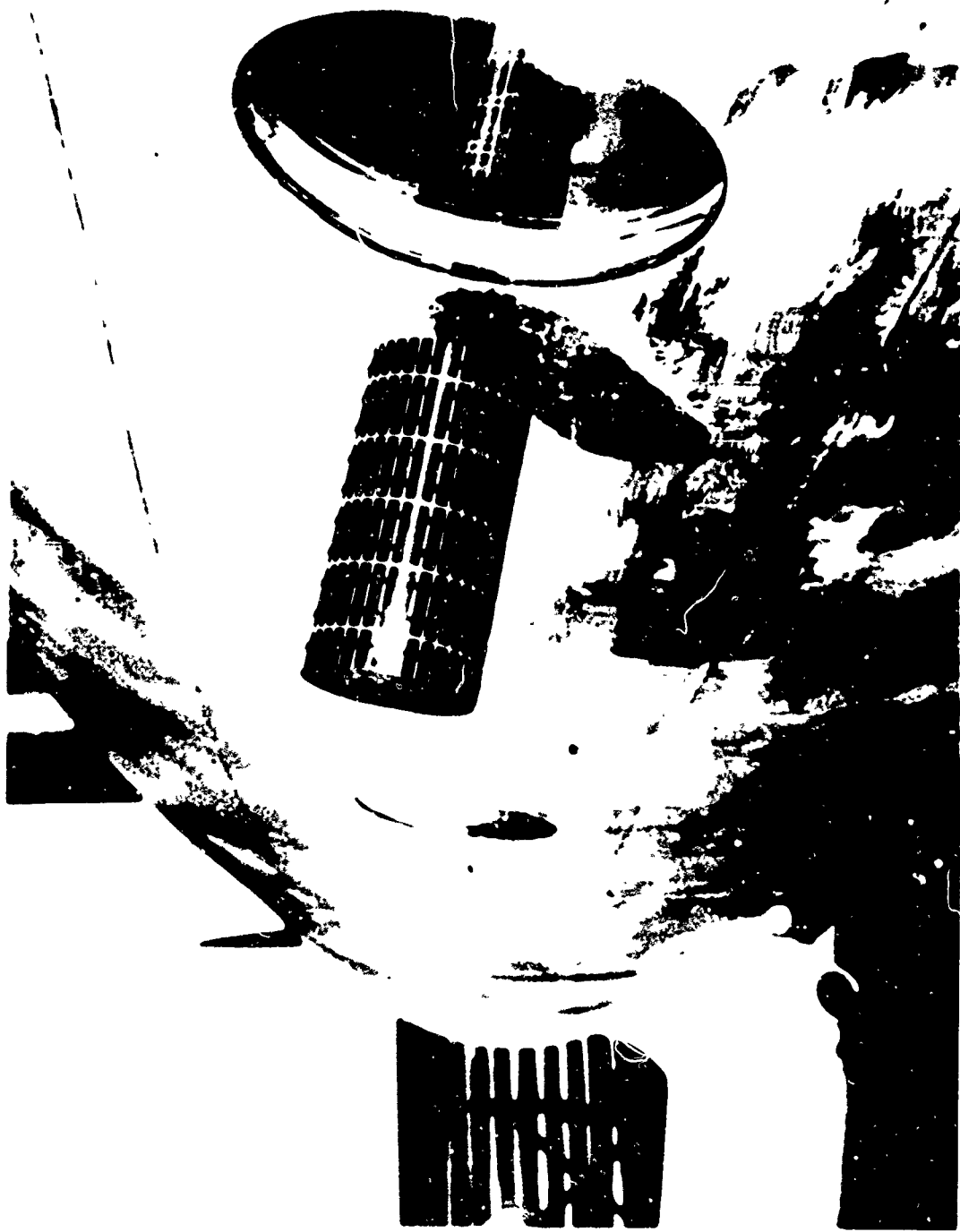
FIG. 7 . DROPLET SIZE INDICATOR CYLINDER AS INSTALLED ON A
CONSTELLATION TYPE AIRCRAFT.

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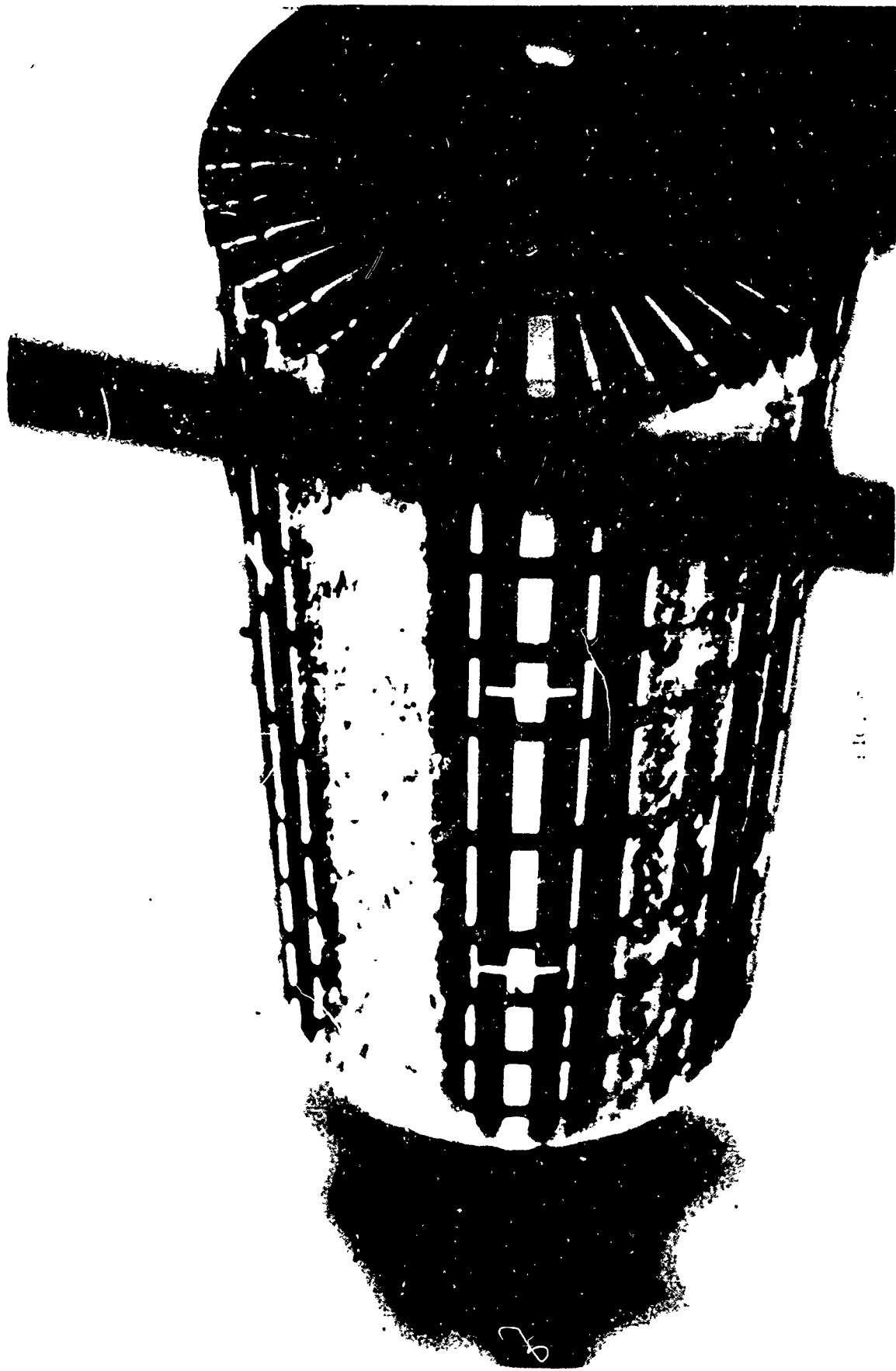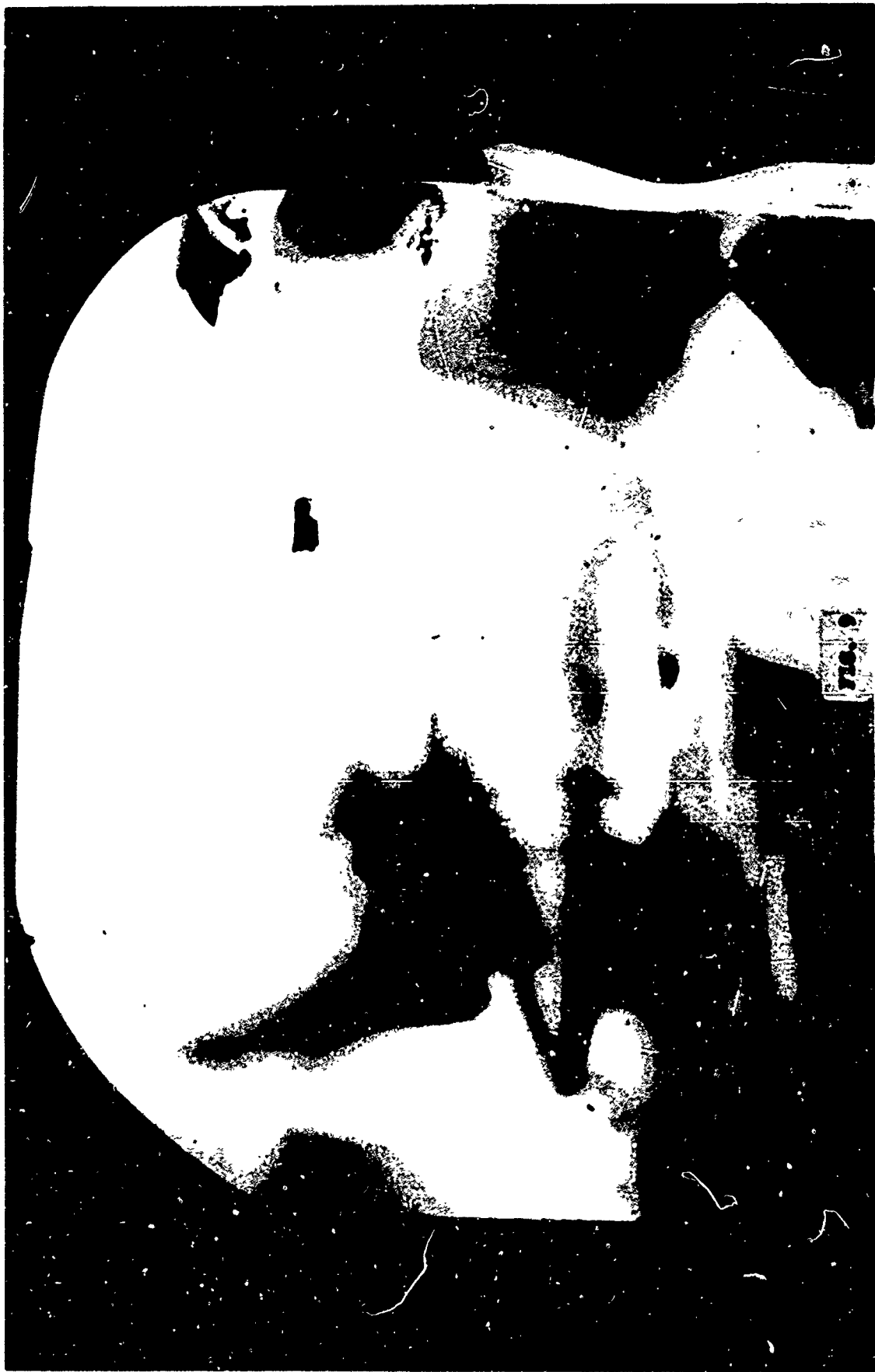
FIG. 10   ICE IMPINGEMENT "TOTALIZER" INDICATOR PARTIALLY ICED.

FIG. 11

FIG. 12

FIG. 13

225

FIG. 14

FIG. 15

FIG. 16

FIG. 17

FIG. 18

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FIG. 19

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FIG. 20

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FIG. 21

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FIG. 22

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FIG. 23

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FIG. 24

236
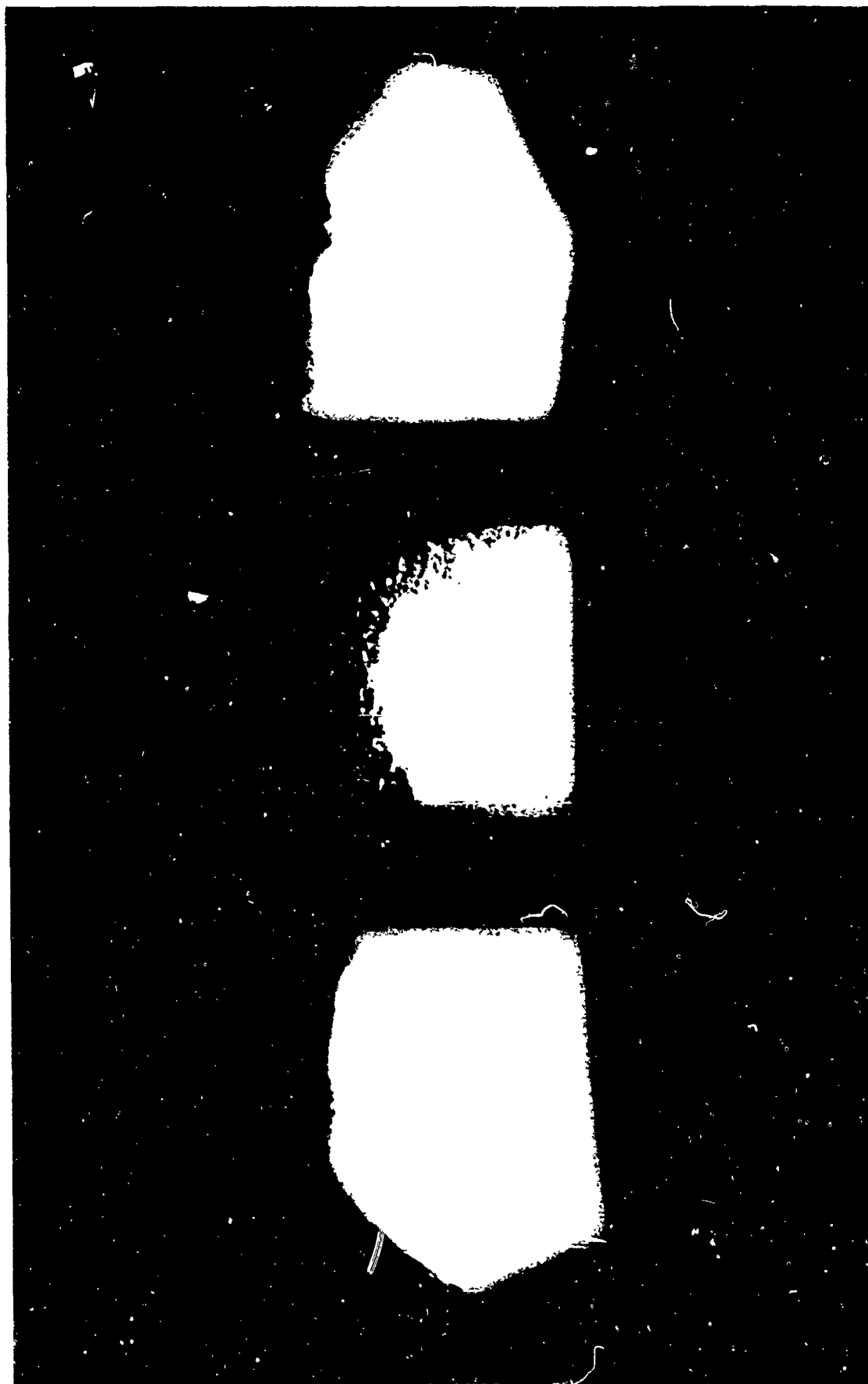
DISCUSSIONS FOLLOWING MR. MESSINGER'S PRESENTATION ON

"AIRFRAME DESIGN FOR PROTECTION AGAINST ICING"

Question: What opinion is there on tests performed with tanker versus tunnel?

Answer: There is a higher confidence level with tunnel, not tanker.

Question: Could you elaborate on the TKS system used for de-icing?

Answer: The system comprises two slots above and below stagnation point through which an alcohol and glycol mixture is pumped.

Question: Is this system selected for the C-5?

Answer: Yes, it will be considered if needed.

Question: Can you rely on hot wire instruments?

Answer: Yes, when used in our tunnel tests, data obtained was consistent with other instruments used. Reliability is delicate, however.

Question: What about limitations on bleed air systems?

Answer: There is a larger penalty with newer engines which need this airflow for performance, at a time when bleed air for de-icing is needed.

Question: Are ice shapes on airfoil beyond mushroom shape critical?

Answer: These are caused by turbulence in tunnel.

by
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I. INTRODUCTION

Federal Aviation Regulations (FAR) Part 25, Paragraph 1419(a), states "If certification with ice protection provisions is desired, compliance with this section must be shown." Section 25.1419 further requires an analysis to show adequacy of the ice protection system, and laboratory and flight tests to show effectiveness of the ice protection system. This paper outlines the methods used by the Douglas Aircraft Company to comply with the flight-test requirements of the Federal Aviation Agency (FAA).

The system referred to in this paper is the hot-gas anti-icing system which utilizes engine compressor bleed air for airfoil ice protection. Other type systems, such as the pneumatic boot de-icing, cyclic electric de-icing, and fluid ice protection are not in general use in today's transport aircraft and, therefore, are not considered.

The paper is divided into the following sections:

- Introduction
- Program Planning
- Instrumentation Methods
- Flight Test Procedures
- Follow-on Tests
- Analysis of Results
- Concluding Remarks

II. PROGRAM PLANNING

To comply with FAR requirements for safe operation in continuous maximum and intermittent maximum icing conditions (Reference Appendix A), high-speed digital computer programs are used to analytically determine the performance of the airframe and engine inlet ice protection systems. These systems are defined in terms of heat available from the engine bleed air and the heat requirements of the systems. The performance of the system is then investigated throughout the aircraft operating envelope using the computer program and the FAA icing envelope defined in Appendix A. Several cases result which are critical combinations of icing and flight conditions. The flight-test program is planned to evaluate these critical conditions.

Planning the flight program consists of resolving the following:

- Instrumentation requirements — sufficient to substantiate analytical data at the critical design conditions.

- Instrumentation locations — on the airframe and engine at which icing is critical.

- Flight conditions — which will integrate the flight profile with the system configurations.

- Aerodynamic evaluation — to evaluate the airplane handling characteristics with ice shapes and/or artificial ice.

INSTRUMENTATION REQUIREMENTS

Instrumentation is required to substantiate analytical data and design criteria for the following:

1. Engine bleed airflow quantity and distribution.

2. Outer skin surface spanwise and chordwise temperature distribution.

3. System pressure and temperature losses.

4. Icing severity.

5. Miscellaneous systems.

6. Photographic documentation.

Engine bleed airflow quantity and airflow distribution must be obtained during these flight tests. Therefore, all locations within the system at which airflow is required are instrumented, and the system, along with the instrumentation, is calibrated in the laboratory. The instrumented segments are then integrated into the aircraft systems followed by flow tests on the aircraft to ensure no changes have occurred to the calibrations. The instrumentation must be distributed throughout the system to ensure that data quantity and quality are adequate to reveal any deficiencies.

Outer surface temperature profiles are obtained by installing thermocouples in selected sections of the heated surfaces. These sections are selected to coincide with the areas which are analyzed during the design analysis. If natural icing tests are required, externally routed instrumentation leads may provide an unacceptable degree of interference to the normal ice catch and require internally routed instrumentation in chemically milled passages. If internal instrumentation is required, it is essential to incorporate the probes and routing within the surfaces early in the fabrication process of the aircraft.

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System pressure and temperature losses are obtained by the installation of probes throughout the pneumatic and ice protection systems.

Icing severity instrumentation must be installed to measure liquid water content and water drop size. Since the data from this instrumentation are quite often controversial, a redundant method of obtaining the liquid water content may be desirable such as an icing rate meter from which the liquid water content may be calculated.

Miscellaneous systems such as airspeed and altitude sensing devices and cockpit windshields must be instrumented to show the adequacy of their ice protection provisions.

Film documentation must be obtained through adequate camera coverage. This coverage should include the instrumented areas of the airfoils, for correlation with recorded data, and coverage of the areas where runback from heated areas could occur. Photographs will also provide documentation of the thickness and type of ice encountered.

When using an ice cylinder, photographs are necessary to document the ice catch for determining the water drop size Photographs are also helpful for studying the deicing characteristics of the airfoil leading edges, and observing for ingestion of ice into the engine when separating from other areas of the aircraft.

In defining the instrumentation requirements, the difference between cyclic and noncyclic ice protection systems must be considered. For the cyclic systems, such as the DC-8 empennage and wing, and the DC-9 empennage, the instrumentation must be capable of recording transitory parameters. To define the instrumentation there must be an understanding of the system hardware characteristics, i.e., the thermal inertia of the skin, structure and ducts; valve cycle time and actuation rate; thermocouple lag; and pressure transducer response rate. The noncyclic steady-state operating system generally has less stringent instrumentation requirements and, therefore, dynamic recording devices are not required.

INSTRUMENTATION LOCATION

The numbers and locations of the thermocouples in the wing and horizontal stabilizer leading edges are that amount required to define chordwise and spanwise temperature profiles. The number of instrumented stations, or spanwise locations, are based on the number of analyzed sections within the wing or stabilizer.

Placement of pressure probes to measure airflows and system pressure losses is dependent on the geometry of the ducting, i.e., a long, constant section for total and static pressure probes is usually nonexistent. For this reason, extreme care must be used in instrumenting and calibrating the air ducts and leading edge airflow passages. Locating the thermocouple leads and pressure line routing must be accomplished in a manner to allow normal heat transfer and not interfere with normal water impingement.

The icing rate and liquid water content probes must be located in an area outside the boundary layer and outside any trajectory shadows to measure accurately the icing environment. The proximity of the liquid water content probe to the power supply, and the power supply to the control unit, may be restrictive due to interconnecting cable length. The location of these probes may depend on available space for locating the power supply. Orientation of some probes may be critical, such as the Johnson-Williams liquid-water content probe, which is sensitive to pitch.

FLIGHT CONDITIONS

Planning the flight conditions consists of establishing the aircraft flight and system configurations to be flown for data acquisition. These configurations are dictated by the design analyses which define the critical combinations of aircraft altitude, aircraft angle-of-attack, engine power setting, and ambient air temperature. For clear air tests a flight profile can be established which will efficiently integrate the ice protection tests with other system or aircraft tests.

Natural icing flight tests cannot be integrated effectively with other aircraft system tests because icing conditions are not so prevalent that the selection of the flight conditions can be predetermined. Therefore, flight conditions must be left to the discretion of flight personnel. The icing conditions which are encountered during a flight-test program are limited usually in severity and extent and must be pursued until a satisfactory icing exposure is encountered. This pursuit often entails many hours of flight in search of reported icing conditions which no longer exist or have changed to the extent that they are not adequate for test purposes.

System configuration entails establishing sequential operation of the ice protection systems and other aircraft systems to obtain the data necessary to assure a complete evaluation. For example, valve cycle time may require optimizing, or, probable system failures may be simulated to observe results and confirm corrective or abnormal procedures.

Among the many conditions flown on the DC-8 and DC-9 airplanes, a typical flight profile with the system configuration requirements is given below:

For each test run, the aircraft was stabilized at the test altitude and airspeed, with the wing anti-icing system on, to permit all pertinent temperatures to reach steady state. The temperature and pressures were monitored visually during flight to ensure steady-state conditions and normal values prior to automatic recording of the data. The aircraft was flown at the flight altitudes with both engines operating; both airconditioning units operating; both wing ice protection switches "ON"; both crossfeed valves "OPEN"; and with engine and nose cowl anti-icing "ON."

AERODYNAMIC CHARACTERISTICS

The aerodynamic characteristics of the aircraft with an ice buildup must be evaluated for two reasons:

1. In the event the ice protection system fails to function.

2. In the event an icing encounter is experienced without adequate warning or pilot recognition.

The first case can be evaluated with the use of simulated ice shapes. The second case requires demonstrating the de-icing capability of the ice protection system and can be accomplished with either an artificial cloud or tunnel tests.

III. INSTRUMENTATION METHODS

The instrumentation must be installed to preclude interfering with the functional processes of the system. For this reason, when only dry air (non-icing) tests are required, thermocouples are routed externally to the surface to reduce installation costs and minimize their influence on the system function. If natural or artificial icing cloud tests are required, externally routed wires

and pressure pickups are not permitted because of interference with the airflow over the heated surfaces which would alter the water-catch characteristics. For these tests all skin thermocouples and their leads are imbedded in chemically milled passages and sealed to minimize the effect on the ice protection system airflows.

Figure 1 shows the DC-9 airplane and depicts the external airframe areas of concern. These areas were instrumented as summarized in Tables I through V which contain a tabulation of the instrumentation used on a typical ice protection system test airplane.

FIGURE 3. ICE PROTECTION INSTRUMENTATION – AIRCONDITIONING SCOOP

FIGURE 1. ICE PROTECTION DEMONSTRATION (TYPICAL AIRCRAFT EXTERNAL TEST AREAS)

FIGURE 4. ICE PROTECTION INSTRUMENTATION – PRESSURE REGULATOR AND SHUTOFF VALVE

TABLE I
TEMPERATURE AND PRESSURES
DC-9 AIRPLANE

NO OF PICKUPS TEMP	PRESSURE	LOCATION	REMARKS
45	10	L H Wing Leading Edge	Three Span Stations $X_{0.5} = 136\ 327\ 547$
27	9	L H Horizontal Stabilizer Leading Edge (Figure 2)	Two Span Stations $X_{0.5} = 19\ 197$
18	3	R H Engine Inlet Cowl	Three Radial Stations at Clock Position = 30° 150°, 225°
11	2	Airconditioning Scoop (Figure 3)	Base of Vertical Stabilizer Two Longitudinal Stations
8	4	Pneumatic Supply (Figure 4)	Engine Bleed Air
3		Windshield Copilot (Figure 5)	Defog and Anti-Ice Sensors
1		Airspeed Static Port R H	External Skin

FIGURE 5. ICE PROTECTION INSTRUMENTATION – FIRST OFFICER'S SIDE WINDSHIELD

FIGURE 2. ICE PROTECTION INSTRUMENTATION – HORIZONTAL STABILIZER

TABLE II
AIRFLOWS DC-9 AIRPLANE

LOCATION	REMARKS
Engine Bleed	8th Stage, 13th Stage, Engine Inlet Anti-Icing, Engine Inlet Cowl Anti-Icing
Pneumatic Supply	To Horizontal Stabilizer, to Airconditioning Scoop
Wing Anti-Icing	To L H Wing Piccolo Tubes at Stations 136, 327, 546 for Upper and Lower Surfaces
Horizontal Stabilizer	To L H Horizontal Piccolo Tubes at Stations 19, 197

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TABLE III
ELECTRICAL POWERS MEASUREMENTS
DC-9 AIRPLANE

HEATERS FOR	REMARKS
"Q" Limiter Pitot Tube	In Leading Edge of Vertical Stabilizer
Airspeed Pitot Tube	Forward of Center Windshield
Windshield	Anti Fog and Anti Ice Sensors

TABLE IV
RECORDING DEVICES DC-9 AIRPLANE

ITEM	PURPOSE/REMARKS
Photorecorder	To Document
	1 Airspeed
	2 Altitude
	3 Time
	4 Angle of Attack
	5 Liquid Water Content
	6 Engine Parameters
	7 Pneumatic System and Ice Protection System Pressures
	8 Pneumatic System and Ice Protection System Function Lights
	9 Pneumatic System and Wing Ice Protection System Temperatures
Oscillograph	To Document
	1 Pneumatic System and Ice Protection System Dynamic Pressures
	2 Engine Bleed Temperatures
	3 Tail Ice Protection Temperatures
	4 Outside Ram Air Temperatures
	5 Windshield Heater Voltage
Closed Circuit Television With Monitor and Video Tape Ref Figure 6	To record for instant playback the icing and shedding of the L H horizontal stabilizer leading edge and the R H engine inlet
Icing Rate Meter Recorder Ref Figure 7	NACA Icing Rate Oscillograph to Record
	1 Airspeed
	2 Altitude
	3 Pressure Switch Differential Pressure
	4 Heater Circuit Solenoid Voltage
Cameras	To Document Conditions of
1 35mm	1 The Cockpit Windows
2 16mm Movie	2 Ice Cylinder
Ref Figure 8	3 Lower Wing Surface through a Periscope
	4 R H and L H Wing Leading Edges
	5 Vertical and Horizontal Stabilizer Leading Edges through a Periscope
	6 Engine Inlets

FIGURE 6 VIDEO TAPE DECK AND MONITOR (DC-9)

FIGURE 7 NACA ICING RATE METER (DC-9)

FIGURE 8 ICING INSTRUMENTS AND CAMERA COVERAGE

TABLE V
SPECIAL ITEMS DC-9 AIRPLANE

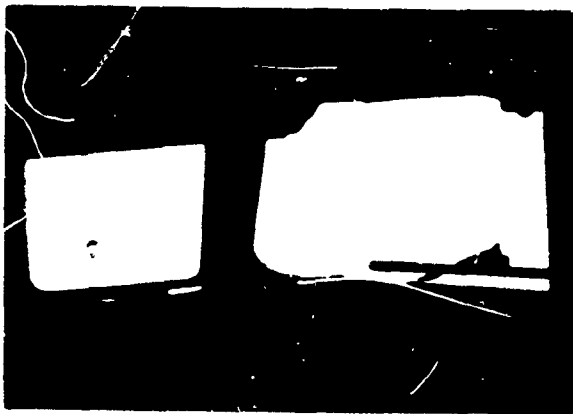| ITEM	PURPOSE/REMARKS
Liquid Water Content Probe (Figure 9)	To measure cloud water content mounted forward of windshield
Water Drop Size Cylinder (Figure 10)	To measure drop size of catch and indicate icing rate
Periscopes Two	To view the lower wing surface from the forward cargo compartment and the air conditioning scoop at the base of the vertical fin from the aft cabin
Shut-off Valves Two (Figure 4)	One to close off ice protection air to the air conditioning scoop and one to close off the L H wing ice protection air
Fail Valve	To simulate failure of the ice protection pressure regulator
Painted Surfaces Red	To provide contrasting background for photographing ice and to outline the antitrum ice areas and internal ducts
Bladder Fuel Tank 1000 Gallons	To extend the range of the aircraft for extended ferry flights and ice cloud penetration

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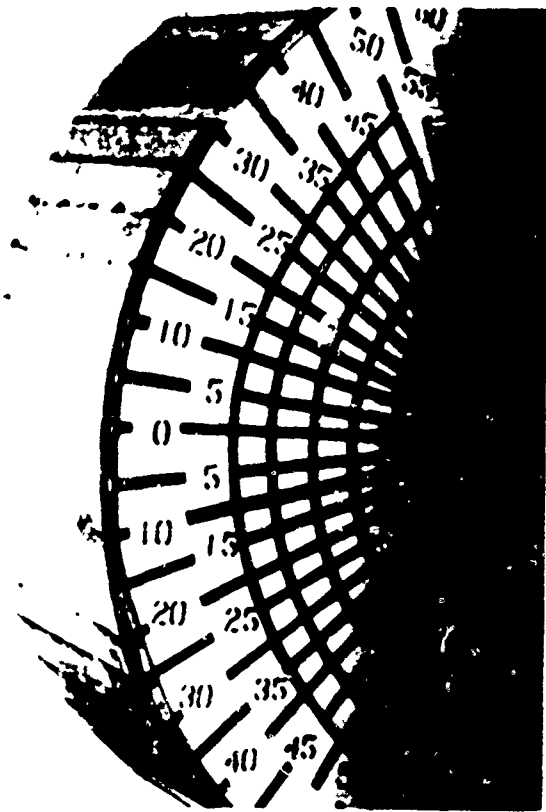FIGURE 9 JOHNSON WILLIAMS LIQUID WATER CONTENT PROBE (DC-9)

FIGURE 10 WATER DROP SIZE CYLINDER NATURAL ICE (DC-9)

IV FLIGHT TEST PROCEDURES

The flight program was composed of two parts the dry- or clear-air tests and the natural-ice tests

CLEAR AIR

The clear air flights or non-icing conditions are flown to substantiate the system design analysis heat transfer calculations On the DC-9 airplane one set of the flight conditions flown was holding speeds at 5000 15 000 22 000 and 30 000 feet altitude At each of these altitudes the ice protection systems were turned

on, one at a time (airfoil, engine, and airconditioning scoop) and the operation and warning annunciators observed At each altitude, a stabilized level flight run was made to obtain system and surface temperatures. In addition, the system operation was observed while making throttle lever changes, with one and with two pneumatic systems operating. Simultaneously, data were obtained on the following

1   Airspeed static port temperatures

2   "Q" bellows heater power

3   Windshield temperatures

4   Pitot probe heater power

5   Airconditioning scoop temperatures

ICING CLOUD

A planned flight profile is not feasible because of the difficulty in finding adequate natural icing conditions It is possible, though, to establish the system configurations to be used and the sequence of events to be followed when ice conditions are encountered On the DC-9 demonstration, the following series of events was planned

1   At recognition of icing conditions, turn all ice protection systems "ON" and demonstrate anti-icing capability Observe systems operation and aircraft handling characteristics

2   After adequate buildup of ice on the unheated areas, return to VFR conditions and perform sideslips at 0 and 50 degrees flap angle with landing gear up and gear down at 1.6 V_s

3   Perform stalls at 0- and 50-degree flap angle with landing gear both retracted and extended

4   Turn "OFF" ice protection to the following systems

   a   Copilot pitot probe

   b   R H wing

   c   R H engine

   d   Airconditioning scoop

   e   Static port

   f   Copilot windshield anti-ice and anti-fog

The following to remain "ON"

   a   L H wing

   b   L H engine

   c   Ram air temperature

   d   Stall warning

   e   Pilot and auxiliary pitot heater

   f   Rudder limiter probe heater

   g   Pilot's windshield heat

5. With gear and flaps retracted and the auxiliary power unit operating, return to icing conditions. At the holding speed for the altitude at which the icing temperatures exist, observe the following for ice buildup

   a. R.H. wing

   b. R.H. engine

   c. Airconditioning scoop

   d. Copilot pitot probe

   e. Copilot windshield

6. After sufficient ice buildup, turn on the "RIGHT" engine ice protection and observe the effects.

7. Repeat with the R.H. wing.

8. Turn on copilot's pitot heat when instruments indicate icing exists on the pitot probe.

9. Turn on copilot's windshield heat

10. Turn on tail de-icing for 150 seconds. (A manual switch was used for flight test in lieu of the production timer.)

11. If ice buildup exists on the airconditioning scoop, perform sideslips to evaluate the effect on the airconditioning system, then turn its ice protection system "ON."

12. Observe the APU for unstable operation

13. Operate the following and observe for normal operation

   a. Lower the flaps to 20°

   b. Lower the gear

   c. Lower the flaps to 50°

   d. Extend the wing landing lights

14. Simulate a go-around, raising the gear and flaps.

15. Shut down the APU and perform an air start

16. Operate VHF while in storm conditions to evaluate the effects of 50 percent of the static wicks being removed

V. FOLLOW-ON TESTS

In addition to the basic system development and certification program, additional tests may be required. Below are some examples of follow-on tests and their purpose

1. Ice Shape – to demonstrate the effect of ice buildup on unheated areas.

   a. Spare engine pod

   b. Vertical stabilizer

2. Dry Air Only – to demonstrate the ice protection system performance following minor revisions to the basic system

3. Artificial Cloud – to evaluate the ice protection system using an aerial tanker to produce an artificial cloud.

Specific examples of the above tests are

1. Ice Shapes

Spare Engine Pod – DC-8 airplane (see Figure 11), shows the artificial ice shapes used for the spare engine pod of the DC-8 airplane. The flight-test program consisted basically of the following

   a. A buffet investigation at 20,000 feet throughout the speed range.

   b. A qualitative evaluation of airplane handling characteristics for

     (1) Slow flight - aileron rolls with fixed rudder to 25 and 30 degrees airplane bank angle

     (2) A stall in the landing configuration 50 degrees of flap and landing gear down

FIGURE 11 SIMULATED ICE SHAPE – SPARE ENGINE POD AND PYLON OF DC-8

Vertical Stabilizer Figure 12 shows the leading edge of a DC-8 with simulated ice shapes installed. This test was conducted to demonstrate that ice protection of the vertical stabilizer was not required. The flight program consisted basically of

   a. Approach climb performance double-heading climbs with 25 degrees of flaps and landing gear retracted

   b. Buffet investigation to V_{NE}/M_{NE}, to 30,000 feet and during a high Mach number descent and combinations of the above with and without powered rudder and aileron

FIGURE 13. WING ANTI-ICING SYSTEM FLOW-TEST INSTRUMENTA-
TION
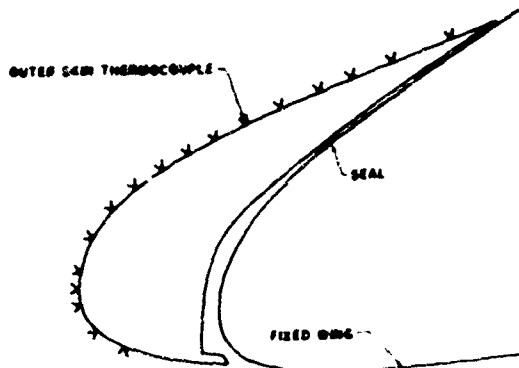
FIGURE 14. WING SLAT THERMOCOUPLE LOCATIONS (X_{FS} = 189.918')

FIGURE 12. SIMULATED ICE SHAPE ON VERTICAL STABILIZER
(DC-8)

c. Steady state V_{MC} in the takeoff configuration, flaps
25 degrees landing gear retracted with engines 1 and 2
shut down

d. Directional control with engines 1 and 2 shut down
at the aft center of gravity

2. Dry Air

Wing Slats DC-9 Figures 13 and 14 show the DC-9
leading edge slat instrumentation used on the Series 30 and
40 aircraft. Because of changes to the ice protection system
on incorporating slats, dry-air tests were required. The
flights included stabilized holding conditions with slats
extended at 15,000 and 22,000 feet pressure altitude, slats
retracted at 15,000, 22,000, and 30,000 feet pressure
altitude.

3. Artificial Cloud

In an attempt to evaluate the feasibility of using an artificial
cloud for developing ice protection systems, an Air Force
KC-135 icing tanker was contracted for, and a test program
flown using the DC-9 airplane following its certification in
natural ice. These tests were flown from Edwards Air Force
Base, California, in November of 1965, and consisted of five
flights (see Figure 15).

FIGURE 15. ARTIFICIAL CLOUD DISPERSEMENT

The following goals were established

a. Comparison of the test instrumentation NACA icing
rate meter, Johnson Williams liquid-water content
meter, and the water-drop size cylinder

b. To subject the DC-9 ice protection systems to severe
ice conditions and observe the adequacy of these
systems (see Figure 16)

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FIGURE 16 WATER DROP SIZE CYLINDER, ARTIFICIAL ICE (DC-9)

c To determine the feasibility of using the Air Force icing tanker as a method of flight testing in an artificial ice cloud

d To demonstrate the adequacy of the ice protection systems to perform the de-icing function (see Figure 17)

e To evaluate the windshield wipers and rain repellent system.

f To determine the best method for pilot recognition of an ice encounter (see Figure 18)

g To accrue a 45-minute ice buildup on the horizontal tail to correlate with analytical data (see Figure 19)

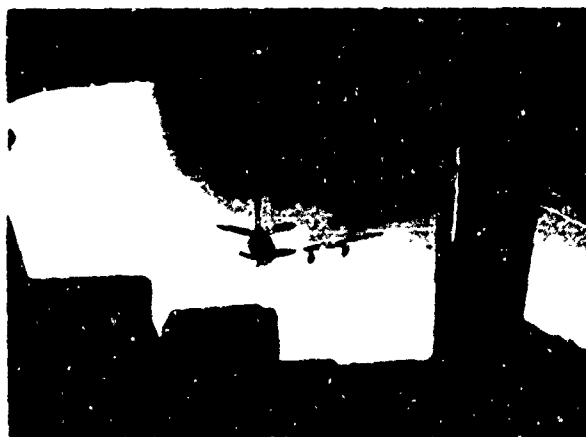A comparison of natural ice versus artificial ice on the engine pylon is shown in Figure 20.

17 HORIZONTAL STABILIZER DURING DE-ICING CYCLE (ARTIFICIAL)
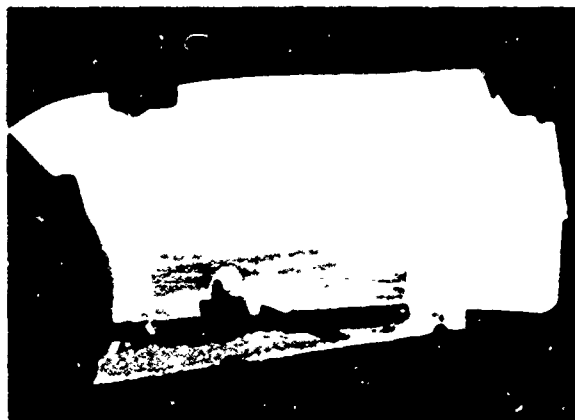
FIGURE 18 HEATED PILOT WINDSHIELD, ARTIFICIAL ICE (DC-9)

FIGURE 19 DC-9 HORIZONTAL STABILIZER PRIOR TO DE-ICE (ARTIFICIAL)

FIGURE 20 ENGINE PYLON ICING – NATURAL ICING, LEFT, ARTIFICIAL ICING, RIGHT (NOTE THICKNESS AS COMPARED TO NATURAL ICING)

The procedure employed for the tanker tests was to fly at a stabilized altitude and airspeed with the instrumentation probes in the cloud and obtain the icing rate, drop size, and liquid water content. The aircraft was then flown to position the appropriate test section in the cloud. The areas tested were the left wing, left horizontal stabilizer, air conditioning ram air scoop, APU inlet engine inlet, and windshield. The last flight evaluated the windshield wipers and rain repellent systems under simulated rain conditions.

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VI ANALYSIS OF RESULTS

Dry Air

Again using the DC-9 as an example, the dry-air test results are correlated based on comparing recorded surface temperatures against predicted surface temperatures. A typical curve is shown in Figure 21. The same type of correlation is used for the engine inlet cowl, engine bullet and horizontal stabilizer leading edge. Figure 22 shows a typical airflow comparison curve for the slats. In the case of dry-air tests the water catch is not a factor, therefore, the results are used primarily to verify the accuracy of the analytical approach used in the analysis, and to prove that the required amount of heat is being supplied

FIGURE 21 COMPARISON OF EXPERIMENTAL AND THEORETICAL WING SLAT TEMPERATURE PROFILES
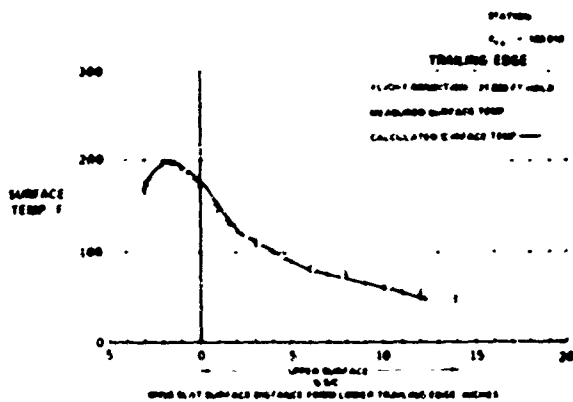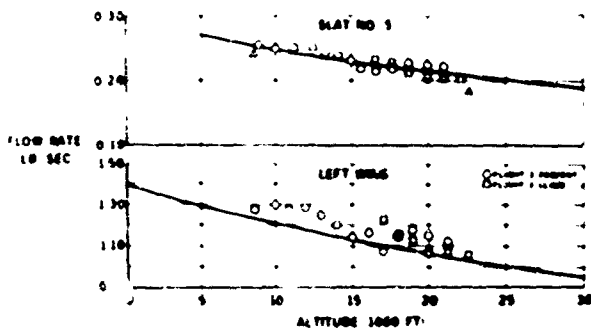

FIGURE 22 ANTI-ICING AIRFLOW

Icing Cloud

The icing cloud or natural icing flight test data are also used to verify the analytical approach. Since the maximum continuous and intermittent maximum icing conditions are not generally available a certain amount of acquiescence accompanies the approval of a system based on natural ice

In addition to the problem of not being able to obtain natural icing conditions which even approach the design criteria, it has been difficult to measure the icing conditions due to repeated malfunctions of the instrumentation. For this reason, analyses of the results of natural icing has been sketchy

VII. CONCLUDING REMARKS

It should be mentioned that a considerable amount of time and money are expended in conducting natural icing tests. For example, in the DC-9 natural icing tests (a minimum program), the following statistics are history

Number of Flights	14
Flight Hours	32.5
Cost of Operation	Approx. $260,000
Areas Covered	Los Angles, California Seattle, Washington Dallas, Texas Kansas City, Missouri Minneapolis, Minnesota
Time of Year	October
Elapsed Time	10 Days

It is estimated the DC-10 natural icing flight test operations will approximate $320,000

It is interesting to note that of the model DC-8 and DC-9 icing programs, no changes to the system were required. This is attributed to the analytical techniques which have evolved over a considerable period of time. Prior to the use of digital computer programs and when digital computer methods were in their infancy, analysis of ice protection system performance required a great many hand calculations and the use of research information which was being generated at the time by the NACA. As familiarity increased with the NACA research data and as the FAA regulations began to reflect this NACA data, the current approach to ice protection system design began to be formulated. The rapid increase in the complexity of problems which could be handled by the digital computer greatly increased the number of variables and interactions which could be accounted for simultaneously. As these programs have been refined through more sophisticated techniques and through comparisons to laboratory, clear air flight icing, and flights and icing tunnel tests, they have permitted the design of ice protection systems which have proven to be conservative. In all cases investigated in recent years the use of these computer programs has consistently produced ice protection systems whose measured performance is superior to the calculated performance. These consistently conservative results produce high confidence in the analytical methods used in the computer programs and have created the situation which permits the system to be designed with a very low probability of changes to the system after the aircraft is test flown

Because natural ice tests have contributed very little to proving the adequacy of the ice protection systems, and comparisons of analytical to actual data do not enhance the comparison of analytical to clear air flight test data, the natural icing tests are of dubious value when weighed against the cost of conducting these tests. In addition, and just as important, are the following reasons to support the deletion of natural ice tests

● The experience to date shows conservative ice protection systems designed from analytical data utilizing the computer programs which can accommodate the numerous variables involved including the various combinations of flight and icing conditions possible

- With the current generation of jet aircraft, the exposure time to icing is a minimum. This is due to both their higher cruise speed and reserve thrust, which make high climb rates possible.

- The current weather reporting technique makes the present-day pilot more knowledgeable of expected weather conditions; he is prepared, therefore, to submit more intelligent flight plans to avoid icing, or is at least sufficiently alerted when the icing hazard exists to have the ice protection systems turned "ON."

If there are any points to be made from this paper it would be the following two: (1) The dire need for more reliable and accurate instrumentation to measure liquid water content and water droplet size for airborne use and (2) to improve the technique of simulating an icing cloud.

REFERENCE

Federal Aviation Regulations (FAR) Part 25, Airworthiness Standards Transport Category Airplanes

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Extracts from FAR Part 25 pertaining to ice protection system certification 25.1419

25.1419 Ice Protection

(a) If certification with ice protection provisions is desired compliance with this section must be shown

(b) The airplane must be able to safely operate in the continuous maximum and intermittent maximum icing conditions determined under Appendix C. An analysis must be performed to establish, on the basis of the airplane's operational needs, the adequacy of the ice protection system for the various components of the airplane

(c) In addition to the analysis and physical evaluation prescribed in paragraph (b) of the section, the effectiveness of the ice protection system and its components must be shown by

(1) Laboratory dry air or simulated icing tests or a combination of both of the components or models of the components

(2) Flight dry air tests of the ice protection system as a whole or of its individual components

(3) Flight tests of the airplane or its components in measured simulated icing conditions or

(4) Flight tests of the airplane or its components in measured natural atmospheric icing conditions

(d) For turbine engine powered airplanes the ice protection provisions of this section are considered to be applicable primarily to the airframe. For the powerplant installation certain additional provisions of Subpart E of this part may be found applicable

25.773 Pilot Compartment View

(b)(1)(ii) The icing conditions specified in 25.1419 if certification with ice protection is requested

25.1093 Induction System De-Icing and Anti-Icing

(a) Turbine Engines Each turbine engine must be able to operate throughout its flight power range without adverse effect on engine operation or serious loss of power or thrust, under the icing conditions specified in Appendix C In addition, there must be means to indicate to appropriate flight crewmembers the functioning of the powerplant ice protection system

FAR Definitions - (Appendix C of Part 25)

(a) Continuous Maximum Icing The maximum continuous intensity of atmospheric icing conditions (continuous maximum icing) is defined by the variables of the cloud liquid water content, the mean effective diameter of the cloud droplets, the ambient air temperature and the inter-relationship of these three variables as shown in Figure 1 of this appendix. The limiting icing envelope in terms of altitude and temperature is given in Figure 2 of this appendix. The inter-relationship of cloud liquid water content with drop diameter and altitude is determined from Figures 1 and 2. The cloud liquid water content for continuous maximum icing conditions of a horizontal extent, other than 17.4 nautical miles, is determined by the value of liquid water content of Figure 1, multiplied by the appropriate factor from Figure 3 of this appendix

(b) Intermittent Maximum Icing The intermittent maximum intensity of atmospheric icing conditions (intermittent maximum icing) is defined by the variables of the cloud liquid water content, the mean effective diameter of the cloud droplets, the ambient air temperature and the inter-relationship of these three variables as shown in Figure 4 of this appendix. The limiting icing envelope in terms of altitude and temperature is given in Figure 5 of this appendix. The inter-relationship of cloud liquid water content with drop diameter and altitude is determined from Figures 4 and 5. The cloud liquid water content for intermittent maximum icing conditions of a horizontal extent, other than 2.6 nautical miles, is determined by the value of cloud liquid water content of Figure 4 multiplied by the appropriate factor in Figure 6 of this appendix
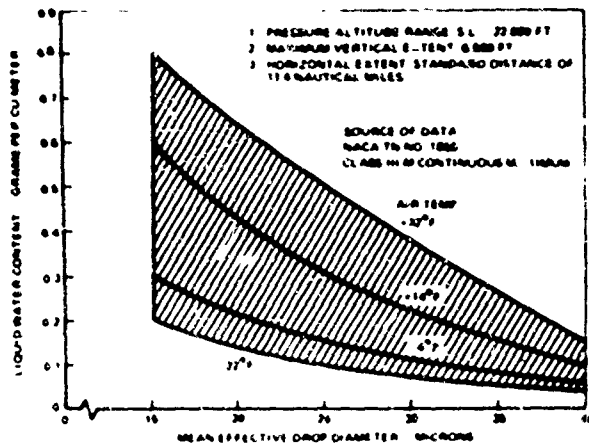
FIGURE A 1 CONTINUOUS MAXIMUM (STRATIFORM CLOUDS) – LIQUID WATER CONTENT VS MEAN EFFECTIVE DROP DIAMETER
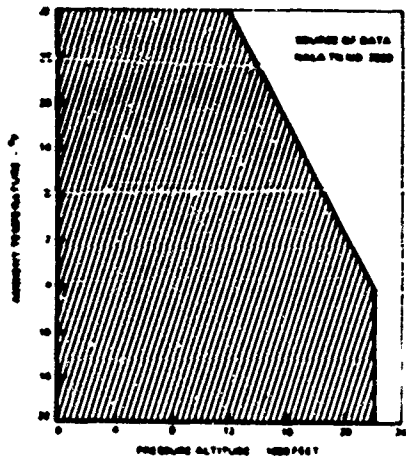
FIGURE A-2. CONTINUOUS MAXIMUM (STRATIFORM CLOUDS) –
ATMOSPHERIC ICING CONDITIONS – AMBIENT
TEMPERATURE VS PRESSURE ALTITUDE

FIGURE A-3. CONTINUOUS MAXIMUM (STRATIFORM CLOUDS) –
ATMOSPHERIC ICING CONDITIONS – LIQUID WATER
CONTENT FACTOR VS CLOUD HORIZONTAL DISTANCE

FIGURE A-5. INTERMITTENT MAXIMUM (CUMULIFORM CLOUDS) –
ATMOSPHERIC ICING CONDITIONS – AMBIENT
TEMPERATURE VS PRESSURE ALTITUDE
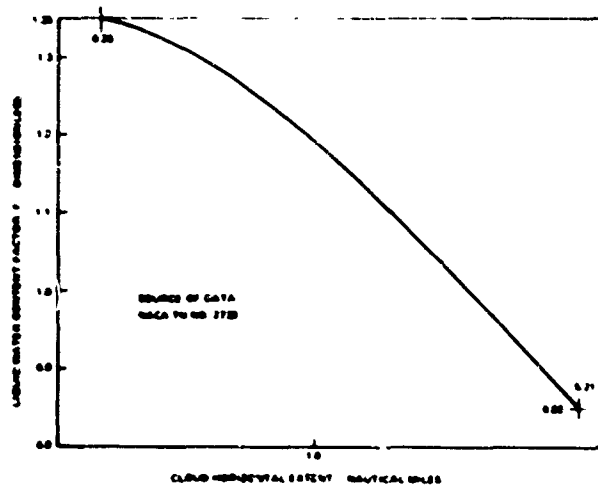
FIGURE A-6. INTERMITTENT MAXIMUM (CUMULIFORM CLOUDS) –
ATMOSPHERIC ICING CONDITIONS – VARIATION OF
LIQUID WATER CONTENT FACTOR WITH CLOUD
HORIZONTAL EXTENT
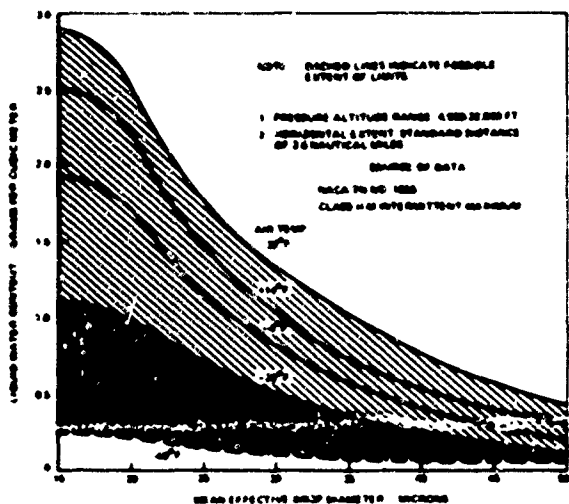
FIGURE A-4. INTERMITTENT MAXIMUM (CUMULIFORM CLOUDS) –
ATMOSPHERIC ICING CONDITIONS – LIQUID WATER
CONTENT VS MEAN EFFECTIVE DROP DIAMETER

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DISCUSSIONS FOLLOWING MR. COOK'S PRESENTATION ON

"FLIGHT TESTING IN DRY AIR ICING CLOUD"

Question: You made the statement that natural icing tests are
not worth the cost involved. Are you going to use
this method on the next program?

Answer: Yes, because FAA is requiring it.

Question: Are natural icing tests not like laboratory icing
tests?

Answer: The kind of icing we get in natural icing tests is
not as severe.

Question: Why not use natural icing conditions purely for
verification?

Answer: Natural icing tests are very expensive and time
consuming. We have used natural icing for
verification several times, and correlation has
shown that Douglas computations are satisfactory.
Question arises--is this method worthwhile when
considering the cost?

TECHNIQUES USED TO DETERMINE
ARTIFICIAL ICE SHAPES AND ICE SHEDDING
CHARACTERISTICS OF UNPROTECTED AIRFOIL SURFACES

by

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ABSTRACT

To determine the need for airfoil ice protection systems and the effects of large ice shapes on airplane performance, The Boeing Company has conducted comprehensive flight test programs utilizing artificial ice shapes attached to tail and wing surfaces.

The ice accretion information available from published data for determining the ice shapes was applicable to unswept airfoils at limited angles of attack. Therefore, Boeing initiated a research program to obtain basic ice accretion and ice shedding data on typical jet transport swept airfoils. This program sponsored by the Federal Aviation Agency was conducted in the NASA 6-foot by 9 foot icing tunnel at Cleveland, Ohio.

Ice accretion tests were conducted on two swept airfoil sections representative of the inboard and outboard wing or horizontal stabilizer airfoil sections of typical jet transports. The size and shape of these ice accretions were measured through photographs and actual plaster casts of the ice cap. Tests were conducted over a range of simulated flights and icing conditions designed to give the rough or glaze shape, which results in the highest drag penalty. These test results were then correlated with theoretical water impingement parameters obtained from a digital computer program.

Ice accretion characteristics are discussed and shown to be dependent on airfoil shape, particularly leading edge radius, camber and angle of attack. The test data and results are comparable to limited published ice accretion data on an unswept 65A004 airfoil.

An empirical relationship is developed which correlated measured ice accretion rates with theoretical water impingement parameters. The correlation was obtained primarily by use of glaze ice heights and angles measured from the plaster casts of the actual ice shapes as taken from the two swept airfoil models.

A calculation procedure for determining artificial ice shapes is also developed using the ice shape correlation curves and illustrated for the 747 horizontal stabilizer.

The complex trends of the data obtained in this test program precluded a general ice accretion relationship with other airfoils. Airfoil camber or shape and angle of attack were found however, to be significant in determining the size and shape of the ice cap. Additional testing of other airfoil shapes and angle of attack would be desirable to provide for broader application of the ice cap calculation procedures developed herein.

Airplane performance penalties associated with icing in terms of landing weight penalties and when these penalties are assessed are also discussed. Destination airport temperatures and ice shedding characteristics are shown to be significant in determining the frequency of aerodynamic penalties due to ice.

A method of calculating the airfoil ice interface temperature and predicting the time the ice will shed has been developed using icing tunnel test data in conjunction with a heat transfer analysis. The ice shedding calculation procedure is demonstrated and shown to be conservative from natural icing flight test data. Different types of descent profiles are considered and operating procedures are discussed to ensure ice shedding prior to approach flight conditions.

DETERMINATION OF ICE SHAPES

Introduction

Jet engine aircraft are less susceptible to icing for several reasons. The kinetic temperature rise, due to higher flight speeds, reduces the icing temperature envelope and prevents ice from forming in the higher liquid water content clouds occurring just below 32 F. The aerodynamic characteristics of swept airfoils, use of movable horizontal stabilizers for trim, rapid rate of climb and descent of jet aircraft, all contribute to minimizing exposure to icing conditions and to reducing the effects of ice on airplane performance. In addition, the size of current jet transports and the large power reserve of jet engines reduce the drag effects of airplane icing.

As a result of the greater tolerance to icing of jet aircraft, there arises the question of the need for ice protection on certain areas of the airplane. Inboard wings have on some piston engine aircraft not been protected. Military aircraft such as the B-52 and KC-135 have had tail and wing ice protection systems removed as a result of adverse weather flight test programs in natural icing and behind the tanker.

It is logical then to assess the need for airfoil ice protection in terms of airplane handling characteristics and performance. To do this on a consistent basis requires a wind tunnel and flight test program whereby the effects of ice can be simulated since natural icing is not consistent, is difficult and time consuming to obtain and is subject to shedding before the testing can be completed. This simulation of icing effects has been accomplished on jet transports through the use of artificial ice shapes attached to unheated portions of the wing and tail surfaces. This report summarizes some of the methods and procedures used to determine these ice shapes and presents a new method of obtaining ice shapes based on recent ice accretion test data correlated with theoretical impingement data. In addition, airplane performance penalties due to these ice shapes are discussed and when these penalties must be applied in terms of the airplane destination temperatures.

Icing Conditions

The current meteorological design standard for ice protection systems on commercial aircraft is Appendix C of Federal Aviation Regulations Part 25 (Reference 1). These design icing conditions or icing envelopes were based on NACA reports on statistical studies of aircraft icing probabilities. Current service experience with aircraft ice protection systems, designed and certified to these standards, indicate these standards are conservative.

The icing data is presented in terms of cloud liquid water content, drop size, temperature, horizontal extent and altitude. These data are divided into two classes: continuous maximum (stratus or layer type clouds) and intermittent maximum (cumulus clouds). The average cloud liquid water content decreases with an increase in water drop size and cloud extent. Figure 1 shows the amount of ice collected on a one inch diameter rod versus cloud distance for a 15 micron drop diameter. The largest amount occurs for the continuous maximum icing condition at the maximum cloud length. From

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probability studies, encounters of more than 150 to 175 miles are unlikely.
At this distance, the ice accumulation is three times that for the standard
20 mile distance. Also shown on this figure is the amount of ice collected
at temperatures other than 32 F corresponding to the icing temperature limit
at various aircraft speeds. Thus, at normal jet aircraft low altitude cruise
or holding speeds, there is sufficient ram air heating available to prevent
supercooled water droplets from freezing above an icing temperature limit
determined by the heat exchange at the airfoil leading edge. These higher
speeds associated with jet aircraft effectively reduce the icing envelope
and the maximum ice accretion size for a single icing encounter.

Flight Conditions

Commercial jet aircraft are designed for high climb and descent speeds
which limit the time the aircraft would be in an icing condition. Normal
cruise altitudes are also above the icing altitudes so icing at cruise flight
conditions is either not encountered or the temperature and corresponding
cloud liquid water content are too low to produce appreciable ice accretion
sizes. In addition to normal flight patterns, the terminal holding phase and
in some cases dispatch holding must be considered. It is during these low
altitude, low speed flight conditions where icing is most likely to be
encountered. This latter flight condition is closely controlled by the
FAA air traffic control center.

Artificial ice shapes for the early 707 series airplanes were based on
the largest water catch obtainable in a continuous maximum icing encounter,
which agreed with the maximum ice accretion obtained during Phase V Air
Force Adverse Weather testing on the B-52 airplane. These data (Figure 1)
indicated the 707 would have to fly 160 miles in maximum continuous icing
conditions as defined in CAR4b (now FAR Part 25) before 3 inches of ice would
accumulate. The icing data for FAR Part 25 is based on a standard 20 mile
cloud. Duration of the icing encounter is accounted for by the cloud extent
factor. Consideration of a half hour holding icing encounter resulted in
approximately the same amount of ice for a 150 mile icing cloud. Therefore,
the 3 inch ice shapes were considered consistent with a half hour holding in
the worst conditions specified in the Civil Air Regulations. Probability
studies indicated this 3 inch ice shape would accumulate about as often as
four engines would fail simultaneously in flight. To date, no known tail
ice accretion thickness of this magnitude on Boeing jet aircraft has been
authenticated or any serious incident occurred due to ice on jet aircraft
surfaces.

Recent interpretation of FAR Part 25 for icing flight requirements
has resulted in a 15 minute "dispatch holding operation" after takeoff
plus 30 minutes destination holding prior to landing. The cloud extent factor
and time in the icing cloud have been open to interpretation. In Reference 2,
the FAR Part 25 icing conditions have been used for a standard 20 mile cloud
and applied for a 45 minute icing encounter. The resultant water catch with
this encounter is substantially higher, as shown in Figure 2, than that based
on the maximum water catch for a single icing cloud which has an exceedance
probability of one in 1000 icing encounters. The use of this procedure also
neglects air traffic control procedures and meterological phenomena as to
duration of the icing condition

Although the different interpretations of the FAR Part 25 icing envelope have resulted in a substantial difference in design conditions, as shown by Figure 2, the resultant ice thicknesses have been remarkably similar. This is due in part to the calculation procedures which will be discussed later.

Theory of Ice Shapes

Ice shapes on airfoils are classified as "glaze" or "rime" although many ice shapes will be a mixture of the two. Rime ice is found at combinations of low temperatures and low liquid water contents. The water droplets freeze on impact resulting in a milky-white ice shape, Figure 3, dictated by the airfoil impingement characteristics in terms of water catch, distribution, and impingement limits. The drag and other aerodynamic effects of rime ice are much less severe than glaze ice because of the streamline form and therefore this type of icing is not considered in determining the airplane tolerance to icing.

Glaze ice forms at combinations of high liquid water contents and surface temperatures near freezing. Not all of the water droplets freeze on impact, but some run a short distance before freezing, resulting in a blunt or double horn ice shape as shown in Figure 4. This ice is usually clear since there is little or no air entrained in the ice. The upper surface horn acts as a spoiler, increasing drag and reducing lift. The lower surface horn usually has little effect because of low local air velocities. This ice shape, because of its "spoiler" action, can affect aerodynamic characteristics in terms of increased drag and decreased maximum lift coefficient. On highly swept airfoils, glaze ice tends to form as a series of discontinuous cup shapes due to the spanwise velocity component

The shapes and type of ice is dependent on the surface temperature, which is a complex function of airspeed, liquid water content, ambient air temperature, local flow field around the object and altitude. A correlation of ice shapes on a small 2 inch diameter unswept cylinder, with these parameters, is shown in Figure 5 where n is the freezing fraction defined in Reference 3 as that part of the water catch that freezes where it impinges. In general terms, rime ice is likely to occur at total air temperatures between 25 and 32 F. Between 10 and 25 F, a mixture of rime and glaze ice will occur with glaze predominantly in the stagnation area and for high liquid water content conditions.

Calculation Procedures

Procedures developed for determining the ice cap size by various manufacturers are based on calculating the airfoil water catch and adjusting this water catch or ice thickness into a typical mushroom ice shape. For rime ice, the ice thickness and shape can be calculated directly from the local water catch and ice density since the water freezes immediately on contact with the airfoil. The local ice thickness is related to the local water catch by:

$$\delta_c = \frac{\omega_\beta \theta}{\gamma_c} \tag{1}$$

Thus, a theoretical ice shape for rime ice can be estimated by calculating the local water catch for various positions in the impingement area by:

$$\omega_\beta = 0.38 \beta V \cos \Lambda \, \omega \tag{2}$$

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This procedure, with some modifications, was used for calculating the ice shapes for 707 and 727 series airplanes. To account for glaze icing and the effects of ice shape on water impingement, the following procedure was used. The maximum local collection efficiency, β max, was assumed to be 1.0, that is all of the water in the cloud in the path of the airfoil would impinge on the airfoil. This assumption was made to account for the effects of ice shape on water collection efficiencies. This assumption is approximately correct for small airfoils where the maximum local collection efficiency is near 0.8, but becomes overly conservative for larger inboard wings and stabilizers where the collection efficiencies are less than 0.5. The ice thickness calculated using β max equals 1.0 was then adjusted to give a typical mushroom or glaze ice shapes using the known impingement limits.

In other procedures, References 2 and 6, the ice shape is determined from the calculated total water catch from bare airfoil impingement data as:

$$\omega_c = 0.38 \, V \cos \Lambda \, E_m \, H/c \, C \, \omega \tag{3}$$

This water catch rate is in terms of pounds of ice per hour per foot of span. The cross-sectional area of the ice cap is then:

$$A = \frac{144 \, \omega_c \theta}{\gamma_i} \tag{4}$$

A double peaked glaze ice shape such as shown in Figure 6 is then drawn by trial and error which contains the calculated theoretical cross-sectional area.

The above calculation procedures only approximate the actual ice shape since accurate ice accretion data for most airfoils is not available. Also, water drop sizes and resultant collection efficiencies must be checked for the maximum water catch. Figure 7 shows a typical plot of the effect of drop size on collection efficiency and cloud liquid water content. This calculation will generally show that the maximum catch rate will occur with 20 to 25 micron droplets.

A correlation of measured ice shapes from icing tunnel tests with theoretical impingement parameters has been reported in Reference 4 (NACA TN 4151) for an unswept symmetrical four percent thick airfoil. The data in this report for mushroom ice plotted in a slightly different manner is shown in Figure 8. It indicates the measured maximum ice height is less than the theoretical height based on the maximum local water catch. This is not surprising since all of the impinging water does not freeze at the point of maximum collection efficiency under these icing conditions. Unfortunately, there is no similar published data for highly cambered swept airfoils. Therefore Boeing initiated a research program to obtain basic ice accretion data on two airfoils representative of the inboard wing and horizontal stabilizer configuration of typical current jet transport aircraft. This program was conducted in the NASA 6 foot by 9 foot icing tunnel at Cleveland, Ohio. From ice accretion data obtained in the test program, an empirical relationship was obtained which correlated ice accretion thickness and ice angles with theoretical impingement parameters. Use of these relationships allows the direct determination of ice shapes adjusted for any given icing and flight condition as well as for size and sweep of the airfoil.

The revised 737 inboard wing and 747 tail surface ice shapes have been determined from these data. These shapes show good agreement with the 707/727 ice thicknesses at the horizontal stabilizer tip. However, the ice accretion test data indicated a more blunt ice shape due to the effects of airfoil sweep than the "hammerhead" shape used in previous 707/727 flight test programs.

Since this procedure is substantially different than currently used in the aircraft industry, the test program and results are of interest and will be briefly discussed.

Ice Accretion Test Setup and Procedure

The models used in this study were chosen to represent the type of airfoils used on present-day commercial jet aircraft. Cross-sections of these airfoils are shown in Figure 9. One model, designated BAC 450, was typical of an inboard wing section with a 12.5 percent thickness ratio and 27.5 degree sweep angle. The other model, designated BAC 470, represented outboard wing and horizontal stabilizer sections with an eight percent thickness ratio and 40 degree sweep angle. These models, shown in Figure 10, have a 6 foot streamwise span and chord length and were mounted vertically in the Lewis icing tunnel at Cleveland, Ohio. Each model was fabricated from aluminum with six thermocouples and three electrical heater pads marked A, B, and C in Figure 10, bonded to the inner surface of the leading edge. The thermocouples were used to monitor the leading edge surface temperature during the icing runs and the heater pads were used to assist in removing ice samples.

Icing conditions in the tunnel were obtained and measured according to previously established techniques and calibrations. Icing cloud factors considered in this study were cloud liquid water content, icing time, airspeed, and temperature. Cloud droplet size could not be varied independently due to the limitations in the design of the tunnel spray system. As a result, the cloud droplet sizes increased with increased liquid water content and decreased with an increase in airspeed.

An icing run consisted of a 7.5 or 15 minute exposure of the model to a particular set of icing conditions and airfoil angle of attack. On completion of the prescribed icing time, the tunnel was stopped and measurements taken of the final ice shape. One or more sections of the ice cap, approximately six inches in length, were removed using the heater pads and the ice scraper used in Reference 4 tests. This scraper is steam heated and has an internal vacuum chamber to assist in drawing off the melted ice so as not to affect the sample weight or shape. The removed sections were then dipped repeatedly in liquid paraffin to create a mold of the ice shape. When the ice in the mold melted, it was poured into a beaker and weighed. The resultant cavity was then refilled with tap water which was then poured into the beaker and weighed to determine the specific gravity of the ice. Representative values of the specific gravity of the ice cap measured in this manner were from 0.75 to 0.91.

A replica of the ice sample was then made by pouring plaster of paris into the mold and later melting the wax in an oven.

Photographs of the equipment used to obtain plaster casts of the ice cap are shown in Figures 11 and 12. Sample plaster ice cap photographs are shown in Figures 13 and 14.

After the ice sample was removed from the mold, the cross-section of the
ice cap was photographed against a 1/4-inch wire mesh grid held normal to
the airfoil leading edge. A typical ice cap cross-section is shown in
Figure 15. Due to the difficulty in discerning the cross-sectional outline
from the photographs, all ice cap measurements were made from the plaster
casts as defined in Figure 16.

The majority of the ice samples were of the glaze type with typical double
horn protuberances. A few rime ice samples were obtained and the remainder
were mixtures of the two. Figure 17 shows representative ice shapes obtained
during this test program. The effect of the wing sweepback was most noticeable
in the discontinuous cup shapes formed in the spanwise direction as shown in
Figures 18 and 19.

--The separations were most prominent in the glaze ice formations and became
larger as the ice thickness increased. In those samples which tended toward
rime ice, the distance between individual cups decreased and in some cases
formed a continuous solid ice cap along the span of the airfoil.

The leading edge temperatures for the glaze icing runs varied between
25 and 29 F. Due to the relatively high thermal conductivity of the aluminum
leading edge (typical of current aircraft configurations) the chordwise
temperature gradient under the ice cap was negligible. Had the leading edge
been made of an insulating material, the ice cap could have had a significantly
different shape since the impinging water would see a warmer stagnation
point surface temperature. This would allow the water to flow further along
the surface before freezing. No attempt was made in this study to determine
the magnitude of this effect of material properties on ice shape.

Theoretical Impingement Characteristics

The theoretical impingement characteristics in terms of water drop
collection efficiency and impingement limits is shown in Figure 20 for the two
angles of attack considered in this study. These data were obtained from a
water droplet trajectory computer program and are plotted as a function of
a modified inertia parameter Xo. This parameter described and defined in
Reference 5 allows the impingement data taken for one flight condition to be
used for other flight conditions.

The projected height of the airfoil as shown in Figure 21 was used in this
study as the characteristic dimension for overall water drop collection efficiency
and in the ice shape correlation parameters.

This is in line with the impingement data as presented in Reference 2.

Ice Accretion Test Results

Correlation of the measured ice cap dimensions was based on the water
catch parameters which are indicative of the ice thickness. Under conditions
of glaze icing, the ice thickness is more a function of total water catch or

$$ S_i = f \left(\frac{\omega_c \theta}{\chi_i \Delta s} \right) \qquad (5) $$

where the total water catch is calculated from

$$ \omega_c = 0.38 \; V \cos \Lambda \; E_m \; H_k \; C \; \omega \qquad (6) $$

An icing parameter indicative of the ice thickness in terms of the water catch can be defined from the relationship in equation (5) as:

$$\frac{\omega c \theta}{\gamma_i \Delta S} = \frac{0.38}{\gamma_i} V \cos \Lambda \frac{E_m}{\Delta S/c} \frac{H}{C} \omega \theta$$

(7)

The ice density under glaze icing can be assumed relatively constant, and further, the term $E_m/\Delta S$ is a single-valued function for a given Ko value. Since ΔS is difficult to measure or obtain accurately and is a particular value for E_m, only the total colleciton efficiency was used in this correlation. Thus, the icing parameter indicative of a theoretical average ice thickness reduces to:

$$I = \frac{\omega c \theta}{\gamma_i \Delta S} \cong V \cos \Lambda \, \omega \theta \, E_m \left(\frac{H}{c}\right)^X$$

(8)

where X is the factor used to correlate angle of attack effects.

Measured ice thicknesses in terms of the stagnation, upper and lower ice cap protuberances are plotted against the icing parameter defined by equation (8) in Figures 22 and 23 for both the BAC 470 and 450 airfoils. The effect of angle of attack was resolved for the BAC 450 airfoil by raising the projected height to the fifth power. No factor was found necessary for the BAC 470 airfoil since the projected height to chord ratio (h/c) provided sufficient angle of attack correction. These factors are emperical for the range of the test data or from 0 to 4.5 degrees. However, some extrapolation beyond these limits is felt to be valid and within the accuracy of the test data.

These curves define the ice thicknesses, but not their relative positions. The angles, which the upper and lower pinnacle dimensions made with the geometric chord line, were measured and correlated in a similar manner. This correlation is shown in Figure 22 for the 470 airfoil. These data were not as orderly as the ice thickness data, but they provide a definite trend which is useful in defining the ice shapes. It is not recommended that this ice angle data be extrapolated much beyond the airfoil angles of attack from which the data was obtained without correlating impingement data.

The frontal heights obtained through these ice angles are maximum dimensions since the test data was obtained at or near maximum icing temperatures where the impinging water can run farther aft before freezing. The range of flight and icing conditions during holding or approach is within the test icing conditions, so these dimensions will also be valid for flight conditions.

Some significant trends are readily apparent from these curves obtained by this correlation (Figures 22 and 23). The most significant of these is the distinct reduction in slope, which occurs once the ice attains a thickness between 1-1/2 to 2 inches. This change in the slope is indicative of a reduced rate of growth for the ice shapes. This can be explained by the physics of the ice accretion. As the ice pinnacles associated with the glaze ice shape builds to these heights, the droplets impinging near the stagnation area become trapped and assisted by the spanwise velocity component of the swept wing freeze within the pinnacles instead of contributing to additional growth of the pinnacles. This is apparent in the more blunt ice shapes. For the larger ice shapes, the ratio of stagnation ice thickness to pinnacle heights $(\delta_{ST}/\delta_{US}, \delta_{ST}/\delta_{LS})$, approaches unity i.e.:

Icing Parameter I	$(\delta_{st})_n$	$(\delta_\omega)_n$	$(\delta_{st})_n / (\delta_\omega)_n$
3	.54	.76	.710
8	1.5	1.75	.857
20	2.33	2.61	.893

A comparison of the curves for the two airfoils also illustrates the influence of camber and leading edge radius on the maximum ice thickness. The BAC 450 airfoil, being blunter, has a larger actual ice accretion area. This resulted in a larger ice cap both in thickness and area over the less blunt highly cambered BAC 470 airfoil.

Application of Ice Shape Correlation Curves

Knowing the ice thicknesses, angles and impingement limits, an ice shape can be constructed which more closely duplicates icing of swept wing aircraft. Knowledge of the water drop trajectories impingement limits, and stagnation point will indicate where the ice shape should be relative to the airstream. This method will be illustrated for the 747 horizontal stabilizer shown in Figure 24. Also shown on this figure is the 707 horizontal stabilizer. The following flight design condition will be used, which is representative of that used on early 707 ice protection system delation studies:

Flight Conditions

θ	=	30 minute hold
ALT	=	15,000 ft altitude
V	=	377 mph True Airspeed
		(256 knots indicated airspeed)

Icing Conditions (FAR Part 25, Appendix C)

t_0	=	21 F Icing limit temperature (Ambient air temperature)
d_m	=	15 Micron drop diameter ("A" drop distribution)
F	=	150 Mile cloud
	=	0.266 g/m^3 cloud water content (150 mile cloud)

Airfoil and Impingement Data

Stab. Sta.	Angle of Attack	Sweep Angle	Chord Length	(H/C)* (Fig. 21)	(H/C)o* (Fig. 21)	Em (Fig. 20)
197.5	-2.38°	43°	260 in.	.095	.087	.020
410	-2.38°	43°	120 in.	.095	.087	.051

*Projected height for 0 degree angle of attack.

Knowing the impingement and flight conditions, the icing parameter, I, can now be calculated for the horizontal stabilizer station SBL 410 as:

$$I = V \cos \Lambda \, \theta \, \omega \, E_m \, (H/c)$$
$$= 377 \, (\cos 43°) \, (30) \, (.266) \, (.051) \, (.095)$$
$$I = 10.66$$

From Figure 22, the ice pinnacle heights are

Stab. Sta.	Icing Par. I	Ice Thickness (Normal to L.E.)			Ice Thickness Streamwise		
		Upper $(\delta_{us})_n$	Stag. $(\delta_{ST})_n$	Lower $(\delta_{ls})_n$	Upper $(\delta_{us})_s$	Stag. $(\delta_{ST})_s$	Lower $(\delta_{ls})_s$
197.5	4.1	1.0	.75	.99	1.37	1.025	1.36
410.	10.66	2.03	1.84	2.10	2.78	2.52	2.87

The ice angles can now be calculated from the ratio of ice thicknesses and Figure 22.

Stab. Sta.	Projected Ht. Ratio H_α/H_0	Ice Thickness Ratio $\left(\frac{\delta_{ST}}{\delta_{us}}\right)_n$ $\left(\frac{\delta_{ST}}{\delta_{ls}}\right)_n$		Upper Ice Angle Par. $\left(\frac{\delta_{ST}}{\delta_{us}}\right)\left(\frac{H_\alpha}{H_0}\right)^2$	Upper Ice Angle (Fig. 22) [1]	Lower Ice Angle Par. $\left(\frac{\delta_{ST}}{\delta_{ls}}\right)\left(\frac{H_\alpha}{H_0}\right)^2$	Lower Ice Angle (Fig. 22) [2]
197.5	1.091	.908	.878	1.08	26°	.736	-38.5°
410	1.091	.749	.752	..893	46°	.63	-44°

From the above ice angles and pinnacle heights, the resultant ice shape
is drawn as shown in Figure 25. The corresponding nominal 3 inch 707 ice
shape is also shown for reference based on the previous method whereby
all of the impinging water was assumed to collect on the airfoil.
Reasonably good agreement between the two methods is shown at the tip.
However, due to the lower collection efficiency at the inboard end of the
stabilizer, the latest calculation procedure gives a much smaller ice
thickness. This is in line with observations on natural icing flight
tests. The difference in the location of the ice caps is due to the
higher angle of attack of the less cambered 707 airfoil. This angle of
attack is determined from airplane trim requirements.

The method of determining ice shapes developed from the Cleveland test data
is applicable to any airfoil. Extrapolation from this data will generally
be satisfactory if the airfoils are similar. Consideration should be given
to obtaining ice accretion data if the airfoil is considerably different than
that tested here, or the surface is considered particularly critical from a
flight safety or performance standpoint.

No attempt was made in this test program to obtain ice shapes for extended
leading edge devices such as Kruger flaps or slats since these are normally
retracted during icing conditions. Ice shapes on extended leading edge devices,
if required, can and have been determined from estimated water collection
rates.

[1] Measured clockwise from geometric chord

[2] Measured counter-clockwise from geometric chord

EFFECTS OF ICE ON AIRPLANE PERFORMANCE

Wind Tunnel Testing

A preliminary evaluation of the effects of ice on airplane performance and stability is usually obtained from wind tunnel testing with ice shapes attached to the unheated airfoil sections. Wind tunnel test results showing the effect on the lift coefficient and pitching moment curves of a typical Boeing jet transport are shown in Figure 26. At angles of attack associated with level flight, the ice has little effect other than to increase drag. This effect on airplane drag, with flaps extended, is shown in Figure 27. As indicated in this figure, the drag increase due to ice, increases sharply with landing flap settings. It is under these conditions where ice has the most effect on airplane performance.

Flight Testing

The final check of the airplane tolerance to icing is usually obtained through flight testing with simulated ice shapes unless previous data is available or sufficient to determine aerodynamic characteristics or penalties. These ice shapes are made up from a styrofoam core attached to a fiberglas glove which fastens over the airfoil leading edge. Epabond or body putty is applied over the styrofoam ice shape to give a rough outside texture. A typical ice shape used on the 727 horizontal stabilizer is shown in Figure 28. Exact simulation of the cup-like protrusions, shown in Figure 19, is not considered necessary since the horn or ice pinnacle acts as the spoiler which results in airflow separation. In some conditions, the cup-like protrusions could act like vortex generators and promote reattachment of the airflow to the airfoil. Therefore, only the external ice shape is duplicated, including the sharpness of the ice pinnacles.

The flight test evaluation by FAA pilots includes basic airplane performance data as well as flight characteristics for the following at the most critical center of gravity:

1. Demonstration of stalls, sideslip, heading changes under engine out conditions and windup turns.

2. Demonstration of elevator effectiveness through pushovers starting at 1.4 V_g to flap placard speeds and down to 1.1 V_g.

3. Demonstration of high speed handling characteristics including lateral control evaluation, pushovers, and pull ups.

4. Flap retraction and extension during simulated go-around.

5. Demonstration of approach and cruise stability through trimming the airplane and stabilizing on airspeed through elevator only.

This latter condition usually is the most difficult in that the aircraft must have sufficient elevator control available to attain speeds between 1.1 V_g and 1.7 V_g for approach without retrimming the aircraft. Using a movable horizontal stabilizer for trim usually means more elevator control available,

especially for fully powered or directly controlled elevators. Aircraft
with fixed stabilizers have experienced severe nose down pitching due to loss
of elevator control from the effects of ice on the stabilizer leading edges.
This is usually associated with a change in flap positions or speed, which
requires the tail surfaces to work harder. These surfaces already being
at a high lift coefficient condition "stall out" resulting in loss of elevator
effectiveness.

Performance Penalties

In addition of evaluating flight characteristics, airplane performance must
also be considered due to the ice effects on drag. Figure 29 shows a typical
drag polar obtained from flight tests on a Boeing jet transport. These data,
along with wind tunnel test data, are used to evaluate the flaps down approach
and landing climb performance as required for use in the flight manual.
Figure 30 shows the effect of ice in terms of climb gradient and aircraft
gross weight. The increment between the ice on and ice off curves must be
subtracted from the aircraft maximum allowable landing weight. On short haul
aircraft, where the maximum landing weight is near the takeoff weight, this
weight decrease can come out of the payload. This performance penalty has been
assessed anytime icing conditions enroute are anticipated, and the destination
airport temperature is below the temperature at which the ice will shed.

ICE SHEDDING CHARACTERISTICS

Introduction

Ice shedding characteristics are also of interest in determining the
need for airfoil ice protection since they determine the frequency of application
of the airplane performance penalty. This penalty in terms of the airplane
maximum landing weight is presented in the performance section of the FAA
flight manual in terms of destination ambient air temperature. To determine
this maximum allowable air temperature requires a knowledge of the airplane
descent flight conditions, the resultant airfoil surface temperature under the
ice cap and the surface temperature at which the ice sheds.

These time-temperature relationships for the descent flight profile are
illustrated in Figure 31. As the airplane starts the descent phase from
cruise conditions, the ambient air temperature starts to increase due to the
temperature-altitude lapse rate as shown by the lower line in Figure 31. The
total temperature, upper line, follows directly as a function of velocity.
The surface temperature starts to follow the air temperatures but lags due to the
thermal inertia of the ice and airplane leading edge. At some point in the
descent, the frictional heating (ram temperature rise) is sufficient to melt
the ice-metal bond and the ice sheds. During this time, the surface temperature
either remains constant or climbs slowly, due to the latent heat of fusion
being supplied to the ice-metal interface. After shedding, there is an abrupt
rise in surface temperature as insulation due to the ice is lost and the airfoil
is heated by aerodynamic heating effects.

Ice Shedding Temperature Equations

The airfoil surface temperature under the ice cap must be known in order to determine the time at which the ice will shed during a descent. This temperature differs from the total or recovery temperature during descent because of the ice cap thermal capacitance (thermal lag). A method of predicting the time the ice will shed has been developed by Boeing, using laboratory test data in conjunction with a heat transfer analysis. This method has been verified using data from a 737 natural icing flight test.

The airfoil surface temperature for that portion of the descent before the ice begins to melt is determined from using classical heat transfer equations (Newtonian heating) with constants determined from laboratory tests. Laboratory tests are also used to determine the surface temperature during that portion of the descent where the ice starts to melt. Figure 32 shows the heat balance on the ice cap and airfoil, during steady state conditions at holding and during the descent.

The process whereby the ice cap and ice metal interface is heated during descent is closely approximated by Newtonian heating except for the unsteady boundary condition, due to the temperature lapse rate. Figure 33 shows the classical heat transfer equation for a step change in recovery temperature and the equation derived for this study which represents a linear or ramp temperature change. The derivation of this equation is shown in Figure 34 in terms of temperature differentials between the recovery temperature and airfoil ice surface temperature. The driving force for ice shedding is the recovery temperature which varies with time as:

$$t_r = t_{r_0} + W\theta \tag{9}$$

Where W is the warm-up rate which is a function of descent rate, temperature lapse rate and airplane velocity.

The effects of sublimation of the ice cap is felt in lower airfoil surface temperatures as shown in Figure 32. This occurs also during the descent phase and is accounted for empirically in the calculation procedure by correcting the calculated surface temperature by the relationship shown in Figure 32. The inclusion of the sublimation effect in the differential equation shown in Figure 34 was not considered since this would result in a non-linear differential equation difficult to solve. This is due to the ice sublimation being a function of ambient air temperature and altitude as well as surface temperature. This sublimation effect is small compared to the change in airfoil-surface temperature during descent, especially near 32 F, and therefore, will not significiantly affect the ice shedding analysis.

The time constant τ and Δ Test (established temperature lag) were determined for an iced airfoil from icing tunnel data. Figure 35 is a typical time-temperature history of an ice airfoil tested in the Boeing icing tunnel. The temperatures of the ice cap airfoil interface follows, but lags the tunnel air temperature. As the ice cap begins to melt, there is a leveling out of the surface temperature (point of inflection). This inflection point and the time of ice shedding are readily determined from the test data.

Icing Tunnel Data

Figure 36 is a plot of several icing tunnel runs and illustrates the relationship between warm-up rate and the established temperature lag. From these data, values for established temperature lag (Δ Test) equal to W/γ and the time constant γ can be determined. The warm-up rate in degrees F per minute numerically equals the established lag in degrees F for three inch ice shapes. Therefore, the time constant γ is equal to 1.0 min.[-1]. These data used in the solution to the heat transfer equation enable the surface temperatures to be calculated up to a point where melting of the ice begins.

To determine the time it takes the ice to shed from the point where it starts melting (inflection point), icing tunnel data were plotted as warm-up rate versus ice shedding time and inflection temperature. These data are also shown in Figure 36 and are used directly for determining the inflection temperature and the ice shed times for a given flight warm-up rate.

Calculation Procedure

As previously shown in Figure 32, the equation for determination of the temperature under the ice cap is:

$$\frac{\Delta T}{\Delta_{Test}} = 1 + \left(\frac{\Delta T_{ro}}{\Delta T_{est}} - 1\right) e^{-\gamma\Theta} \tag{10}$$

This equation is valid until the ice cap begins to melt. The laboratory test data indicates that ΔTest is numerically equal to the warm-up rate and the time constant γ is equal to one. The warm-up rate, W, is the slope of the recovery temperature line OR

$$W = \frac{t_{r_2} - t_{r_1}}{\Theta_2 - \Theta_1} \tag{11}$$

The results of equation (10) need to be adjusted for the effects of ice cap sublimation using the equation:

$$\Delta T_{SUB} = 2.9 \ L_s \ \frac{e_{so} - e_{ow}}{P_o} \tag{12}$$

This use of equation (12) from References 2 and 3 was checked using 737 flight test data. It will res. t in a reduction of the surface temperature under the ice cap by approximately 3 F during the low temperature cruise flight conditions. Sublimation cooling is less than 1 F at temperatures near the point of ice shedding.

After the ice cap begins to melt, (at the inflection point) the laboratory test data in Figure 36 are applied directly to determine the shedding time.

For a typical descent profile, as shown in Figure 37, the ambient air temperature profile is drawn starting with the desired destination field temperature and temperature lapse rate. Although the normal lapse rate is 3-1/2 F/1000 feet, a conservative value of 5.5 F/1000 feet has been used in

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Boeing certification work. The total temperature and recovery temperature profiles can now be added based on the given airplane speed schedule. Recovery temperature profiles are based on:

$$T_r = t_{amb} + 0.9(t_{TOTAL} - t_{AMB})$$ (13)

where 0.9 is the recovery factor for turbulent flow.

Surface temperatures are calculated starting from the initial point of descent where the airfoil temperature under the ice cap is the recovery temperature minus the temperature difference due to sublimation from equation (13). At a calculated surface temperature of 32 F or greater, the ice will start to melt. Figure 36 must then be used to determine the inflection point time.

It is desirable to have the ice shed at or above 1500 feet or before final approach. Thus, the inflection temperature must be reached prior to 1500 feet by the amount of the ice shed time. Various landing field temperatures, airplane speeds, or descent profiles may be assumed to obtain this objective.

Application

Applying these curves and equations to a 737 descent profile flown during a natural icing flight test (Figure 38) shows the predicted and actual ice shedding times. The actual flight test data notes indicate that 90 percent of the ice was shed 30 seconds after the first ice shed. The predicted time for all ice shedding using the method developed here was 45 seconds after the first ice was observed to have shed during the natural icing flight test. This shows the method to be conservative.

Figure 39 shows the time temperature profile resulting from application of the above method to the descent profile of Figure 37 when utilizing a conservative lapse rate of 5.5 F/1000 feet. The resultant destination airport temperature below which the ice accretion penalty must be applied is 44 F.

It is conceivable, with increasing traffic, that descent profiles will be used which will result in more severe conditions than presently considered. To assure flexibility of descent profiles, as necessary, it is desirable to consider operating procedures to be established for a range of destination temperatures.

The descent profile required at John F. Kennedy when an airplane comes in over LaGuardia is a case in point. See Figure 40. Here the airplane must descent from 10,000 feet to sea level in a very short distance. It is possible that this descent profile would require a descent rate of 3000 feet per minute down to the start of approach at 1500 feet. The required destination airport temperature for this profile would be 59 F using the above method. If the US Standard lapse rate of 3-1/2 F/1000 feet were used (which is more normal), the required destination airport temperature would be 45 F.

In the John F. Kennedy (JFK) case, the gross weight penalty could be eliminated between airport temperatures of 45 F and 59 F by controlling the descent rate, by limiting the time for descent or by using a different flap setting which is allowed for long runways. At JFK, use of a higher landing flap setting would eliminate the requirement for shedding the ice to meet the climb gradients. This configuration would be established at the time of dispatch into the possible icing condition.

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If the runway is so short that higher landing flaps cannot be used, it will be necessary to specify at the time of dispatch to an airport with temperatures between 46 and 60 F that a minimum descent rate be used below a given altitude. For example, 1500 ft/min below 5000 feet. These operational procedures would be specified in the Flight Manual.

The procedures for determining the need for airfoil ice protection may be summarized as follows:

1. Calculation of a realistic artificial ice shape preferable using test ice accretion data.

2. Evaluation of the effects of this ice shape on airplane handling characteristics and performance through wind tunnel and flight testing.

3. Determination of airplane performance penalties and/or operating procedures.

4. Determination of when these penalties must be applied through calculation of ice shedding characteristics.

If the airplane handling characteristics are satisfactory and the performance penalties tolerable then the airfoil ice protection system is not required or can be eliminated.

CONCLUSIONS

The determination of the need for airfoil ice protection requires the establishment of the large ice accretions on airplane performance. The ice accretion test program conducted by Boeing provides a basis for accurately determining the size and shape of these ice accretions. This has been accomplished by correlating the measured ice cap dimensions with theoretical impingement parameters. Use of this correlation will enable the calculation of artificial ice shapes representative of those which would accrete on the airplane during a severe icing encounter.

Boeing icing tunnel testing and analysis have shown that ice shedding characteristics can be analytically determined for a given descent profile. Use of the procedures illustrated here will enable the determination of the time and altitude at which the ice will shed or what destination airport temperature is required to assure ice shedding prior to approach.
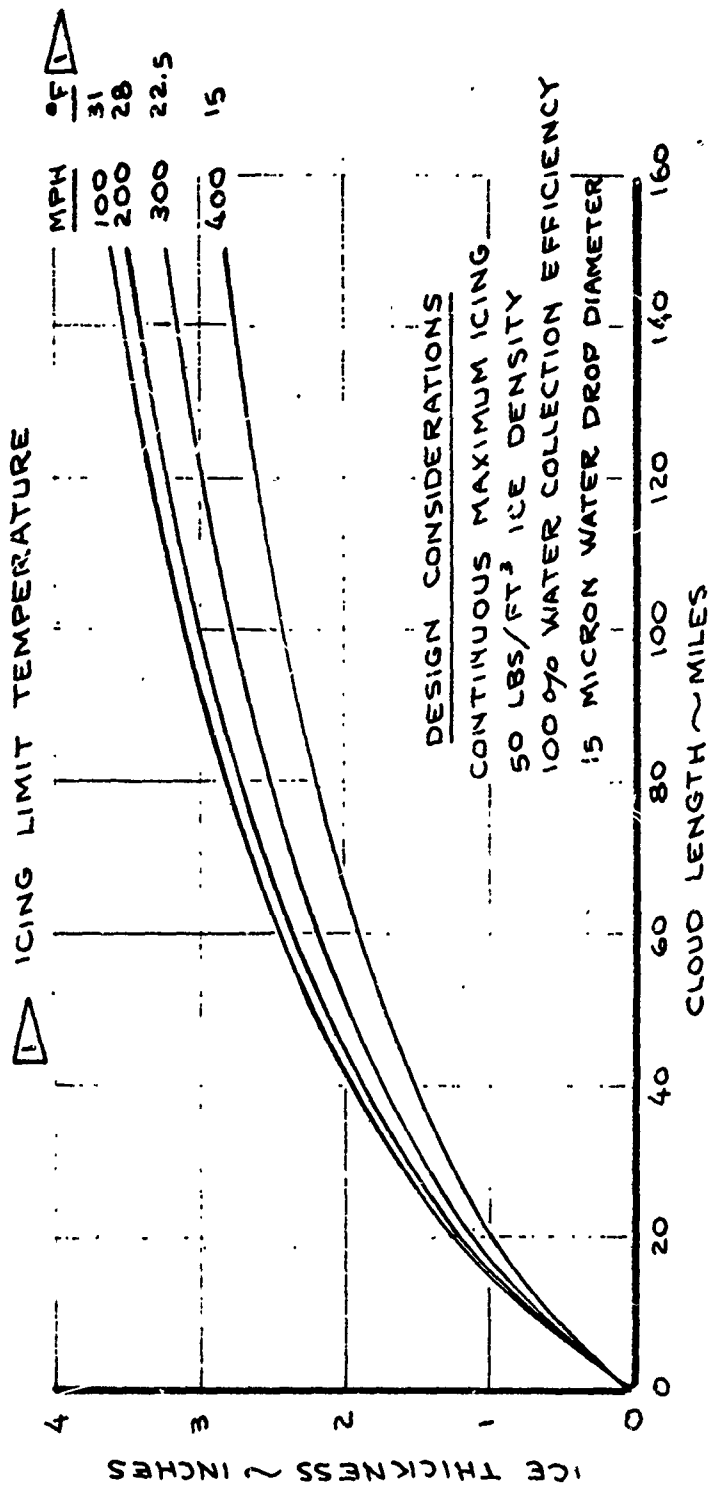
NOMENCLATURE

Symbol	Unit	
A		Ice cap cross-sectional area
β	Dimensionless	Local water catch efficiency
c	Feet	Airfoil chord length
C	BTU/°F	Thermal capacitance
E_m	Dimensionless	Total water collection efficiency
H	Feet	Airfoil projected height
I		Icing parameter defined by Equation (7)
γ	Dimensionless	Recovery factor
S	Feet	Impingement distance
t_{amb}	°F	Ambient air temperature
t_r	°F	Recovery air temperature
t_{total}	°F	Total air temperature
t_{ro}	°F	Initial recovery temperature
ΔT	°F	Temperature differential between recovery temperature and airfoil surface temperature
ΔT_{est}	°F	Established temperature lag between recovery temperature and airfoil surface temperature
T_o	°F	Initial temperature lag between recovery temperature and airfoil surface temperature
U	BTU/hr °F ft^2	Overall heat transfer coefficient
V	Knots	Free stream velocity
W	°F/min	Recovery air temperature warm up rate
ω_β	lbs/hr-ft^2	Local water catch rate
ω_c	lbs/hr-ft. span	Total water catch rate
θ	Hours or minutes	Icing time
S_i	Feet	Ice thickness
ω	Grams/cubic meter	Cloud liquid water content
Λ		Airfoil Sweep angle
γ_i	lbs/ft^3	Ice density
τ		Time constant $= \dfrac{U}{C}$

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5. Sherman, P., Klein J. S. and Tribus, M.; "Determination of Drop Trajectories by Means of an Extension of Stokes Law," University of Michigan, Engineering Research Institute, Contract AF18(600)-51, 1952.

6. Stoffel, G. J., "Determination of the Necessity of Tail Ice Protection on Commercial Jetliners," Proceedings of the 5th Annual National Conference on Environmental Effects on Aircraft and Propulsion Syst s, 1965.

EFFECT OF CLOUD LENGTH AND
AIRPLANE SPEED ON ICE THICKNESS
FOR ONE INCH DIAMETER ROD

⚠ ICING LIMIT TEMPERATURE

DESIGN CONSIDERATIONS

CONTINUOUS MAXIMUM ICING
50 LBS/FT³ ICE DENSITY
100% WATER COLLECTION EFFICIENCY
15 MICRON WATER DROP DIAMETER

MPH	°F
100	31
200	28
300	22.5
400	15

ICE THICKNESS ~ INCHES

CLOUD LENGTH ~ MILES

FIG. 1

274

EFFECT OF AIR SPEED ON ICE THICKNESS
FOR A ONE INCH DIAMETER ROD

FIG. 2

275

TYPICAL RIME ICE FORMATION ON SWEPT AIRFOIL.
BOEING ICING TUNNEL PHOTO

FIG. 3

CALC				REVISED	DATE
CHECK					
APPD					
APPD					

THE **BOEING** COMPANY
RENTON, WASHINGTON

PAGE
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TO 973 D R3
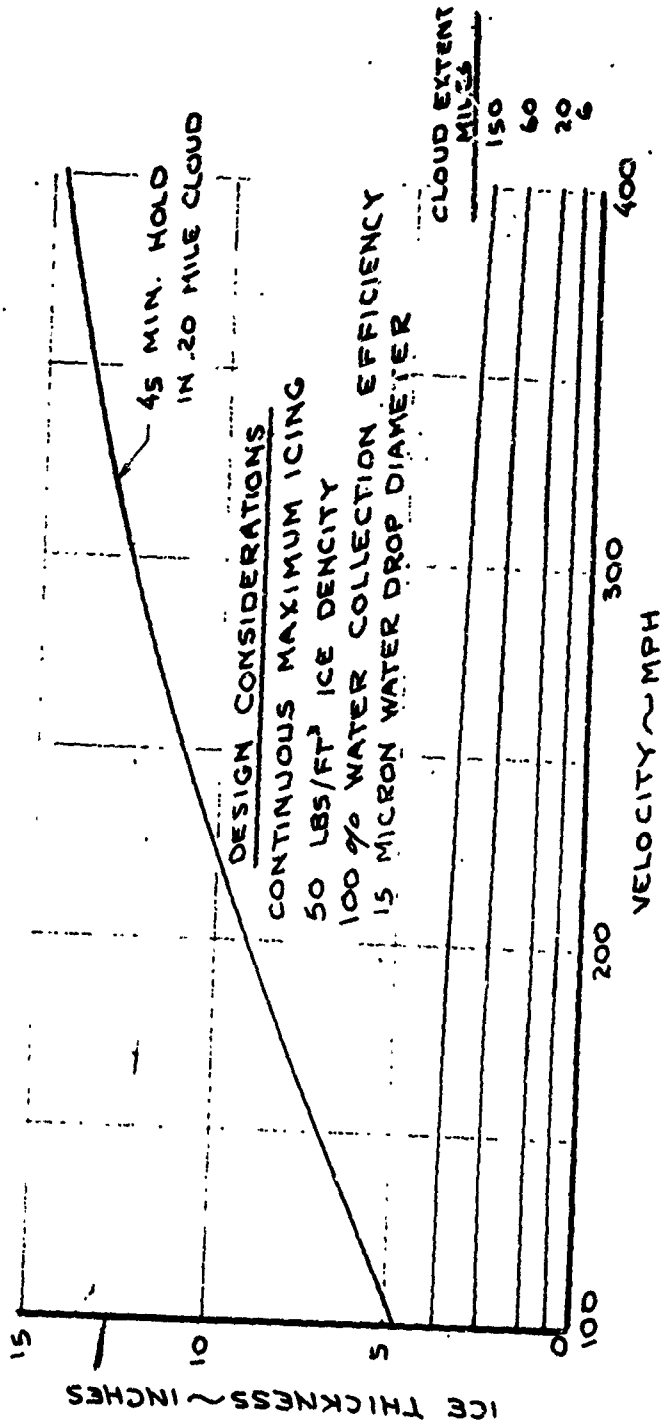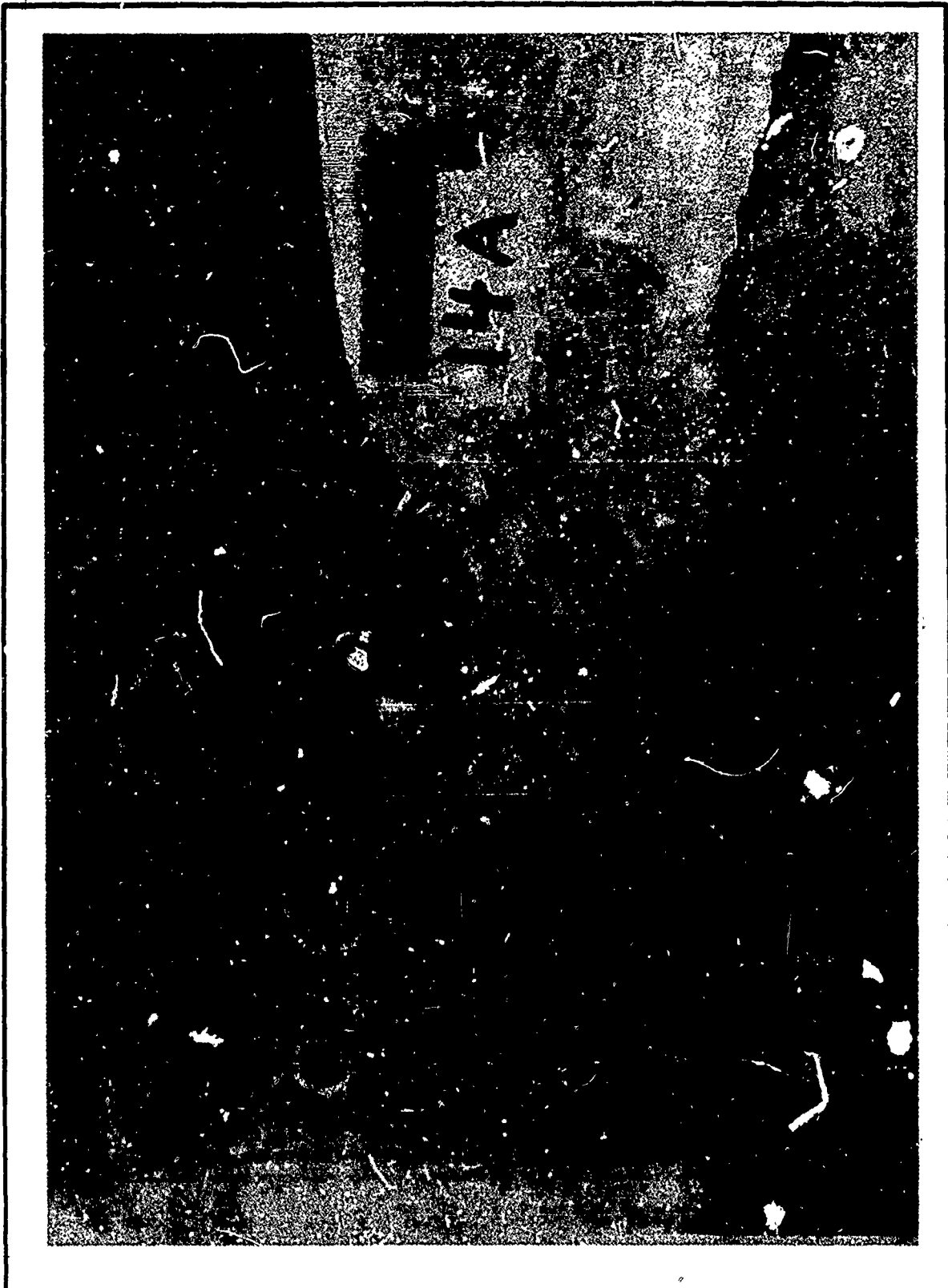
CALC			REVISED	DATE	TYPICAL GLAZE ICE SHAPE	FIG. 4
CHECK					ON SWEPT AIRFOIL	
APPD					CLEVELAND ICING TUNNEL PHOTO	
APPD					THE **BOEING** COMPANY	PAGE
TO 973 0 R3					RENTON WASHINGTON	277

TYPICAL GLAZE ICE SHAPE ON SWEPT AIRFOIL — CLEVELAND ICING TUNNEL PHOTO

ICE SHAPE TYPES AS A FUNCTION OF SPEED AND AMBIENT TEMPERATURE

FIG. 5

278
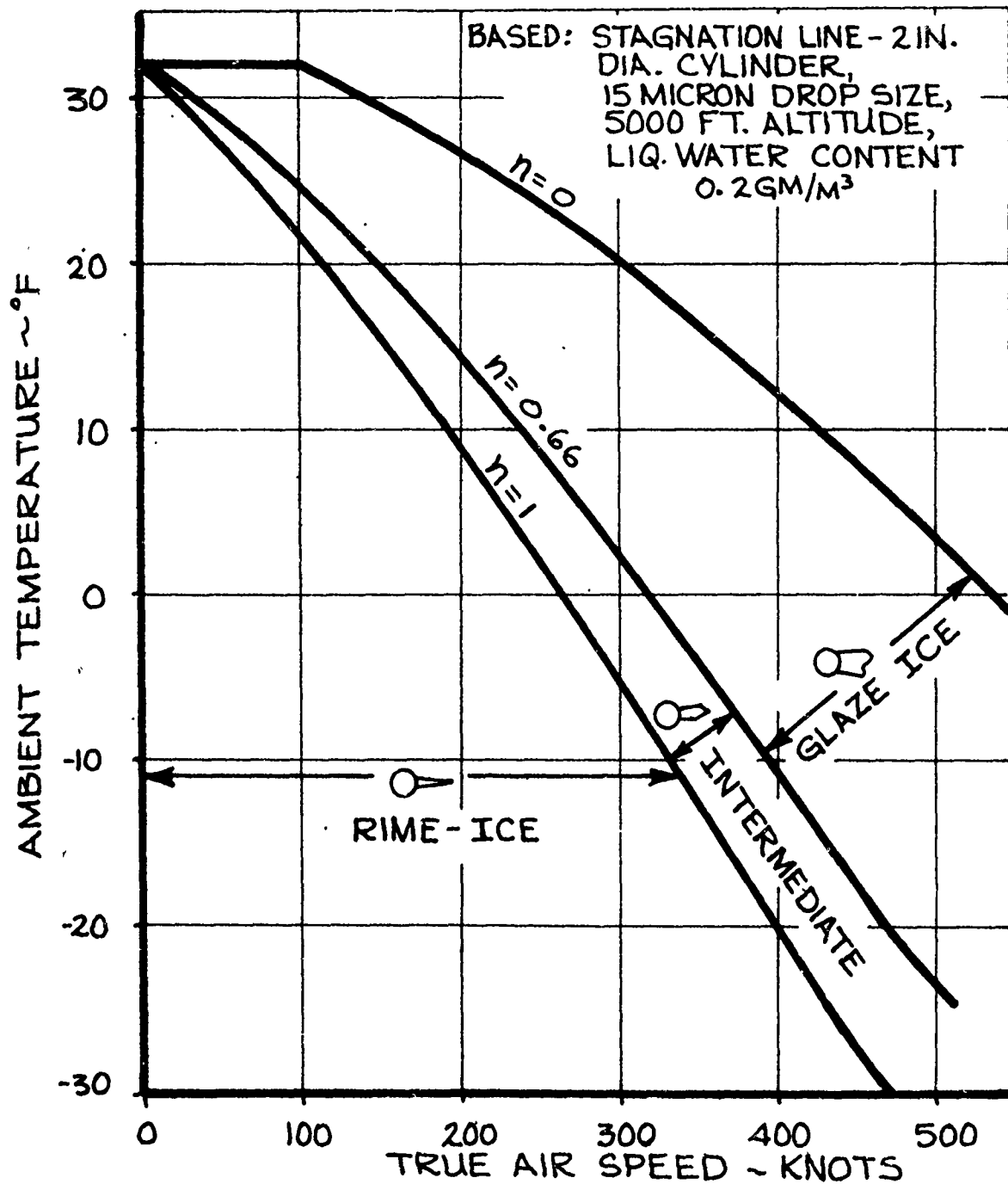
ICE CAP CALCULATION EQUATIONS

RIME ICE

THE LOCAL ICE THICKNESS IS CALCULATED FROM:

$$\mathcal{F}_i = \frac{W_\theta \, \theta}{\mathcal{F}_i} \quad (1)$$

WHERE:

$\mathcal{F}_i$ = ICE THICKNESS, FT
W = LOCAL WATER CATCH RATE, LBS/HR-FT^2
θ = ICING TIME, HRS
$\mathcal{F}_i$ = ICE DENSITY, LBS/FT^3

THE LOCAL WATER CATCH IS DEFINED BY:

$$W_\theta = 0.38 \, \beta V_{\cos} \Lambda \, \omega \quad (2)$$

WHERE:

W = LOCAL WATER CATCH RATE, LBS/HR-FT^2
β = LOCAL COLLECTION EFFICIENCY, DIMENSIONLESS
V = FREE STREAM VELOCITY, KNOTS
Λ = SWEEP ANGLE
ω = CLOUD LIQUID WATER CONTENT, g/m^3

ICE CAP CALCULATION EQUATIONS

GLAZE ICE

THE TOTAL WATER CATCH RATE IS DEFINED BY:

$$W_c = 0.38 \, E_m \, V \cos\Lambda \, \frac{H}{c} \, c \, \omega \qquad (3)$$

WHERE:

W_c = TOTAL WATER CATCH, LBS/HR-FT. SPAN
E_m = TOTAL WATER COLLECTION EFFICIENCY, DIMENSIONLESS
V = FREESTREAM VELOCITY, KNOTS
Λ = SWEPT ANGLE, DEGREES
H = AIRFOIL PROJECTED HEIGHT, FT
c = AIRFOIL CHORD LENGTH, FT
ω = CLOUD LIQUID WATER CONTENT, g/m^3

FOR A KNOWN WATER CATCH RATE, THE THEORETICAL CROSS-SECTIONAL AREA OF THE ICE IS CALCULATED FROM:

$$A = \frac{144 \, W_c \, \theta}{\gamma_i} \qquad (4)$$

WHERE:

A = CROSS-SECTIONAL AREA, FT^2
θ = ICING TIME, HRS
γ_i = ICE DENSITY, LBS/FT^3

280

TYPICAL ICE SHAPES FOR UNPROTECTED TAIL SURFACES FROM REF. 2
45-MIN. HOLD AT 5,000 FT. ALTITUDE

5.4 SQ. IN. CROSS-SECTIONAL AREA →

2.5 IN.

2.7 IN.

2.7 IN.
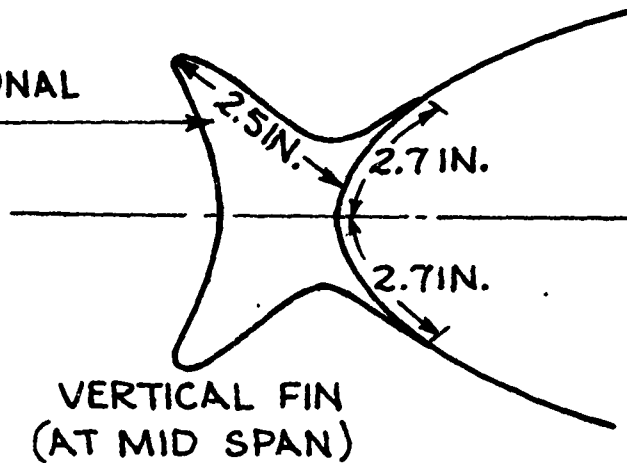
VERTICAL FIN
(AT MID SPAN)

4.8 SQ. IN. CROSS-SECTIONAL AREA →

2.9 IN.

1.3 IN.

0.7 IN.
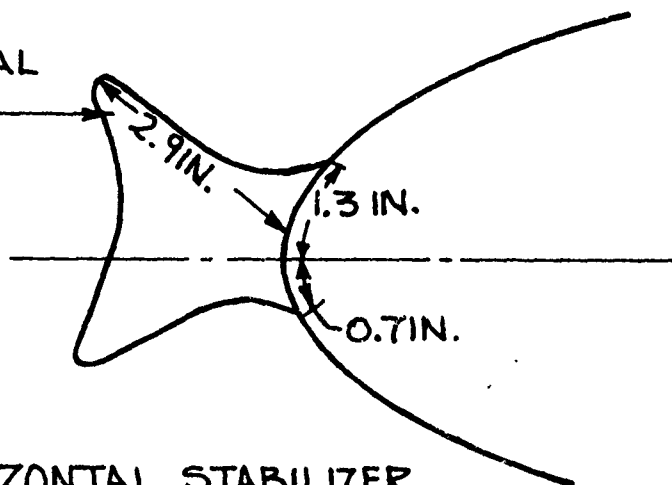
HORIZONTAL STABILIZER
(AT MID SPAN)

FIG. 6

EFFECT OF DROP SIZE ON WATER CATCH PARAMETERS HOLDING FLIGHT SPEEDS
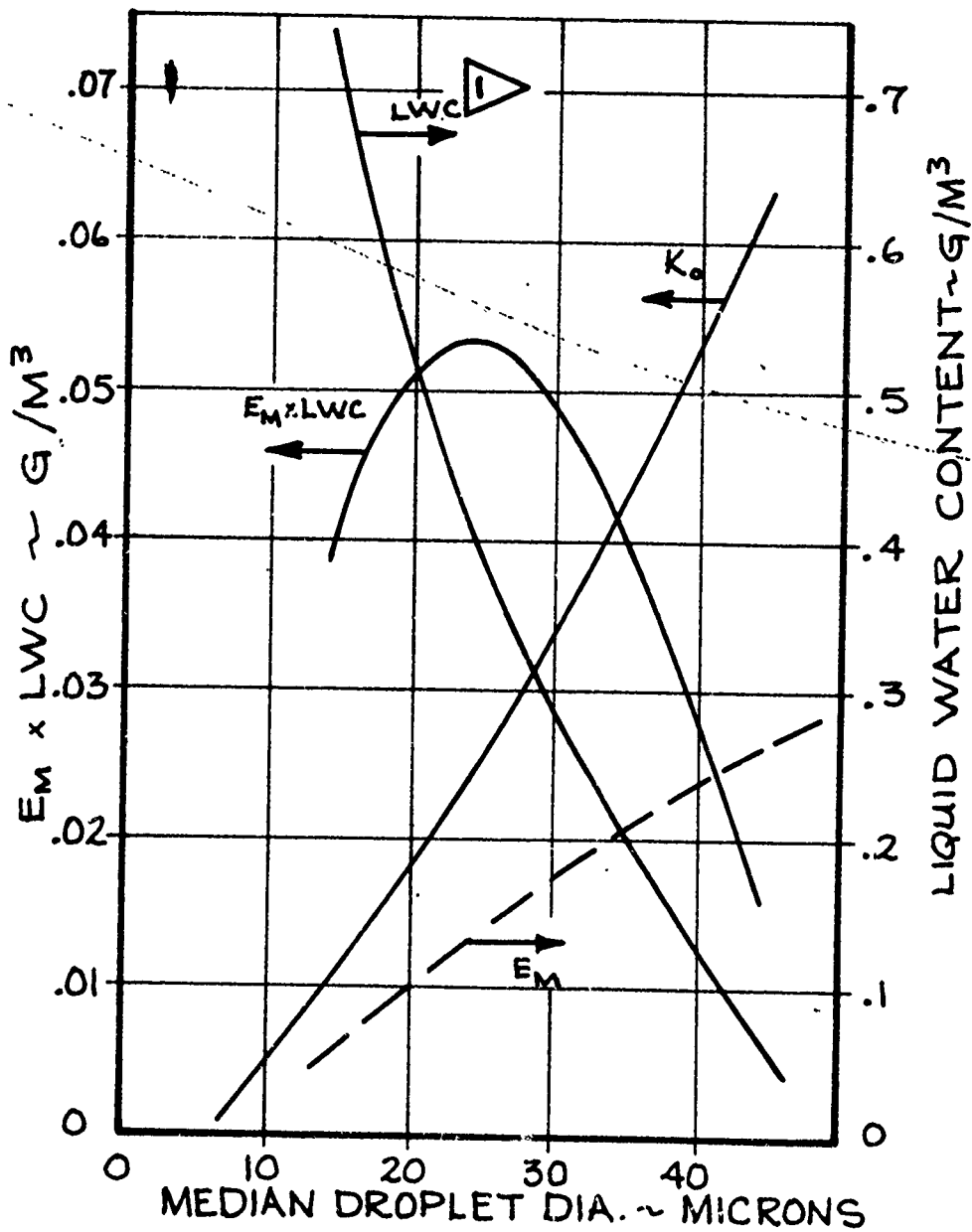
FIG. 7

CORRELATION OF ICE HEIGHT WITH THEORETICAL IMPINGEMENT UNSWEPT 4% THICK AIRFOIL

283
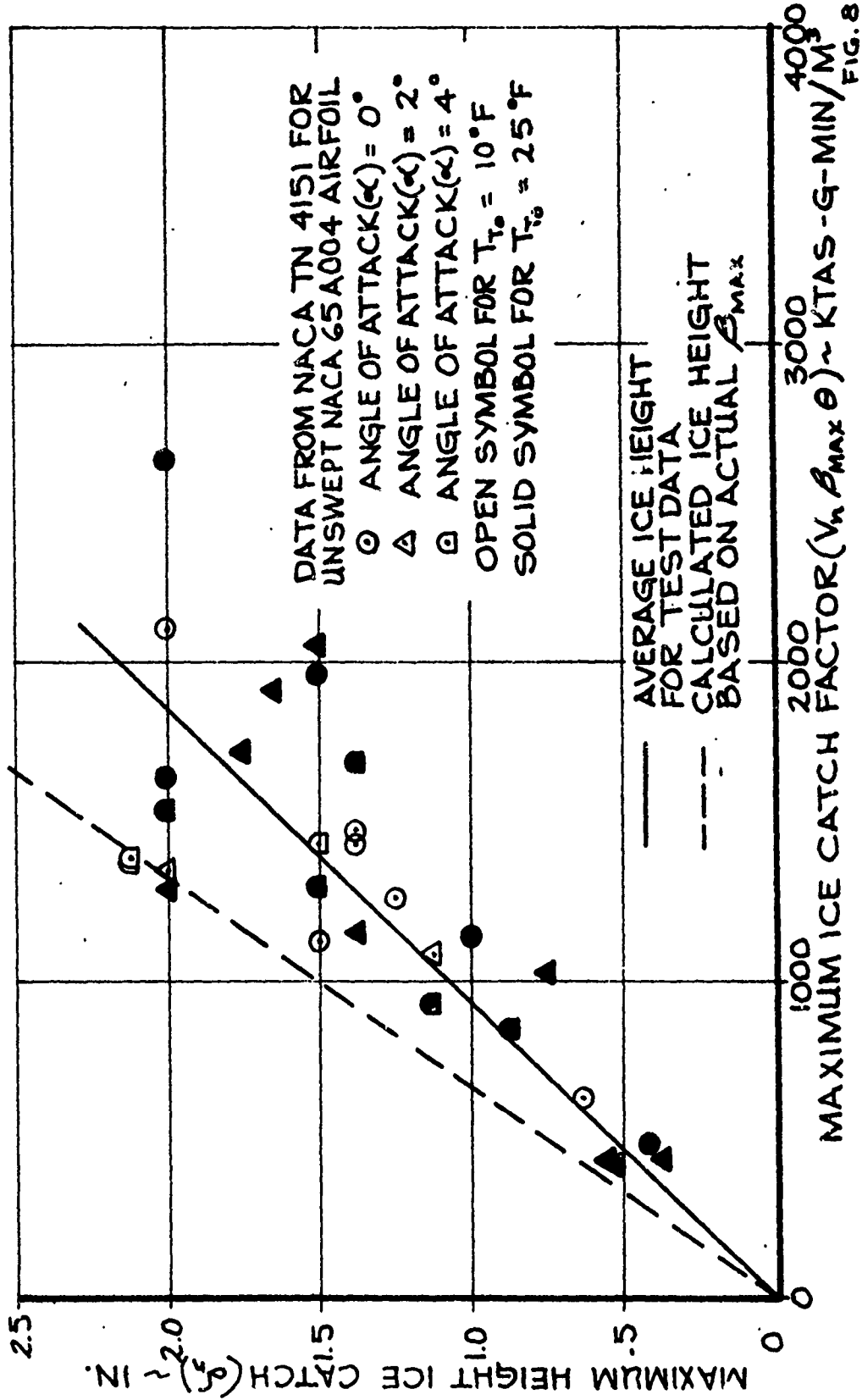
AIRFOIL CROSS - SECTION
STREAMWISE DIRECTION

GEOMETRIC CHORD LINE

BAC 470 (L.E. SWEEP 40°)

GEOMETRIC CHORD LINE

BAC 450 (L.E. SWEEP 27.5°)

THICKNESS ~ % CHORD

LENGTH ~ % CHORD

FIG. 9

284

6A73470-3

BAC 470 AIRFOIL

BAC 450 AIRFOIL

ZONE A
ZONE B
ZONE C

C-ANICAL
ENTAL CHAMBER
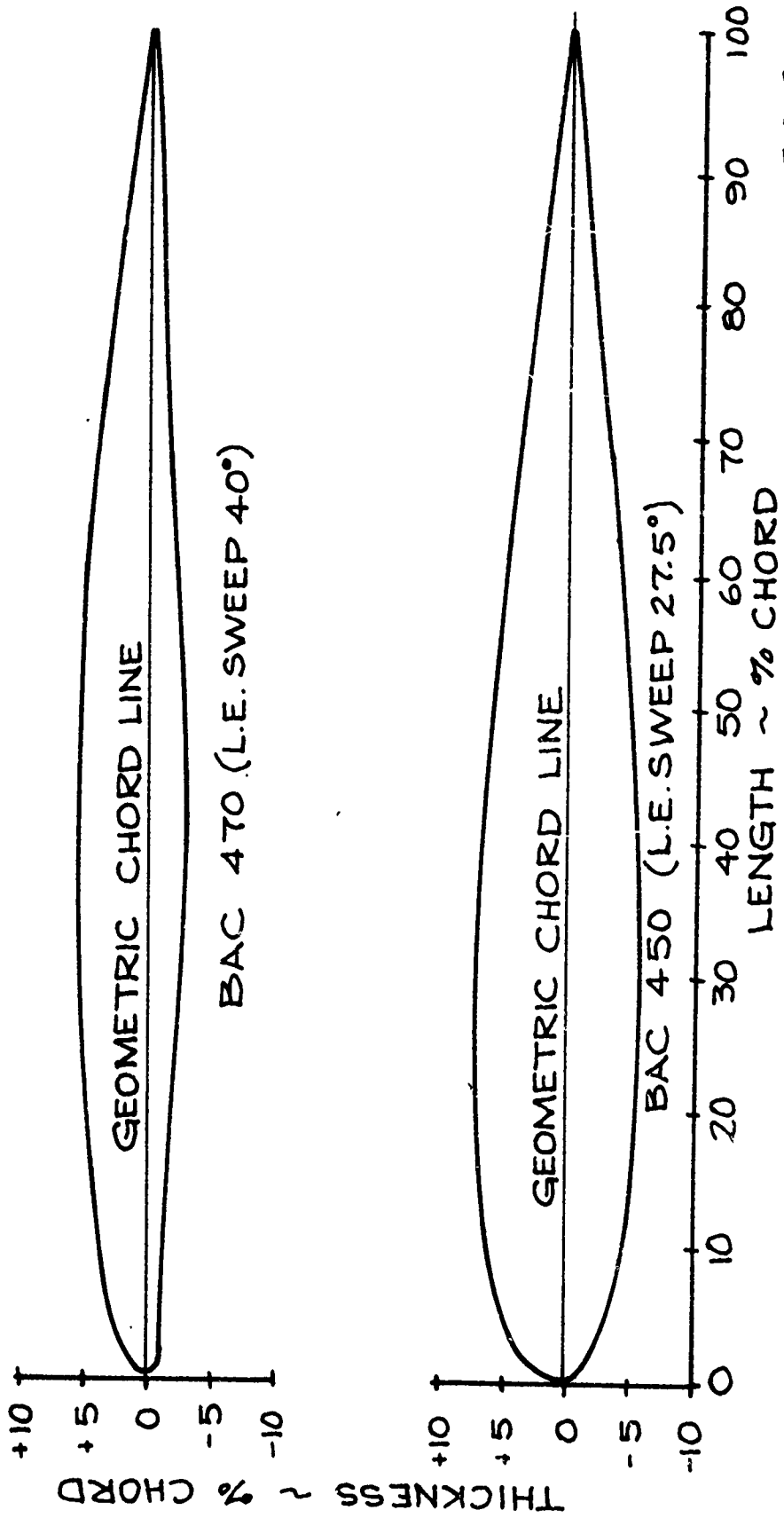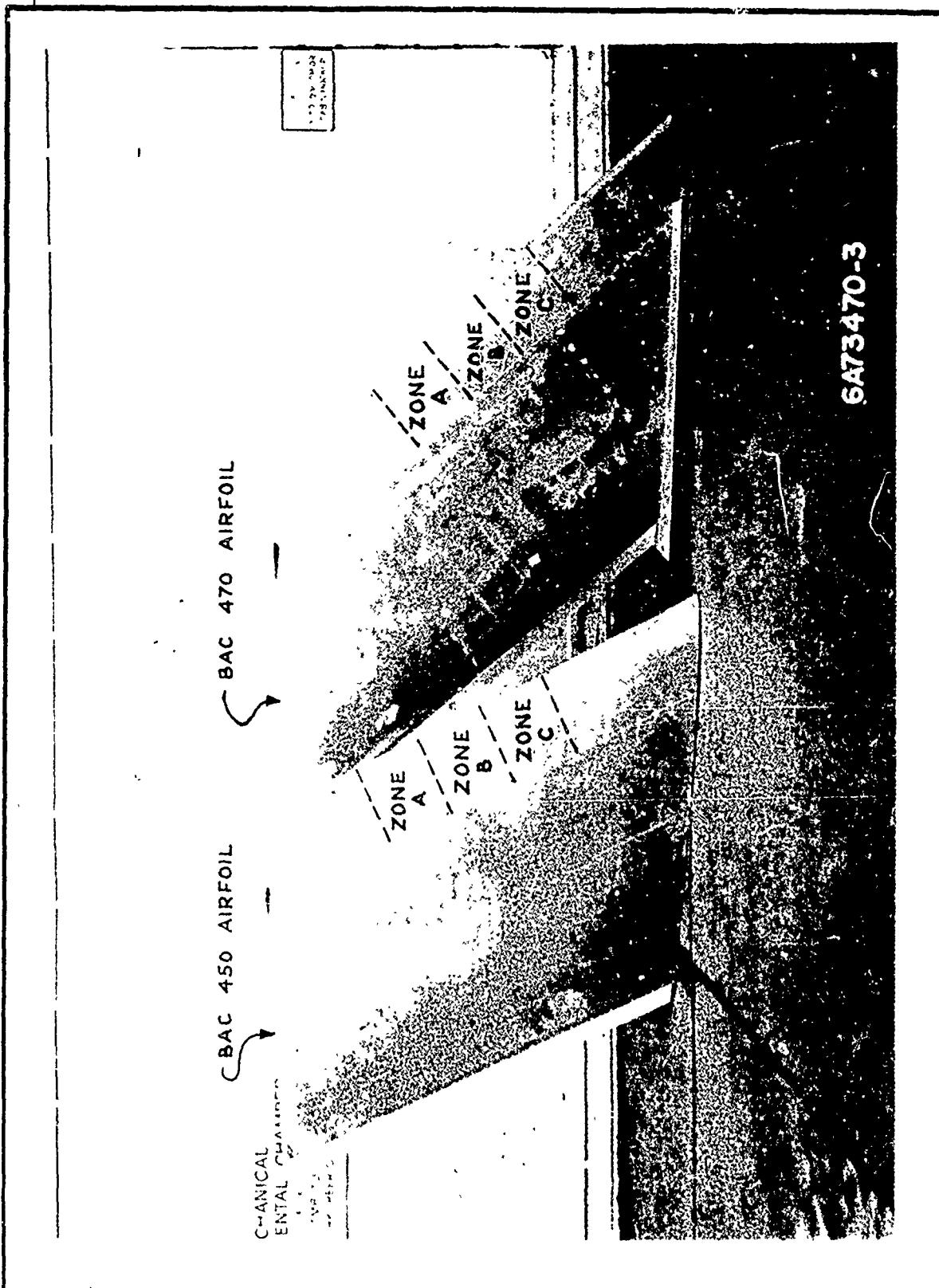
CALC				REVISED	DATE	ICE ACCRETION TEST MODELS	FIG. 10
CHECK						BAC 450 AND BAC 470	
APPD							
APPD						THE *BOEING* COMPANY	PAGE
						RENTON, WASHINGTON	285

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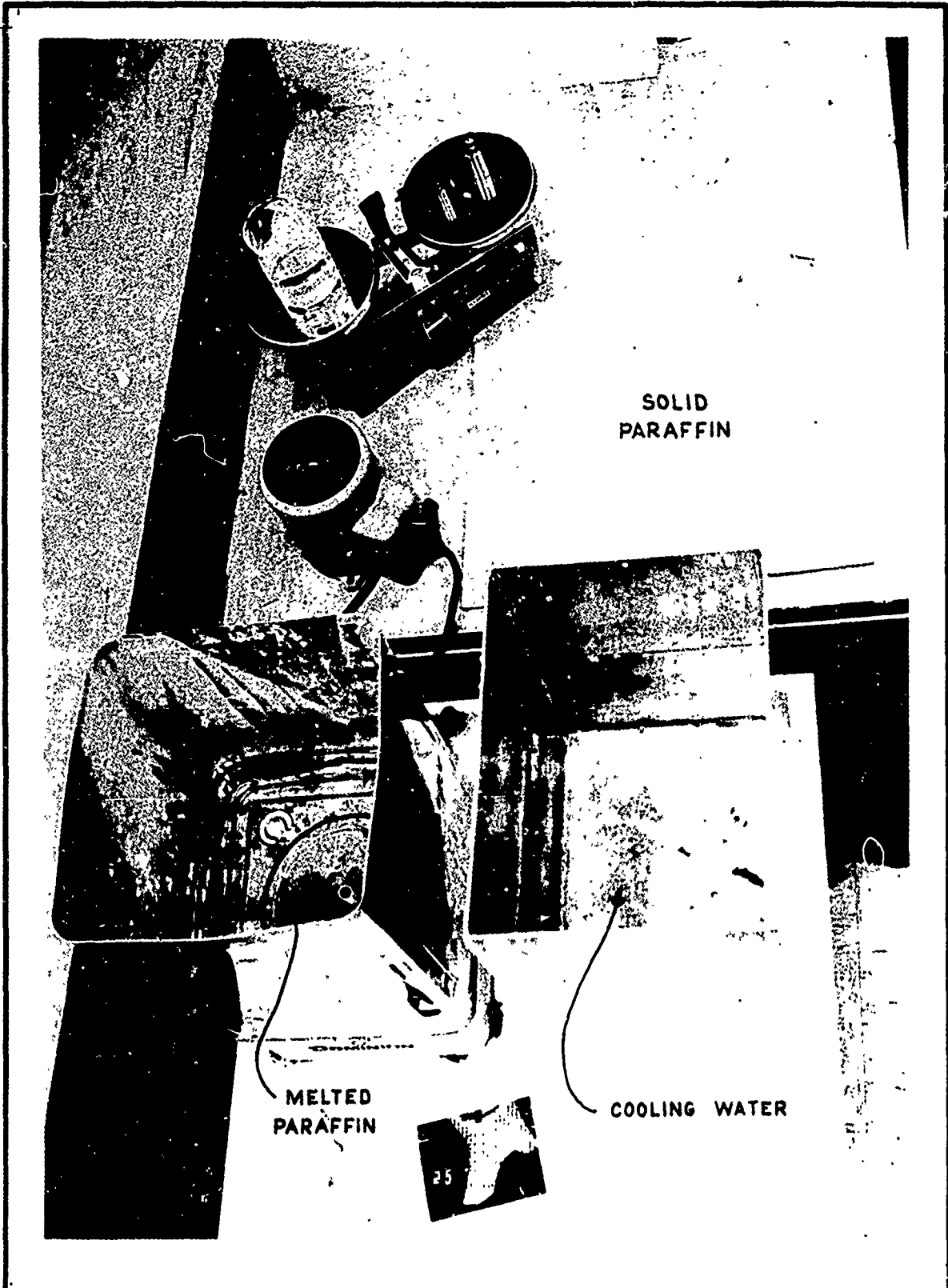
SOLID
PARAFFIN

MELTED
PARAFFIN

COOLING WATER

CALC			REVISED	DATE	TEST EQUIPMENT FOR	FIG. 11
CHECK					WEIGHING AND OBTAINING	
APPD					ICE SHAPE MOLDS	
APPD					THE **BOEING** COMPANY	PAGE
					RENTON, WASHINGTON	286

TEST EQUIPMENT FOR WEIGHING AND OBTAINING ICE SHAPE MOLDS

THE *BOEING* COMPANY
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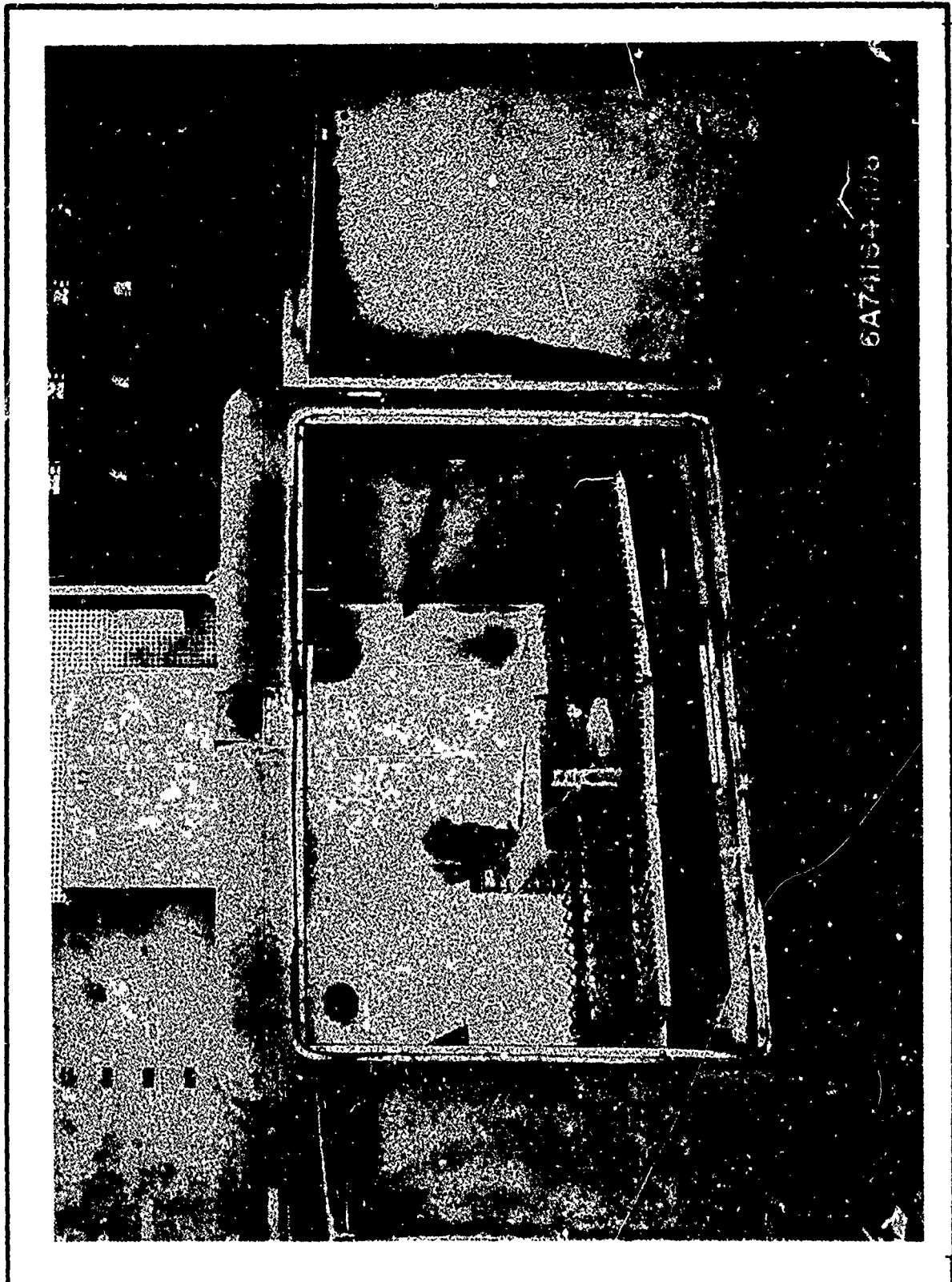
MELTING PARAFFIN FROM PLASTER ICE CAST

FIG. 12

CALC			REVISED	DATE
CHECK				
APPD				
APPD				

THE **BOEING** COMPANY
RENTON, WASHINGTON

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6A74164-109

CALC				REVISED	DATE	COATING ICE CAP WITH	FIG. 13
CHECK							
APPD						MELTED PARAFFIN	
APPD						THE *BOEING* COMPANY	PAGE
						RENTON, WASHINGTON	288

TD 973 D.R3
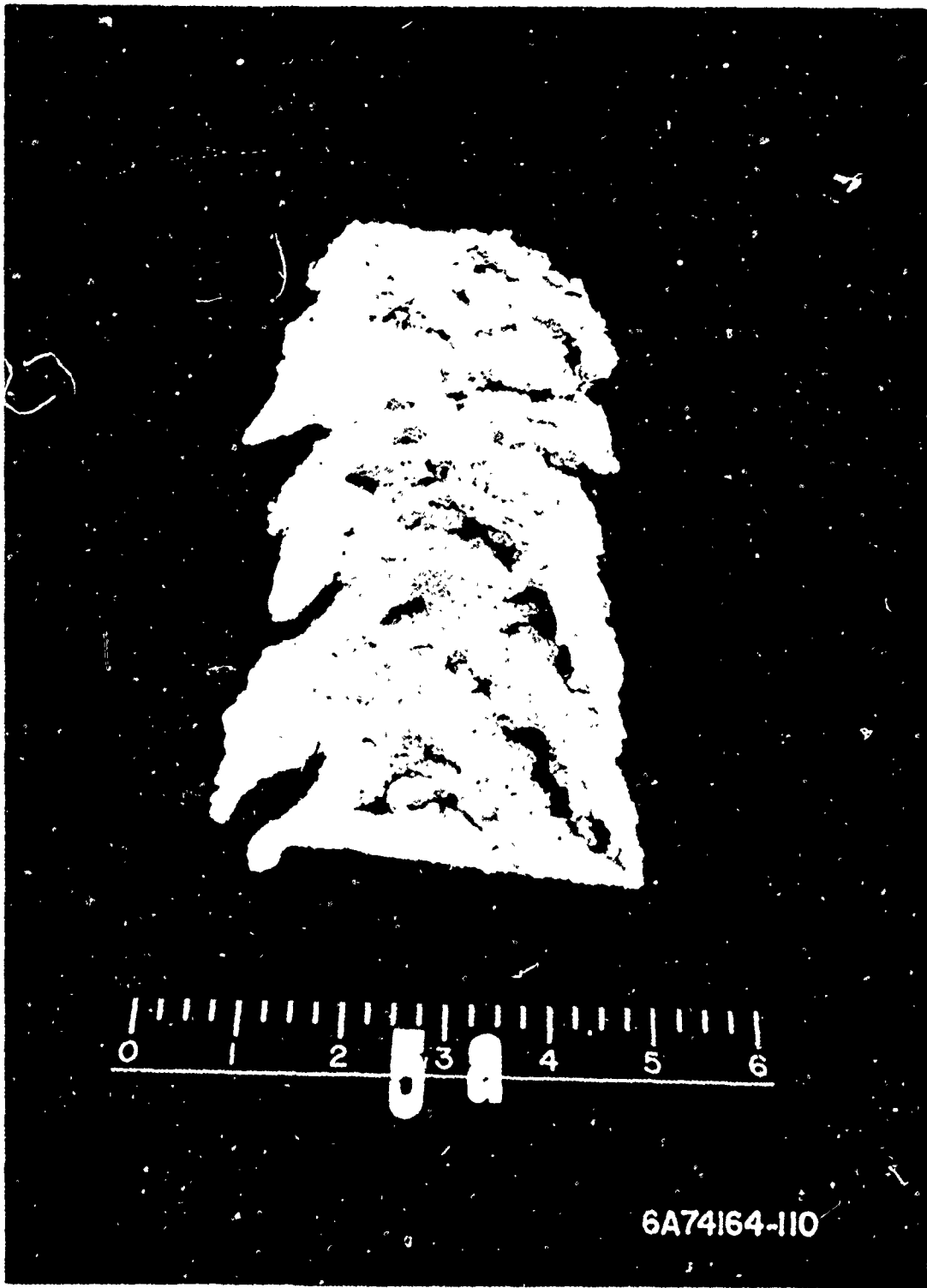
6A74164-110

CALC			REVISED	DATE	SAMPLE PLASTER ICE CAST	FIG. 14
CHECK						
APPD						
APPD					THE *BOEING* COMPANY	PAGE
					RENTON, WASHINGTON	289

TD 073 D R3
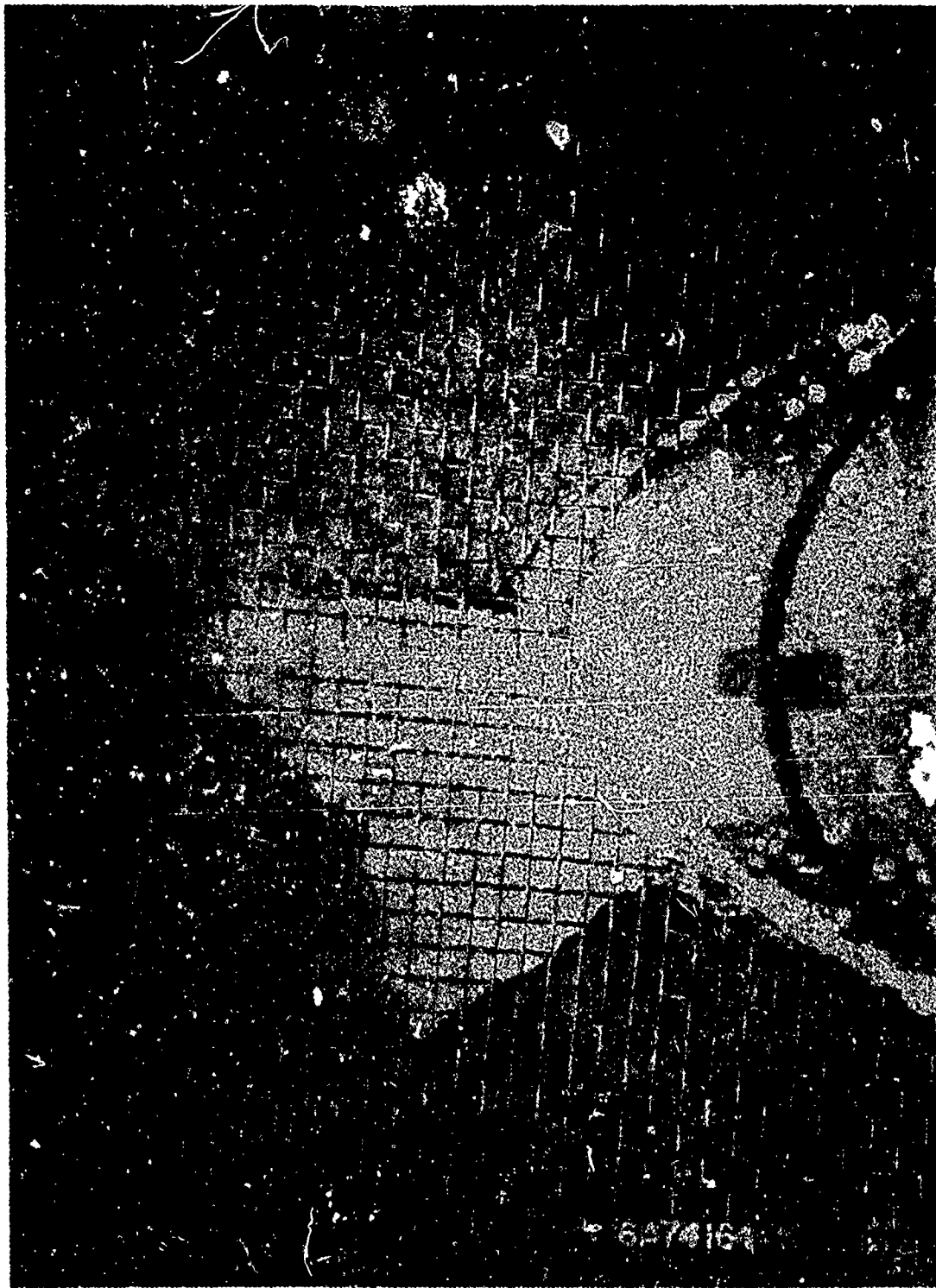
CALC			REVISED	DATE	INSTALLATION OF WIRE GRID	FIG. 15
CHECK					OVER THE ICE CAP	
APPD						
APPD					THE **BOEING** COMPANY RENTON, WASHINGTON	PAGE 290

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CHORD LINE

UPPER ICE
SURFACE THICKNESS

STAGNATION
STREAMLINE

STREAMLINE THICKNESS

LOWER ICE
SURFACE THICKNESS

6A74214-8

CALC			REVISED	DATE	PLASTER ICE CAP REPLICAS	FIG. 17
CHECK						
APPD						
APPD					THE **BOEING** COMPANY RENTON, WASHINGTON	PAGE 292

6A74164-130

CALC			REVISED	DATE	GLAZE ICE SHAPE	FIG. 18
CHECK					BAC 470 AIRFOIL	
APPD					SIDE VIEW	
APPD					THE **BOEING** COMPANY RENTON, WASHINGTON	PAGE 293

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CALC			REVISED	DATE	GLAZE ICE SHAPE	FIG. 19
CHECK					BAC 470 AIRFOIL	
APPD					FRONTAL VIEW	
APPD					THE **BOEING** COMPANY	PAGE
TD 973 D-R3					RENTON. WASHINGTON	294
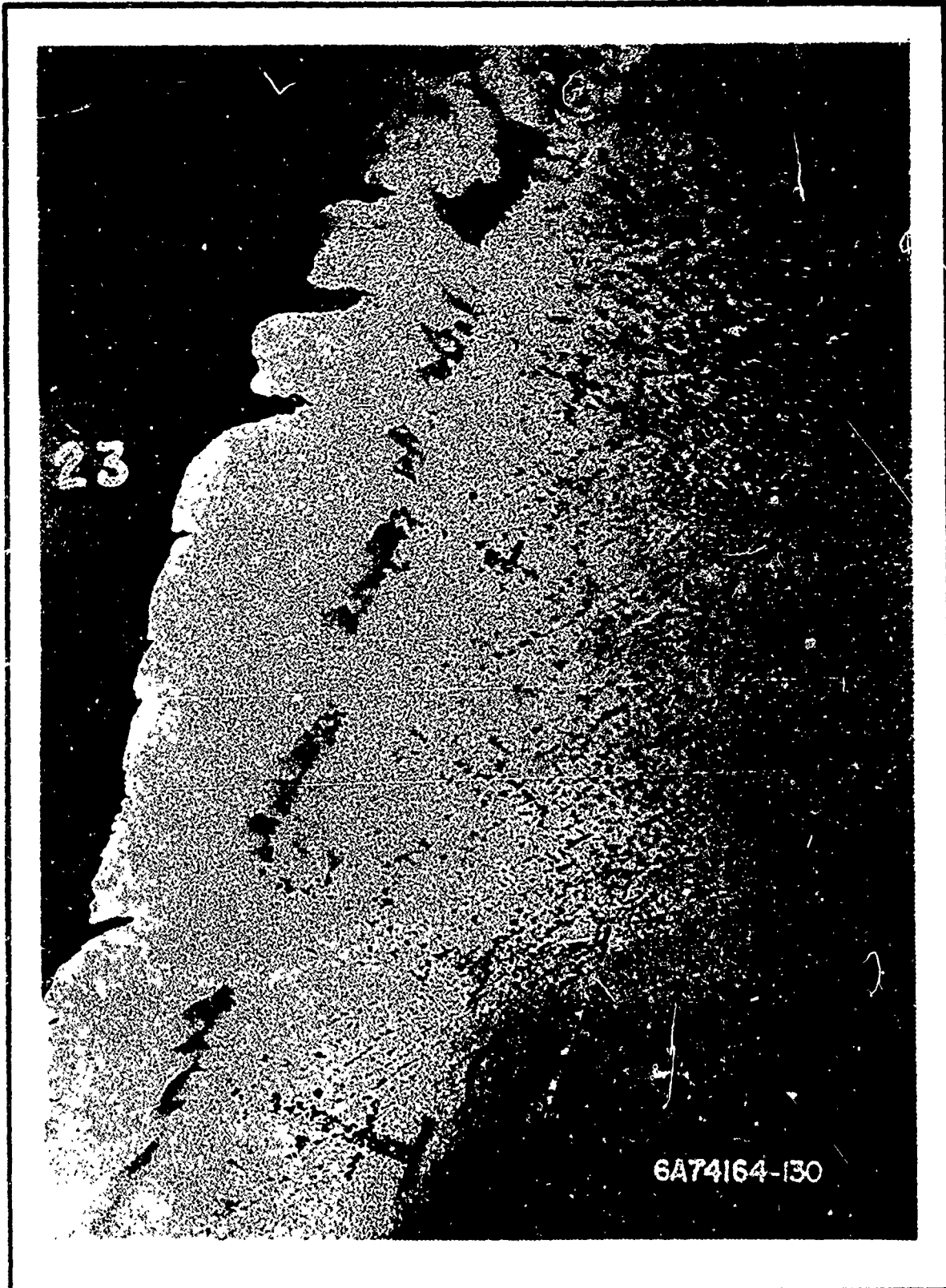
GLAZE ICE SHAPE
BAC 470 AIRFOIL
FRONTAL VIEW

TEST AIRFOIL IMPINGEMENT CHARACTERISTICS

FIG. 26
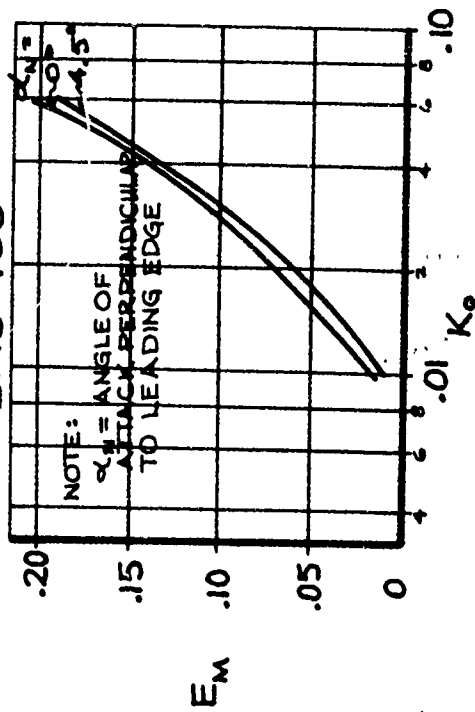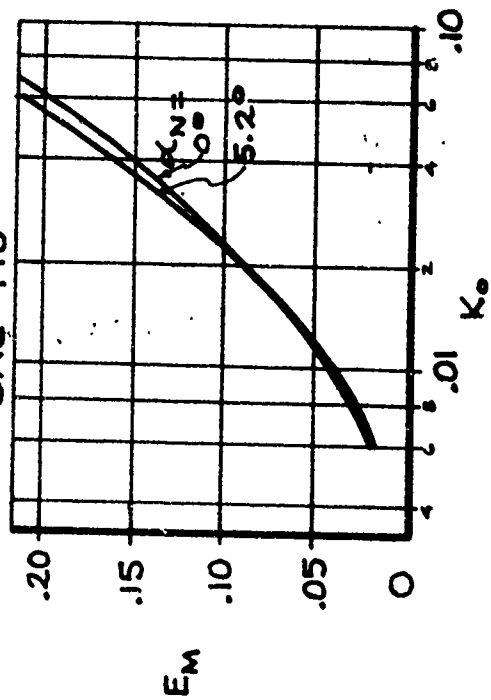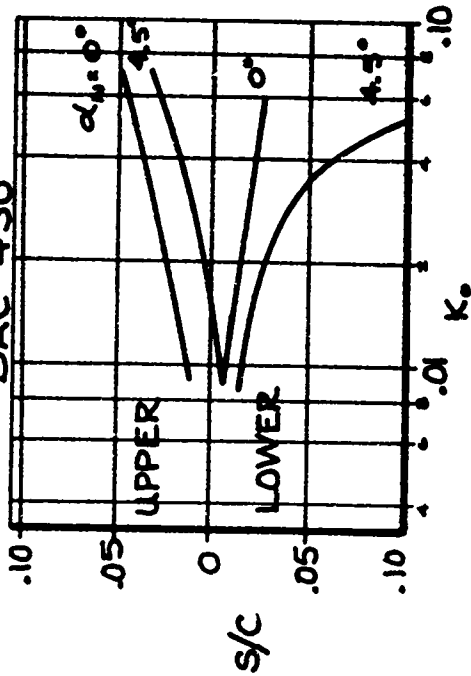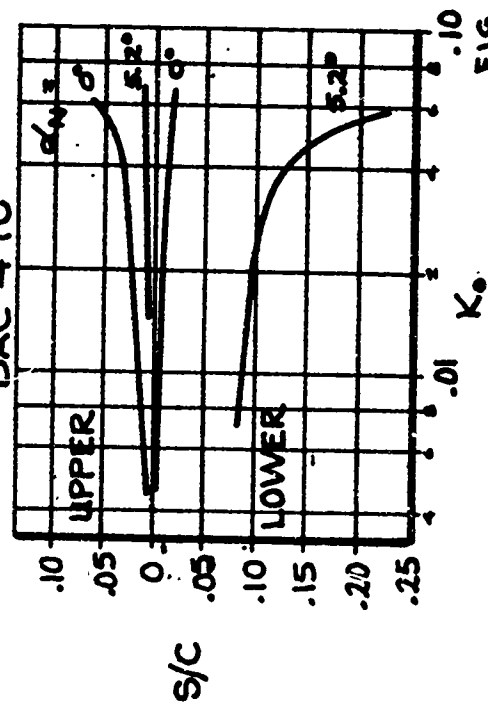
AIRFOIL PROJECTED HEIGHT
BAC 450 AND 470
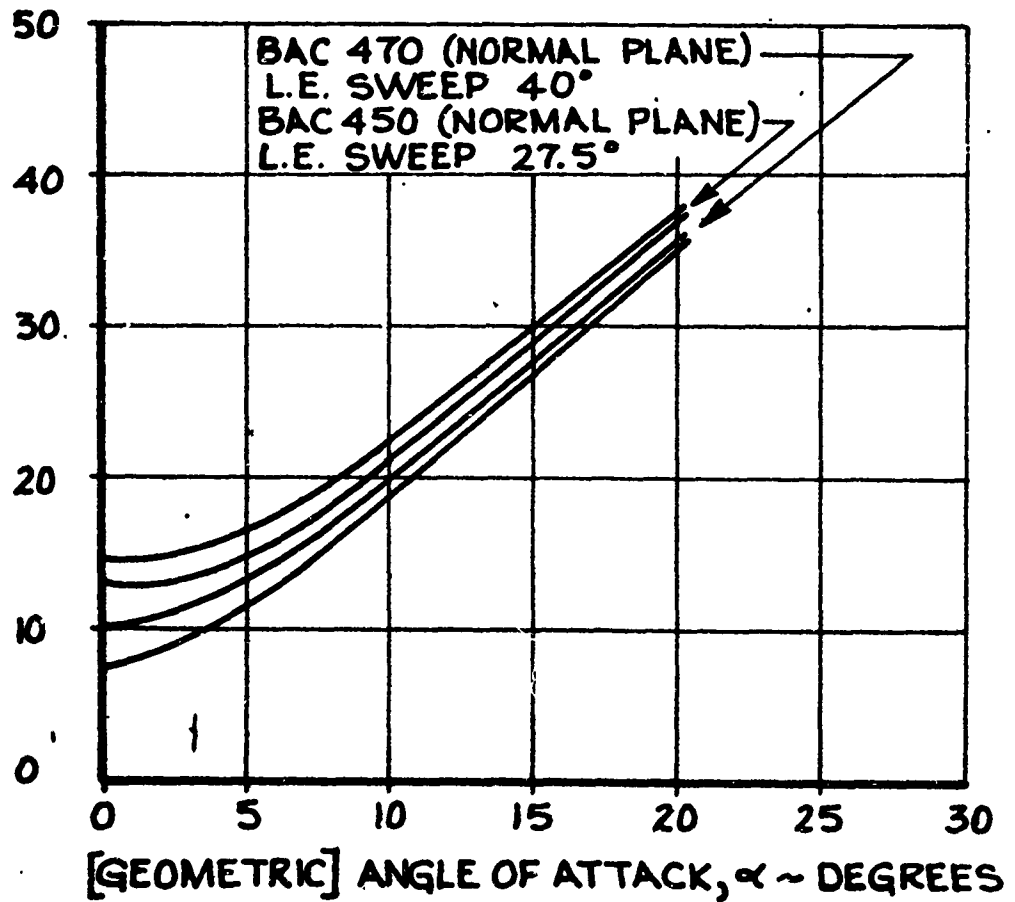
FIG. 21

ICE CAP CORRELATION EQUATIONS

FOR GLAZE ICING, THE ICE THICKNESS IS A FUNCTION OF THE WATER CATCH OR

$$S_i = f\left(\frac{W_c \theta}{\delta_i \Delta S}\right) \quad (5)$$

WHERE:

S_i = CHARACTERISTIC GLAZE ICE THICKNESS, FT
W_c = TOTAL WATER CATCH RATE, LBS/HR-FT SPAN
θ = ICING TIME, HR
δ_i = ICE DENSITY, LBS/FT^3
ΔS = IMPINGEMENT DISTANCE, FT. (AIRFOIL SURFACE AREA/FT. SPAN BETWEEN IMPINGEMENT LIMITS)

A WATER CATCH PARAMETER IS DEFINED FROM EQUATION (5) AS:

$$I = \frac{W_c \theta}{\delta_i \Delta S} = \frac{0.38}{\delta_i} V \cos \Lambda \frac{E_m}{\frac{H}{c}} \frac{H}{c} \omega \theta \quad (6)$$

CONSIDERING THE ICE DENSITY CONSTANT AND THE TERM $\frac{E_m}{H/c}$ TO BE A SINGLE VALUED FUNCTION FOR A GIVEN K_o VALUE, THEN EQUATION (6) SIMPLIFIES TO:

$$I = \frac{W_c \theta}{\delta_i \Delta S} \cong V \cos \Lambda \omega E_m \left(\frac{H}{c}\right)^x \quad (7)$$

WHERE X IS AN EXPONENT ON THE PROJECTED HEIGHT TO CORRELATE ANGLE OF ATTACK EFFECTS, THE VALUE OF WHICH IS DETERMINED EMPIRICALLY FROM TEST DATA.
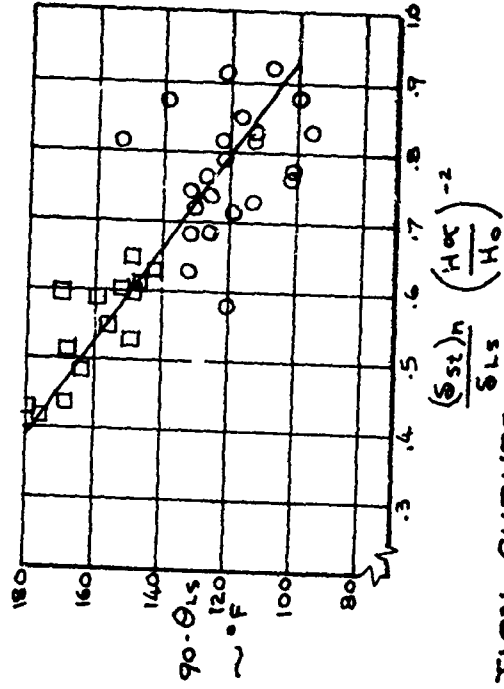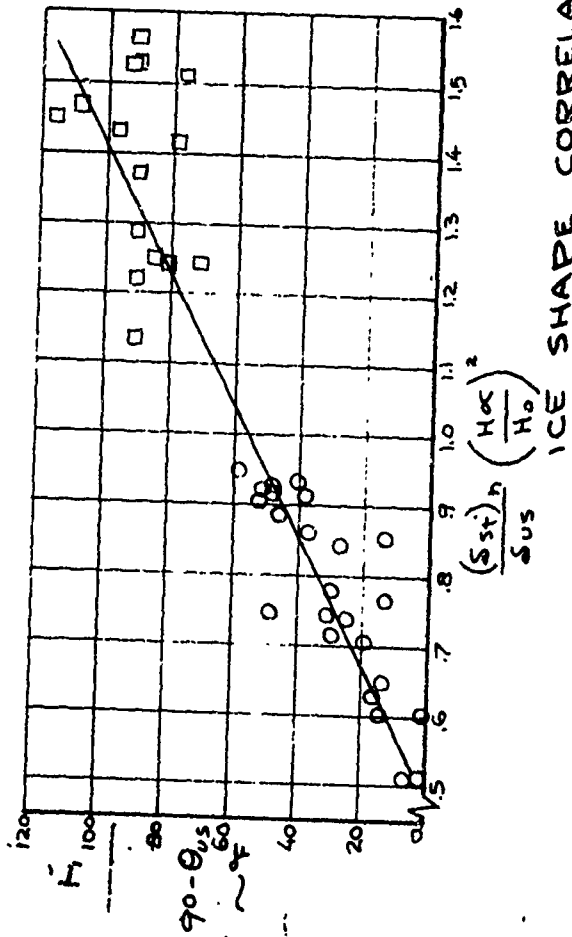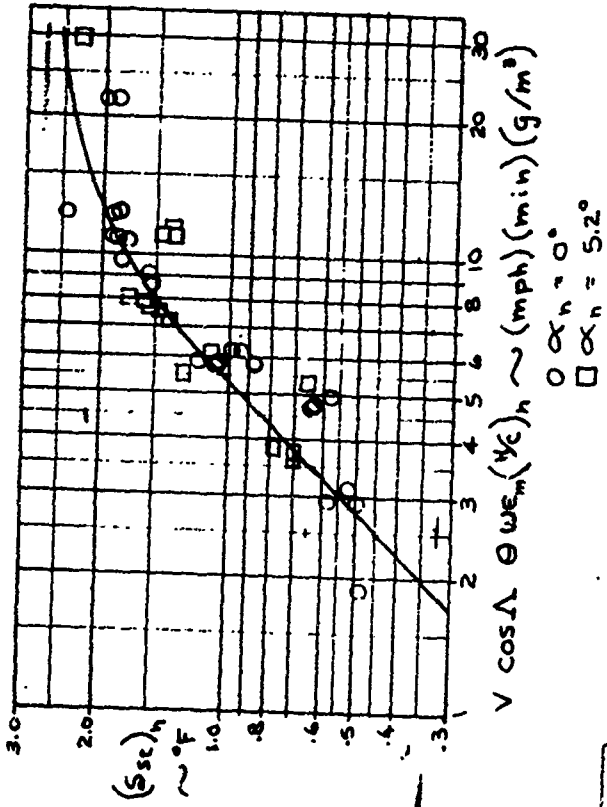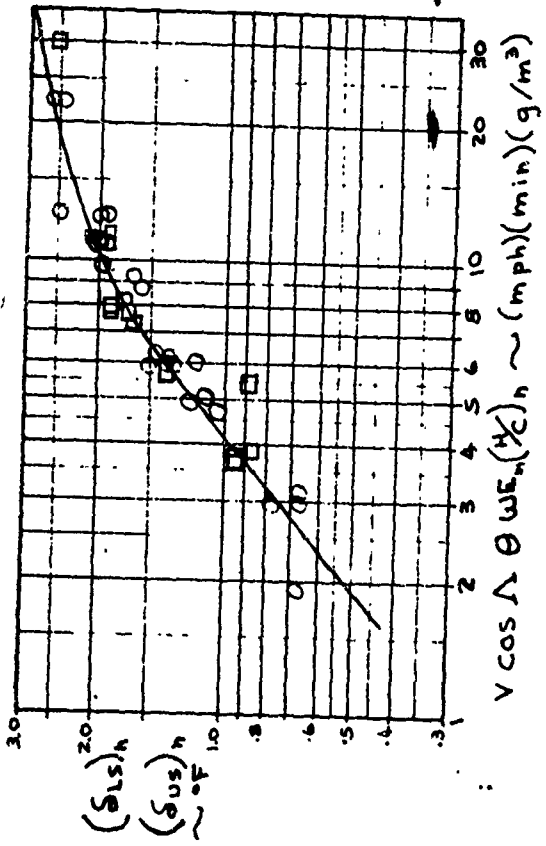
FIG. 22

ICE SHAPE CORRELATION CURVES
BAC 470 AIRFOIL

ICE SHAPE CORRELATION CURVES
BAC 450 AIRFOIL

○ $\alpha_n = 0°$
□ $\alpha_n = 4.5°$

$(s_{us})_n \sim IN.$

$I = V \cos \Lambda \, \theta \, \omega \, E_m \, (H/c)_n^s \times 1000$

$(s_{st})_n \sim IN.$

$I = V \cos \Lambda \, \theta \, \omega \, E_m \, (H/c)_n^s \times 1000$

$(s_{Ls})_n \sim IN.$

$I = V \cos \Lambda \, \theta \, \omega \, E_m \, (H/c)_n^s \times 1000$

FIG. 23

299
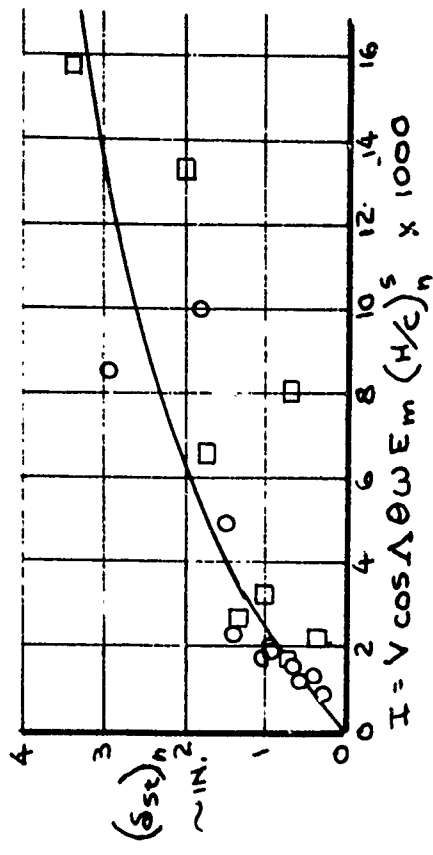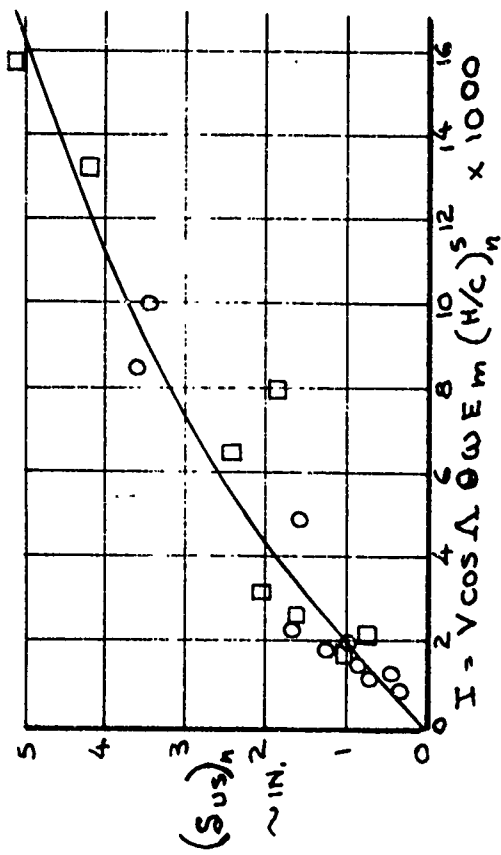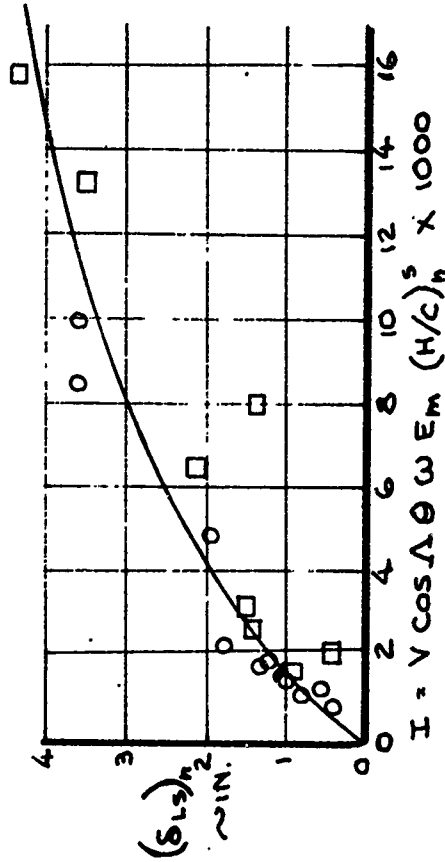
ICE CAP GROWTH CHARACTERISTICS

ICING PARAMETER $I = V \cos \Lambda \omega \mathcal{E}_m \frac{t}{c}$	STAGNATION ICE THICKNESS - IN. $(\delta_{sr})_n$	UPPER ICE PINNACLE HEIGHT IN. $(\delta_{vs})_n$	ICE THICKNESS RATIO $(\delta_{st}/\delta_{us})_n$
3	.54	.76	.710
8	1.50	1.75	.857
20	2.33	2.61	.893

300

COMPARISON OF 747 AND 707
HORIZONTAL STABILIZER SIZES

747
℄

747 FUSELAGE

707-300
℄

707 - 300 FUSELAGE

SBL 197.5
C = 280 IN.

BL 85

SBL 310
C = 200 IN.

BL 234

SBL 410
C = 120 IN.

FIG. 24

301
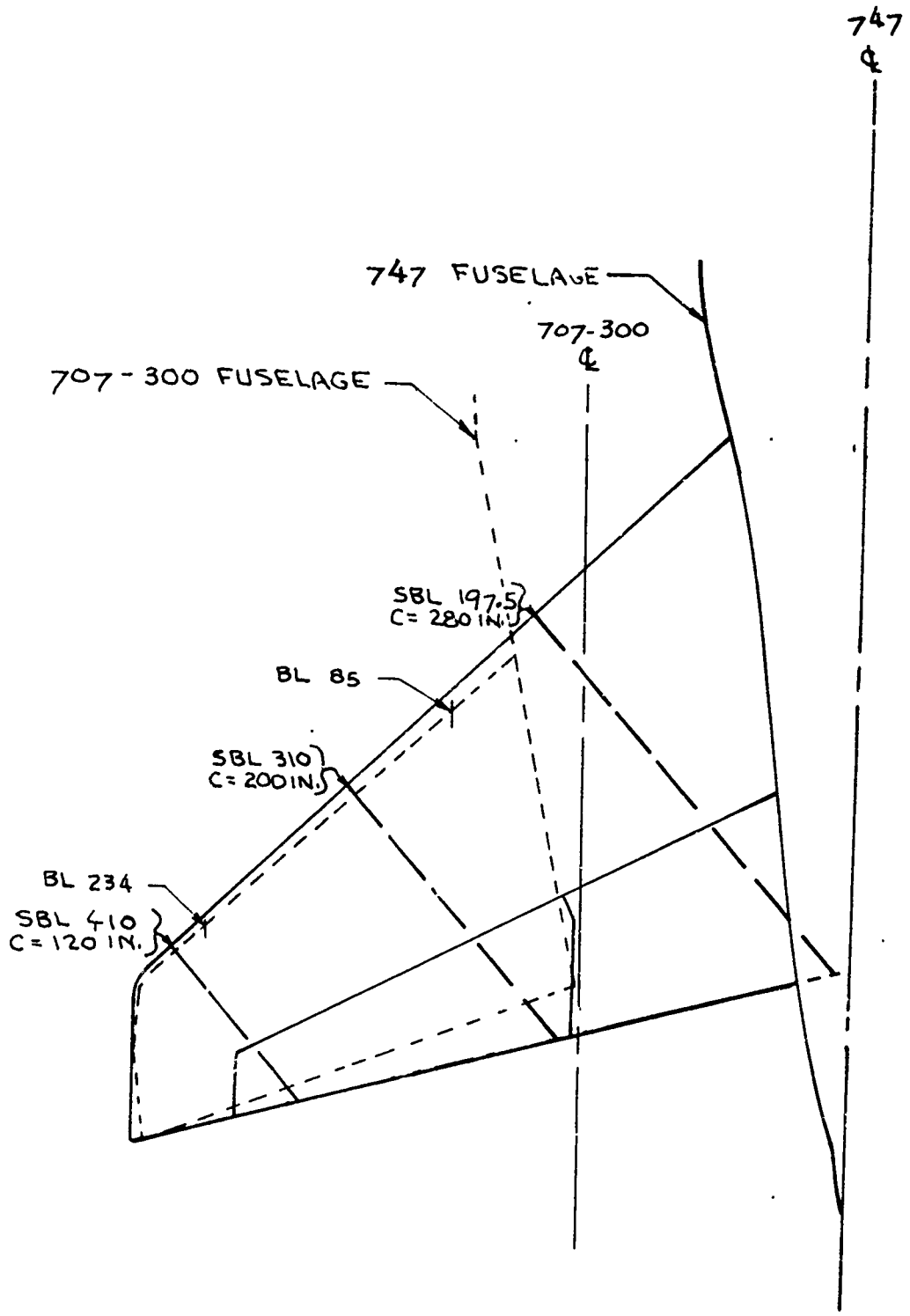
747 HORIZONTAL STABILIZER ICE SHAPES

747 STREAMWISE CUT
SBL 410   1/5 SCALE

707 STREAMWISE CUT
THROUGH BL 234

2.8"

707

747

3.0"

747 STREAMWISE CUT
SBL 197.5 1/5 SCALE

707 STREAMWISE CUT
THROUGH BL 85

2.5"   707

747

1.4"

FIG. 25

302
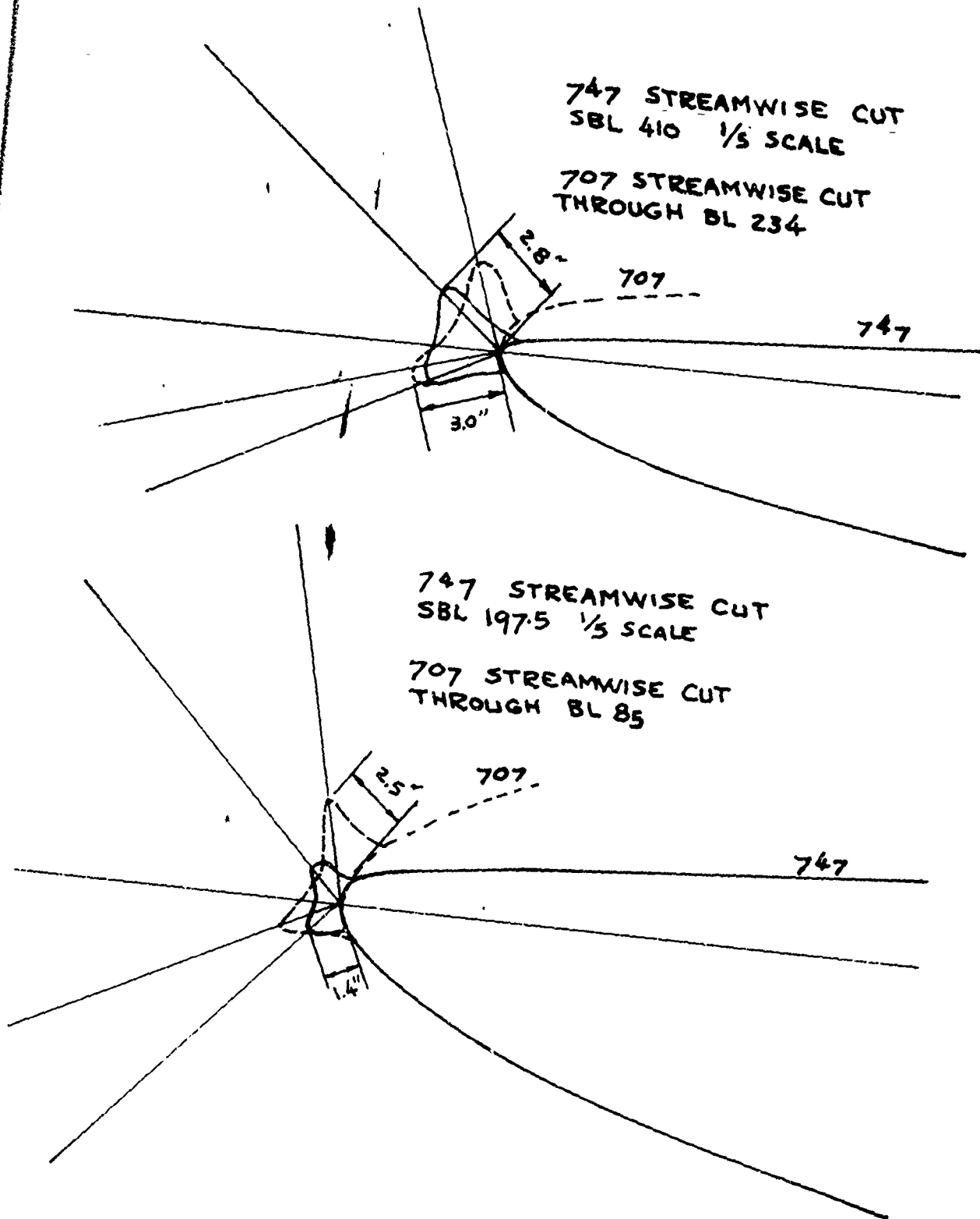
SAMPLE ICE CAP CALCULATION

FLIGHT CONDITIONS

θ = 30 MINUTE HOLD

ALT = 15,000 FOOT ALTITUDE

V = 377 mph TRUE AIRSPEED
    (256 KNOTS INDICATED AIRSPEED)

ICING CONDITIONS (FAR PART 25 APPENDIX C)

t_o = 21°F ICING LIMIT TEMPERATURE
     (AMBIENT AIR TEMPERATURE)

d_m = 15 MICRON DROP DIAMETER
      ("A" DROP DISTRIBUTION)

F = 150 MILE CLOUD

ω = 0.266 g/m³ CLOUD WATER CONTENT (150 MILE CLOUD)

AIRFOIL AND IMPINGEMENT DATA

STAB STA	ANGLE OF ATTACK	SWEEP ANGLE	CHORD LENGTH	(H/C) (FIG.21)	(H/C)₀* (FIG. 21)	Em (FIG. 20)
197.5	-2.38°	43°	280in	.095	.087	.020
410	-2.38°	43°	120in	.095	.087	.051

*Projected Height for 0° angle of attack.

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SAMPLE ICE CAP CALCULATION CONT -

Knowing the impingement and flight conditions the icing parameter, I, can now be calculated for the horizontal stabilizer station SBL 410 as:

$$I = V \cos \Lambda \; \theta \; \omega \; Em \; \left(\dfrac{H}{c}\right)$$

$$= 377 \; (\cos 43°) \; (30) \; (-256) \; (.051) \; (.095)$$

$$I = 10.66$$

From figure 22 the ice pinnacle heights are

STAB STA	ICING PAR.	ICE THICKNESS (NORMAL TO L.E.) UPPER $\left(\dfrac{\delta vs}{s}\right)_n$	STAG. $\left(\dfrac{\delta st}{s}\right)_n$	LOWER $\left(\dfrac{\delta ls}{s}\right)_n$	ICE THICKNESS STREAMWISE UPPER $\left(\dfrac{\delta vs}{s}\right)_s$	STAG $\left(\dfrac{\delta st}{s}\right)_s$	LOWER $\left(\dfrac{\delta ls}{s}\right)_s$
197.5	4.1	1.0	.75	.99	1.37	1.025	1.36
410.	.10.66	2.03	11.84	2.10	2.78	2.52	2.87

The ice angles can now be calculated from the ratio of ice thicknesses and figure 22.

STAB STA	PROJECTED HT. RATIO Hp/Ho	ICE THICKNESS RATIO $\left(\dfrac{\delta st}{\delta vs}\right)_n$	$\left(\dfrac{\delta\eta}{\delta ls}\right)_n$	UPPER ICE ANGLE PAR.	UPPER ICE ANGLE (FIG. 22)	LOWER ICE ANGLE PAR.	LOWER ICE ANGLE (FIG. 22)
197.5	1.091	.908	.878	1.08	26°	.736	-38.5°
410	1.091	.749	.752	.893	46°	.63	-44°

EFFECT OF ICE ON LIFT DRAG AND PITCHING MOMENT FOR A
TYPICAL JET TRANSPORT FROM WIND TUNNEL DATA -
(FLAPS UP)

FIG. 26

305
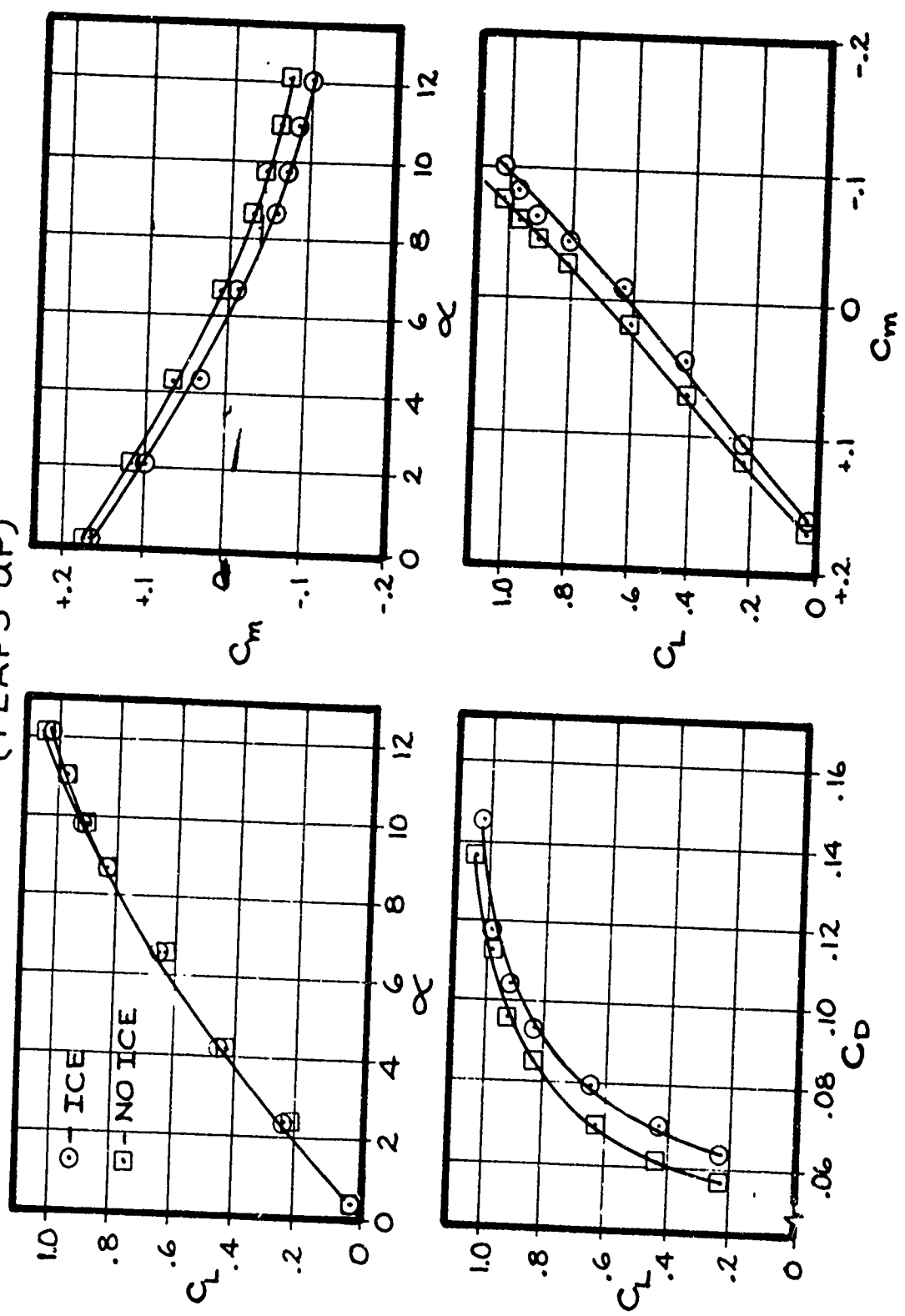
EFFECT OF ICE ON DRAG FOR A TYPICAL
JET TRANSPORT
(FLAPS EXTENDED)
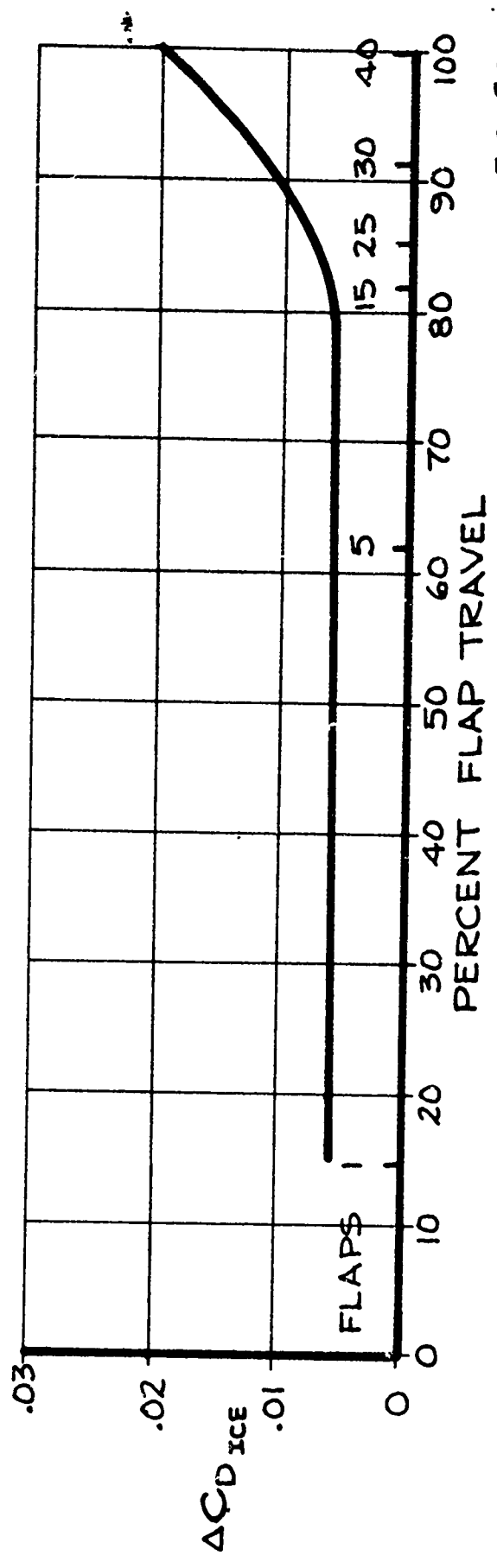
FIG. 27
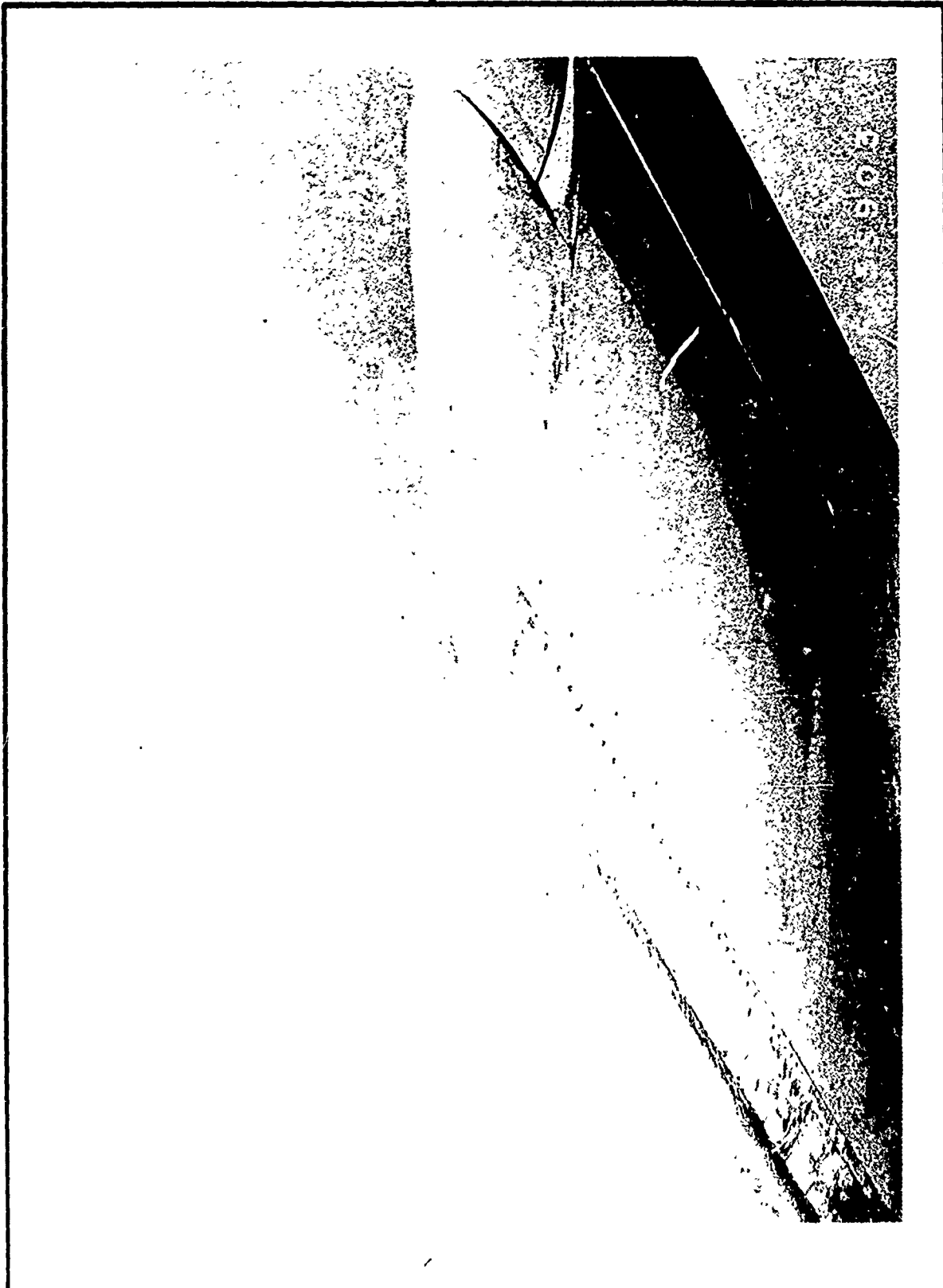
CALC			REVISED	DATE	727 ARTIFICIAL ICE SHAPE	FIG. 28
CHECK						
APPD					FOR HORIZONTAL STABILIZER	
APPD					THE **BOEING** COMPANY	PAGE
					RENTON, WASHINGTON	307

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EFFECT OF ICE ON LOW SPEED DRAG POLARS - 25° FLAPS - ALL ENGINES OPERATING

FIG. 29
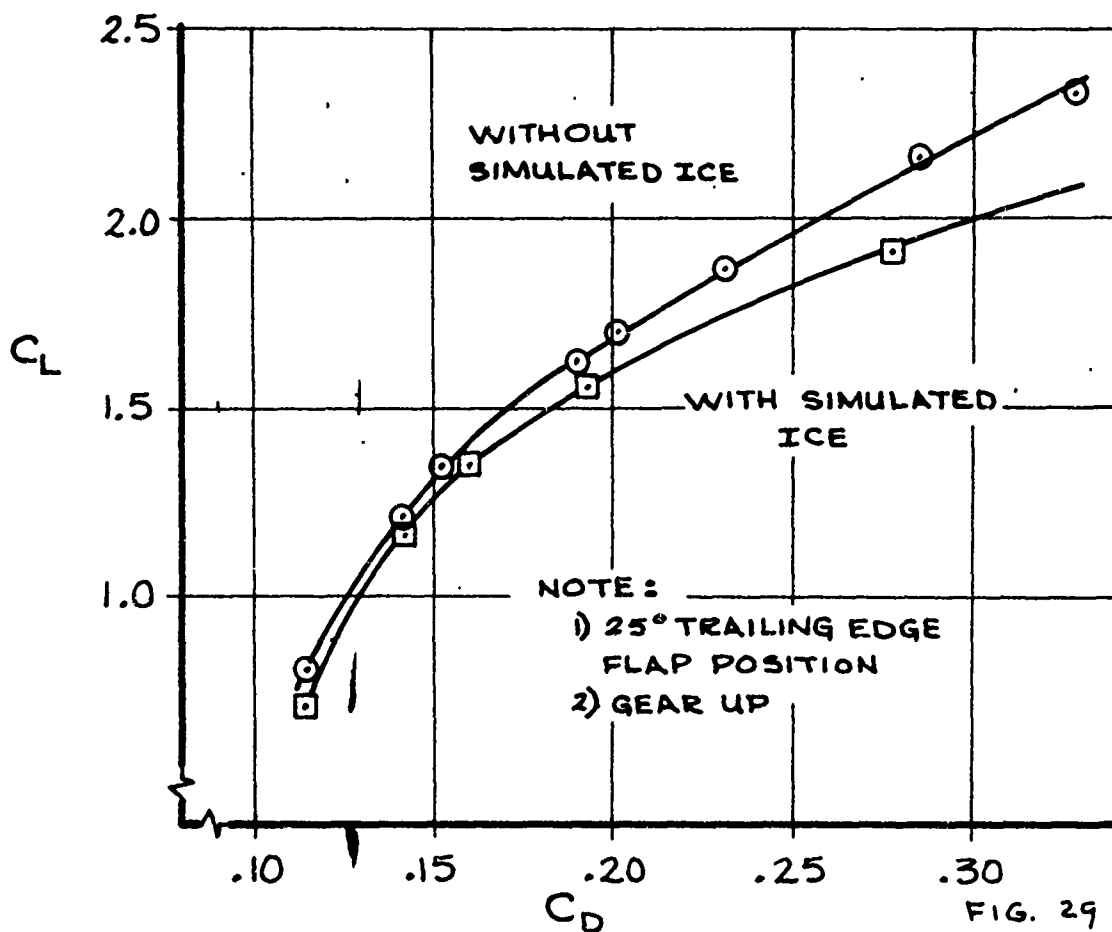
EFFECT OF ICE ON APPROACH AND LANDING CLIMB GRADIENT- 7000FT. ALTITUDE, 40°F DAY.

NOTES:
    1. APPROACH CLIMB CONFIGURATION:
        a. 25° T. E. FLAPS
        b. POD ENGINE OUT
        c. GEAR UP
        d. C_L @ $(L/D)_{MAX.}$
    2. LANDING CLIMB CONFIGURATION:
        a. 40° T. E. FLAPS
        b. GEAR DOWN
        c. C_L @ $1.2 V_S$
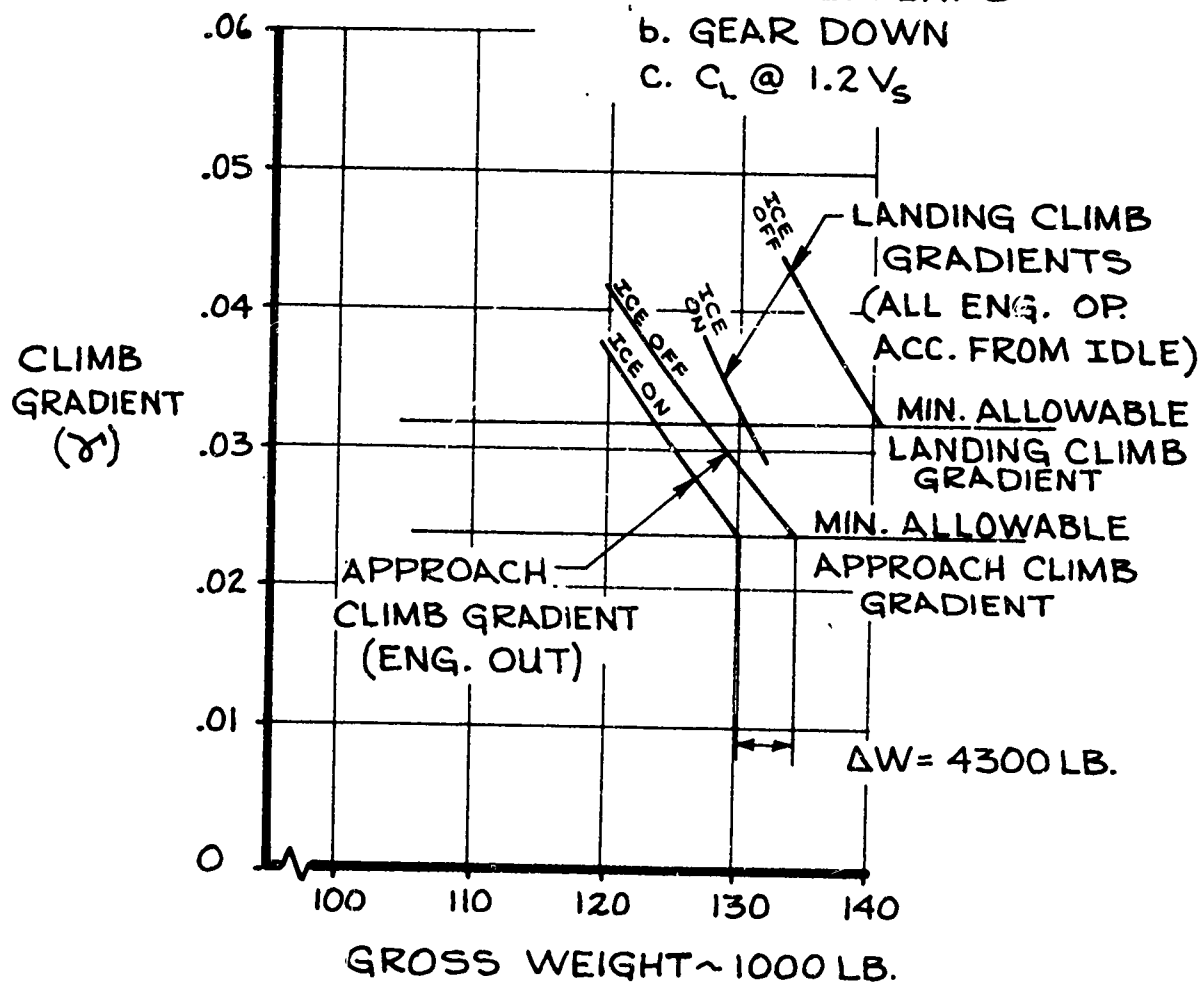
FIG. 30

TYPICAL TIME - TEMPERATURE PROFILE DURING DESCENT

FIG. 31

310
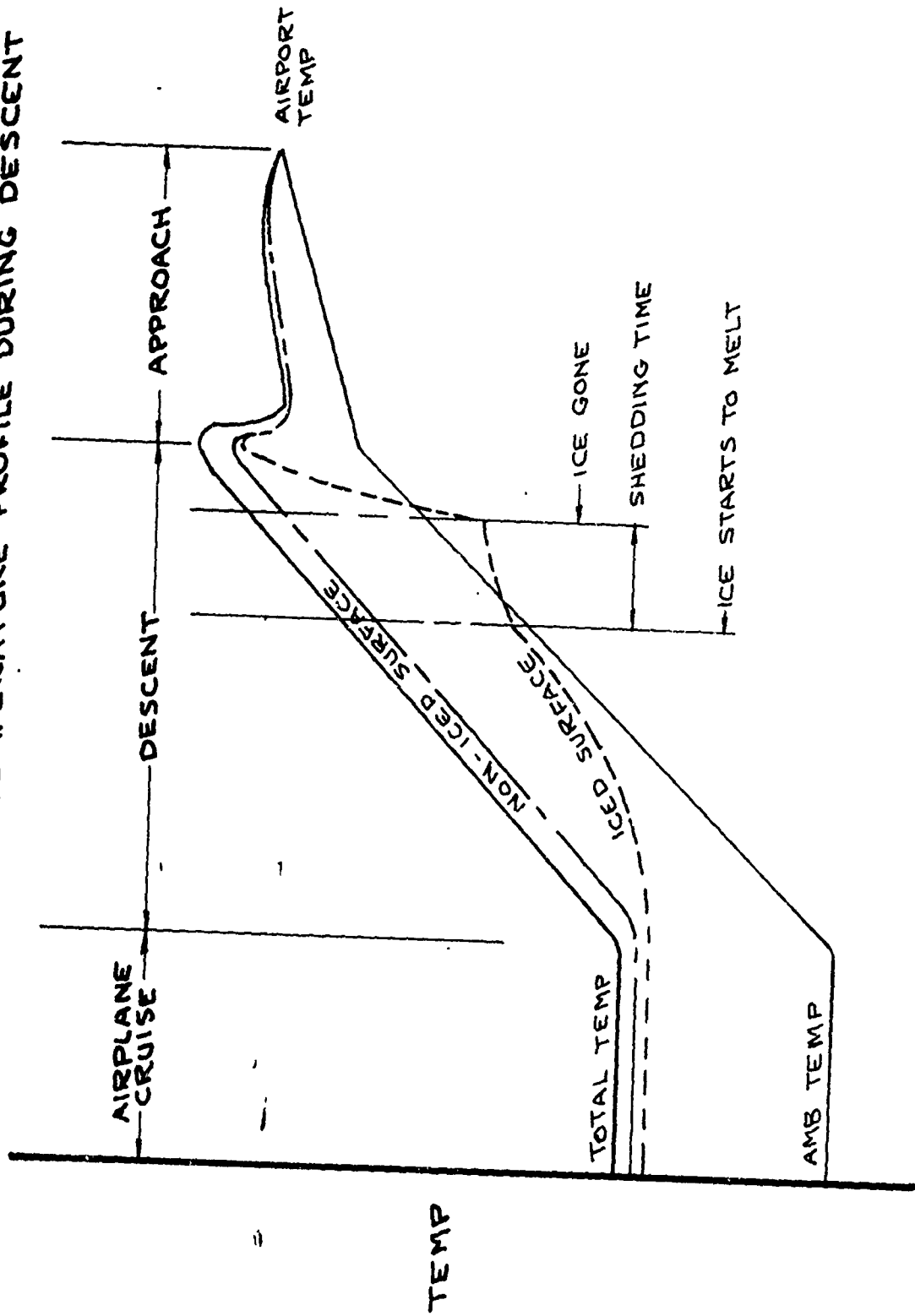
ICE CAP-AIRFOIL HEAT BALANCE

Q = HEAT TRANSFER

t_r = RECOVERY TEMPERATURE

t_s = ICE CAP-AIRFOIL INTER-FACE TEMPERATURE

θ = TIME

C = THERMAL CAPACITANCE OF THE AIRFOIL AND ICE CAP

u = OVERALL HEAT TRANSFER COEFFICIENT

τ = TIME CONSTANT

$$Q_{sub.} = 2.9uL_s \frac{e_{si}-e_{ow}}{P_o} \qquad Q_{IN} = Q_{sub.}$$

$$u(t_r-t_s) = 2.9uL_s \frac{e_{si}-e_{ow}}{P_o}$$

$$(t_r-t_s) = 2.9 L_s \frac{e_{si}-e_{ow}}{P_o}$$

$$Q_{IN} = u(t_r-t_s)$$
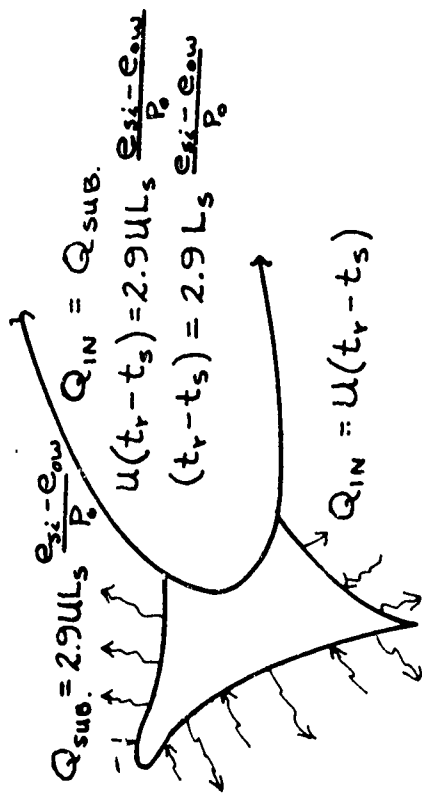
STEADY STATE HEAT BALANCE

$$Q_{IN} = Q_{STORED}$$

$$u(t_r-t_s) = C\frac{dt_s}{d\theta}$$

$$\tau(t_r-t_s) = C\frac{dt_s}{d\theta}$$

$$Q_{STORED} = C\frac{dt_s}{d\theta}$$

$$Q_{IN} = u(t_r-t_s)$$
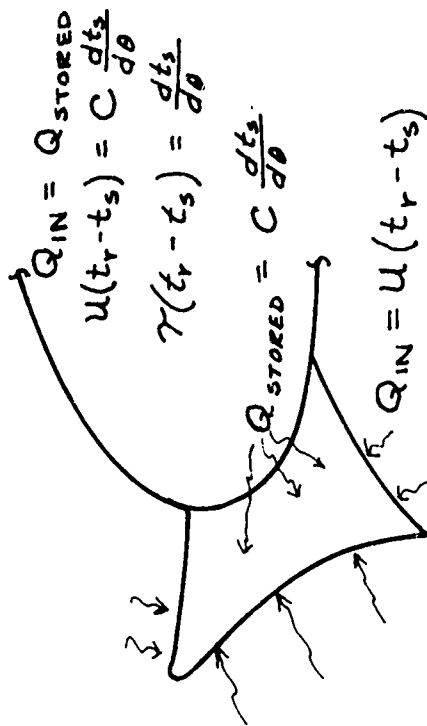
TRANSIENT(DESCENT) HEAT BALANCE

FIG. 32

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TIME CONSTANT EQUATION
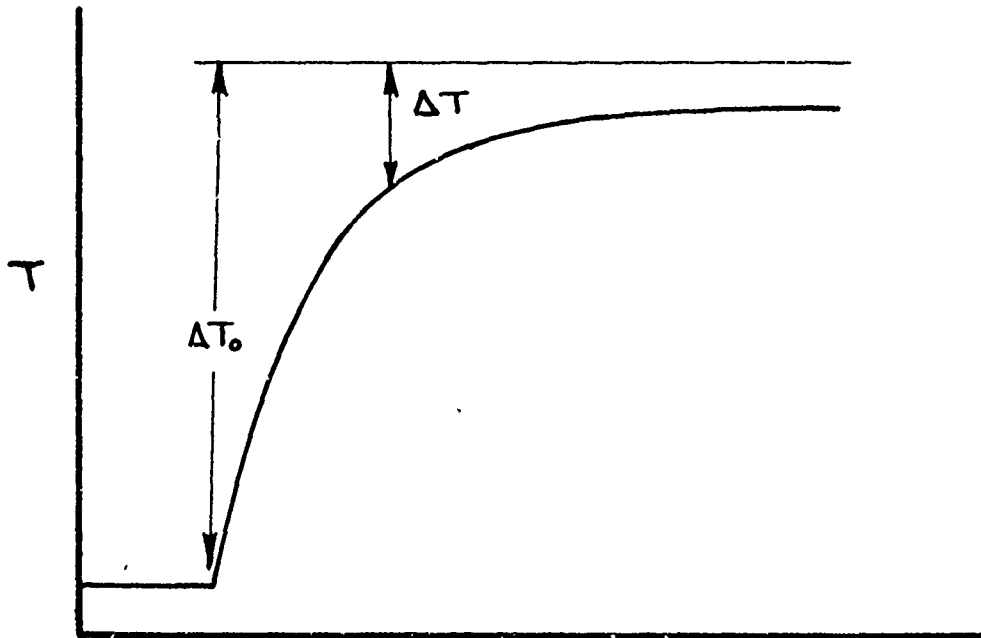
STEP FUNCTION $\dfrac{\Delta T}{\Delta T_o} = e^{-\gamma\theta}$
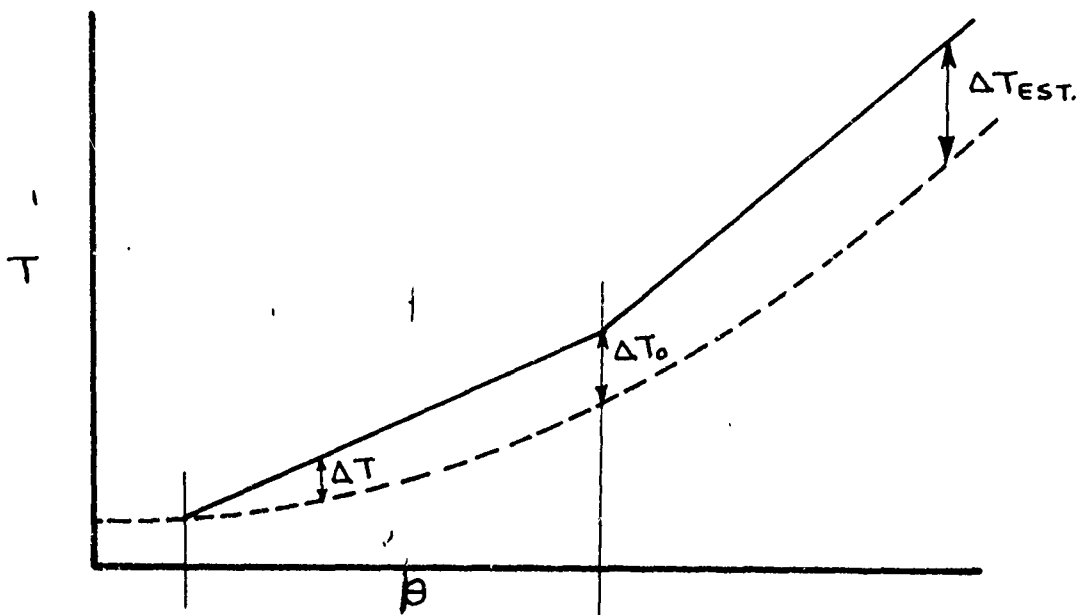
RAMP FUNCTION
$$\dfrac{\Delta T}{\Delta T_{EST.}} = 1 + \left(\dfrac{\Delta T_o}{\Delta T_{EST.}} - 1 \right) e^{-\gamma\theta}$$

FIG. 33

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SURFACE TEMPERATURE EQUATION DERIVATION

HEAT BALANCE

$$Q_{in} = Q_{stored}$$

$$U(t_r - t_s) = C\;\frac{dt_s}{d\theta}$$

or

$$\frac{dt_s}{d\theta} = \frac{U}{C}(t_r - t_s) = \tau(t_r - t_s)$$

DRIVING FUNCTION

$$t_r = t_{r_0} + W\theta$$

BOUNDARY CONDITIONS

AT $\theta = 0$ $T_r - T_{s_0} = \Delta T_0$

$\theta = \infty$ $T_r - T_s = \Delta T_{est}$

$\theta = \theta$ $T_r - T_s = \Delta T$

DIFFERENTIAL EQUATION

$$\frac{d(t_r - t_s)}{d\theta} + \tau(t_r - t_s) - W = 0$$

SOLUTION OF DIFFERENTIAL EQUATION

FROM B.C. AT $\theta = 0$

$$t_r - t_s = \frac{W}{\tau} + Ce^{-\tau\theta} = \Delta T$$

$$t_r - t_{s_0} = \frac{W}{\tau} + C = \Delta T_0$$

FROM B.C. AT $\theta = \infty$

$$t_r - t_{s_\infty} = \frac{W}{\tau} = \Delta T_{est}$$

THEREFORE

$$\Delta T = \Delta T_{est} + (\Delta T_0 - \Delta T_{est})e^{-\tau\theta}$$

OR

$$\frac{\Delta T}{\Delta T_{est}} = 1 + \left(\frac{\Delta T_0}{\Delta T_{est}} - 1\right)e^{-\tau\theta}$$

FIG. 34

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ICING TUNNEL TIME-TEMPERATURE CURVES

FIG. 35

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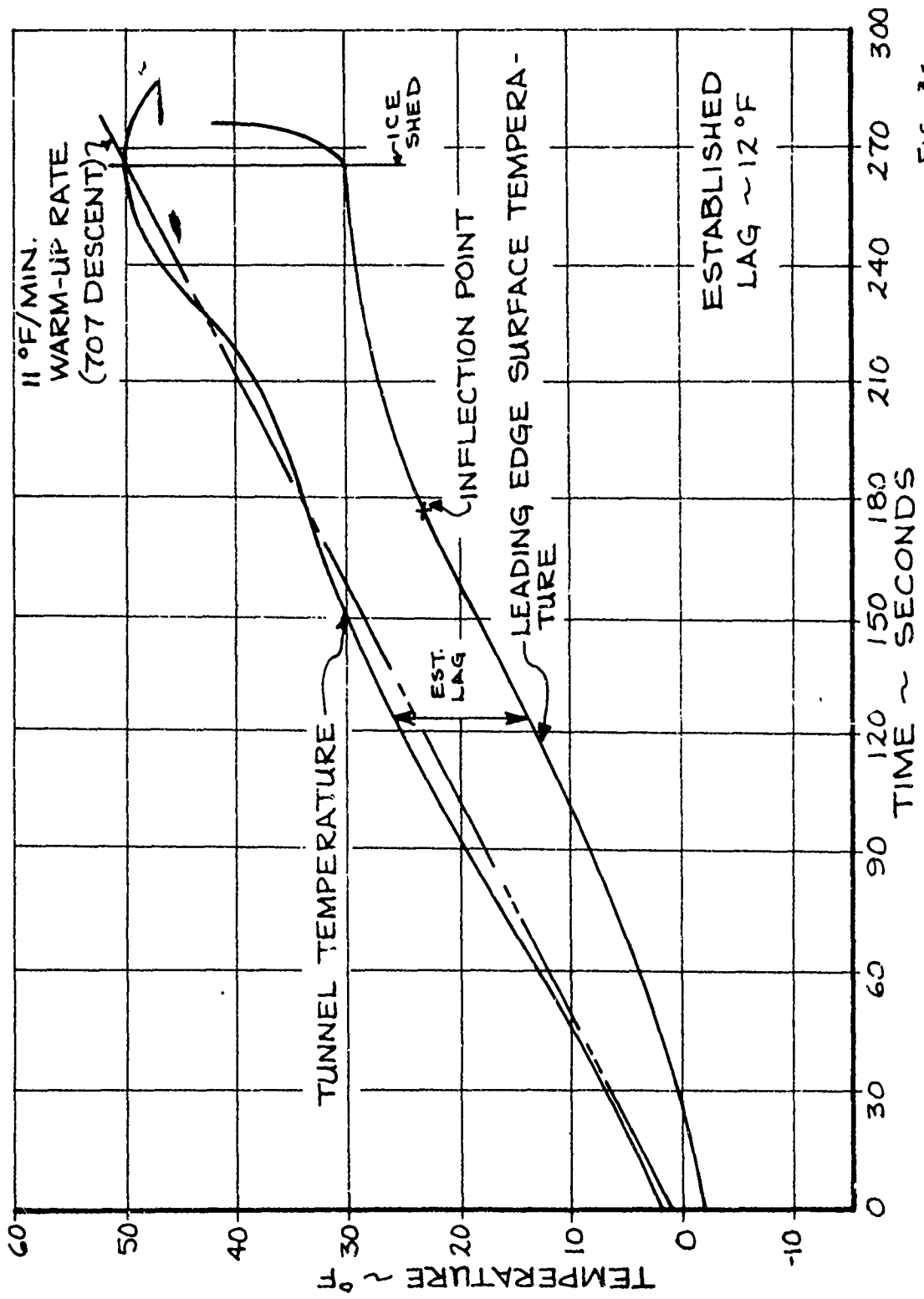
ESTABLISHED LAG AND ICE
SHEDDING CHARACTERISTICS
(ICE TUNNEL DATA)
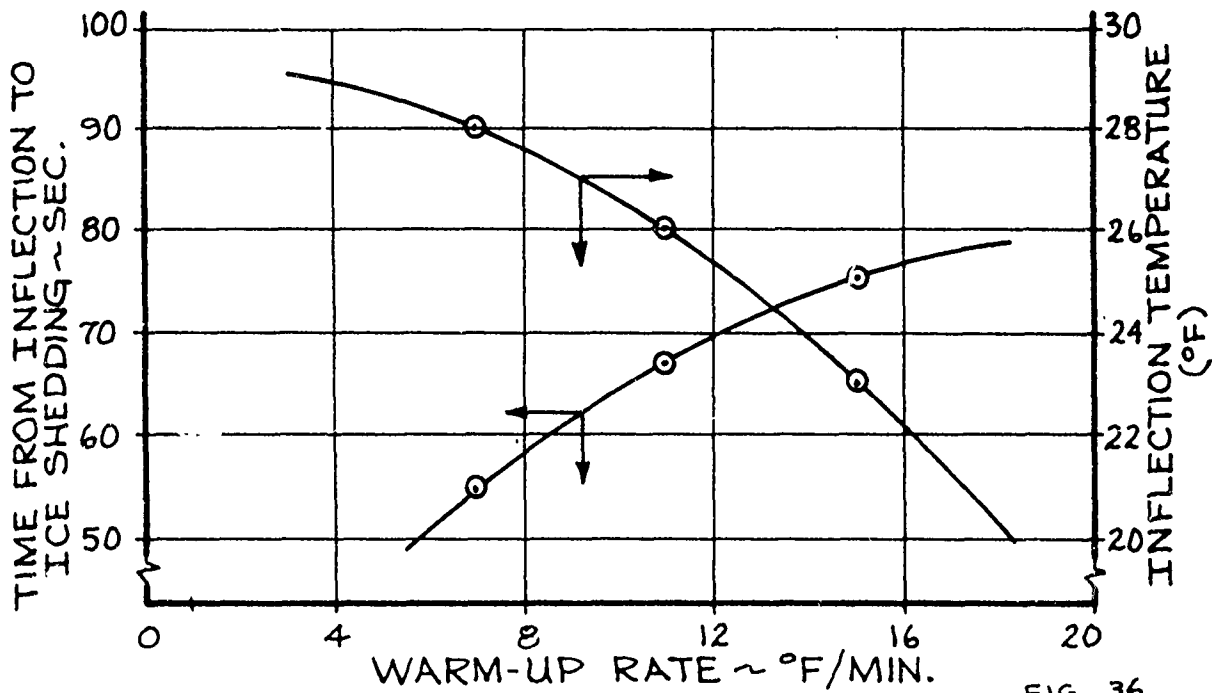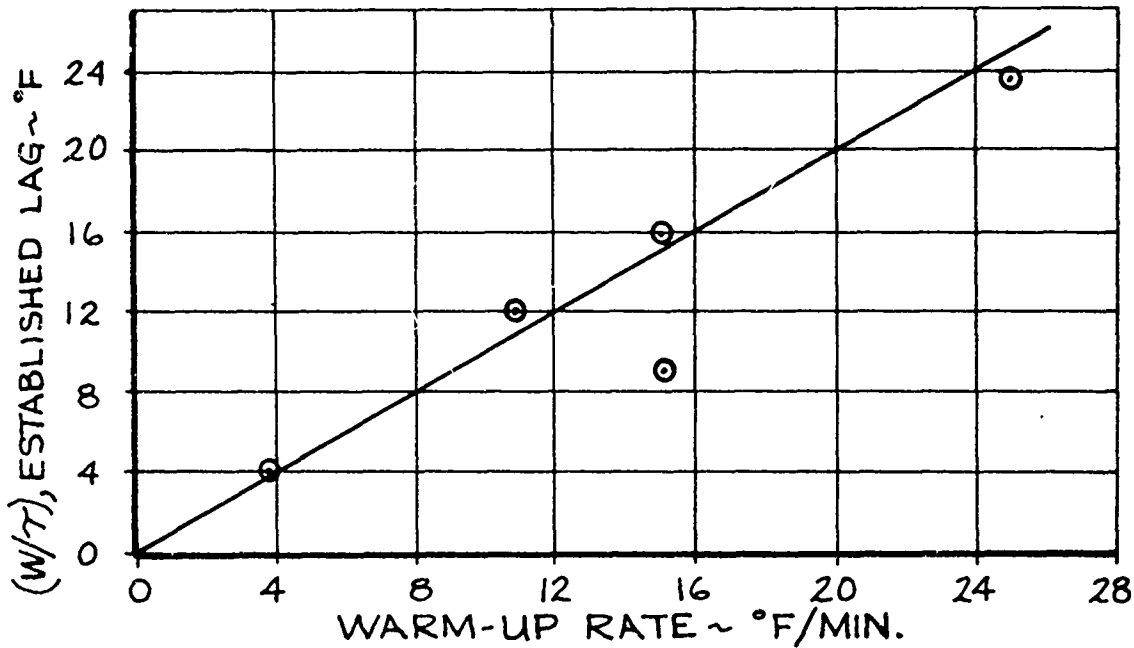
FIG. 36

ICE-AIRFOIL SURFACE TEMPERATURE
CALCULATION PROCEDURE

1. The temperature under the ice cap is calculated from:

$$\frac{\Delta T}{\Delta T_{\text{Test}}} = 1 + \left(\frac{\Delta T_{\text{ro}}}{\Delta T_{\text{Test}}} - 1\right) e^{-\tau \theta} \qquad (10.)$$

where:

ΔT_{Test} = Warm-up rate, W.

$W = \dfrac{tr_2 - tr_1}{\theta_2 - \theta_1}$ $\qquad (11.)$

τ = Time Constant From Icing Tunnel Data

2. The calculated temperature differential, ΔT, from equation 10 is adjusted for ice sublimation effects by

$$\Delta T_{\text{CORR}} = \Delta T - \Delta T_{\text{SUB}}$$

where $\Delta T_{\text{SUB}} = 2.9 \angle_s \left(\dfrac{e_{\text{so}} - e_{\text{ow}}}{P_o}\right)$ $\qquad (12.)$

3. When the inflection point temperature is reached (ice begins to melt) the laboratory test data shown in figure 36 are applied directly to determine the shedding time.

TYPICAL DESCENT PROFILE

W = 73,000 LBS
GEAR UP
SPOILERS DOWN
ICE PENALTY INCLUDED

M = .78

290 KIAS

FLAPS UP

200 KIAS FLAPS UP

160 KIAS FLAPS 5°

ALTITUDE ~ FT × 1000

RATE OF DESCENT ~ FT/MIN. × 1000
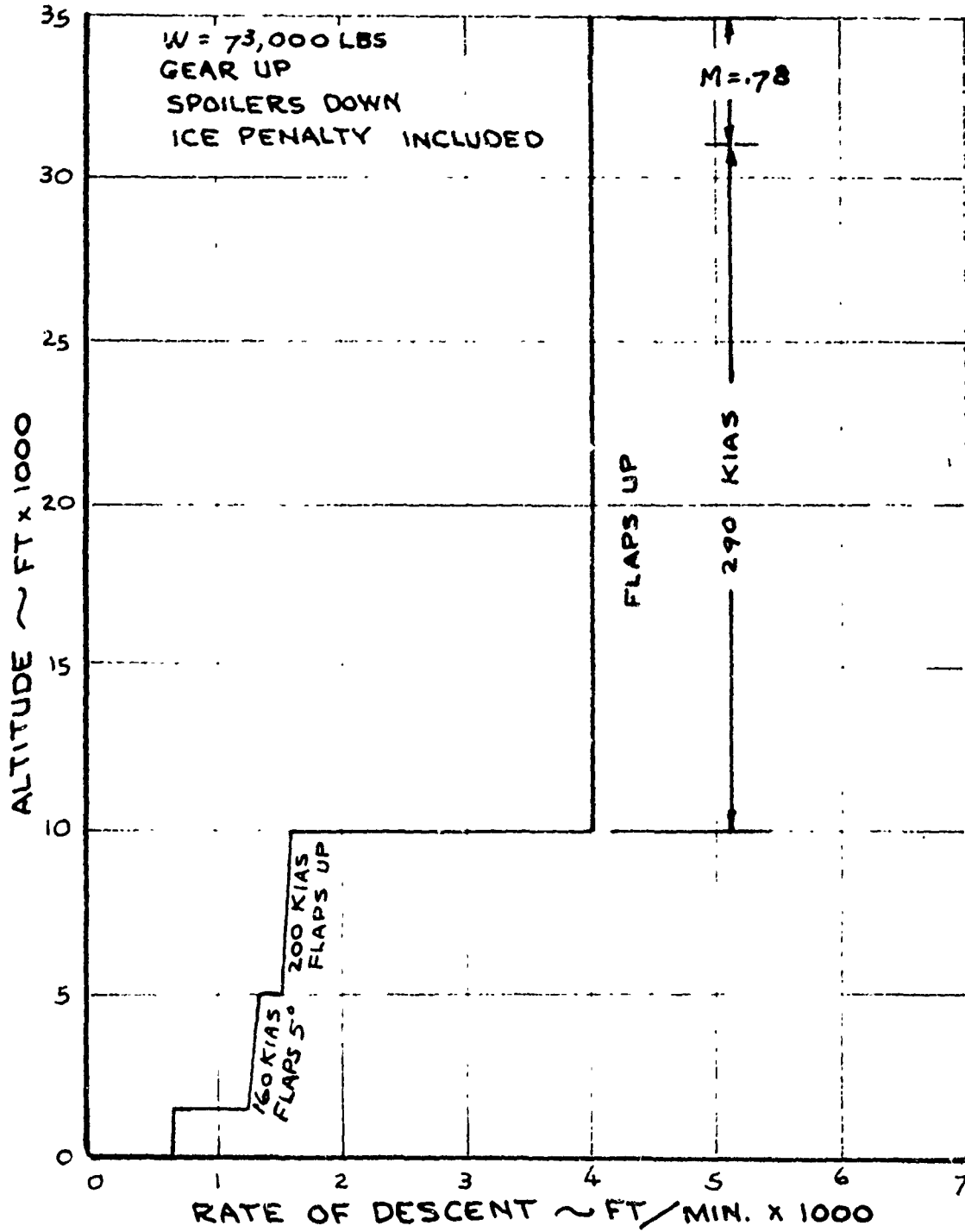
FIG. 37

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RECOVERY TEMPERATURE EQUATIONS

DEFINITION

$$t_r = t_{amb} + r \Delta t_{ao}$$

$$= t_{amb} + 0.9 \, (t_{total} - t_{amb})$$

AS USED IN THIS STUDY

$$t_r = t_{ro} + W\Theta$$

t_r = RECOVERY TEMPERATURE

t_{amb} = AMBIENT AIR TEMP.

r = RECOVERY FACTOR = 0.9 FOR TURBULENT FLOW

t_{total} = TOTAL AIR TEMP

Δt_{ao} = ADIABATIC TEMP. RISE

V = AIR VELOCITY

Cpa = SPECIFIC HEAT OF AIR

t_{ro} = INITIAL RECOVERY TEMP.

W = WARMUP RATE

Θ = TIME

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CALCULATED ICE SHEDDING TIME COMPARED TO FLIGHT TEST DATA
(737 FLIGHT 25-6)

FIG. 38

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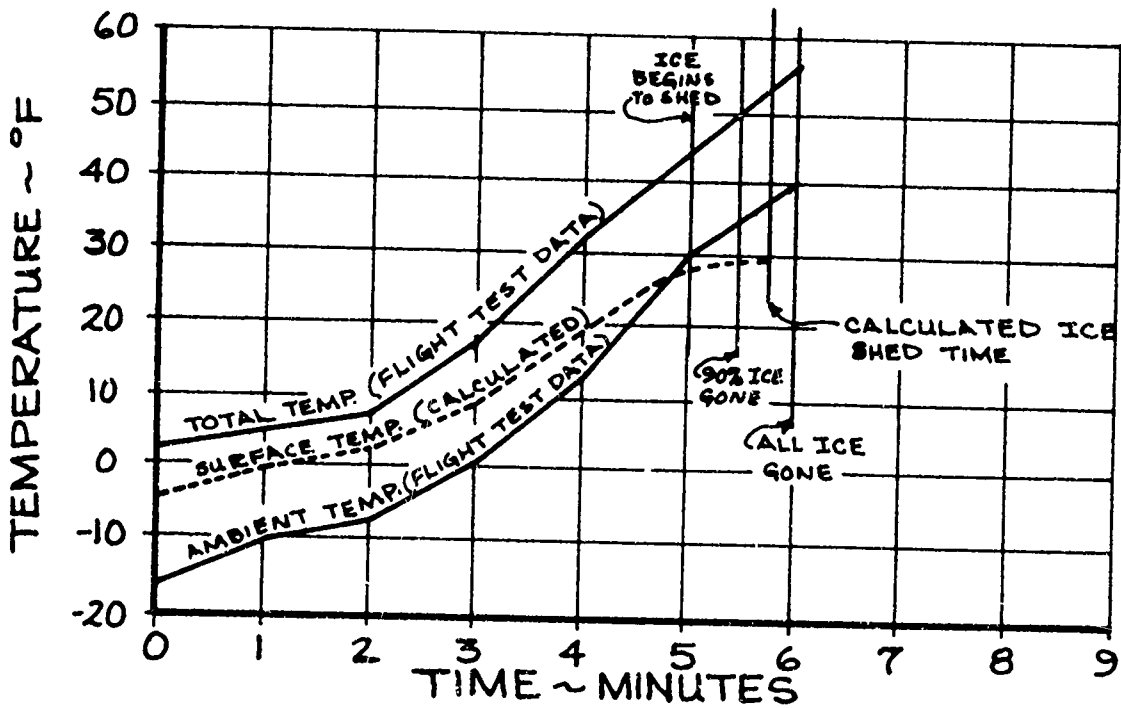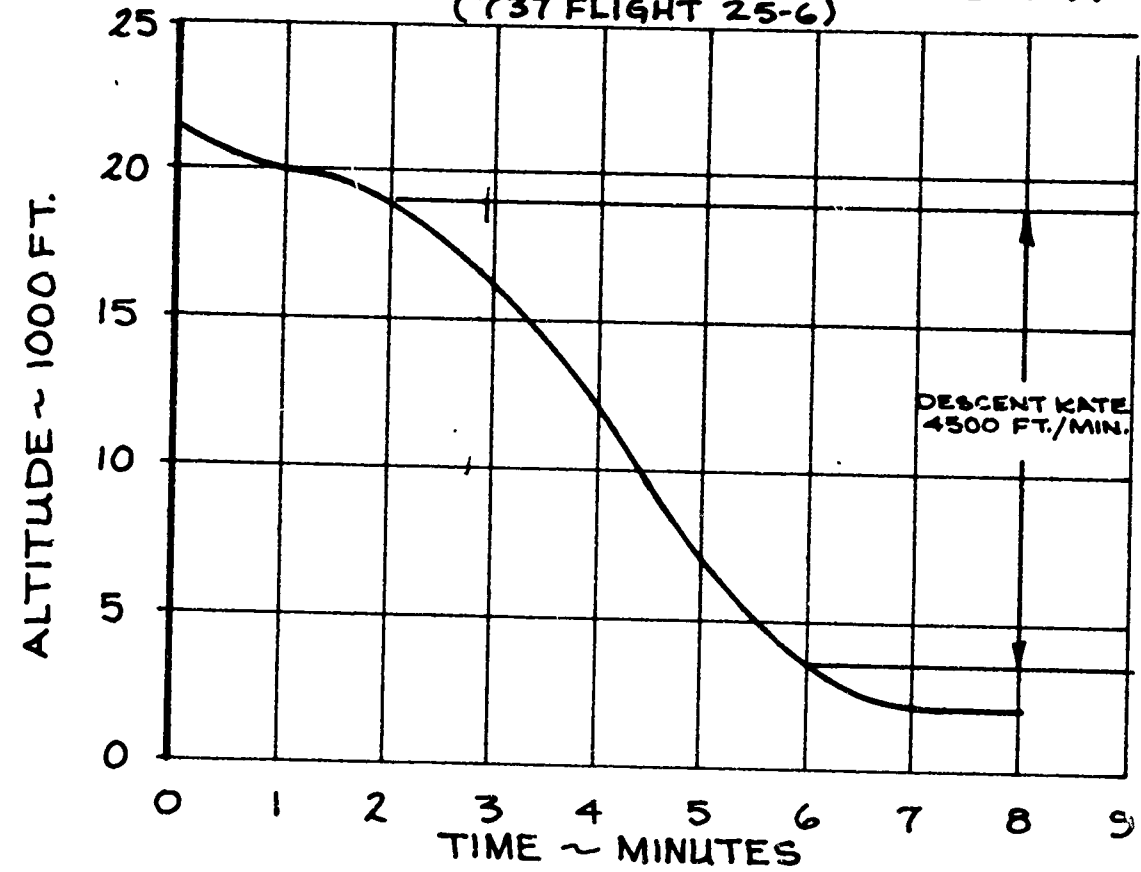
CALCULATED TIME-TEMPERATURE PROFILE FOR TYPICAL DESCENT
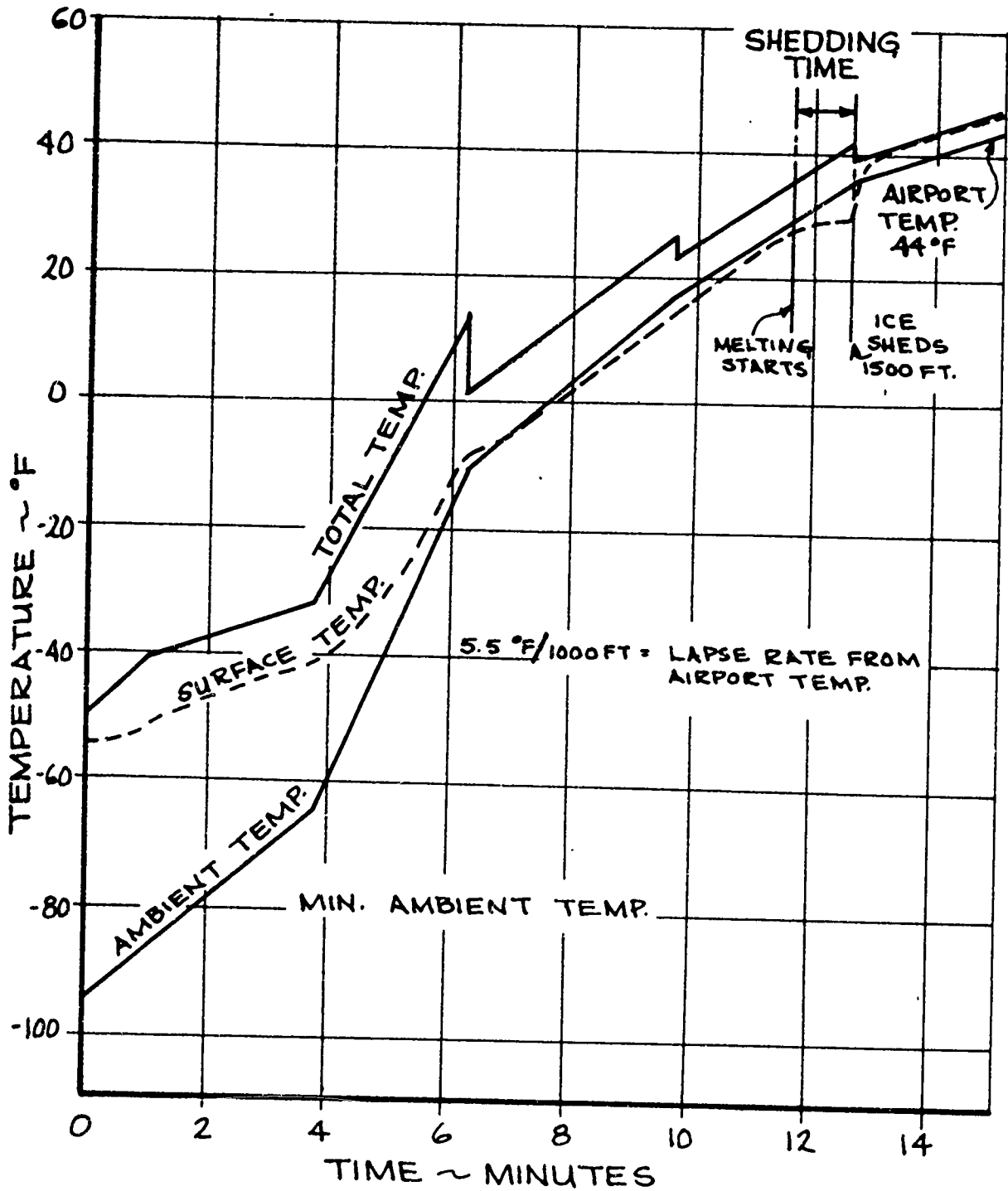
FIG. 39

TIME-TEMPERATURE PROFILE FOR
SPECIAL TRAFFIC CONTROL DESCENT

W= 73,000 LB
FLAPS 15°
ICE EFFECT INCLUDED
160 KIAS
GEAR DOWN
SPOILERS DETENT(31°)

ALTITUDE ~ 1000 FT.

RATE OF DESCENT ~ 1000 FT/MIN.

TEMPERATURE ~ °F

CRUISE

TOTAL TEMP.

SHEDDING TIME

MELTING STARTS

SURFACE TEMP.

ICE SHEDS 1500 FT.

AIRPORT TEMP. = 59°F

AMBIENT TEMP.

TIME ~ MINUTES

FIG. 40

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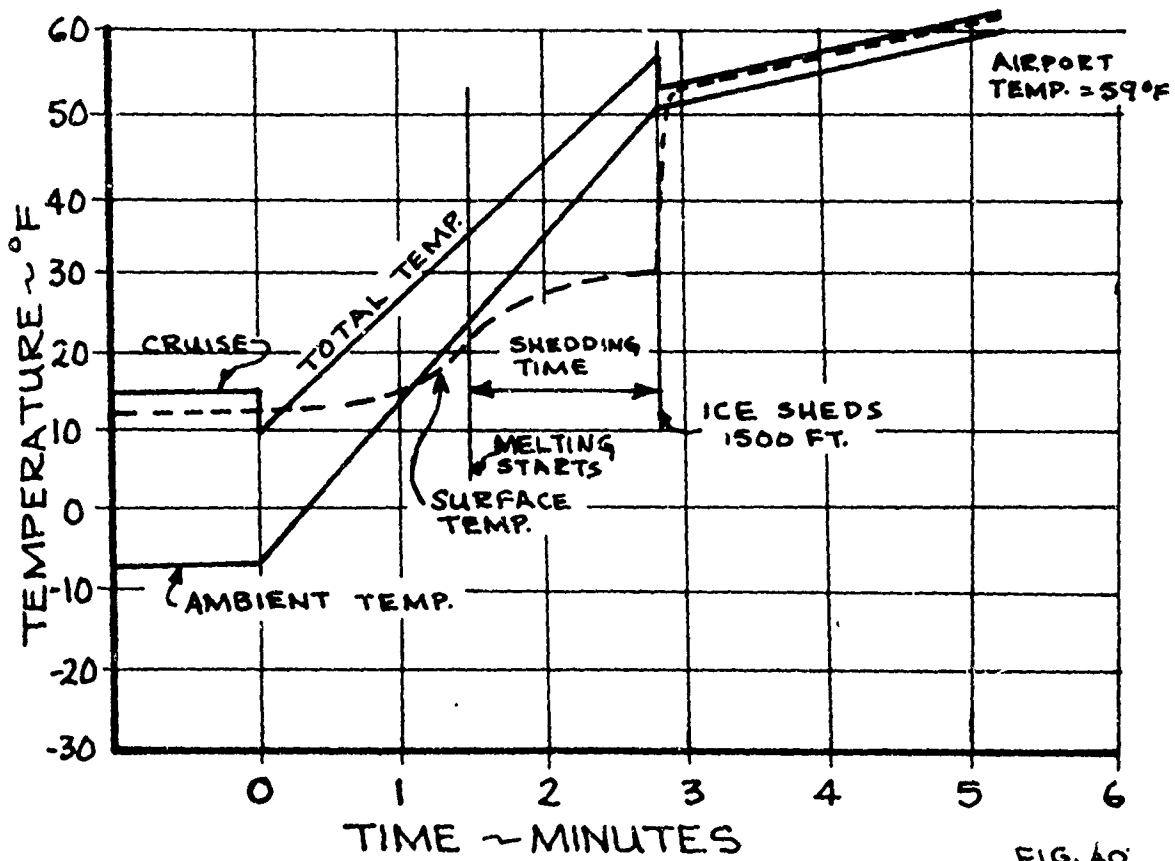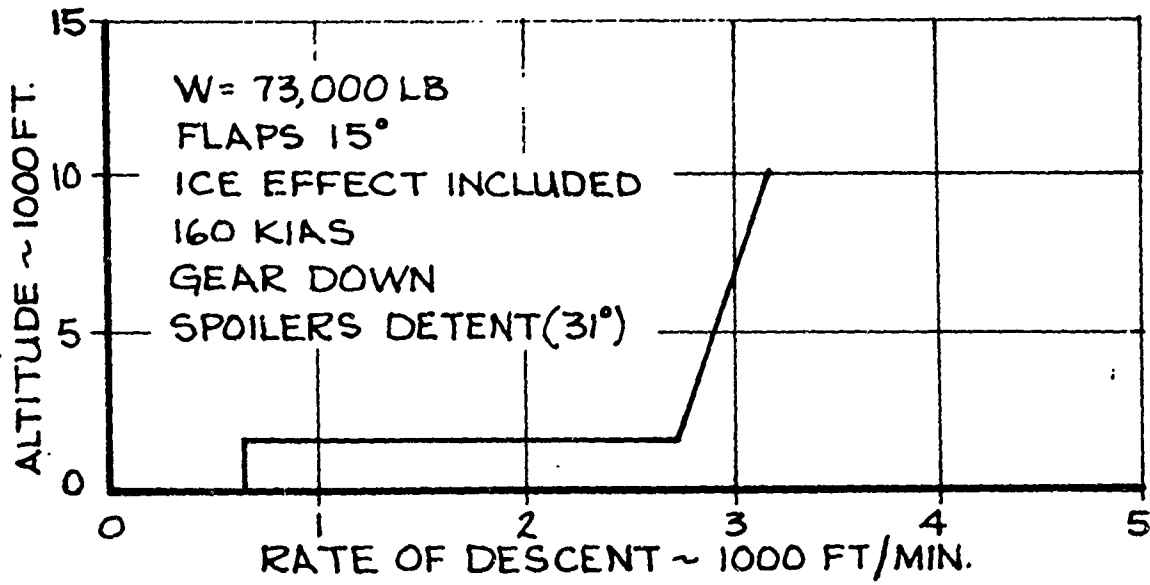
DISCUSSIONS FOLLOWING MR. WILDER'S PRESENTATION ON

"TECHNIQUES USED TO DETERMINE ARTIFICIAL ICE SHAPES AND ICE SHEDDING;

CHARACTERISTICS OF UNPROTECTED AIRFOIL SURFACES"

Question: Was there any evidence, in watching the formation
             of an ice shape, of liquid water running between
             projections?

Answer: Yes, the pinnacles would disappear, narrowing the
             impinging area.

Question: What happens to the size of shapes when breaking off?

Answer: Based on tunnel test, on swept wings, ice shapes shed
             and break up in flight in small chunks.

Question: When you find most critical shapes, do they effect
             lift in some manner?

Answer: Yes, lift as well as drag.

Question: Was .9 factor of double horn type right? Isn't 1.0
             better?

Answer: No difference based on icing tunnel tests.

EXPERIMENTS WITH ICEPHOBIC
SURFACES

by

George C. Hay
Program Manager
.....General Aviation Safety Division
Aircraft Development Service
Federal Aviation Administration
Washington, D. C.

Presented
to

THE FAA SYMPOSIUM ON AIRCRAFT ICE PROTECTION

April 30, 1969

FAA WASHINGTON HEADQUARTERS

ABSTRACT

Twenty-three low-cost, anti-icing materials were tested by the Aircraft Development Service at the NASA/Lewis Research Tunnel, Cleveland, Ohio. These materials were passive in nature and were of the type that can be sprayed, wiped, or otherwise added to the aircraft wing structure without special skills or equipment. Each product was examined in a manner that would enable a determination of its ice accretion characteristics and ice release properties. No effort was made to stimulate the natural ice release characteristics of each product, i.e., parting strips, vibration devices, etc. Ice formed on all materials tested. There was no observed release of ice due to aerodynamic forces, however, all of the materials evaluated did reduce adhesion to the wing in varying degrees. The minimum value obtained during the test program was on Dow Corning Cationic Silicons (E-1044-32-1 and XZ-83057).

INTRODUCTION

These tests by the FAA of anti-icing materials have been initiated as
a follow-up effort to the Engineering Summary of Airframe Icing
Technical Data (ADS-4) completed in 1963. The above-mentioned report
served as the vehicle for bringing together all known technical
experience in the area of airframe icing. The basic research conducted
by NACA/NASA comprising over 130 separate reports, formed the major
part of the statistical data in ADS-4 and serves as the basis for most
U.S., Canadian, and British commercial and military design criteria.

In September 1967, the Aircraft Development Service, FAA, received
two requests for R&D effort from the two major subdivisions of the
U. S. civil aviation industry, the Aircraft Owners and Pilots
Association, representing a major segment of general aviation, and
the Air Line Pilots Association safety representative for Air West
representing the air carrier segment. The Seattle Area Office, Western
Region, coordinated the operational interests of both the general
aviation and air carriers in the Pacific Northwest. The above parties
requested that the Aircraft Development Service investigate the ice
accretion characteristics and release properties of certain relatively
new developments in the field of passive materials that may offer
improvements in the release of ice from aircraft structures.

The problems faced by these parties, particularly operators of
small aircraft, are the relatively high cost and weight penalties of

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current generation de-icing/anti-icing systems available for small aircraft. Further, large aircraft operators have a continuing interest in systems that will provide for easier and more complete release of ice from aircraft structures.

The past efforts of the NACA committee on icing problems had resolved the basic research issues involved in large aircraft operation in in-flight icing conditions. However, at the time (1957) the subcommittee was disbanded, small aircraft utilization had not increased to the point of major prominence in air-taxi, arilines, and business use that exists today.

A number of the passive materials suggested for examination are relatively new developments and have received considerable attention due to their low frictional characteristics experienced in non-aviation uses such as encountered in the food and textile industries.

The points focused upon in this investigation centered on the ice accretion characteristics and release properties of each material submitted for examination. Free entry to the tests was offered to all parties which included both civil and the military services. No restraints were placed on the participation of any interested individual.

MATERIAL

Requirements for test articles as established by NASA required " . . .
steady state stresses shall be designed with a factor of safety of 5
relative to stresses induced by aerodynamic forces in smooth airflow at
260 knots." This requirement necessitated the complete design to
fabrication of a NASA 2412 airfoil section. The new material included
4130 steel wing ribs and spars covered with 2024-T3 sheet aluminum.
The reconstructed test article did not exhibit any unsatisfactory
aerodynamic characteristics during the test series. The twenty-three
materials tested are described below.

Teflon-S 958-211. A material that requires   curing   at approximately
600°F. It is brown in color and exhibits a dull surface appearance.
Teflon-S 954-101. A material that requires   curing   at approximately
450°F. It is green in color and exhibits a dull surface appearance.
Both Teflon products were .0007" in thickness on a .003" thick aluminum
foil with an adhesive backing.

Formica UHM. An ultra-high molecular weight thermal plastic material .030"
thick in sheet form.

Xaton MSX. A proprietary chemical treatment for metal surfaces in liquid
form that requires appxoximately 1/2 hour curing time.

Xaton PRX. A proprietary chemical treatment for metal surfaces in liquid
form requiring approxin.. ely 1/2 hour curing time.

Polyurethane - Astro-coat RM 115pi. Four coats are required for a total
thickness of 6 mils. thickness plus a primer 1 mil. in thick.ess. The
product requires approximately 4-5 days curing time in place at room
temperature.

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Polyox. A high molecular weight polyurethane oxide film 6 mils. thick. This material is water soluble.

Union Carbide Y-4112. A solvent solution of reactive silicone.

Union Carbide Y-4828. A cationic silicon grease deposition.

Cab-0-Sil (Trademark) ST-D. A super-hydrophobic amorphous colloidal silica.

Coating applicators. Teflon paint. Two different compositions were offered for test. Their contents were proprietary in nature. A heat lamp was required for curing.

Product Development Company 2-D-10A. A proprietary grease composition.

Dow Corning Cationic Silicones. Two products were offered; E-1044-32-1 and XZ 83071 proprietary grease deposition.

Scientific Products Corporation. S.P.C. A proprietary metal surface treatment in liquid form.

Interlock. A product with Teflon particles locked into an aluminum foil by a patented process.

General Electric. Four products were offered: "Insulgrease" an aerosol application of silicon grease; "Insulgrease" a silicon grease composition; GE G-660 - G-635 both silicons.

Glidden - Glidair. A proprietary aerosol ice repellent.

A hydraulically actuated device was designed and constructed to measure the shear forces (lb) necessary to dislodge a 10 square-inch sample of the ice coating the leading edge of the wing. Basically, this device consisted of a tripod, secured to the floor of the tunnel immediately

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adjacent to the leading edge of the wing. Mounted thereon was a hydraulic actuator supporting a template of the wing leading airfoil manufactured from heavy stock aluminum. Immediately subsequent to each test run, the tripod was mounted adjacent to the leading edge of the wing, the periphery of the measured ice test sample was cleared with a hot iron, and the airfoil template was placed against the wing leading edge. Following this, hydraulic pressure was exerted to move the template spanwise to dislodge the measured ice test area. The resulting hydraulic force required was then simply divided into the size (10 square inches) of the ice test section and the pounds per square inch noted on the record sheet.

All test runs were followed by documentation of the ice formation and buildup by polaroid color film. Products that exhibited particularly desirable characteristics were documented by color motion picture film.

All tunnel test condition calibrations and the tunnel operation were established and run by NASA/Lewis personnel. All records of test conditions were recorded from the established tunnel instrumentation.

METHODOLOGY

The test environment was designed to examine each of the previously described materials in two basic operating conditions. These were: (1) Maximum continuous icing, and (2) Intermittent maximum icing. Both of these condition definitions evolved from FAA Technical Report ADS-4, and are included in Appendix C, FAR 25. Further, two different airspeed ranges were established within each of the aforementioned operating conditions. These were, (1) 150 knots, simulating a small aircraft cruising speed with an appropriate angle of attack, and (2) 110 knots, simulating a holding speed, again with an angle of attack appropriate to that flight condition. To summarize, four runs were made on each product that showed promise of desirable release characteristics. Two under maximum continuous icing conditions, and two under intermittent maximum icing conditions.

Each test run was initiated and terminated in accordance with a time period appropriate to that which one would expect to encounter in the specific icing condition established. The determination of the time duration of each run was made based on the statistical data described in ADS-4.

SHEAR TESTING

At the outset it must be stated that it was not possible for this test group to develop a meaningful method of measuring the shear requirements for ice release from untreated aluminum surfaces. While the project personnel discussed this type of test with all facilities known to have experience in such work, each suggested approach, i.e., ice cube, test strip, pull desks, etc., retained the same undesirable characteristic. It could not be determined whether the adhesion force of the ice to the aluminum surface was being tested or whether the simple strength of the ice itself was factor in its release. For example, 10 test runs included an attempt to correlate the ice release from both the treated and untreated aluminum surfaces. There was no case observed where the ice released cleanly from the untreated surface. In each of these observations the ice either crushed or otherwise broke up and flaked away leaving a rough ice coated aluminum surface. A final point, the values related to this type of breakup exhibited considerable scatter, ranging from 9 psi to 36 psi. For the purpose of testing ice release forces, the above values are considered to be highly qualitative if not meaningless.

The shear test results of each material submitted for examination were divided into two categories: (1) The total prepared ice sample was dislodged along or from the wing surface when the maximum ram/template force was recorded (Table II), and (2) Portions of the total ice sample either were dislodged or the ice failed within itself. The variety of scatter noted in the release values of tests on aluminum make all but the first of the above two test result categories highly suspect and qualitative in nature.

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TABLE I

FAA ICING PROGRAM

NASA-Lewis

STANDARD TEST SERIES

Run No.	TAS (Knots)	MPH	Total Temp. (^{o}F)	Liquid Water Content (gms/M3)	Drop Dia. (Microns)	Duration (Min.)	FAR 25, Appendix C Conditions
1.	110	127	25	0.7	15	9.5	Maximum continuous
2.	150	173	25	0.7	15	7.0	Maximum continuous
3.	110	127	14	1.5	25	2$^{+}_{-}$	Intermittent maximum
4.	150	173	14	1.5	25	1.5$^{+}_{-}$	Intermittent maximum

TABLE II

TEST RESULTS

UTILIZING STANDARD TEST SERIES

CATEGORY ONE

Material Tested	Range of Ice Release Factor (PSI)
Teflon-S 954-101	11
Formica-Polyolefin	7-14
Polyurethane	23-36
Union Carbide	
Polyox	18
Y-4828	25
Y-4112	8
Cabot-Dry Overcoat	31
Coating Applicators	
3889-1045	12-25
4010X	5-17
Product Development Company	
2-B-10A	13-25
Dow-Corning	
E-1044-32-1	1.8-2.2
XZ-83071	1.8-2.2
XZ-83057	6-10
S.P.C. "Protect"	13-15
Xaton-PRX	13
Interlock Panel (Teflon)	7-10
General Electric	
Insulgrease	10
G-660	5-11
G-635	3-11
Glidair	5

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RESULTS

The results of these tests can be divided into three categories. These are:

1. Ice formed on all materials examined in the icing research tunnel. Qualitative observations of the amount and type of ice buildup treated versus untreated surfaces indicate little difference between test runs other than that which would be expected from different time durations.

2. The test group was unable to develop a meaningful test for examining the shear force required to release ice from an untreated aluminum surface.

3. All materials tested did reduce the forces required to release ice from the treated aluminum surfaces.

CONCLUSIONS

It is clear that none of the materials examined exhibited any obvious signs of aerodynamic release of ice. However, several points must be kept in mind when analyzing this evidence. First, the icing research tunnel simulates the sub-cooled liquid water droplet cloud; it does not include examination of the effects of snow, ice particles, rain, etc. Second, there are continuing qualitative reports of pilot's "successful" use of passive types of materials in actual flight within reported icing conditions. Third, marked reductions were noted in forces required to release the ice from certain of the treated aluminum surfaces.

Based on the above, further tests are warranted to determine the real life operating environment characteristics, i.e., erosion, life time, etc., of at least those products outlined in Table II. Further, such flight tests would provide correlating data relating to the results obtained in the icing research tunnel.

Additionally, experience gained in these tests indicates the need for a more refined and standardized method for the measurement of ice release forces from all surfaces.

A final point of emphasis, the definition of the relationship of the tests in the I. R. T. to those in the real life operating environment, is as yet undefined.

ACKNOWLEDGEMENTS

TABLE I

FAA ICING PROGRAM

NASA-Lewis

STANDARD TEST SERIES

Run No.	TAS (Knots)	MPH	Total Temp. (°F)	Liquid Water Content (gms/N3)	Drop Dia. (Microns)	Duration (Min.)	FAR 25, Appendix C Conditions
1.	110	127	25	0.7	15	9.5	Maximum continuous
2.	150	173	25	0.7	15	7.0	Maximum continuous
3.	110	127	14	1.5	25	2^+_-	Intermittent maximum
4.	150	173	14	1.5	25	1.5^+_-	Intermittent maximum

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TABLE II

TEST RESULTS

UTILIZING STANDARD TEST SERIES

CATEGORY ONE

Material Tested	Range of Ice Release Factor (PSI)
Teflon-S 954-101	11
Formica-Polyolefin	7-14
Polyurethane	23-36
Union Carbide	
Polyox	18
Y-4828	25
Y-4112	8
Cabot-Dry Overcoat	31
Coating Applicators	
3889-1045	12-25
4010X	5-17
Product Development Company	
2-B-10A	13-25
Dow-Corning	
E-1044-32-1	1.8-2.2
XZ-83071	1.8-2.2
XZ-83057	6-10
S.P.C. "Protect"	13-15
Xaton-PRX	13
Interlock Panel	
(Teflon)	7-10
General Electric	
Insulgrease	10
G-660	5-11
G-635	3-11
Glidair	5

DISCUSSIONS FOLLOWING MR. HAY'S PRESENTATION ON

"EXPERIMENTS WITH ICEPHOBIC SURFACES"

Question: How much force was necessary for removal of the ice
             from the untreated surface?

Answer: From 9 to 36 PSI prior to ice failure.

Question: Did your test include the Minnesota Mining and
             Manufacturing Company adhesive backed tape?

Answer: No, Ed Merkle from Douglas has tested this.

Question: Lear Jet tried Icex, but we persuaded them not to
             use it. Did you test Icex?

Answer: Yes, and we found it was an aid in causing ice
             breakway from boots. A corporation aircraft with
             a professional pilot has used a group of icephobic
             substances. The pilot is still experimenting.

"AIR FORCE OPERATIONAL PROBLEMS

ATTRIBUTABLE TO AIRFRAME AND POWER PLANT ICING"

Presented to

THE FAA SYMPOSIUM ON AIRCRAFT ICE PROTECTION
Washington, D.C.
April 28-30, 1969

by

LT COLONEL BRUCE M. ELVIN, USAF

Air Weather Service Liaison Officer
Directorate of Aerospace Safety
Deputy Inspector General for Inspection and Safety
Norton AFB, California

GENTLEMEN:

I propose to discuss with you the Air Force's operational problems attributable to airframe and power plant icing during the period of 1965 to date.

Let me begin by stating that within this time period, we have had no accidents, major or minor, that have had icing as a primary cause factor. Further, those mishaps which did involve icing were randomly spread between bombers, transports and fighters without an obvious affinity for any one category.

Now - down to some specific case histories.

The aircraft - F-102A Delta Dagger, built by Convair and equipped with a J57-P-23A engine. It is a single place, supersonic, all-weather, delta wing interceptor.

On a routine scramble from Ramstein AB, Germany, the pilot was vectored to FL 250. Because of conflicting traffic, he was held at 4000 feet for 3 to 4 minutes. Departure weather was 1500 feet scattered, 3000 feet broken, 7000 feet broken, with 4 miles visibility in very light snow, a very moist atmosphere. Surface temperature was 28°F with a dew point of 21°F. Light to moderate icing during climb had been forecast.

At level off at 25,000 feet, with 320 kts indicated, 92.5 percent power and an exhaust gas temperature of 630 degrees, the pilot experienced a loud report to the left rear side of the aircraft and an accompanying surge in cockpit pressure. When he checked the engine instruments, they were normal. The power was then retarded to 84% with all

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engine instruments continuing to be devoid of any abnormality. The power was advanced to approximately 89% to conti e the mission but the pilot reported that a roughness in the engine was noticeable. Power was then reduced to 85% for the descent and an emergency declared. Recovery was made without further incident.

A heavy accumulation of clear ice on the duct lips was found after landing. The engine was inspected but no damage was detected. A check of the duct anti-icing system verified its adequate performance. A complete trim check of the engine was made with no discrepancies found. A functional check flight revealed nothing and the aircraft was subsequently released for flight.

The investigator's conclusion was that an accumulation of ice had built up on the intake duct during the initial phase of the climb and a piece of this had broken loose and had been ingested into the engine. This icing condition was undoubtedly aggravated by the delay at 4000 feet. The flight manual states that timely employment of the anti-icing equipment will greatly reduce the probability of inlet duct icing build up, not eliminate it entirely.

Two other F-102 incidents related to the ingestion of ice crystals from cirrus clouds are on record. Before their respective requests for higher elevations could be approved, each aircraft suffered several compressor stalls and a flameout which was fortunately followed by an early restart

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and uneventful recovery. Again, there was no detectable engine damage.

The aircraft - T-37 "Tweety Bird" built by Cessna and powered by two J69-T-25 engines. Two place side by side trainer.

While in descent from FL 230, over Texas, approximately one quarter inch of ice formed on the leading edge of the wing and canopy rim. The aircraft was clear of clouds at 14,000 feet and cancelled IFR with the field in sight. The ice began to melt at 10,000 feet. The right engine flamed out at 8000 feet and was immediately restarted. The left engine quit at 6000 feet and was likewise immediately restarted. Both engines were set at 80% RPM with 240 kts indicated at the time of the trouble. A maximum of 600 degrees exhaust gas temperature was reached during the restarts. Aircraft and engines were ground inspected for damage with negative results.

In a similar case, a T-37 pilot encountered broken clouds at FL 220 and light ice began to accumulate. Before a change of altitude could be affected, the icing ceased. The flight was continued through broken clouds for a full ten minutes before reaching the destination VOR fix. At this time a solid cloud mass was entered and ice began to rapidly accumulate on wings and canopy. A climb request was made and immediately granted. When clear of the clouds, it was noted that 1 1/2 inches of ice was on the leading edge of the wings. Penetration was initiated early and the ice began breaking off at the cloud

base of 12,000 feet and was completely gone at 8000 feet. The pilot raised the speed brakes and brought power back to idle to conserve fuel during this abnormally long penetration. Level off was made at 7000 feet and was accompanied by the flameout of the right engine, followed in 5 seconds by the loss of the left engine. Restarts were accomplished but not before the aircraft had descended below 2000 feet above the surface. Ground inspection failed to reveal any damage to either engine.

The aircraft - T-33A Shooting Star, built by Lockheed and equipped with a J33-A-35 engine, two place tandem trainer.

Three T-birds were recovering at Kadena AB, Okinawa, after fulfilling their respective roles as faker aircraft. Each had been in subfreezing temperatures for 1 1/2 hours.

The first aircraft entered the holding pattern at FL 200 (-16°C). Rime icing, less than 1/2 inch thick, accumulated on the wind screen and the leading edges of the wing. The pilot noticed an RPM fluctuation but attributed it to an inadvertent throttle movement due to the light turbulence he was encountering. Approximately 2 minutes later, at 200 kts indicated and with 83% RPM, the engine flamed out. Relight was immediate but the exhaust gas temperature went to 1000 degrees. The pilot brought the temperature back within limits and landed without further incident.

Number two aircraft entered the holding pattern at FL 210. He encountered heavy precipitation, rime ice accumulation of

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1/2 to 3/4 inch thick and light turbulence. He was advised of the previous incident.

While in descent with 80% power, in moderate to heavy rain, his engine flamed out at 17,000 feet (-10°C). Immediate restart was accomplished but at 13,000 feet (-3°C), the engine rumbled and the RPMs decreased to 65%. The throttle was advanced and the engine recovered within 10 seconds. No further difficulty was experienced.

The third aircraft entered the holding pattern at FL 220 and encountered light to moderate turbulence, 1/2 inch accumulation of rime ice and a mixture of frozen and liquid precipitation. After 15 minutes of holding and having been advised of the two previous flameouts, he began his penetration.

At 17,000 feet he encountered very heavy rain and as he passed through 15,000 (-7°C), still in very heavy rain, the engine compressor stalled and the RPM began to decrease. The gang start switch was activated at 53% RPM and the engine immediately recovered with no further difficulties.

Temperatures at the various altitudes were taken from the most current upper air sounding. Cumulonimbus tops to 35,000 feet were possible in the area with supercooled rain at the incident altitudes. The freezing level was 12,500 feet.

The investigator concluded that induction icing was the most probable cause for the flameouts, affecting the main fuel control and airflow to the engine. He also cited water ingestion as a possible contributing cause.

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The aircraft - T-39A, Saberliner, built by North American, a swept low wing multi-engined jet trainer. Two side by side pilots, four passengers.

The first of two aircraft was scheduled for an early afternoon instrument training mission. The aircraft entered the cloud base at 14,500 feet with engine and wing anti-icing equipment operating. Immediate formation of rime ice was noted on the wing slats. After level off at FL 220, ice accumulation was estimated to be 1/2 - 3/4 inches. Aircraft remained at altitude for 5 minutes and then began penetration. Postflight inspection revealed damage to both engines. Two inlet guide vanes were distorted and 8 first stage rotor blades were bent at the tips in #1 engine. In engine #2, six inlet guide vanes were distorted, 9 first stage rotor blades were bent at the tips, and 2 first stage stators were nicked just above root area. Both engines required replacement.

The second Saberliner's pilots were briefed on the earlier incident and their exposure time within the clouds was purposely minimized. Clouds were penetrated at 15,000 feet with engine and wing anti-icing equipment functioning. Cloud tops were at FL 230. Ice accumulation during initial climb was 1/4 - 1/2 inches on wing slats and windshield wipers. The ice sublimated from wings and wipers while flying on top of the clouds. Aircraft descent was made at 4000 feet per minute. No appreciable ice accumulation was noted during the descent.

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Engines were closely checked upon landing. Damage was minor and confined to the #1 engine and consisted of 5 first stage rotor blades curled at the tips. One third stage stator vane was nicked above the root. Damage was blendable but inaccessible.

The ingested ice could have come from the nose or adjacent fuselage which has no anti-icing protection. It is more likely that the ice accumulation rate was simply in excess of the anti-ice system's capability.

The aircraft - C-141A, Starlifter, built by Lockheed and equipped with 4 TF33-P-7 engines. Flight crew of 6 and 154 troops.

Two aircraft were awaiting weather improvement to takeoff minimums at Elmendorf AFB, Alaska. The delay was in excess of one hour for one aircraft and two hours for the other. Weather conditions were: temperature $9^{\circ}F$, dew point $7^{\circ}F$, calm winds with visibility restricted due to ice fog.

When the flights were cancelled an. the aircraft returned to the ramp, the extensive icing was discovered. The accumulation was not visible from the cockpit and the crew had no warnings from their instrumentation.

The auxiliary air doors in the cowls had been frozen in the open position. Three quarters to one inch of ice covered the inlet guide vanes, first and second stage fans and second stage guide vanes. All of this had occurred despite the full employment of the anti-icing systems.

The inlet screen for the auxiliary power unit had also iced up and created a potential fire hazard.

Current Air Force procedures now call for the delay in starting engines until takeoff conditions exist when ice fog is present. Frequent visual inspection of the APU inlet screen are made to warn of excessive ice buildups when the equipment must be operated under these conditions.

The aircraft - WC-130B/C-130E, Hercules, built by Lockheed and equipped with 4 T56-A-7 engines, 4 crewmembers, 92 troops.

While enroute from Mountain Home AFB, Idaho, to Eielson AFB, Alaska, the aircraft was subjected to light rime ice for 45 minutes. The aircraft commander watched this condition very carefully and when the icing severity increased, he began a descent to a cloud-free area and initiated a return to McChord AFB, Washington.

Shortly thereafter, #4 engine flamed out and the tailpipe inlet temperature peaked at 950 degrees. The engine was shut down.

Engine #3 began to lose power. RPM decreased to 60% and the crew prepared for two engines out on one side, but it unexpectedly recovered and came back up to speed.

Ground inspection and runup of the #4 engine revealed that it required replacement due to excessive vibration.

It is presumed that this incident was caused by the disruption of inlet air flow due to severe inlet icing.

The WC-130B was engaged in routine hurricane recon-
naissance. After penetrating the "eye" of the storm and
measuring the various parameters at that location, the
aircraft moved back out to the edge of the disturbance and
established a box pattern to collect peripheral data.

Although their radar did not show heavy precipitation
in the holding pattern, the aircraft encountered severe icing in
a snow shower. An immediate descent to warmer temperature
was begun.

Shortly after entering the descent, #1 engine flamed out
(outside air temperature 9°C) while simultaneously #4 engine
went into a stalled condition with the turbine inlet tem-
peratures rising to 840°C. Within seconds, the remaining
two engines started to flame out, #2 first, followed by #3.

The pilot increased the throttle settings and #3 kept
running. The copilot was successful in regaining #2 by
going through the airstart procedures. An attempt to feather
#1 by the normal procedure was unsuccessful but the system
did respond to the manual override. Although #4 was still
running, it was not producing power due to the flat blade
angle so it was also feathered.

The aircraft was leveled at 11,500 feet with both inboard
engines running smoothly and all checklist items were accom-
plished. Number 4 was then restarted but the earlier problem
in feathering #1 discouraged the aircraft commander from
stretching his luck too far. The aircraft recovered at

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Kelly AFB, Texas, where the engines were thoroughly inspected
and tested. No damage was found.

The incident was charged to severe icing which blocked
the airflow to the engines and caused the compressor stalls.

The Air Force stresses the need for a detailed weather
briefing before each extended flight and requires letter-
perfect knowledge of the limitations and capabilities of the
airplane by the crew. These requirements forewarn of the
icing potential and other hazardous conditions and permit
alternate flight profiles to be selected.

We have solved the problem by avoiding it whenever
possible. In these generally rare cases in which the equip-
ment design was unable to completely cope with the environment,
the recovery of the aircraft must be credited to the professional
skill of the aircrews involved.

DISCUSSIONS FOLLOWING LT. COL. ELVIN'S PRESENTATION ON

"AIR FORCE OPERATIONAL PROBLEMS

ATTRIBUTABLE TO AIRFRAME AND POWERPLANT ICING"

Question: Do you recall any Pitot tube icing accidents?

Answer: We have nothing on record. Only major and minor
             accidents are investigated. These are incidents,
             so we just have incident reports which are not as
             detailed.

Question: Does the Saberliner have a wing and fuselage
             anti-icing system?

Answer: The portion of the aircraft in front of the engine
             does. I think the icing ingestion problem results
             from nose and fuselage icing breaking off and
             entering engine.

Question: In the case of the loss of all four engines you
             mentioned, are there any provisions for restart
             in this case?

Answer: You need the APU for bleed air. Can air start,
             but prefer not to.

MILITARY OPERATIONAL EXPERIENCE

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MILITARY OPERATIONAL EXPERIENCE

The guidelines provided by the Icing Symposium technical program notes were rather broad in nature and at first glance, offered a limited time frame in which to complete this presentation. I find, however, the research and development effort of the separate military departments, federal agencies, and private industry coupled with the "hard knock" experience gathered through the rapid development of the aerospace art, have so reduced icing problems within naval aviation that the time alloted presents absolutely no problem.

In order to gather information on pilot squawks, unsatisfactory reports, etc., the fixed-wing and rotary-wing analysts from the Safety Center's Aircraft Analysis Division were contacted. Our training analyst reports the limited icing exposure allowed by our training command consists of an occasional inadvertent IFR/icing encounter. Students are not flown in known icing conditions.

The missions flown by fighter and attack aircraft allow exposure for only brief periods of time and, as a result, little or no icing problems are involved in high performance aircraft.

One problem noted in the fighter/attack area seems to involve the OV-10A made by North American. The OV-10A NATOPS Manual contains the "standard" ice warning. Talks with pilots indicate icing conditions are a terrorizing experience to be avoided at all costs. It appears that the horizontal stabilizer loads itself rapidly in an icing environment and due to the change in "CG" the aircraft becomes somewhat unstable in pitch modes. Appropriate cautionary notes have been issued and conferences are scheduled in June for resolution of the problem.

If holding pattern times for fighter/attack aircraft are limited by good planning and expeditious handling the only other problem area of note is minimized.

Patrol/antisubmarine aircraft and their associated avionics equipments have improved at a steady pace, allowing for less exposure time at low altitudes in favorable icing areas. The only major icing problem is with the Sikorsky H-3 helicopter. Pilot problems and background on its icing problem will be covered in detail during the discussion of icing reports on turbine powered aircraft.

No particular operational problems have been encountered which relate directly to airframe icing. Restricted operation in other than dry snow conditions during normal training operations has been necessary in the H-3 due to power plant damage by ice FOD.

The data storage facilities of the Naval Safety Center have been questioned and the sanitized list of all suspected icing aircraft accidents, ground accidents involving aircraft and aircraft incidents since 1965 is provided in the handouts you have received. I will read the briefs of the four possible ice caused accidents.

The first aircraft was flown by a rather lucky individual. I suspect he was an Ensign in the Navy. While flying an A-1A he collided with trees during a daylight emergency landing approach due to intermittent power problems. The pilot had noted backfiring and a cylinder head temperature of 220 degrees. He selected rich fuel mixture and observed a cylinder head drop. Torque rose from 88.5 to 98 psi. Alternate air was selected and carburetor air temperature rose from 5 to 32 degrees. He reselected direct air and the carburetor air temperature returned to 5 degrees. Deciding to

make a precautionary landing, the pilot was cleared number two behind a C-130 on a three mile final. This placed him three-quarters of a mile downwind of the 180-degree position. The engine quit on base and the pilot prepared for an emergency landing while continuing his approach. Realizing he could not reach the runway he attempted to land in a small clearing. The aircraft began to contact several small trees 70 to 80 feet high. At this time the engine started to run again, the pilot made a dramatic recovery and landed the aircraft on the runway. The cause of this accident was attributed to pilot failure to use alternate air when carburetor icing induced engine power loss.

The second accident shown on your handouts involved an A-3B aircraft. The aircraft was on a cross-country flight and had filed for his alternate airfield due to poor weather forecast at his destination. The alternate airfield selected was reporting 2000 feet overcast with two miles visibility in light drizzle, snow and fog. Given immediate descent on a radar vector to GCA pickup, he complied with all instructions. On GCA final at 2000 feet and eight miles from the runway he was given a heading change. He acknowledged the change, but did not initiate the turn. A keyed mike was noted with heavy breathing, no voice. He was lost from radar and crashed. The cause was considered to be aircraft stall due to wing icing during the approach.

The next accident noted in your handouts concerns another A-3 aircraft, which had a dual engine failure and subsequent loss of all generator powered electrical components at 41,000 feet. The result was one lost A-3. The accident itself was aggravated by many pilot factors but the loss of both engines was attributed to compressor stall due to ice.

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The only training command accident involving icing is a TF-9J executing
a TACAN approach. On final approach the instructor reported his windshield
obscured by ice. Observers noticed the aircraft appeared low and slow as
it approached the runway. At 4000 feet from the runway threshold the air-
craft was observed to roll first 25 degrees to the right, then 45 degrees
to the left, and finally into a 90-degree right bank followed by ground
contact. The cause was listed as undetermined with a possibility of pilot
induced stall aggravated by structural icing encountered during his approach.

The ground accident reports are of interest. Of 11 reported ground
accidents 8 were caused by improper towing operations.

A typical brief will read:

"Aircraft was being towed outside for servicing. The aircraft was
being turned close to a snowbank. When director saw that the aircraft was
going to hit the snowbank he blew his stop whistle. The brake rider and
tractor driver both hit the brakes, but the aircraft skidded into a snow-
bank. Recorded as supervisory error in judgment of the director with icy
taxiway contributing."

Following a discussion with our facilities analyst on methods of icy
runway treatment, I believe that FAA Project Report 430-006-023, prepared
by Mr. Murray S. Boris, gives an excellent thumbnail sketch of current
removal equipment improvements: the ethylene glycol/sand mixture and Urea
(sodium nitrate) treatment. Currently, the Navy finds the only airfield
icing problems are associated with fields such as Norfolk. This is due
primarily to limited snow removal equipment. Those fields that are nor-
mally provided with severe weather are adequately outfitted with equipment
to handle the problem.

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With respect to military icing reports on turbine powered aircraft
the H-3 aircraft provides the only problem of any major proportion. Roughly
30 incidents of ice ingestion have been reported since 1964. The effort
to provide adequate H-3 engine FOD protection from ice/snow ingestion has
been under active discussion since at least 1964 and tests have been made
since 1965. The first H-3 ice deflector was developed by Sikorsky Aircraft
for the USAF as a quick fix to avoid engine FOD during an in-flight icing
test behind a C-130 tanker aircraft. This quick fix was necessitated by
the actual loss of engines due to ice FOD during the initial test. The FOD
deflector enabled completion of the structural icing test without further
engine FOD under conditions of extremely heavy structural icing. Successes
enjoyed by the USAF in this operation were responsible for procurement of
additional ice deflectors as general FOD deflectors on many other USAF H-3
helicopters--some presently in use in SEA. In 1965 the Canadian government
procured CHSS-2 engine inlet foreign object deflectors, known as "The FOD
MOD." These deflectors have remained in service ever since. Informal liaison
with the Canadian Defense Liaison Staff, Washington, D. C., discloses that
since installation no cases of CHSS-2 in-flight FOD to engines has been
reported. Occurrences of inadvertent icing environment entry, including
some instances of heavy structural ice build-up, are reported. Performance
data available to the Canadian Department of National Defense when consider-
ing procurement of the deflectors was regarded as, "...Minimal but was
considered adequate at the time due to the urgency of a solution to the
problem of engine ice ingestion for winter operation in Canada. The expe-
rience of the USAF with a similar shield on the CH-3 was also considered."
The Canadian Department of National Defense was aware of USN reservations

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regarding installation of H-3 Airframe Change 247 (ice deflector installation),
but feels that their operational experience with FOD deflectors installed
is satisfactory evidence of deflector effectiveness and that the available
performance data is operationally adequate. This is also true of the USAF.
Additional civil H-3 series customers are reported by Sikorsky Aircraft to
have procured the engine FOD deflector and have subsequently operated with-
out FOD mishap.

Current Naval Air Test Center ice deflector tests have been concluded
and installation of ice deflectors will be completed prior to the coming
winter season. Some easing of H-3 NATOPS flight restrictions where actual
structural icing conditions do not exist, may be expected. However, con-
siderable work must be done to provide rotor blade and airframe ice
protection which can allow unrestricted all-weather operation of rotary-
wing aircraft.

Adequacy of manufacturers' instructions for operation, maintenance and
overhaul of ice protection equipment is not currently questioned by any of
our analysts. We must, therefore, assume that they are completely adequate
and that the manufacturers have kept ahead of us in this area.

The airframe which is the Navy's first good source of operational ice
detection equipment experience is the Lockheed P-3. The deicing/anti-icing
systems are considered adequate and it is a common practice to turn on
engine anti-ice whenever icing conditions are expected. The detection of
structural icing is normally determined by visual reference to the areas
around the windshield or the leading edges of the wings. At night an aldis
lamp is utilized to check ice on the wings. The airframe ice detection
system is not usually relied on, as pilots report the system has not proven
consistent in its reliability.

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As the experience of aircraft operators increases, in-flight icing encounters decrease. With the improvements in ice protection and detection equipment provided by industry our operational problems should soon "melt" away.

DISCUSSIONS FOLLOWING LT. COL. LUNSFORD'S PRESENTATION ON

"MILITARY OPERATIONAL EXPERIENCE"

Question: Have you any incidents where air speed systems are bothered by ice or precipitation?

Answer: Yes, but these are only incidents. Pilots have reported water refreezing in the system. This is no big problem.

Question: Has any work been done on air heated screens?

Answer: United Aircraft Company of Canada states these are hard to design because they have such high air and electrical requirements. There were incidents on the Model A-4, where, at 20,000-30,000 feet, generators are icing, and the proposed fix was to use a heated screen system. I don't know if this answered the problem, but we have not heard of its occurrence lately.

Question: Was the incident on the CH-46 due to water runback freezing or inlet guide vane icing?

Answer: The aircraft had been left overnight in a freezing rain. It was preheated, but, due to a time lapse, water froze in the low spots of the engine inlet. Starting the engines ruined them.

Question: Does your computer data include thunderstorm incidents?

Answer: No, but I feel that turbulence and lightning, rather than icing, are the worst part of thunderstorms.

Question: P-3 operators have encountered icing during loiter operation (two engines operating); how badly do the shut-down engines ice up?

Answer: Moderate to severe icing has been experienced on the inlets and the inlet guide vanes.

Question: Has this icing been severe enough to cause engine start failure?

Answer: No, but they have damaged engines on start.

Question: What do you do about this?

Answer: Run anti-icing on the engines or run icing protection
            with the shut-down engines at idle. We have
            considered heating from the operating engines.

Question: You mentioned that C-130 on hurricane reconnaissance
            having a number of engines shut-down. We have
            noticed that flying in high water concentration is
            a problem.

Answer: Lockheed states that in a steady state condition
            engines can consume very large amounts of water.
            Water input on a slug basis may extinguish an engine
            with less water.

ICE PROTECTION SYSTEMS,
COMMERCIAL MAINTENANCE EXPERIENCE

Paper for the FAA
Icing Symposium
April 28-30, 1969
Washington, D. C.

Presented by
R. H. Johnson
United Air Lines
Engineering Department

I have been asked to review the maintenance aspects of commercial aircraft ice protection systems. I will try to answer the following questions about the ice protection systems presently in use on commercial aircraft.

1. How effective from an engineering point of view are our current ice protection systems?

2. What types of maintenance problems do we have with the various aircraft anti-ice systems?

3. Are the overhaul and maintenance procedures provided by the manufacturers adequate?

Before I attempt to answer the questions that have been posed, I would like to quickly review the ice protection systems used on our current jet transports.

Slide 1   1. The thermal (pneumatic) anti-ice system is used to protect the leading edge of the wing, wing slots, slot lower doors (DC-8), slats, leading edge flaps (Boeing), leading edge of the horizontal stabilizer

Slide 2   (DC-8), air inlets, engine nacelle inlets, inlet guide vanes and the engine nose bullet.

Slide 3   2. Electrical units are used to heat pitot tubes, static ports, drain masts, stall warning sensors, cockpit windshields and windows.

The systems are all designed to be anti-ice systems rather than de-icing. To be effective, they must be activated prior to the formation of ice.

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There is one other system which I have not discussed yet, and that is the ice detection system. United currently uses an ice detection system only on the Caravelle. Our early DC-8's and 720's had ice detection systems installed. However, experience showed that icing of the Pt$_2$ probe mounted in the engine nose bullet, causes fluctuation of the Engine Pressure Ratio (EPR) gauges, and is a more sensitive indicator of icing conditions than the ice detection system. Since the Caravelle does not have an Engine Pressure Ratio system, an ice detection system is used.

"How effective are the current ice protection systems?" Major problems with anti-ice systems on jet transport aircraft are few and far between compared to earlier piston aircraft. Considering the millions of miles jet aircraft fly each year in all types of weather, the number of icing problems is small. The majority of the ice protection systems have adequate heating capacity to keep the aircraft ice free when used properly. From a maintainability point of view, the ice protection systems with the exception of a few components such as the engine anti-ice valves and ducts, do not have a high failure rate. Using United's jet fleet of 316 aircraft

Slide 4   as an example; in January and February 1968, the anti-ice systems accounted 4.5% of the delays. 2% of the delays were caused by the above mentioned engine anti-ice valves and ducts.

The next question to be answered is: "What types of maintenance problems do we have with the various anti-ice systems?"

    1. The thermal anti-ice system is relatively trouble free between aircraft overhauls. The pneumatic system is

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a simple design and only has a few moving parts which
are the valves and telescoping ducts going to the lead-
ing edge devices. In this type of system, it is the
valves and thermal switches which cause most of the
problems in service. A look at some typical examples
from our Aircraft Mechanical Irregularity Report shows
that for the first two months of 1968 there were a
total of 2299 maintenance caused delays and cancellations
on United aircraft and only 58 (2.5%) were caused by the
thermal anti-ice system. United aircraft flew 121,903
hours during these two months. A look at the 727 fleet
for February 1968 will give a general idea of the types
of maintenance problems we see. You will notice that
although many of these problems are with valves there
are 7 examples of line or duct failures. The duct
failures are caused by (1) the basic design which does
not allow enough for thermal expansion, or (2) inadequate
clearances between components which cause contact and
wear through when the engine is running. As an example
of not enough allowance for thermal expansion, the JT8D
13th stage bleed duct is basically an "L" tube. When
the tube (which carries air at up to 850°F) expands, it
does so at a different rate than the cool fan duct case.
The result is that after repeated cycles of heating and
cooling, it cracks at the flange. The Boeing 737 left
engine provides us with an example of a design which
does not provide adequate clearance between the 8th

Slide 5

Slide 6

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stage bleed duct and other nacelle hardware. In service the coupling wears into the 8th stage bleed duct with eventual leakage. We are currently working with Boeing and Pratt & Whitney and believe we have solutions to these problems.

2. The electric anti-ice systems have two basic problems -- heating element and control unit durability. I will use the Boeing 727 February 1968 experience as an example again. The pitot system and the Ram Air Temperature System both had a heater element failure. The windows' and windshields' anti-ice system had heater control unit problems. To put these systems into perspective, let's look at the slide covering January and February 1968 delays and cancellations again. The electrical anti-ice system caused 45 (2% of the total) out of a total of 2299 maintenance caused delays or cancellations.

Slide 7

Slide 8

"Are the overhaul and maintenance procedures provided by the manufacturers adequate?" A direct answer is that the procedures provided by the airframe and engine manufacturers are generally adequate. However, as with all things, there are areas which could be improved. We have found that in order to achieve the maximum reliability out of some of the anti-ice systems, additional procedures were required. As an example, on our Boeing 720 and 727 aircraft we had to further subdivide the thermal anti-ice ducting to facilitate checking the system for leakage at aircraft overhaul, rather than checking the system as a whole per the manual. We found that only in this way

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could we reduce leakage to what we consider to be an acceptable level, which is lower than on new aircraft. The Boeing 727 engine anti-ice valve is another area where we have had to deviate from the manufacturer's procedures in an effort to fix a problem. As I mentioned before, the valves cause the greatest amount of non-scheduled maintenance in the thermal anti-ice systems. The engine and cowl anti-ice valves have the lowest reliability. The problem is that the range of temperatures, which these valves see, makes it difficult to get a satisfactory service life from them. The valve as delivered from the factory is a motor operated butterfly valve. It uses plain bearings lubricated with a sicilone based grease. To follow the manufacturer's overhaul procedures would mean continuing the same failure rate. To make the unit more durable, we are (1) installing a better armature bearing and (2) using a petroleum based lubricant which has proven to be better in this application.

Slide 9   The slide shows the reduction in removals due to these modifications. The unscheduled removals per 10,000 unit hours dropped from 2.5 to less than 1.0. The new aircraft, such as the 747, uses all solenoid actuated-pressure operated valves which appear to be a much more durable valve.

So far I have only touched on the thermal system, the same type of problems exist with the electric anti-ice devices. Most of these devices are supplied to the aircraft company by a vendor. Many of these vendors then do not provide the degree of product support we as a user would like to see. For example, the durability of the heater elements in the pitot system is not good enough so that the system will go the eight to nine thousand hours between aircraft overhauls, as well as some lacking adequate heating capacity to

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prevent occasional icing at high altitudes. We, of course, want the vendors to upgrade their equipment so that it will do its job correctly and for the length of time we desire. The same holds true for the control units which give us maintenance problems. I have no answer for black box durability. Why will one light bulb last only minutes while another for hundreds of hours? There are many people in the industry working on this and perhaps one day there will be an answer. The only thing we as an airline can do is to insure that the black box control units are properly ventilated and protected from moisture. In order to accomplish the above requires frequently that we modify the design or modify the manufacturers' maintenance procedures.

To recap the question "Are the overhaul and maintenance procedures provided by the manufacturers adequate?" the answer is yes; but we have revised or modified many of them in order to either reduce the size of a problem or to extract longer intervals between overhauls from other components. No system is perfect so that there are always changes which could be made to improve them. At times we do not get the action we request on the vendors' part based on our failures. His response to our request too frequently is that: "Of the dozens of airlines operating this equipment, why is it only United that wants this change? Everyone else appears to be happy with things the way they are."

I think I have covered the current systems well enough, but I would like to add this to the discussion. Nothing has been said so far about whether other areas of the aircraft require ice protection. Two areas that United is concerned with are (1) icing on the landing

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gear and (2) icing on the Boeing 737 flaps. During the takeoff on slushy runways, ice and water can accumulate on the landing gear and on the 737, the flaps. The flap assembly can be badly damaged

when it is retracted with ice on it. The slide shows a typical fowler flap extended and retracted and how ice on the leading edge of the various segments can interfere with the segment ahead of it. The ice and the water which freezes on the landing gear at altitude, gets into the anti-skid units, up and down gear position indicators. This can result in blown tires on touch-down if the anti-skid becomes inoperative, as well as causing numerous problems with gear and doors not indicating up and locked or down and locked. The best solution for these problems is in the design stage. They should be designed so that ice will not be accumulated. If this cannot be done, then the design should be such that ice will not interfere with its function.

In conclusion, although there are maintenance problems with the various ice protection systems used on current jet transports, they are not major ones: (1) The systems are dependable causing only about 4.5% of the delays and cancellations. The average time per delay is 30 minutes. (2) The manufacturers' instructions for the maintenance and overhaul of ice protection equipment are adequate.

UNITED

WINDSHIELD RAIN REMOVAL SHUTOFF VALVE

NOSE LANDING GEAR OLEO SWITCH

TO LH WINDSHIELD

DIFFERENTIAL PRESS. SW.

TAIL DUCT VALVE PRESSURE SW. (DC-8-61, N8073U AND SUBS.
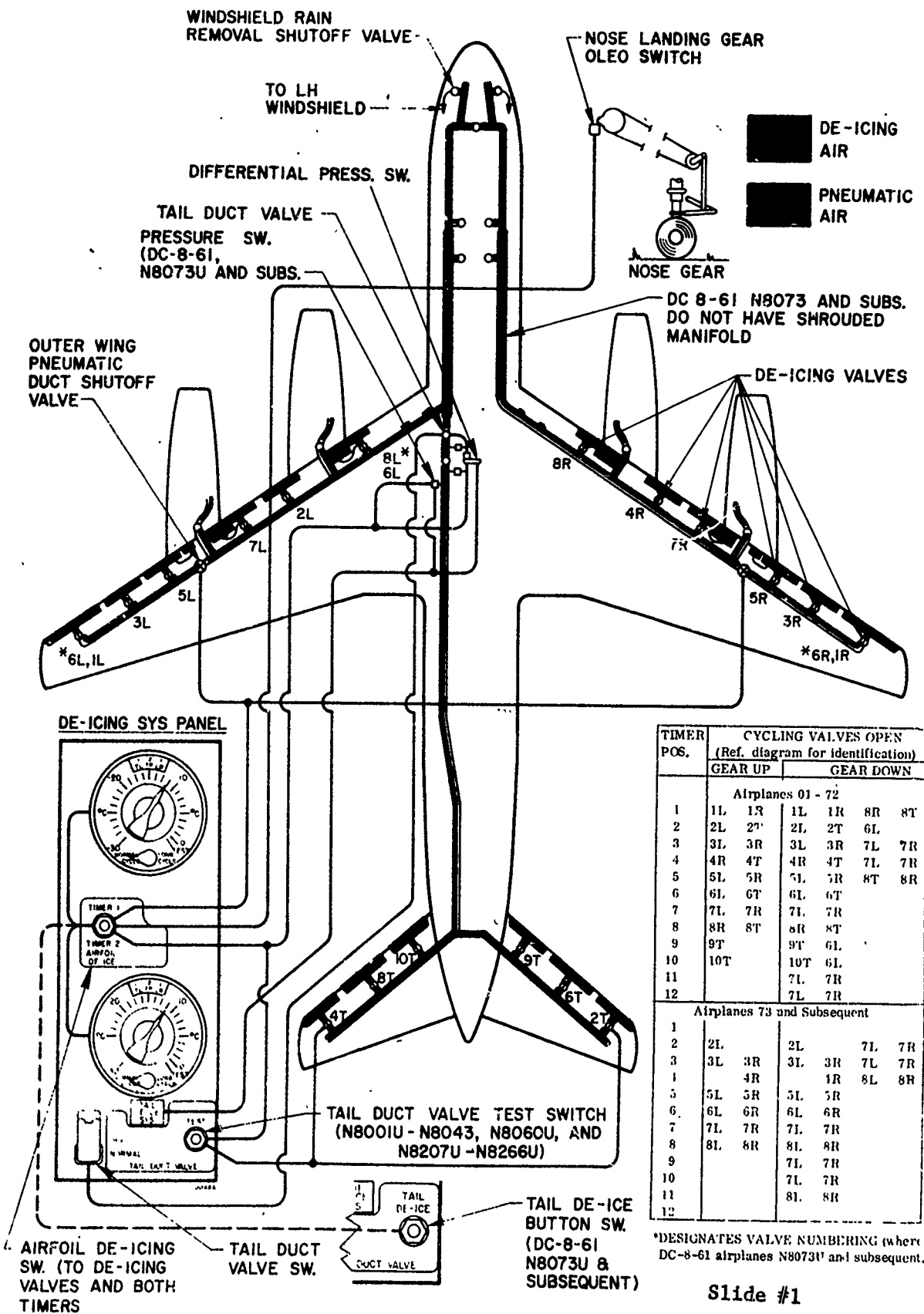
DE-ICING AIR

PNEUMATIC AIR

NOSE GEAR

DC 8-61 N8073 AND SUBS. DO NOT HAVE SHROUDED MANIFOLD

OUTER WING PNEUMATIC DUCT SHUTOFF VALVE

DE-ICING VALVES

8L* 6L

8R

2L

4R

7L

7R

5L

5R

3L

3R

*6L,1L

*6R,IR

DE-ICING SYS PANEL

TIMER 1

TIMER 2 AIRFOIL OF ICE

10T

9T

8T

6T

4T

2T

TAIL DUCT VALVE TEST SWITCH (N8001U - N8043, N8060U, AND N8207U -N8266U)

NORMAL TAIL DUCT VALVE

TAIL DE-ICE

DUCT VALVE

TAIL DE-ICE BUTTON SW. (DC-8-61 N8073U & SUBSEQUENT)

AIRFOIL DE-ICING SW. (TO DE-ICING VALVES AND BOTH TIMERS

TAIL DUCT VALVE SW.

TIMER POS.	CYCLING VALVES OPEN (Ref. diagram for identification)					
	GEAR UP		GEAR DOWN			
Airplanes 01 - 72						
1	1L	1R	1L	1R	8R	8T
2	2L	2T	2L	2T	6L	
3	3L	3R	3L	3R	7L	7R
4	4R	4T	4R	4T	7L	7R
5	5L	5R	5L	5R	8T	8R
6	6L	6T	6L	6T		
7	7L	7R	7L	7R		
8	8R	8T	8R	8T		
9	9T		9T	6L		
10	10T		10T	6L		
11			7L	7R		
12			7L	7R		
Airplanes 73 and Subsequent						
1						
2	2L		2L		7L	7R
3	3L	3R	3L	3R	7L	7R
4		4R	1R		8L	8R
5	5L	5R	5L	5R		
6	6L	6R	6L	6R		
7	7L	7R	7L	7R		
8	8L	8R	8L	8R		
9			7L	7R		
10			7L	7R		
11			8L	8R		
12						

*DESIGNATES VALVE NUMBERING (where DC-8-61 airplanes N8073U and subsequent.

Slide #1

DEICING SYSTEM SCHEMATIC

380
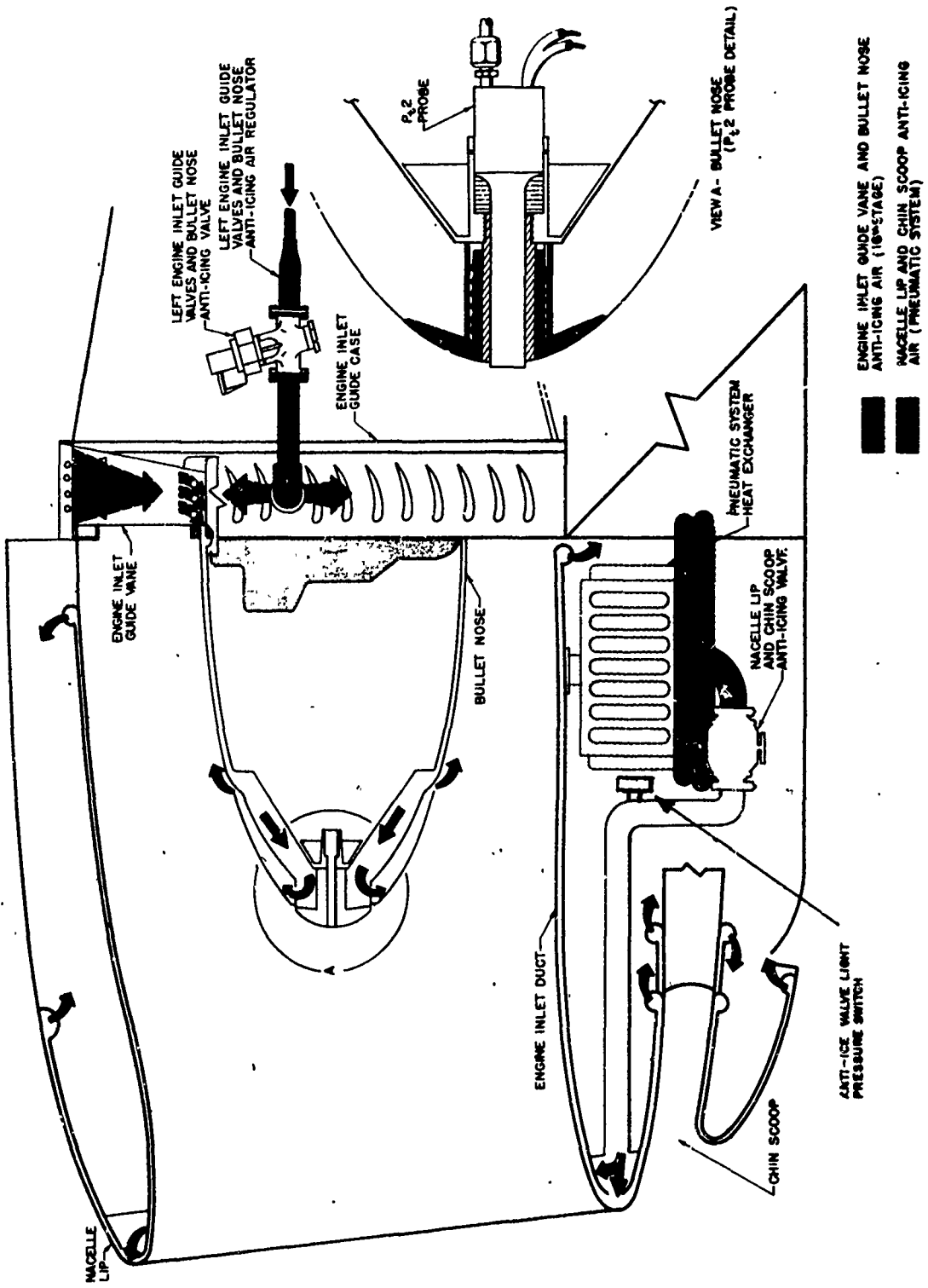
ENGINE ANTI-ICING

Slide #2

381
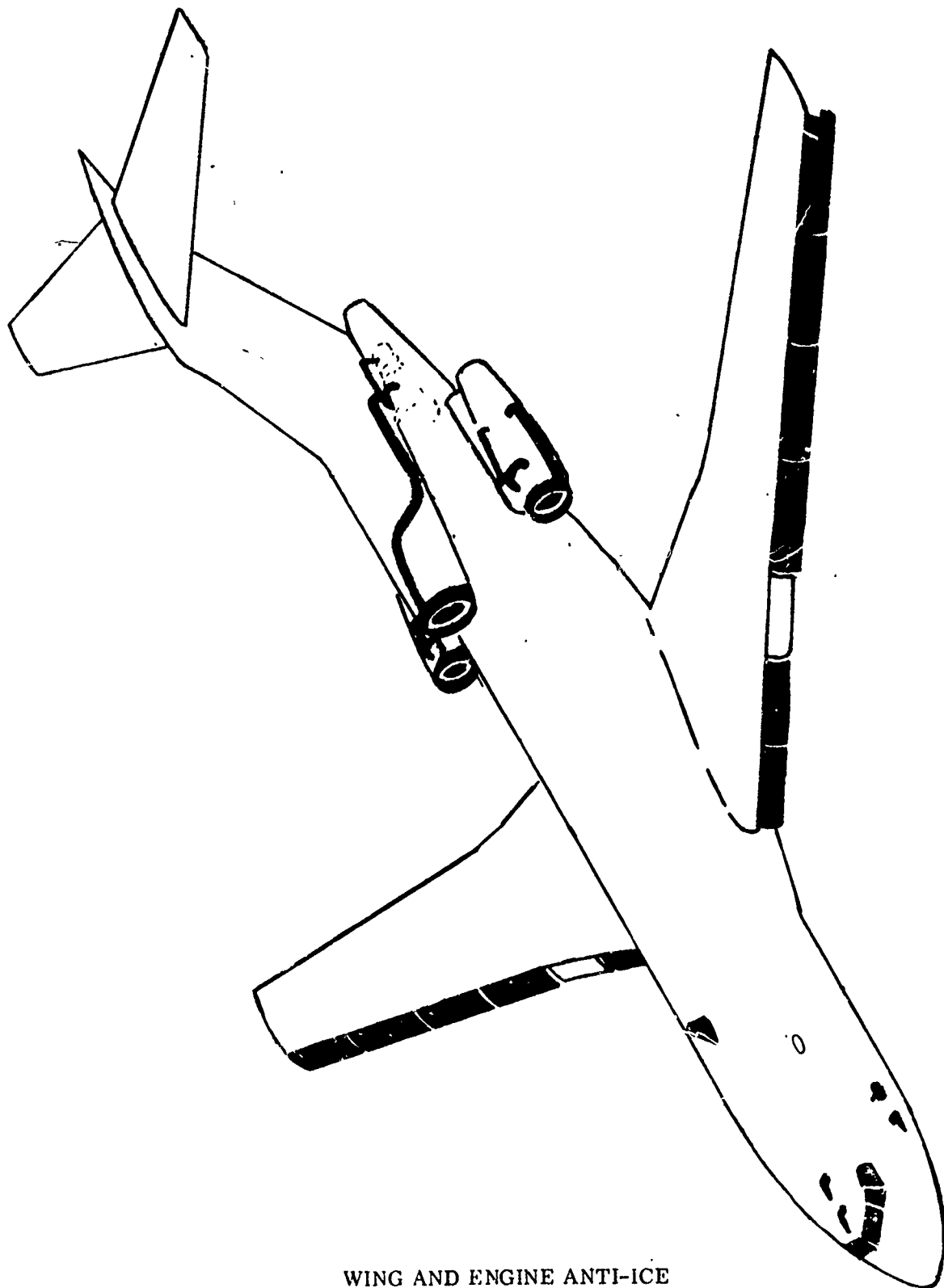
WING AND ENGINE ANTI-ICE

Slide #3

382

NUMBER OF DELAYS/CANCELLATIONS
JANUARY-FEBRUARY 1968
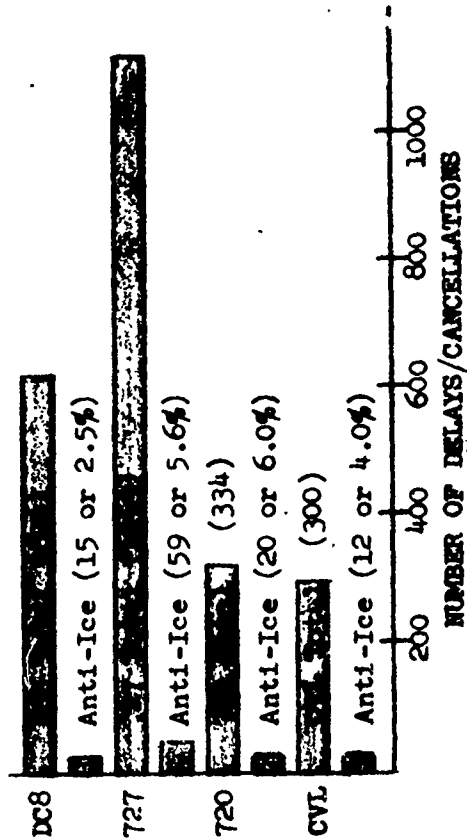
SFOEG - R. H. Johnson - 4/18/69

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Slide #4

MAINTENANCE EVENTS CAUSING DELAYS OR CANCELLATIONS
JANUARY AND FEBRUARY 1968

Total (2299)

Thermal Anti-ice (58 or 2.5%)

Electrical Anti-ice (45 or 2.0%)

Ice Detection System (3)

50 100 150 200   300   400   2300 2350

NUMBER OF MAINTENANCE EVENTS

SFOEG - R. H. Johnson - 4/18/69

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Slide #5
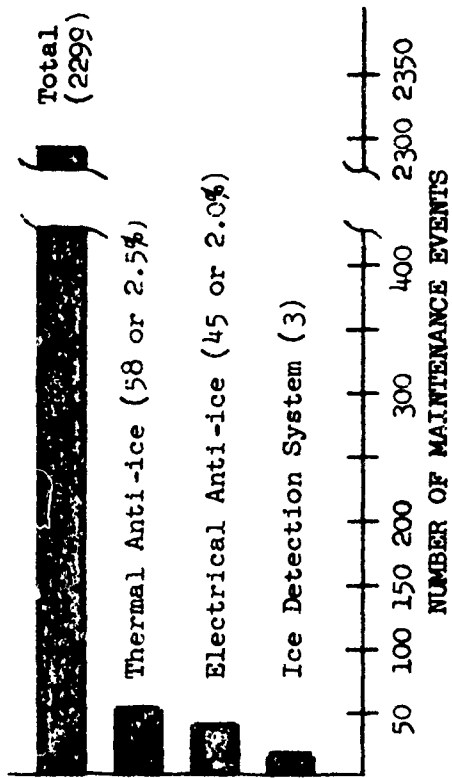
ID NO	DATE	STA	PART NO	A/A CHG SEQ	DESCRIPTION OF IRREGULARITY	TIME HRS-HUN	CLASSI	CURRENT MONTH	LAST MONTH	SECOND MONTH
					DISTRIBUTION					
7546	02-05	DEN	0294	74-20-	32 RP FLT START IGN LO-INOP	3.00	D	1.0	1.0	2.0
7428	02-11	CLE	0225	74-20-	T IGN INOP					
7428	02-11	TNG	0225	74-20-	83 RP 87 IGNITR & LO-FLT IGN INOP	1.72	D	0.3		0.3
7428	02-11	CLE	1529	74-20-	83 RP 87 COMBUS CHAMB IGNITR & HI TEN LO-FL	3.29	D	0.5		
7533	02-14	ORD	1811	74-20-	82 RP SHORT IGN LO-ENG NO START	5.86	D	0.5		
7321	02-15	ORD	0278	74-20-	82 RP R IGNITR PLUG-HUNG START	5.75	D	0.5		
7321	02-15	ORD	0278	74-20-	82 RP R IGNITR PLUG-ENG HUNG START	.63	D	0.5		0.5
					TTL DELAY	4.78	D	1.5	1.0	10.0
					TTL OTS	10.47	B	1.0	0.0	1.0
					TTL CANCEL		C	0.0		
					MAINT INDEX		M	98.6	99.4	98.5
					SWITCHING					
				74-30-	**B-727 IGNITION**					
				74-						
					TTL DELAY	9.00	D	4.5	2.0	10.0
					TTL OTS	21.95	C	3.7	3.0	1.6
					TTL CANCEL		B			
					MAINT INDEX		M	99.7	99.8	99.6
				75-	**B-727 AIR**					
				75-00-	**GENERAL**					
				75-10-	**ENGINE ANTI-ICING**					
7587	02-09	BAL	0373	75-10-	81 RP ENG A/I SW-NO MOVE	.17	D	1.0		
7527	02-05	EWR		75-11-	1 RP 8TH STG A/I SW-CRCKD	9.50	B	1.0		
7419	02-13	ORD	0352	75-11-	82 RP IGV HT DUCT-CRCKD		C	0.3		
7403	02-13	ORD	2547	75-11-	82 RP IGV HT DUCT-CRCKD	14.66	B	1.0		
7425	02-22	ORD		75-11-	83 RP Y DUCT & 8TH INLET A/I DUCTS-LKG	8.92	B	1.0		
7569	02-28	DEN	0736	75-11-	82 RP 8TH STG A/I DUCT-CRCKD	4.00	B	0.5		
7569	02-28	MIA	0736	75-11-	81 RP ENG AFT DUCT-BROKN		C			
7556	02-03	MIA	4769	75-11-	81 RP ENG AFT A/I DUCT-FAILD/BLO OUT PNL HI					
7580	02-04	SEA	C464	75-11-	SSG		D	0.0		
7408	02-06	EWR	0269	75-12-	82 RP A/I VLV ACTR-STUCK OPEN	.77	D	1.0		
7311	02-16	ORD	0236	75-12-	83 DEACTIV ENG INLET A/I VLV-INOP-DEF RPR	.13	D	1.0		
7311	02-16	PIT	0566	75-12-	83 REACTIV R IGV A/I VLV ACTR-STUCK OPEN	.17	D	1.0		
7473	02-21	BAL	1572	75-12-	83 REACTIV R IGV A/I VLV-SLOW TO OPER-DEF R					
7526	02-21	PDX	2648	75-12-	83 PR RP ENG R A/I VLV-ERRAT OPER	2.30	B	1.0		
					82 RP L A/I VLV-INOP	2.42	D	1.0		
					TTL DELAY	4.08	D	7.0	9.2	9.0
					TTL OTS	44.08	B	3.8	1.5	3.5
					TTL CANCEL		C			
					MAINT INDEX		M	98.0	97.2	98.4
				75-20-	**ACCESSORY COOLING**					

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UNITED AIR LINES
AIRCRAFT MECHANICAL IRREGULARITY REPORT

G2/01/68-02/28/68

WINDOWS AND WINDSHIELDS

ANTENNAS AND RADOMES

WATER LINES

B-727 ICE AND RAIN PROTECTION

B-727 INSTRUMENTS

GENERAL

PANELS

INDEPENDENT INSTRUMENTS

Slide #7

MAINTENANCE EVENTS CAUSING DELAYS OR CANCELLATIONS
JANUARY AND FEBRUARY 1968

Total (2299)

Thermal Anti-ice (58 or 2.5%)

Electrical Anti-ice (45 or 2.0%)

Ice Detection System (3)

NUMBER OF MAINTENANCE EVENTS

50 100 150 200   300   400   2300 2350

STOEG - R. H. Johnson - 4/18/69

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UNITED AIR LINES
ENGINEERING DEPT

MONTHLY

PAGE ____ OF ____

SUBJECT ___ MK75120 HI-PRESS S/O VALVE ACTUATOR - 727 ___ FILE REF. _____

NO. OF REMOVALS 51 52 47 25 49 47 50 33 45 51 46 44 55 46 48 47 46 47
52 49 42 49 20 49 51 50 29 43 42 42 52 51 56 55 43

UNSCHEDULED REMOVALS PER 10,000 UNIT HOURS

GOAL
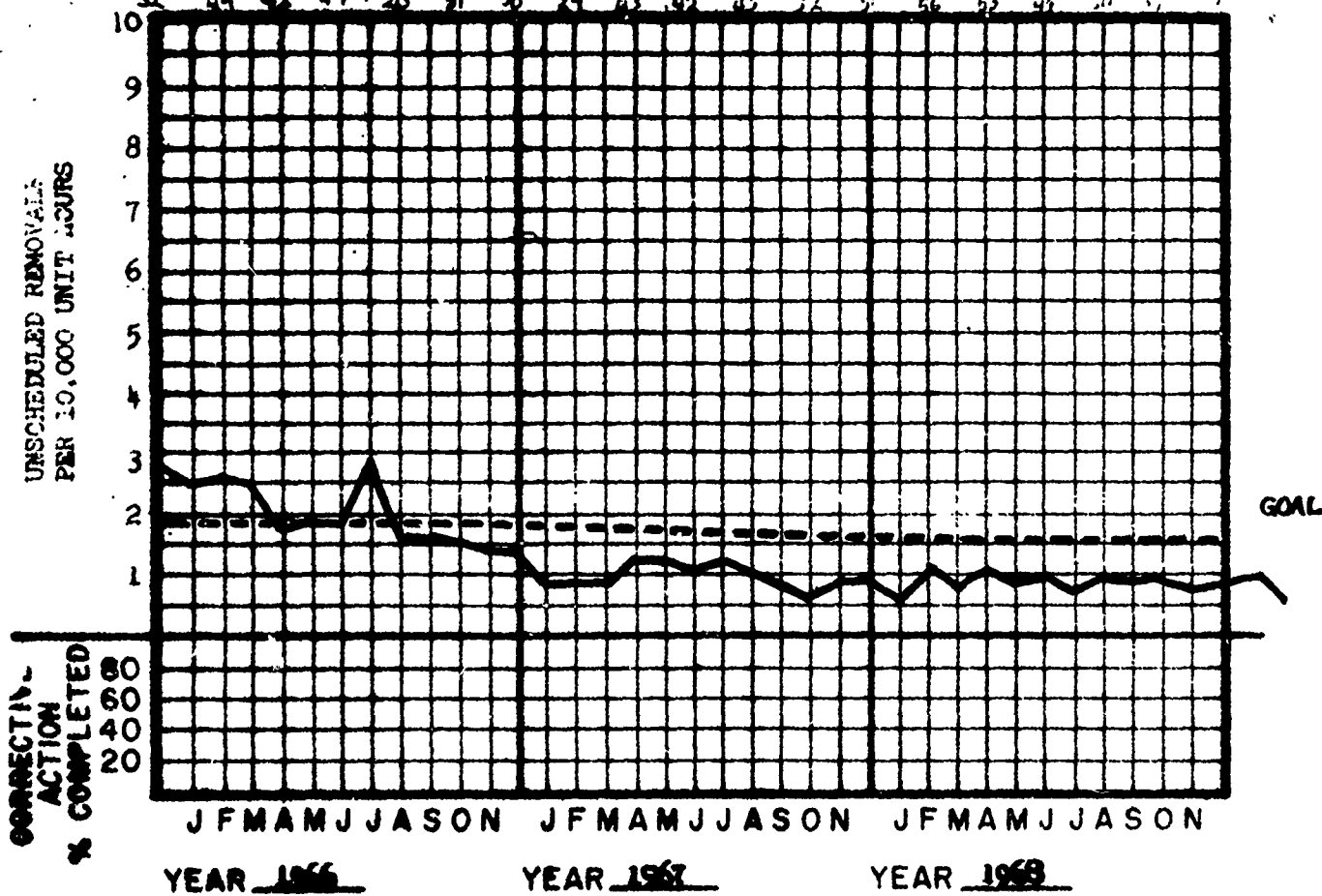
CORRECTIVE ACTION % COMPLETED
80
60
40
20

J F M A M J J A S O N   J F M A M J J A S O N   J F M A M J J A S O N

YEAR 1966   YEAR 1967   YEAR 1968

NOTE: This unit is used in 19 locations: (17 on N7010U & subs)

    3 - Fuel Heater Air
    6 - Inlet Guide Vane Anti-Ice
    3 - Nose Cowl Anti-Ice
    3 - CSD Oil Cooler Ejector
    2 - Wing TAI Hi-Press. Shutoff
    2 - Hydraulic Oil Cooler Ejector (N7001 - N7009)

Slide #9

GPO 875-083

DESCRIPTION.

TE FLAPS
RETRACTED

FORE FLAP

MID FLAP

TE FLAPS EXTENDED 40°

AFT FLAP

Slide #10

DISCUSSIONS FOLLOWING MR. JOHNSON'S PRESENTATION ON

"ICE PROTECTION SYSTEMS, COMMERCIAL MAINTENANCE EXPERIENCE"

Question: Is heating on the pitot inadequate? What about ice on anti-skid devices? Have you any record of blown tires?
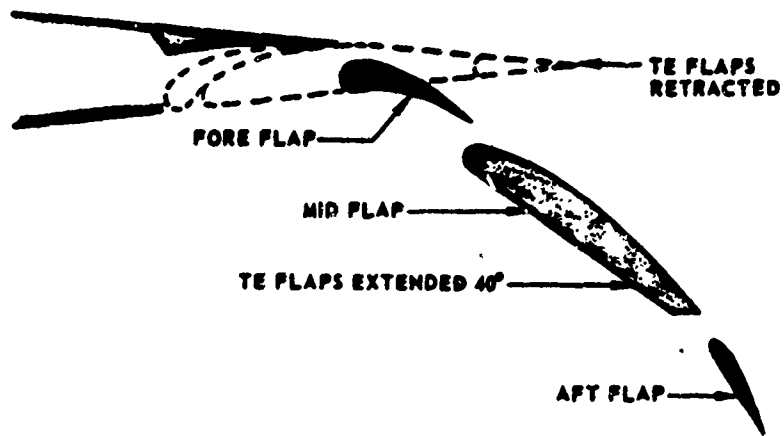
Answer: We have no details on pitot icing. At high altitudes we have had ice crystals freezing in the pitot. Problems with the anti-skid are difficult to track down because after an incident the ice melts, and the evidence is gone. We have suspicions that ice or water have caused problems.

Question: Have nose gears frozen?

Answer: Yes, but rarely. We have deactivated the nose gear brakes.

Question: Icing on pitot tubes is a function of the internal design, and ice crystals can form internally.

Answer: We have had problems with some aircraft, but most of our problems are on the way to a solution.

Question: Have you had problems from slush on the runway with the Boeing 737 forward flap assembly?

Answer: Yes.

Question: What type of ice detector do you have on the Caravelle?

Answer: A pressure differential type made by Smith Instrument Company of England. We have had difficulty with it.

F.A.A. Summary of Presentation
by
Capt. Soderlind, Northwest Airlines
on
Airline Operational Experience in Icing Environment

Capt. Soderlind stated that his presentation was limited to

operational experience with jet airplanes. He remarked that

Northwest Airlines operates one type of turboprop airplane,

the Electra, and about 100 jet airplanes. They have not

experienced any icing incidents which indicate a problem with

the protection systems. Capt. Soderlind mentioned that, in

preparation for this presentation, discussions were held with his

counterparts in other airlines and other organizations.

Three types of icing have operational significance, namely,

windshield icing, airframe icing, and engine icing. DC-3 pilots

were cited as an example of those who used the wiper-up method.

If the pilot put the windshield wipers straight up before takeoff,

it would keep a little hole about an inch and a half or two inches

in diameter during an icing encounter, through which the pilot could

see to land. According to Capt. Soderlind, many landings were

accomplished under these circumstances; however, he emphasized

that windshield icing is not a problem today with heated windshields.

Capt. Soderlind said that a statistical study of the icing exposure

over the U.S. and on international flights indicates that the piston

airplane would experience icing once in twenty flights; the jet,

once in 100 flights; and the jet airplane would have a severe icing

encounter only once in 100,000 flights. He remarked that Northwest

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Airlines experience has been even better than this. Over
one million hours of jet experience have been accumulated by
Northwest Airlines since 1960, and not a single significant icing
problem has been experienced.

Capt. Soderlind said that the jet's susceptibility to icing is
much less, for several obvious reasons. One is the high climb
and descent rate. Jet aircraft usually spend little time in icing
environments. Also, jet aircraft operate at high altitude, where
the air is usually much dryer and the temperature is well below
freezing, so most of the moisture is frozen already. The jet
airplane has available to it a ram temperature rise to prevent
icing, or the capability to get rid of icing once you have it.
Capt. Soderlind said that there is about a 15° C. temperature
rise at 350 knots indicated airspeed at 5,000 feet. This can
be used in an emergency. It was also mentioned that excess
thrust is available, so that you can carry a lot of ice. A modern
jet transport requires, depending on the type, weight, speed, etc.,
as little as 8,000 pounds of thrust to remain airborne. Several
times this minimum thrust is usually available, according to
Capt. Soderlind.

It was noted that the most serious icing problem, under the
airframe icing category, occurs on the ground. It's far more
serious than in flight, and the answer, according to Capt. Soderlind,
is obvious; but it doesn't seem to be too simple to apply. One
recent jet transport accident was cited as an example of this
problem. No one was killed, but the airplane was destroyed. In

the wreckage, there was found to be from ¼ to ½ inch of ice on

the leading edge of the wing and tail. The ice had been

accumulated on the prior descent. In other words, the takeoff

was made with this ice on the airplane, and the airplane became

uncontrollable and rolled shortly after liftoff and was put

back on the ground.

In response to some comments that were made about engines

ingesting water with subsequent flameouts, Capt. Soderlind stated

that in this particular case, one engine continued to run for an

hour and a half in the wreckage. It seems that someone tried to

convince the firemen to drown out this engine. It couldn't be

shut down; the linkage was broken.

Capt. Soderlind commented that there has been one relatively

recent fatal accident with a turboprop airplane, in which the

findings were that the airplane took off with snow on the wings.

He remarked that engine flameouts, due to water, slush, and snow

ingestion on takeoff, have not been rare, but on the other hand,

they haven't been common. A twin-engine jet airplane took off

in two inches of wet snow. This happens to be the limit. Both

engines dropped down to very low thrust output. Both engines

had compressor stall. Takeoff was aborted safely. Water

ingestion was attributed to main gear slush throwback. Supposedly,

fenders are being incorporated to prevent a recurrence.

Capt. Soderlind felt that ice, snow, and frost on the airplane

before takeoff are the most serious problems, or at least very

serious problems. The remark was made that, when you have to

stand in a line of thirty or forty or fifty airplanes for an hour

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or two in freezing rain, there is little assurance that you will always take off in a "clean" airplane. It was reported that many cases of heavy frost accumulations occur on the underside of the wing before takeoff, or as the result of descent into high-humidity conditions with cold-soaked fuel. But it was stated that this seems to have no adverse effect whatsoever. A few cases of the reverse were noted, namely, cold fuel from a ground supply and a full tank operation, resulting in frost forming on the top of the wing. Since the real effects of this are unknown, Northwest Airlines requires that frost on the upper wing surface be cleared off. The Air Force ran some tests on a F-86 and a B-47 to investigate the effects of frost on the wing. These tests concluded that there was no significant effect on the ground roll or the lift-off speed with an accumulation of frost up to 3/10 inch. However, it was stated that Northwest Airlines requires that the top of the wing be free of frost before takeoff. In previous discussions with Douglas and Boeing, Capt. Soderlind was advised that, when they used flow visualizing tufts attached to the leading edge of the wing during wind tunnel tests, the tufts and the tape used to attach them reduce the maximum lift capability of the wing by approximately 4 to 20 percent. The aircraft manufacturers claimed that this is indicative of what frost can do. According to Capt. Soderlind, this is why Northwest Airlines insists on a clean wing, even if there's only a thin layer of frost on top. It was reported that a few cases of pitot static systems freezing have occurred due to loose snow, thrown up by the wheels or by reversing prior to landing.

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It was said that engine icing in flight has not been a problem
to safety, as long as the anti-ice systems are used as they were
intended. The windshield itself, and the windshield wiper, were
mentioned as good warning devices to the pilot as to when he
should use the engine anti-ice, since he can't see any inlet. It
was recognized that this is not a foolproof warning at temperatures
slightly above freezing, because the ice will not form on the
airframe itself. Due to the pressure drop in the inlet, it will
form in the inlet.

The airlines prefer not to have to anti-ice PT-2 probes with
engine bleed air. The main reason is that turning on the engine
anti-ice system just to anti-ice the PT-2 probe consumes about
five percent of the fuel. Capt. Soderlind remarked that this
seems like a lot to pay to anti-ice the PT-2 probe alone.
Capt. Soderlind commented that a great deal of fuel goes down
the drain, so to speak, since the pilot can't be certain when
he's going to get engine ice, he turns on the engine ice protection
system just in case. It was the speaker's contention that about
95 percent of this is purely wasted. In other words, the heat
is turned on just in case. As an example of the cost of this
precautionary action, it was pointed out that Northwest Airlines,
last year, spent $48,000,000 for fuel, for just the jet fleet
alone. The comment was made that probably one percent of the
time, the engine anti-ice was turned on, and, probably the largest
percent of that time, it's on "just in case."

In response to previous comments on ice detectors, Capt. Soderlind
said that the airlines are very interested in ice detectors. They

haven't been as interested in the past, because the ice detectors have performed poorly. It was said, however, there appear to be good ones on the horizon, and the airlines intend to service test some. The comment was made that ice detectors certainly will pay their way, if they can tell us specifically when to turn on the engine anti-ice.

Capt. Soderlind said that a big problem, in fact about the biggest problem in flying the jet airplane, is to make it come down when you want it to. He claimed that when you use the engine anti-ice, you have to maintain r.p.m. well above idle, in order to have adequate heat. This presents a problem. For example, on one typical contemporary jet transport, you have to maintain 70 percent N_1 r.p.m., in moderate or greater icing, if the outside air temperature is below -7° C. It was explained that you can't make the airplane come down when it's "clean," with 70 percent N_1 r.p.m. This is more than necessary to make level flight, and you can't pull off power enough to descend to a lower altitude. It was explained that you could add drag; you could put the gear down, and possibly ice up the gear; or put the flaps down, and possibly ice up the flaps, and damage the structure when they're retracted. You could pull out the speed brakes, as another alternative, to add the drag necessary to counteract the extra power, but then the speed brakes buffet the airplane and make it unpleasant. It was noted that this hasn't proven to be a big safety problem, because even though there are disadvantages with having to carry this much thrust, you know that it's necessary and somehow manage to provide the necessary drag.

It was stated that by far the most potentially serious icing problem in the jet airplane is engine icing on the ground. This really became known in the last six months.

In one incident, it was reported that a twin-engine jet transport taxied out early in the morning in . shallow ground fog. Ground fog was only 30-50 feet deep. The sun was clearly visible, so the crew didn't feel that engine anti-icing was necessary. They left it off. The temperature was 26° F. The visibility was below the limits for this particular takeoff, so the crew taxied up and down the runway a couple of times to observe the actual runway visibility. By the time they had finished their round trip up and down the runway, the visibility was up to minimums. They started the takeoff. One engine accelerated poorly. As they went a little further down the runway, they heard a thump, which was a compressor stall. They aborted the takeoff without difficulty and returned to the ramp. They shut the engines down, and they found extremely heavy buildups of ice on the nose bullet, 1½-2 inches thick; ice on the bottom of the cowl; and sufficient damage to both engines to cost $100,000 to repair.

Capt. Soderlind remarked that on the evening of January 8, 1969, the industry really came face to face with this problem. At O'Hare, early in the evening, the conditions were 700-1,200 feet overcast, with light freezing drizzle falling. The temperature was 26°, and the dew point was 24°. As usual, in Chicago, in the early evening, there were long ground holds for takeoff. At one point, there were 40 airplanes in line, two of which happened to be Northwest's. Takeoffs were aborted with various kinds of engine

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problems, compressor stall, slow acceleration, etc. Airplanes
waiting for takeoff reported that those ahead had sparks coming
out of the tailpipes. One 727 had a compressor stall at rotation,
and many, many, sparks coming out of the tailpipe, such that the
following airplane asked the tower to have a truck pull out on
the runway and look for metal parts before he took off.

It turned out that when the tower queried the 727 that had just
taken off, that they had no indication of any problem, except at
rotation they had one compressor stall. That was all. The
airplane continued on without ʼ further trouble.

Another aircraft from one of the other major airlines, flight 208,
returned to the ramp at 4:30 that afternoon, on account of reported
backfiring. The compressor stalled when the pilot tried to advance
the thrust levers.

The aircraft returned to the ramp when the pilot could not obtain
over 1.2 EPR. An examination at the gate revealed a massive
buildup of ice on the inlet guide vanes and the nose domes. The
crew advised their flight operations of the seriousness of the
existing icing conditions. Flight operations of this specific
carrier ordered all of their aircraft, holding for takeoff, to
return to the gate for an engine inlet inspection, and to await
an improvement in weather conditions. Other carriers were
likewise advised of these findings.

The buildup of ice on all four engines on the aircraft which
returned to the gate (flight 208) occurred during the
evening. Pictures were taken of one of the engines and other
icing formations on the aircraft. These photos were placed on

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display in Dispatch, so that all crew members would view them.
All the nose domes were covered with approximately 3/4 inch
thickness of ice around their entire circumference, extending
forward to the EPR probe by 1½ inch, terminating in a sharp point.
The EPR probe was visible through the clear ice. The entire inlet
guide vane assembly, at its base, was completely iced over for
a distance of 6 to 8 inches from the hub. Then a slight separation
appeared, gradually increasing, so that at the outer extremities
of the inlet guide vanes, you could just put your finger between
the buildup of ice on the vanes. The leading edges of the inlet
duct were iced up, extending around the outside of the cowl's
leading edges by approximately 3 to 4 inches. There were pieces
of ice in the bottom of the inlet cowl, caused by the engine
surging. The compressor surges were sufficiently heavy to blow
the ice off the inlet guide vanes, but not strong enough to
blow them clear to the inlet duct. Trip 208 was holding in
freezing drizzle for 37 minutes. The first two 727's examined
upon their return were found to be free of ice in all respects;
however, the third and fourth had ice buildups on the dome and
inlet guide vanes. Both had chunks of ice in the bottom of
the engine inlet.

Photos of these aircraft showed ice buildup on the number three
engine. This was observed during normal taxi power as torching
at the tailpipe.

A photo of a 707, which was holding for 2 hours, showed that
the upper portion of the inlet guide vane assembly was clean,
while the lower half was completely iced over, and started to

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progress outward to the extremities of the vane assembly.
As reported, all of the airplanes that were holding, with very
few exceptions, had sufficient ice, that they would almost
certainly have had a serious problem had they started takeoff.
Capt. Soderlind reported that Northwest Airlines had two airplanes
in this line of 40, and neither of them had any difficulty. This
incident and other experience showed that the engine anti-ice will
take care of almost all of these icing conditions, even at idle
or near idle power, if the anti-ice is turned on as soon as the
engines have started. According to Northwest Airlines' procedure,
as soon as the engines are started in icing conditions, the engine
heat is turned on. As reported, two of Northwest's airplanes were
in this lineup, and took off subsequent to this with no difficulty,
although they both improvised a bit, and ran up the engines
occasionally. This is now an additional part of Northwest's
procedure, because at some conditions of low outside air temperature,
idle thrust is not enough to develop enough heat to keep the engine
"clean."

All of the airlines have revised their procedures to, essentially,
this kind of thing, that is, to turn the heat on as soon as the
engines are running, if icing conditions exist.

In summary, Capt. Soderlind said that serious incidents or
accidents due to icing of the turbine airplane in commercial
service are rare. He also said that airframe ice on the ground
is potentially serious, but the answer is to take off with a
"clean" airplane. Engine icing on the ground is the airline's

most serious problem, according to Capt. Soderlind. But he

contended that the answer is simple--just use recommended

procedures. It was emphasized that there are no icing problems

of any significance, really, as long as the ice protection

systems are used as recommended, and that you take off with

"a clean wing."

DISCUSSIONS FOLLOWING CAPT. SODERLIND'S PRESENTATION ON

"AIRLINE OPERATIONAL EXPERIENCE IN ICING ENVIRONMENT"

Question: The frequency of icing during climb, cruise, and
             holding is most prevalent during holding. What is
             your opinion on present holding procedures and ATC
             procedures versus the procedures in the pre-jet era?

Answer: True, the holding area is the worst for icing.
             However, there is no problem if the crew uses the
             proper procedures. There can be a problem if flap
             hinges ice up and are then retracted.

Question: Are holding speeds adequate?

Answer: We have no problem except when using powers too low
             to enable us to use de-icing equipment.

Question: Is it the airlines' policy to use reverse thrust for
             fast descent?

Answer: Use of reverse thrust in flight is prohibited on
             the Boeing. It is the only speed brake on the DC-8
             and its use was routine during descent.

Question: Does icing on such unprotected surfaces as the tails
             give any buffeting?

Answer: There is no problem, but I feel leery about it.
             Other carriers have felt that the aircraft are
             sluggish on final approach in the elevator control.
             We have considered icing warning for two places,
             engine and horizontal stabilizer.

Question: When one uses the engine run up method to check for
             engine icing on the ground, is there danger of
             skidding?

Answer: Yes. I once had a well planned test for this
             demonstration on an icy unsanded runway. The aircraft
             skidded out of control and the test was terminated.

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Question: Considering your forced landing because of icing in the DC-3, do you feel that loss of lift or the increase of weight was the most significant?

Answer: The ice was about six inches thick except for the boots. They were worthless since the ice formed on the underside of the wing, just back of the boots. I don't think the weight was significant.

LIST OF ATTENDEES

GOVERNMENT

Federal Aviation Administration

<u>Washington</u>

R. S. Sliff, FS-1
H. H. Slaughter, FS-100
S. H. Rolle, FS-140
R. J. Auburn, FS-140
N. N. Shapter, FS-120
P. D. Wilburn, FS-160
E. P. Burke, SS-120
L. E. Tarbell, FS-140
R. Seaman, RD-601
R. B. Karp, FS-300
A. Gross, SS-130
J. Koehler, FS-321
G. C. Hay, DS-33
T. Sanford, FS-109
N. S. Dobi, FS-110
W. E. Koneczny, FS-110
H. Hoekstra, DS-40
J. E. Cayot, FS-20
R. A. Johnson, FS-120
E. R. Lambert, FS-140
R. A. Peterson, FS-140
C. C. Schroeder, FS-108
R. Borowski, FS-130
H. H. Osborne, FS-46
D. R. Marshall, FS-160
D. H. Draut, SS-110
J. Haddad, FS-140
P. Hallick, FS-320
M. A. Lott, FS-140
E. J. Briggs, FS-140
R. S. White, FS-140

<u>Regions</u>

V. Reinert, CE-212
C. W. Dreyer, CE-216
R. W. Stephens, AL-210
G. R. Slusher, NA-542
L. J. Garodz, NA-543
J. J. Shrager, NA-543
R. Gambrill, SW-216
G. Welsh, SW-210·
P. Perrotta, EA-214
C. H. Sweeney, EA-214
F. Jenkins, WE-130
T. C. Dufour, WE-140
C. E. Arnold, EA-216
A. Braun, EA-213
K. J. Holloway, SW-214
F. T. Melton, SW-214
G. W. Wells, CE-214
W. R. Haldeman, EU-100
F. E. McGowan, SO-210
C. W. Kaiser, SO-213
H. A. Schoech, WE-160
J. R. James, SO-214
L. N. Bass, SW-213
C. J. Archer, CE-213

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Naval Air Propulsion Test Center- J. L. Palcza

INDUSTRY

Pratt & Whitney Aircraft-	E. E. Striebel
United Aircraft of Canada Ltd.-	J. P. Beauregard
Cessna-Mil. Twin Div.-	Warren S. Wilson
McDonnell-Douglas-	Lou Cook
	L. E. Fry
General Electric Company-	S. H. Davison
Boeing Company-	R. W. Wilder
Allison Div., General Motors Corp.-	F. M. Krentz
	G. V. Bianchini
Lockheed California Company-	Bernard L. Messinger
United Air Lines-	R. H. Johnson
Northwest Airlines-	P. A. Soderlind

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