Aircraft Ice Protection in the NACA Era

1915 to 1958

From "NACA Conference on Aircraft Ice Prevention A Compilation of Papers Presented by NACA Staff Members" 6505/NACA-1947/8, 1947 (colorized) apps.dtic.mil

A Presentation to the FAA Aircraft Icing Forum
May 13, 2025

In the coming months, the Aircraft Icing Forum will present current aircraft icing technology and challenges.

Here, I will present “old news” which is the basis of our current understanding of icing.

“Every thing was known by 1947”

Well, that is not quite true, but a remarkable progress was made in the NACA era.

We will also meet a Collier Trophy winner and a Nobel Prize winner.

Don Cook

- Over 30 years experience in aircraft icing
- Served on industry committees (AIAA, SAE, other)
- Currently blogging at icinganalysis.com about icing in the NACA era

High altitude, long endurance aircraft

https://www.nasa.gov/aeronautics/global-hawk-uas/

777

https://www.flickr.com/photos/zx4142/27961073368/

787

https://freeaircraftimages.blogspot.com/2013/02/boeing-787-dreamliner.html

While the team that I was on did not win the high altitude, long endurance aircraft contract, I learned how to use LEWICE, and about icing environments beyond typical “Appendix C” icing conditions.

On the 777 program I was the equipment manager for the engine and wing ice protection systems. I conducted numerous icing tunnel and natural icing flight tests.

On the 787 program, I lead the technology development for the electrothermal wing ice protection.

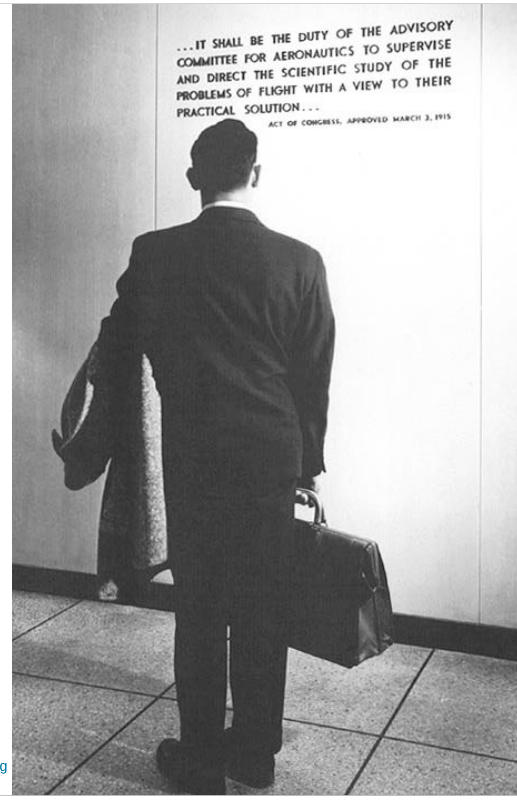
The National Advisory Committee for Aeronautics

Operated from 1915 to 1958

There where numerous achievements in aeronautics,
of which aircraft ice protection was only one area

Became part of National Aeronautics and Space Administration (NASA) in 1958

commons.wikimedia.org



"… it shall be the duty of the advisory committee for aeronautics to supervise and direct the scientific study of the problems of flight with a view to their practical solution"

Other NACA achievements:

NACA standardized airfoils

Supercharged aircraft engines

Supersonic flight

Progress over the NACA Era

“Investigation revealed the trouble to have been caused by the collection of snow somewhere between the entrance to the carburetor and the manifold …”

- NACA-TN-55, “Airplane Crashes: Engine Troubles. A Possible Explanation.”, 1921. ntrs.nasagov

“Transcontinental and transatlantic flying over the northern route can never be entirely safe until a problem (icing) which has thus far baffled ingenuity has been solved.”

- Commentary on attempts to solve icing problems, New York Times, April 9, 1931

"Aircraft are now capable of flying in icing clouds without difficulty, however, because research by the NACA and others has provided the engineering basis for icing protection systems"

- “The Icing Problem”, presented at Ottawa AGARD Conference. AG 19/P9, June 10-17 1955 ntrs.nasa.gov

NACA-TN-55 "A demon was operating the throttle."

NACA induction-system icing program, 1941

A NACA conference in 1947 detailed ice protection solutions.

Ice protection as an enabler

By 1941, a modified Lockheed 12A with complete ice protection was demonstrated.

In 1946, Lewis A. Rodert, Chief of the Flight Research Branch at the Cleveland Laboratory of the National Advisory Committee for Aeronautics, was awarded the Collier Trophy: *"For his pioneering research and guidance in the development and practical application of a thermal ice prevention system for aircraft."*

Weather capable aircraft, along with highly developed analysis methods for the rotating multicylinder instrument, enabled measurements of natural icing conditions.

By 1947, flight test data that established much of the CFR 25, Appendix C icing regulation was completed.

By 1955 CAM 4b was published (including a predecessor to CFR 25 Appendix C), establishing the modern era of ice protection requirements.

Effective ice protection was achieved prior to understanding the icing environment.

However, to reliably engineer solutions to other aircraft, data about the icing environment is required.

Early Flight Test Aircraft

"an airplane that will be immune from the dangers of ice accumulation ... is only a matter of technical development."
NACA-TR-403

Vought E-7, 1929

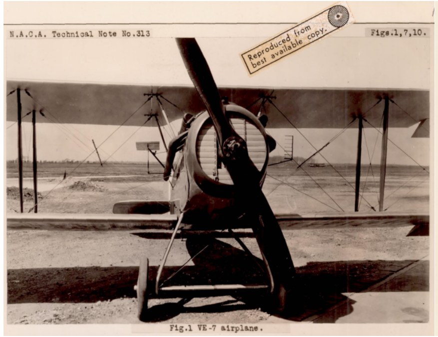


Fig.1 VE-7 airplane.

NACA-TN-313

Fairchild FC-2, 1931

FIGURE 24.—Experimental installation on airplane

NACA-TR-403

XBM, 1938


Figure 1.- General view of XBM airplane, showing wing heated by hot air, and motion-picture camera mounted above and in front of model.

NACA-TN-783

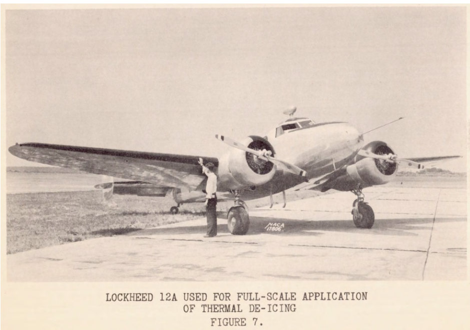
Several aircraft were used in early icing flight research.

Some of the test aircraft had little to no ice protection.

These often used a water spray mounted ahead of a test airfoil to simulate natural icing conditions.

Ice Protection Development
Flight Test Aircraft

Lockheed 12A, 1941



apps.dtic.mil

B-17F, 1943

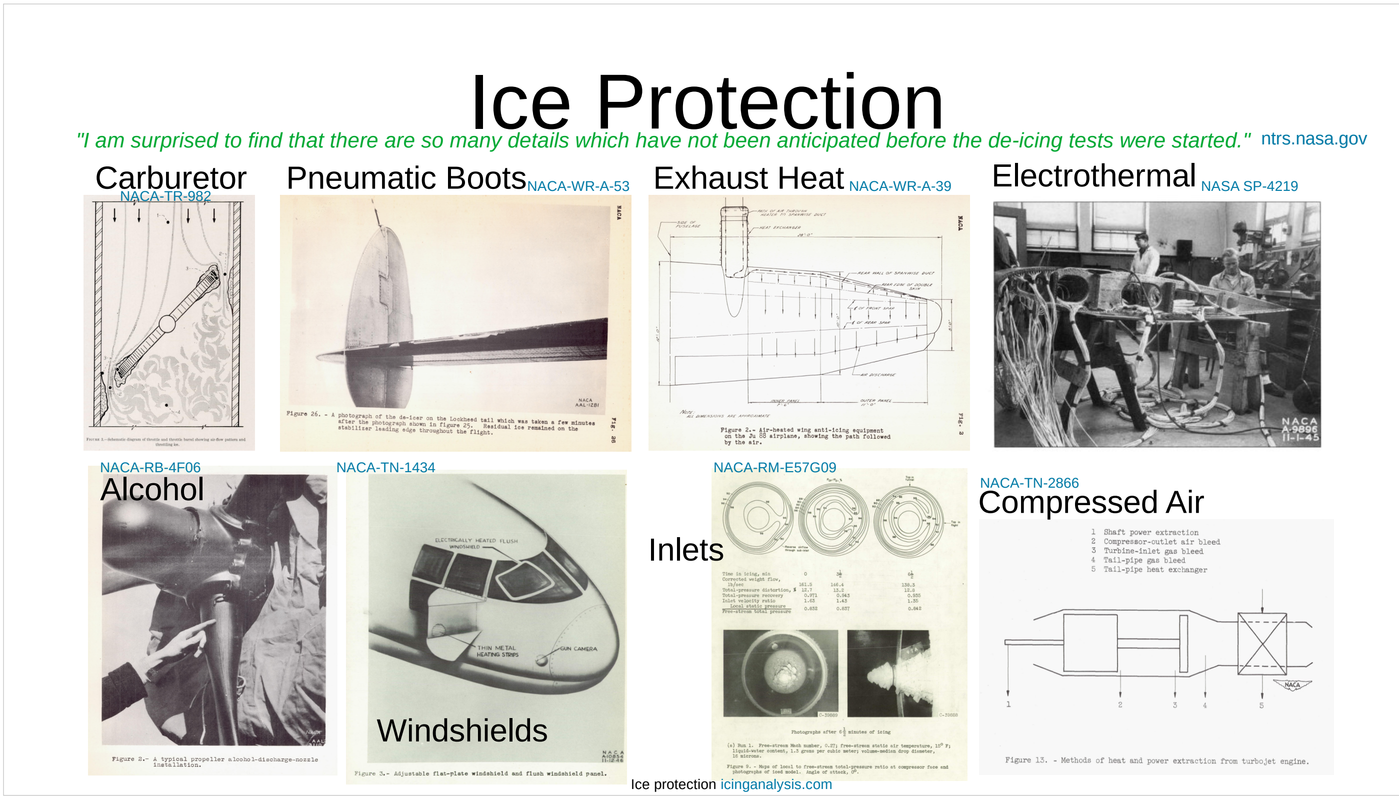
NACA-ARR-3H24

Consolidated XB-24, 1943

apps.dtic.mil

By 1943 several aircraft were equipped with effective ice protection.

The development was largely "cut-and-try" engineering or "practical solution", rather than "scientific study"



Several components have ice protection, and the modes of protection may differ.

The Electrothermal image is the internals of the fin in the image on slide 1. There are numerous, individually controlled electrothermal heater strips that were used to study heat transfer in flight.

Instrumented Flight Test Aircraft

“Without extensive data on the problem that nature presents, the design of the thermal system can only be approached in an empirical manner” Rodert 1947 apps.dtic.mil

North American XB-25E, 1942

nasa.gov

Curtis C-46, 1945

Figure 5.– C-46 test airplane as flown during the winter of 1946-47 showing the position of the airfoil models mounted on the fuselage.

NACA-TN-1472

Douglas C-47, 1946

nasa.gov

These, and several other aircraft, soon produced “extensive data”.

The XB-25E is the “Flamin Mamie”. One NASA site described the artwork as “depicting a fiery woman chasing off icing researchers”

The Rotating Multicylinder Instrument

wikimedia.org

NACA-RM-E53D23

Figure 1. - Rotating multicylinder set extended through top of airplane fuselage.

The rotating multicylinder was the primary instrument for measuring icing conditions liquid water content, average water drop size, and size distribution.

The multicylinders would be exposed in flight to icing conditions for 1 to 5 minutes. The were then withdrawn, separated, and individually weight and measured.

Water Drop Impingement Analysis

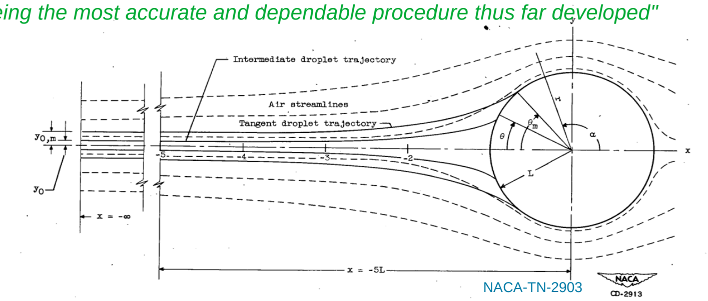
"The rotating-cylinder method ... is generally regarded as being the most accurate and dependable procedure thus far developed"
NACA-TN-1393

Water drop trajectory analysis about a cylinder was well-established by 1945.

Water drop trajectories were analyzed using two-dimensional equations of motion.

Mechanical computers were used to integrate the equations (the Differential Analyzer)

These calculations allowed measurements of multicylinder flight data to determine liquid water content, average drop sizes, and drop size distribution.



NACA-TN-2903

Figure 1. - Coordinate system for cylinder.

NACA-TN-2904

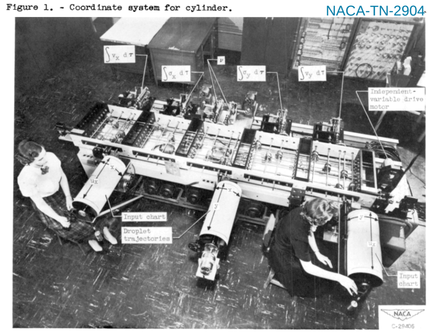


Figure 15. - Water-droplet-trajectory analog.

cylinders icinganalysis.com

Irving Langmuir’s “Mathematical Calculation of Water Drop Trajectories” (1945), a remarkable analysis, established a firm basis.

Instruments

"Progress ... has been handicapped by the lack of sufficient data on the meteorological factors." NACA-TN-1855

Fixed Cylinder

NACA-RM-A9C09

Rotating Disc

Figure 5.- Rotating disk for the measurement of liquid-water content in icing clouds. Note ice-thickness feeler and ice-removal scraper behind disk.

NACA-RM-A9C09

Heated Probe
NACA-RM-E50J12A

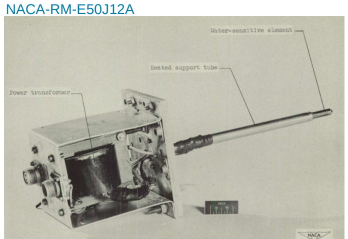


Figure 1. - NACA liquid-water-content meter.

Water Drop Imaging
NACA-RM-E50K01A

Pressure Recording
NACA-RM-E51E16

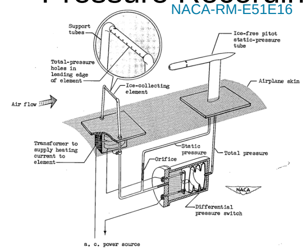


Figure 1. - Principle of operation of NACA pressure-type icing-rate meter.

instruments icinganalysis.com

Other instruments were used and developed in the NACA era. However, they were calibrated against the rotating multicylinder, and used as supplements, not the primary sources of data.

The pressure recording device was used in the 1950s to get long range icing exposure data.

Data for Appendix C Icing definition

"This research has progressed to a point where a tentative listing of icing conditions for design purposes can be attempted" NACA-TN-1855

All flight tests that determined data for Appendix C were complete by 1951.

Flight test data for Appendix C Figure 1 were complete by 1947. The rotating cylinder was the chief instrument used.

CAM 4b and Appendix C Figure 1 are very similar, with only minor formatting and unit differences.

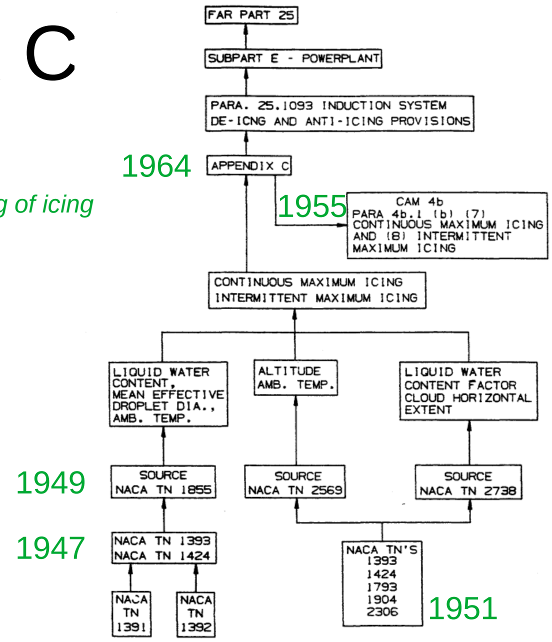


FIGURE 3-1. DERIVATION OF FAR ICING STANDARDS (REFERENCE 3-12)

FAA Aircraft Icing Handbook (1991) apps.dtic.mil

"Everything was known by 1947"

Well, not quite. The LWC Concentration Factor and the altitude-temperature data came later, 1951.

Data points on Appendix C, Figure 1

“The discipline had indeed been placed on a rational basis.”

NACA-TN-1855

NACA-TN-1855, 1949

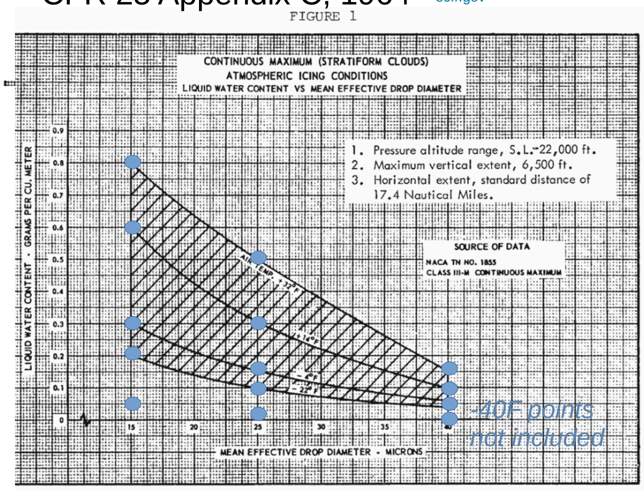
TABLE I.– RECOMMENDED VALUES OF METEOROLOGICAL FACTORS FOR CONSIDERATION IN THE DESIGN OF AIRCRAFT ICE-PREVENTION EQUIPMENT

Class	Item	Air temp. (°F)	Liquid water content (g/m³)	Drop diameter (microns)	Pressure altitude (ft)	Remarks
III – M Continuous, Maximum	31	32	.8	15	3,000 to 20,000	Horizontal extent and duration: Continuous. Characteristic: Moderate to low liquid water content for an indefinite period of time. Applicable to: All components of the airplane; that is, every part of the airplane should be examined with the question in mind, "Will this part be affected seriously by accretions during continuous flight in icing conditions?" Example: Wings and tail surfaces.
	32	14	.6			
	33	-4	.3			
	34	-22	.2			
	35	-40	..05			
	36	32	.5	25		
	37	14	.3			
	38	-4	.15			
	39	-22	.10			
	40	-40	.03			
	41	32	.15	40		
	42	14	.10			
	43	-4	.06			
	44	-22	.04			
	45	-40	.01			
III – N Continuous, Normal	46	32	.3	15		
	47	14	.2			
	48	-4	.1			
	49	-22	<.1			
IV – M Freezing Rain	50	25 to 32	.15	1000	0 to 5,000	Horizontal extent: 100 miles. Duration at 100 mph: 30 minutes. Characteristic: Very large drops at near-freezing temperatures and low values of liquid water content. Applicable to: Components of the airplane for which no protection would be supplied after considering classes I, II, and III. Example: Fuselage static pressure airspeed vents.

NACA

CAM 4b 1955
CFR 25 Appendix C, 1964

ecfr.gov



The data points determined in 1949 map direct to the figure still used today in current icing regulations.

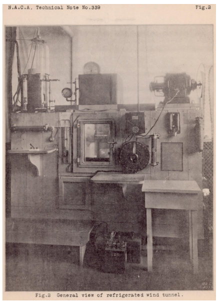
Note the “Freezing Rain” row at the bottom.

Supercooled Large Drop (SLD) icing icing regulations were not adopted until Amdt. 25-140, 79 FR 65528, Nov. 4, 2014 (not quite the same as the freezing rain data).

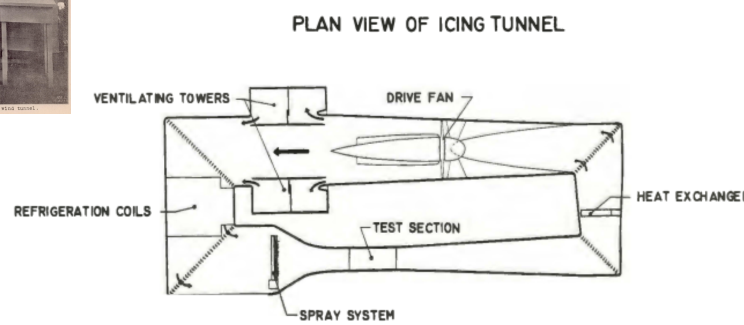
Icing Wind Tunnels

NACA-TN-339

Refrigerated Wind Tunnel at Langley Memorial Aeronautical Laboratory, 1930

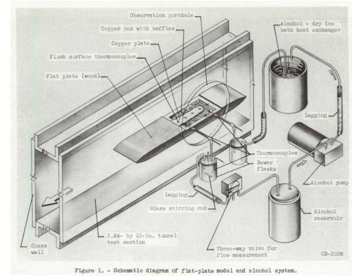


Icing Research Tunnel at NACA Lewis, 1944



NACA-TN-3104

3.84 x 10 inch tunnel, 1954



P-39 in IRT, 1946 NACA-TN-1586

"An International Historic Mechanical Engineering Landmark ICING RESEARCH TUNNEL" www.asme.org

Icing wind tunnels icinganalysis.com

The Refrigerated Wind Tunnel investigated ice phobic materials and large drop icing.

The 3.84 by 10 inch tunnel investigated trans-sonic icing.

The IRT has had many uses over the decades.
The ASME recognizes it as a historic place.

However, the icing tunnels were not the largest contributors to ice protection development (flight tests and analysis were).

“Selected Bibliography of NACA-NASA Icing Publications”

First published in 1969, it was part of FAA AC 20-73 “Aircraft Ice Protection” until 2006. This established a common, expected knowledge and nomenclature of aircraft icing.

132 publications in 16 categories:

- Meteorology of Icing Clouds
- Fundamental Properties of Water
- Meteorological Instruments
- Impingement of Cloud Drops
- Propeller Ice Protection
- Induction System Ice Protection
- Turbine-Type Engine and Inlets
- Wing Ice Protection
- Windshield Ice Protection
- Cooling Fan Ice Protection
- Radome Ice Protection
- Antenna Icing
- Inlet and Vent Ice Protection
- Jet Penetration
- Heat Transfer
- Miscellaneous

Blog post with more information on the Bibliography: icinganalysis.com

My mentors were well versed in the “Selected Bibliography”

A Legacy: Design Manuals

The lessons learned from the NACA era have been encapsulated in design manuals, which are still used today.

“Engineering Summary of Airframe Icing Technical Data” FAA ADS-4, 1964 apps.dtic.mil

While published after the NACA era, it was included in the “Selected Bibliography”. Half of the references are NACA publications, and most of the others are from the NACA era.

“Ice, Frost, and Rain Protection”, SAE Aerospace Applied Thermodynamics Manual, 1969 (regularly updated) sae.org

This also still includes much data from the NACA era.

“Aircraft Icing Handbook, Volume I.” DOT/FAA/CT-88/8-1 (1991) apps.dtic.mil (there are also volumes II and III apps.dtic.mil apps.dtic.mil)

Some of the sections are revised from ADS-4, and so contain much data from the NACA era. There was a perhaps little-known update in 1993 apps.dtic.mil, but no updates since then.

My mentors were well versed in the design manuals.

Some Areas of Continuing Research

	Applicable publications		*Blog posts*
Large drop icing	NACA-TN-1855	NACA-TN-339	SLD in icing tunnels icinganalysis.com
Low ice adhesion coatings	NACA-TN-313	NACA-TN-339	NACA-TN-339 review icinganalysis.com
Ice shape characterization	NACA-TN-313	NACA-TR-446	Ice shapes and their effects icinganalysis.com

The ongoing AIAA Ice Prediction Workshop is looking at ice shape characterization.

More information

"... the recommendation was made that before attacking what appeared to be a new icing problem we should study the icing work of the 1940's and 50's."

NASA-TM-81651

Lew Rodert, Epistemological Liaison, and Thermal De-Icing at Ames, NASA SP-4219, history.nasa.gov

“We Freeze to Please”: A History of NASA’a Icing Research Tunnel and the Quest for Flight Safety ntrs.nasa.gov

"Bringing the Future Within Reach: the NASA John H. Glenn Research Center", NASA-SP-2016-627 history.nasa.gov

Atmosphere of Freedom: Sixty Years at the NASA Ames Research Center NASA SP-4314

"The Wind and Beyond: Journey into the History of Aerodynamics in America, Volume 2, Reinventing the Airplane.", NASA-SP-4409, 2007. (Especially the "Heat Against Ice" excerpt, p. 506-518.) history.nasa.gov

"Engines and Innovation: Lewis Laboratory and American Propulsion Technology". NASA SP-4306, by Virginia P. Dawson, 1991 ntrs.nasa.gov, especially the chapter "Operations Research".

NTRS - NASA Technical Reports Server ntrs.nasa.gov (includes most of the NACA publications)

“Blast from the Past” NACA Icing Publications icinganalysis.com (reviews of NACA icing publications)

Abstract

"Aircraft Ice Protection in the NACA Era 1915 to 1958"

The National Advisory Committee for Aeronautics (NACA) studied aircraft icing through much of its history.

Early studies often looked at direct solutions for icing problems, but were hampered by limited knowledge of icing conditions. Largely “cut-and-try” engineering achieved test aircraft with complete ice protection by 1941.

These flight test aircraft, along with improved icing conditions measurement instrumentation, established much of the modern icing design conditions definition by 1949.

Several areas of icing addressed in the NACA era are still being studied today.