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The NASA Altitude Wind Tunnel: Its Role in Advanced Icing Research and Development

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THE NASA ALTITUDE WIND TUNNEL: ITS ROLE IN ADVANCED ICING RESEARCH AND DEVELOPMENT

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Abstract

Currently experimental aircraft icing research is severely hampered by limitations of ground icing simulation facilities. Existing icing facilities do not have the size, speed, altitude, and icing environment simulation capabilities to allow accurate studies to be made of icing problems occurring for high speed fixed wing aircraft and rotorcraft. Use of the currently dormant NASA Lewis Altitude Wind Tunnel (AWT), as a proposed high speed propulsion and adverse weather facility, would allow many such problems to be studied. The characteristics of the AWT related to adverse weather simulation and in particular to icing simulation are discussed, and potential icing research programs using the AWT are also included.

Introduction

The National Aeronautics and Space Administration, through the work conducted by the Lewis Research Center in Cleveland, Ohio, is committed to the continued advancement of technology for new and improved aircraft propulsion systems. Several recently completed studies[1,2] on a national assessment of the future outlook for aeronautics concluded that major advances in aircraft capabilities are yet to be made. Major conclusions of these studies indicate that to achieve these advances aggressive programs must be pursued in propulsion and in the integration of the propulsion system with the total aircraft. They also concluded that it will be essential that these advanced systems have expanded capabilities for adverse weather operation, primarily icing and heavy rain.

To date the country has had excellent test facilities, however new technologies are evolving which are leading to new and different propulsion systems for new and different aircraft with expanded capabilities like severe weather operation. These new technologies, in turn, will require new and different test facilities to accomplish them. Examples of these new technologies are advanced engine and convertible engine cycles, high speed propeller concepts, materials (e.g., composites), controls, and advanced avionics. These new technologies, in turn, are leading to future aircraft systems which are much more complex in design and mission, and will require a higher degree of system integration compared to present systems. The technical challenges associated with the achievement of these new systems are substantial and will require a combination of continued advances in both computational capabilities and the availability of test facilities with unique characteristics which currently are either severely limited or do not exist at all.

The need for increased severe weather operation of new and different aircraft systems is an example of where the above is particularly true. Recent technological advances have provided the impetus to seek all-weather capability for all aircraft classes including some which had no previous requirement. This in turn has resulted in a revised interest in aircraft icing research and also a renewed interest in icing ground test facilities. As will be discussed in this paper the future of icing research is severely limited by the lack of appropriate ground test facilities. In response to this identified need the NASA, Lewis Research Center has proposed the modification of the now dormant Altitude Wind Tunnel (AWT) into a new, larger, higher performance, wind tunnel test facility appropriate for future propulsion system integration and severe weather R&D, including icing and heavy rain. Since its initial proposal the AWT has been studied by the DOD, FAA, Industry, and AGARD. As a result of significant outside endorsement including the aforementioned groups, as well as the Aeronautics and Space Engineering Board (ASEB) and the Aeronautics and Astronautics Coordinating Board (AACB), NASA is proceeding in its efforts to obtain Formal Project Approval, which will then allow start of construction.

The characteristics of the proposed AWT for simulating adverse weather conditions, particularly icing, are discussed in this paper. Potential icing research programs using the AWT are also included.

Icing Requirements

As stated previously, new technologies are evolving which are leading to new and different aircraft systems. These new technologies are having a profound impact on the future of Icing R&D. Examples of some of these new developments are shown in Fig. 1 which include advanced engines and engine cycles which will have less bleed tolerance to provide the hot gas now used for icing and propulsion system ice protection. Also listed here are advanced materials (e.g., composites) which may impact the use of future hot air and electrothermal ice protection systems; advanced airfoils which may be either more or less sensitive to ice accretion; highly integrated vehicle configurations, which also now need protection; advanced avionics and controls; and new mission requirements. As indicated in Fig. 2 all the current Icing Research and Development (R&D) applications will have to be revisited and new technologies developed for protecting items such as new propulsion system components including inlets, nacelle structures, carburetors, and new and more exotic (higher bypass ratio) fans and new high speed propellers. New ice protection concepts will also be required for fixed wing and now rotary wing aircraft which will also incorporate advanced airfoils, high lift devices, and new fuselage structures.

These recent and continuing advances have provided the impetus to seek all-weather capability for, as indicated in Fig. 3, all aircraft classes including some which had no previous requirement. Today due to technological advances in avionics and flight controls, nearly all helicopters and general aviation aircraft can and are equipped to operate under Instrument Flight Rules (IFR) conditions. Yet only a few military helicopters have icing clearances, and no U.S. civil helicopter has FAA certification for flight into forecasted icing conditions. Many of today's general aviation aircraft are certified for operation in an icing environment, but they rely on ice protection technology that is over 20 years old. The relatively small payload fraction and low power margins of these smaller aircraft mean that their ice protection systems must be light in weight and low in power consumption. Similarly, because of high fuel costs, today's large commercial transports need lighter and more efficient ice protection systems. Tomorrow's transport aircraft will need alternatives to the current hot air ice protection systems because bleed air will be scarce on the more efficient higher-bypass-ratio engines or high speed turboprop engines. Ice protection will also be imperative for the advanced highly survivable military aircraft and cruise missiles which will fly long distances at low altitudes where icing is of major concern. Thus, all of these types of aircraft now share common icing requirements: highly effective, lightweight, low-power consuming deice and anti-icing systems, and detailed knowledge of the aerodynamic penalties due to ice on aircraft surfaces.

To fully exploit the potential of the future energy efficient, high performance, survivable, and operationally flexible aircraft requires that they be capable of successfully operating in all weather conditions. Continuing pressures to expand flight envelopes, geographic routes and flight frequency indicates that the effects of weather phenomena such as icing, heavy rain, and snow must continue to be explored and this can only be done under realistic environmental conditions. Successfully achieving all-weather operational capability in future highly survivable military aircraft and in current and future rotorcraft requires a more thorough understanding of the potential adverse effects of weather on these concepts. For example, the understanding and development of icing technology requires evaluation under realistic atmospheric conditions. Today these conditions can only be found via costly, time consuming and risky flight testing.

In response to the nationally recognized need for new icing and severe weather R&D, NASA has organized a new aircraft icing research program at Lewis to help solve the icing problem for modern aircraft. As schematically indicated in Fig. 4 this program is broad based, and covers both basic research and engineering applications. Specific elements of the program are summarized in Table I and an expanded description of the overall program is included in Ref. 3. This program is well coordinated among the various NASA Centers, the FAA, DOD, universities, industry, and some foreign governments. In fact, the program was formulated with the help of all these groups through a series of workshops and special studies.[4-7] Inputs from these studies identified four main needs for future icing R&D: new and more efficient ice protection concepts; improved icing instrumentation; advanced icing analysis methods; and new and/or improved icing test facilities.

Early in the new icing effort, NASA and others surveyed the icing test facilities throughout the free world[8-10] capable of meeting the modern requirements. These investigations revealed a serious lack of ground icing research facilities for testing in particular helicopters, missiles, general aviation, and higher performance aircraft. These results were further corroborated in the other studies already mentioned, which helped formulate the NASA program.[4-7]

Icing Facility Requirements

As shown in Fig. 5, the phenomena of icing is complex and requires that many variables be simultaneously controlled for correct simulation. Ice can form in two ways, either the droplets freeze immediately upon impact, forming rime ice, or shortly after impact forming glaze ice. Each case results in a different ice formation with different growth patterns and each case can have serious and deleterious effects on the aerodynamic performance of the surface upon which it forms. As shown, the growth of the ice is a function of many variables, including velocity, temperature, pressure, liquid water content, droplet size, airfoil size and shape, and also vehicle angle-of-attack. Therefore, proper icing testing requires not only control of more test variables, but also more exacting control than is required for aerodynamic testing. Likewise, icing phenomena cannot be simply scaled as is the case with aerodynamic testing. As shown in Fig. 6, ice accretion varies greatly with the size of the object. Attempts to properly scale ice accretion have been made over the years, but were never verified as being successful. In these attempts it was found that adjustments must also be made in velocity, liquid water content, time of accretion, and droplet size to begin to achieve any degree of success. As a result, little work has been done with subscale models and icing has been considered a "full-scale" R&D area. Ice scaling research is continuing, but no validation of any scaling law has yet been achieved.

As a result, icing R&D has been conducted at full scale in either flight or in the few ground test facilities capable of testing full scale hardware. The largest current icing facility in the U.S. is the 6 by 9 Ft Icing Research Tunnel (IRT) at the NASA Lewis Research Center. A typical test conducted in this facility, shown in Fig. 7, includes full scale equipment which generally results in severe blockage effects. This tunnel is heavily used, but has been identified by the icing community as being extremely limited, because of these blockage effects and also limitations in speed and altitude capabilities. The test capabilities of the IRT are shown in Fig. 8 and compared to the flight conditions described in the Federal Aviation Regulations (FAR) Part 25 requirement for certification of flight into forecast icing conditions. Although temperature simulation of the IRT is good (-20 to +32 °F), the IRT does not simulate altitude pressure and the top speed is only Mach 0.4 when the tunnel is empty. Large blockage models limit the top speed to something less. Consequently, the IRT does not adequately simulate flight, in particular for the current and future higher performance aircraft configurations.

Consequently, as summarized in Fig. 9, no suitable ground facility exists for proper simulation of flight altitude conditions, at correct flight speeds, with large or full scale equipment. As previously identified, this lack of appropriate ground test facilities has, and will continue to severely limit or impede the technology development necessary for future higher performance aircraft. Without the availability of appropriate test facilities, flight and test development times will have to increase, particularly for the new and more complex flight systems. What is needed, therefore, is a new test facility with the simultaneous capabilities as summarized in Fig. 10. These requirements include the concurrent pressure and temperature simulation of altitude, the ability to test large or full scale hardware, and with speeds to near Mach 1.0. To properly simulate flight test conditions over an extended length of test area the facility should also be a wind tunnel. Sizeable capacity flow services are required for propulsion system operation and/or simulation with large engine simulators. This requires large capacity air services for engine exhaust flow scavenging and make up air supplies to replace that removed by the exhaust system. Lastly, this facility must have the capability of water spray systems appropriate for icing and heavy rain simulation.

In response to the identified need NASA Lewis has proposed the modification of an existing dormant wind tunnel facility that will simultaneously satisfy all the test requirements needed to successfully evaluate and resolve the technological challenges of future high potential aeronautical vehicles.

Proposed Altitude Wind Tunnel (AWT)

The AWT, seen in Fig. 11, was built in 1944 and served NACA as a low speed ($M \leq 0.6$) propulsion wind tunnel until 1958. In 1958 NACA became NASA and the technology focus shifted from aeronautics to space. Because the AWT had low pressure (high altitude) and low temperature capability and also because the aircraft research of the time was in the high speed flight regime, it was decided to convert this wind tunnel into a much needed vacuum test facility. In 1960 the AWT then became the Space Power Facility and served NASA in this capacity until 1970. The tunnel was converted into two large vacuum tanks and was used for many space applications, including extensive Launch Vehicle testing. Since 1970 the facility has been unused and would thereby provide a cost effective foundation upon which to build a new, needed wind tunnel facility.

A schematic of the proposed new AWT is shown in Fig. 12 with its projected test capabilities. The tunnel will have a nominal 20 ft, octagonal, slotted high subsonic speed test section. Mach numbers ranging from near 0 to more than 0.9 will be achievable with large blockage models (10 to 12 percent) including complete operating propulsion systems. The Lewis central altitude exhaust system will provide pressure altitude variation from sea level to greater than 55 000 ft. The tunnel refrigeration system will allow tunnel total temperature variations from 60 °F down to less than -40 °F. Standard wind tunnel components of the facility are shown in Fig. 13. The original AWT had a 20 ft diameter circular solid wall test section with a top speed near Mach 0.6. This will be replaced with a new slotted octagonal configuration more appropriate for high subsonic speeds. Wall boundary layer air will be bled through the slots into a plenum surrounding the test section and then re-injected downstream of the test section, to minimize model blockage effects. At the downstream end of the test section variable finger flaps will also be used. Two 30 000 hp electric motors will be provided to power a two-stage variable speed fan with variable inlet and interstage guide vanes. The number of guide vanes (28 per stage) was selected to minimize the interactions between the vanes and rotor blades and thus minimize the fan noise. A heat exchanger will provide cooling to remove the heat added to the tunnel air by the drive fan and test models, and to simulate the desired altitude static temperatures. Flow conditioners will consist of honeycomb sections and removable screens. The screens would be removed during adverse weather testing. When in place, the flow conditioners will provide good quality (low turbulence) flow to the test section.

Special features which make the AWT a unique test facility are shown in isometric view in Fig. 14. To prevent contamination by exhaust products, an engine exhaust scoop will be located downstream of the test section. This scoop will provide both altitude exhaust and engine exhaust flow scavenging via the laboratory Central Exhaust System. This scoop will be variable in the pitch plane to allow for engine angle-of-attack variation and will have variable and interchangeable tip geometries. It will also be cooled to allow testing even with afterburning engines. Make-up air will be injected just downstream of the fan. A Plenum Evacuation System (PES) will be used to pump the test section plenum to allow for testing with model blockages near 12 percent at high subsonic speeds. The pumped plenum air will also be re-injected into the tunnel just aft of the fan. Heated turning vanes will be used in the two corners upstream of the fan to prevent and remove ice buildups during adverse weather testing. The heat exchanger will be con- nected to a 21 000 ton capacity, Freon-22, two-phase refrigeration system. This system will permit operation at static temperatures that are encountered at altitudes varying from sea level to in excess of 55 000 ft. Lastly, a removable water spray bar system will be inserted into the tunnel upstream of the bellmouth for adverse weather testing (i.e., icing, heavy rain, and possibly snow). This system will have the capability to introduce water in various droplet sizes and water content levels. Details of how the spray bar system will be inserted and removed from the tunnel are also shown in the figure. The spray system will thereby be interchangeable with the tunnel flow conditioners so that flow quality may be preserved for aerodynamic and propulsion tests. As seen in Fig. 14, this large tunnel will be extremely flexible and provide some unique functions and capabilities which are not found in any other existing wind tunnel.

Details of the high speed test section are elaborated in Fig. 15. The octagonal cross section geometry was selected because it provides a convenient configuration for incorporating the necessary special features. This configuration allows for the convenient use of bleed slots and reentry flaps which are necessary for testing of large blockage models at high subsonic speeds. Furthermore, the flat walls allow the extensive use of high quality optical windows necessary for icing testing and for the advanced laser data systems. This design also allows for the easy replacement of the tunnel sidewalls with acoustically treated panels more appropriate for acoustic testing of advanced propulsion systems. The test section will include both floor and side wall model mounting. The floor mount will include a multicomponent force balance for system performance testing. Models will be installed and removed from the test section through a bottom entry which will lower the tunnel floor to the shop level below on screwjacks. The two lower tunnel quarter panels will rotate out of the way so that full span models can be easily installed. These features will provide for rapid model access thereby increasing the productivity of the tunnel.

The nominal pressure altitude/Mach number capability of the tunnel is shown in Fig. 16. Because many of the potential programs to be run in the AWT may be sensitive and/or proprietary, special features are being incorporated into the tunnel design. These features, as shown in Fig. 17, include separate model buildup and checkout areas, restricted access to the flow circuit, secure data systems and control rooms, and special office locations.

As was mentioned previously, one of the requirements for a new propulsion wind tunnel is special support services for propulsion testing including high capacity air systems. A listing of a series of these support services already existing and operating at Lewis is shown in Fig. 18. These system capabilities are unique in NASA and include compressed air supplies capable of continuous operation at high pressures and weight flows, and provide a capital net worth exceeding $200 million.

The AWT will, therefore, provide the U.S. Aeronautics industry with a needed, truly unique, and diverse wind tunnel for future propulsion system integration and icing R&D. The unique capabilities of the AWT to perform icing research are summarized in Fig. 19. The AWT Mach number and altitude capabilities are shown compared to the FAA icing limit and also to the IRT. The AWT will provide the necessary altitude simulation and speeds to cover the complete range of interest and will have a test section area approximately six times larger than the IRT. Lastly, because of its special capabilities, complete propulsion systems may be tested over the complete required range of test conditions. As shown in the figure, in contrast to the isolated nacelle tested in the IRT, the AWT will be able to test complete full scale advanced high speed propeller propulsion systems. Performance testing would be done at the same time as icing testing. In summary, this figure shows that the AWT will be a significant improvement over the capabilities of the IRT which is the largest and most heavily used icing facility in the U.S. Plans also include capabilities to perform heavy rain testing, and if the technology is ever developed for snow simulations, the AWT will also be appropriate.

Further examples of typical test programs, which demonstrate the diverse flexibility of the AWT, are shown in Figs. 20 to 24. These test programs could include general aviation, rotorcraft, highly survivable military, and advanced missile systems. The tunnel would also be appropriate for advanced CTOL propulsion system testing. In each case, multiple tests could be performed such that either performance, acoustics, or severe weather data could be obtained. This feature could reduce the amount of testing in any particular program. As shown in Fig. 24, a unique type of testing could be performed in the AWT. Because the AWT would have cold walls, IR signatures of hot exhaust could be measured which could not be obtained in an unrefrigerated wind tunnel. An expanded discussion of the capabilities of AWT for propulsion system and system integration testing is included in Ref. 11.

The proposed AWT Project schedule is shown in Fig. 25. A Preliminary Engineering Study (PER) was completed in December, 1984. As was mentioned earlier, NASA is seeking approval for a construction (CoF) start. If approval is soon obtained, final design will start in FY 1985, construction will begin in FY 1986, and the facility will be ready for checkout and calibration in FY 1990. At present, to support the final design and to insure the success of the tunnel in meeting its test requirements an extensive modeling program has been initiated at Lewis. A detailed description of this program is included in Ref. 12. In this program, every tunnel component will be tested at 1/10 scale, first alone and then integrated into a complete full circuit loop. Additional model testing is being conducted at Lewis using the other wind tunnel facilities, particularly the IRT. As described in Ref. 13 extensive use is also being made of advanced analytical techniques and analysis. Analytical modeling of the tunnel controls is also underway. These efforts will include the development and use of a real time system simulator whereby the dynamics of the tunnel controls and systems can be studied before the tunnel is first started. As indicated in Fig. 25 these modeling efforts are projected to be very extensive during final design, but will drop off as construction continues. Eventually, a complete scale model of the AWT will come to be which can either be used as a pilot tunnel for AWT or as a separate research facility.

Concluding Remarks

It is projected that many advances can and will be made in future aeronautical systems. However, these advances will only come from a more thorough understanding and resolution of integrated systems technology and solutions to adverse weather related problems. This will require new unique analytical and experimental capabilities appropriate to successfully evaluate these systems integration problems under realistic operating conditions. Not all of the required facilities necessary to achieve these goals exist today.

As indicated in Fig. 26 the proposed modification to the now dormant Lewis Altitude Wind Tunnel provides a cost effective means of achieving a critically needed unique capability that does not currently exist within the U.S. This facility has been substantially endorsed as meeting the needs of the icing research community. The extensive modeling effort that is supporting the facility design is the most complete and comprehensive that NASA has ever undertaken. These efforts will thereby insure the success of this program and will play a major role in maintaining U.S. superiority in Aeronautics well into the 21st Century.

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TABLE I. - ELEMENTS OF NASA'S AIRCRAFT ICING PROGRAM

Ice protection systems	Pneumatic deicers for helicopters Electrothermal deicers Glycol fluid systems Electromagnetic impulse deicers Icephobics
Icing instrumentation	Cloud instrument evaluation Ice detectors
Experimental methods	Icing research tunnel Airfoil performance in icing Testing with artificial ice Helicopter test rigs Icing scaling laws
Analytical methods	Computer codes for • Water droplet trajectories • Ice accretion modeling • Aero performance penalties • Transient deicer analysis
Flight research	Validation data for icing simulation facilities Instrument evaluation Icing cloud data Meteorology Helicopter performance

NEW DEVELOPMENTS IMPACTING FUTURE ICING R&D

- ZERO BLEED ENGINES
- COMPOSITE MATERIALS
- ADVANCED AIRFOILS
- HIGHLY INTEGRATED VEHICLE CONFIGURATIONS
- ADVANCED AVIONICS/ELECTRONICS
- NEW MISSION REQUIREMENTS

FIGURE 1

CD-84-14384

ICING R&D APPLICATIONS

- **PROPULSION SYSTEMS**
  - INLETS
  - NACELLE STRUCTURES
  - CARBURETORS
  - FAN AND PROPELLERS
- **FIXED AND ROTARY WING AIRCRAFT**
  - ADVANCED AIRFOILS
  - HIGH LIFT DEVICES
  - FUSELAGE

FIGURE 2

CD-84-14383

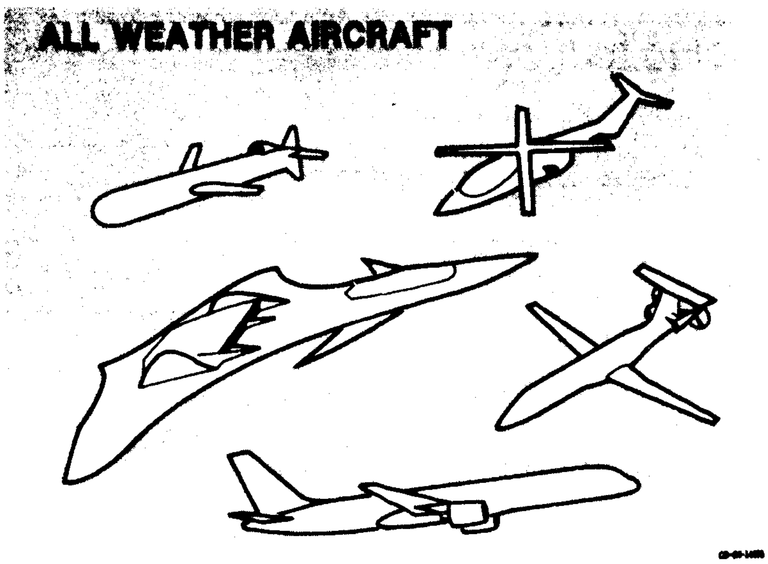

FIGURE 3

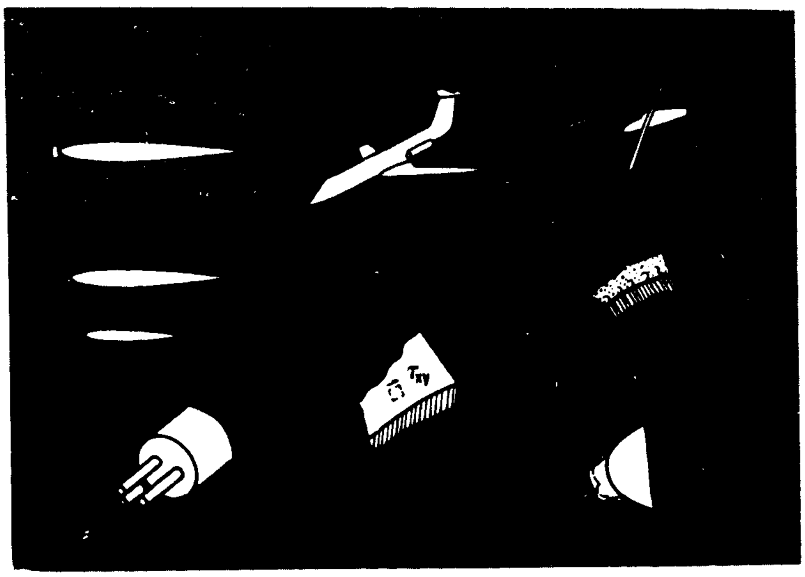

FIGURE 4

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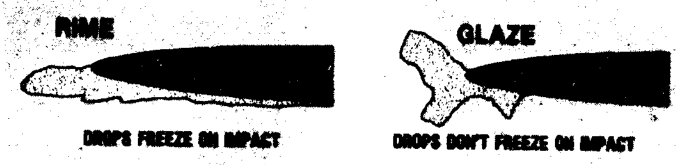
ICING R & D TEST REQUIREMENTS

- TYPES OF ICE GROWTH



- ICE GROWTH IS A FUNCTION OF
  - VELOCITY
  - AMBIENT TEMPERATURE
  - AMBIENT PRESSURE
  - LIQUID WATER CONTENT
  - WATER DROP SIZE
  - AIRFOIL SIZE, SHAPE
  - ANGLE-OF-ATTACK

FIGURE 5

EFFECT OF SIZE OF OBJECT ON ICE ACCRETION

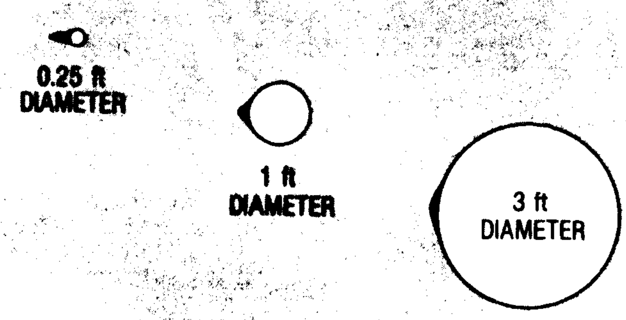
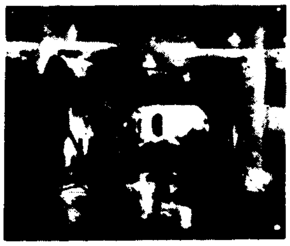
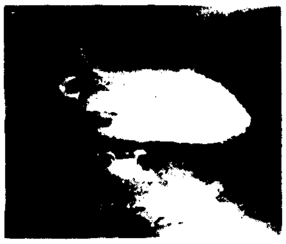


FIGURE 6

ALL WEATHER APPLICATIONS

ICING AND HEAVY RAIN





ICING TEST OF A FULL SCALE GENERAL AVIATION INLET/NACELLE IN THE LEWIS ICING RESEARCH TUNNEL (IRT)

C-84-1345

Figure 7.

EXTENT OF ICING R&D TEST REQUIREMENTS

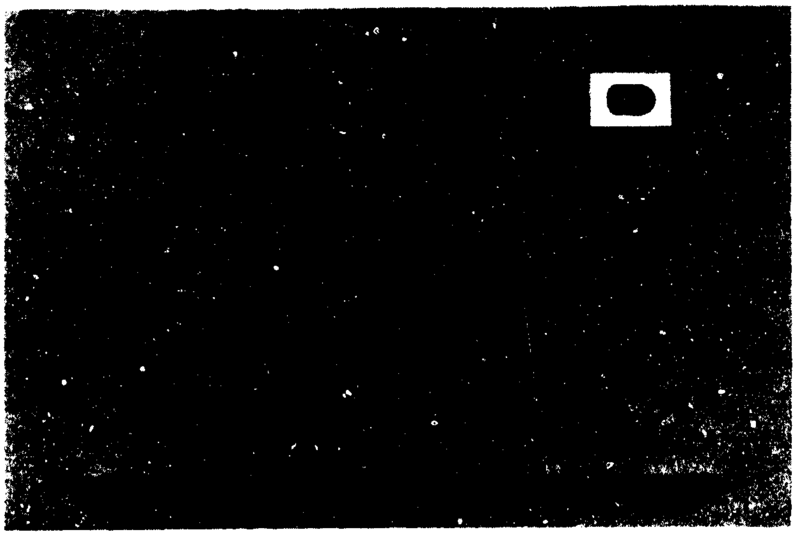


FIGURE 8

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ICING R&D TEST REQUIREMENTS SUMMARY

- FLIGHT ALTITUDE SIMULATION
- CORRECT FLIGHT SPEEDS
- FULL/LARGE SCALE

SUITABLE FACILITY
NON-EXISTENT

FIGURE 9

CD-84-14385

NEW TEST FACILITY REQUIREMENTS

- CONCURRENT PRESSURE AND TEMPERATURE SIMULATION OF ALTITUDE
- LARGE SCALE TEST ARTICLES
- FULL SUBSONIC SPEED RANGE
- WIND TUNNEL CONFIGURATION–AERODYNAMICS/ACOUSTICS
- PROPULSION SYSTEM OPERATION/SIMULATION
- ICING, HEAVY RAIN CAPABILITY

$\boxed{\text{NO EXISTING NOR PLANNED FACILITY MEETS THESE NEEDS}}$

FIGURE 10

CD-84-15026

ALTITUDE WIND TUNNEL

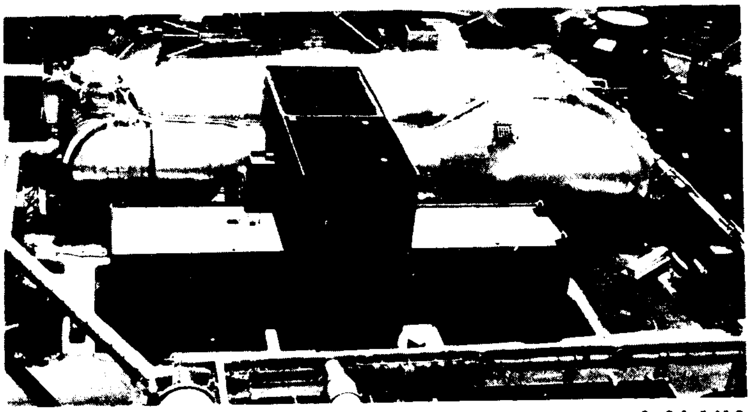

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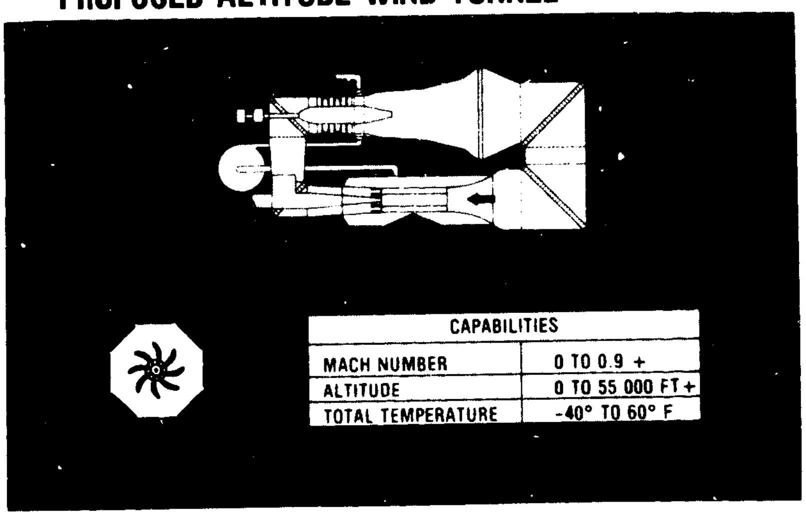
Figure 11.

PROPOSED ALTITUDE WIND TUNNEL



CAPABILITIES	
MACH NUMBER	0 TO 0.9 +
ALTITUDE	0 TO 55 000 FT +
TOTAL TEMPERATURE	-40° TO 60° F

FIGURE 12

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STANDARD WIND TUNNEL COMPONENTS

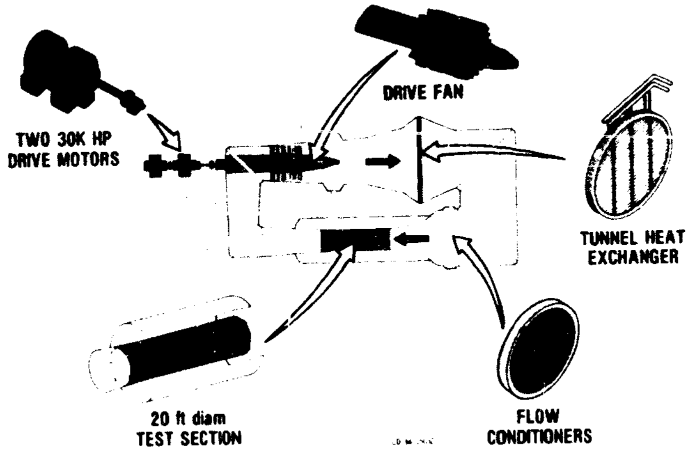


FIGURE 13

ALTITUDE WIND TUNNEL SPECIAL FEATURES

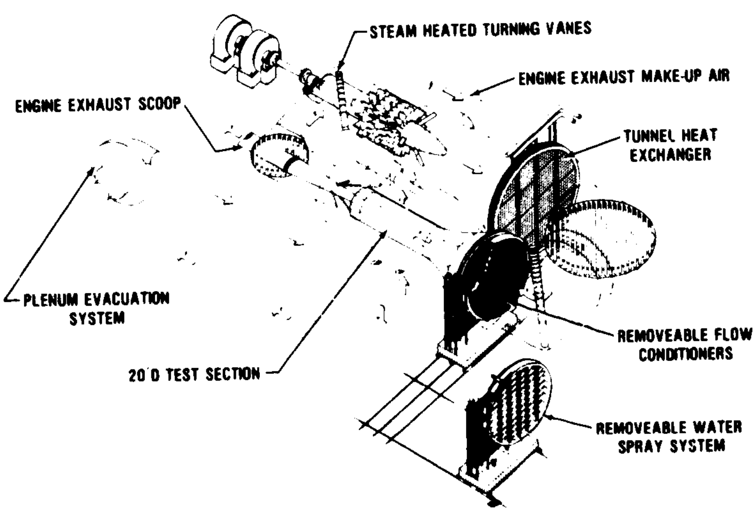
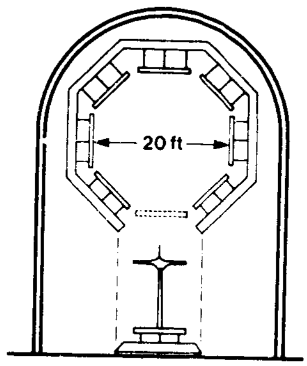


FIGURE 14

TEST SECTION FEATURES



- OCTAGONAL CROSS SECTION
- SLOTTED WALL WITH PLENUM
- FLAT WINDOWS
- FORCE BALANCE
- REMOVABLE ACOUSTICAL WALLS
- BOTTOM MODEL ENTRY
- RAPID MODEL ACCESS

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FIGURE 15

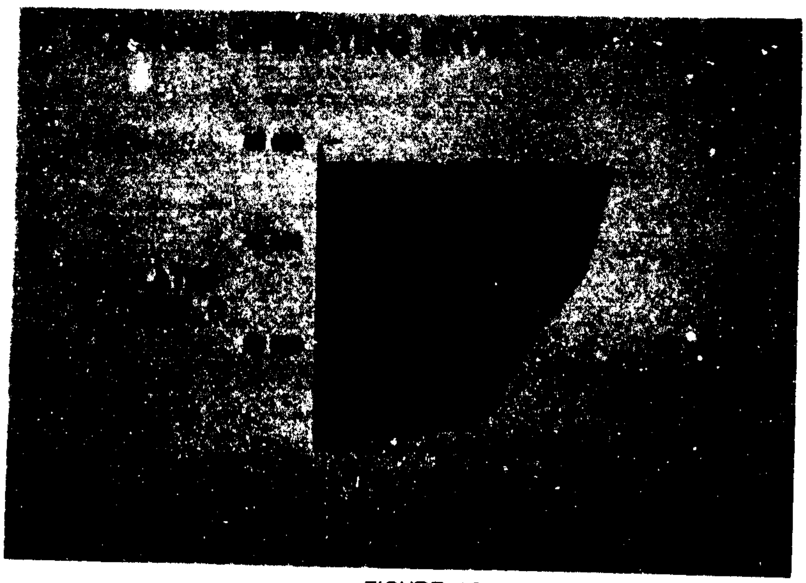


FIGURE 16

FEATURES FOR SENSITIVE PROGRAMS

- ABILITY TO ROUTINELY HANDLE SENSITIVE MODELS
  - THREE SEPARATE MODEL BUILD UP AND CHECK OUT ROOMS
  - MODEL STORAGE PROVISIONS
- RESTRICTED ACCESS TO FLOW CIRCUIT
- DATA SYSTEM AND DATA SECURITY
  - STAND ALONE DATA ACQUISITION/ANALYSIS/DISPLAY CAPABILITY
    - SHIELDED
    - RESTRICTED PHYSICAL ACCESS
  - SECURED OFF LINE DATA REDUCTION AND STORAGE CAPABILITY
- OFFICE SUPPORT

FIGURE 17

ALTITUDE WIND TUNNEL SPECIAL SUPPORT SERVICES

- **CENTRAL CONTINUOUS COMPRESSED AIR SUPPLIES**
  - 450 lb/sec AT 45 psi
  - 400 lb/sec AT 150 psi
  - 76 lb/sec AT 450 psi
- **CENTRAL EXHAUST SYSTEM**
  - 480 lb/sec AT SEA LEVEL PRESSURE AND 70° F

FIGURE 18

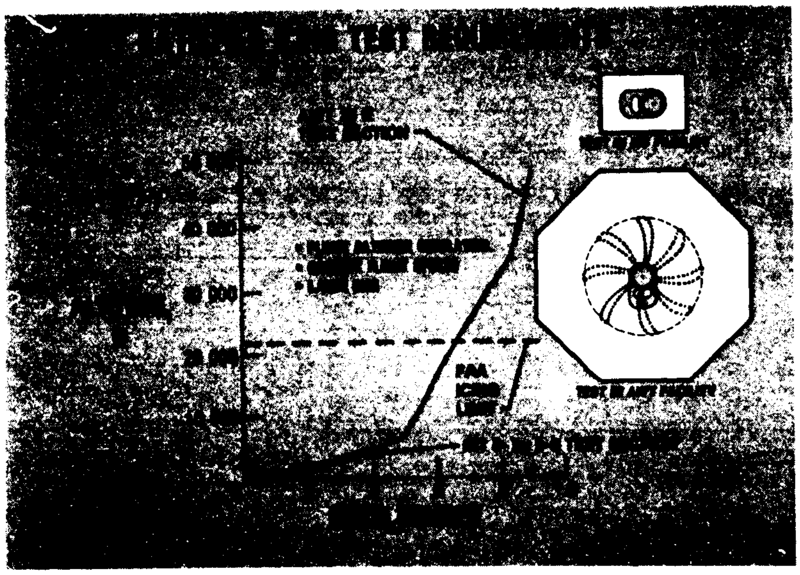
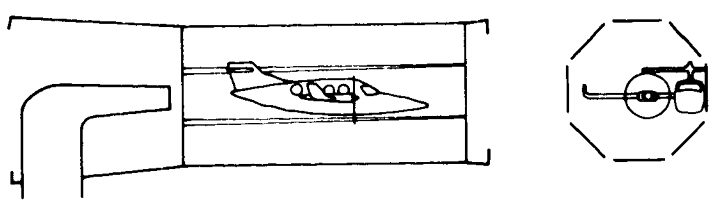


FIGURE 19

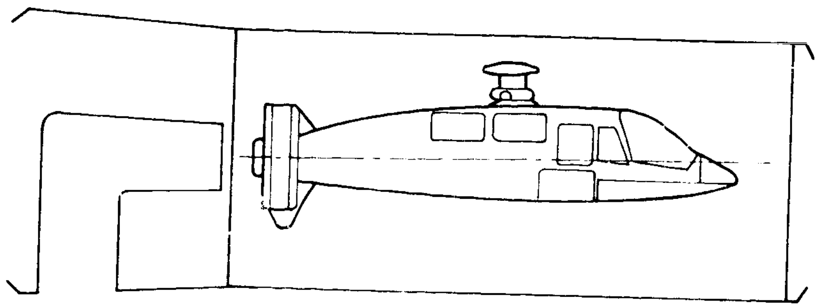
GENERAL AVIATION VEHICLES



- PERFORMANCE
- ICING
- COOLING
- AEROELASTICS
- ACOUSTICS

FIGURE 20

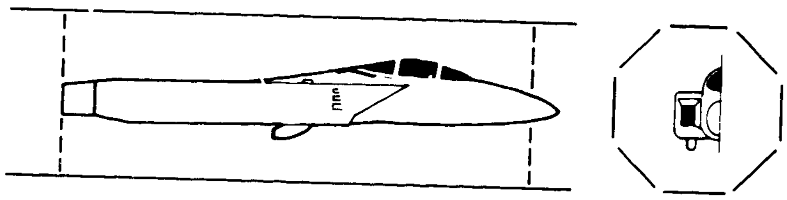
ADVANCED ROTORCRAFT PROPULSION IN AWT



- HIGH SPEED PERFORMANCE
- ACOUSTICS
- ICING
- CONTROLS

FIGURE 21

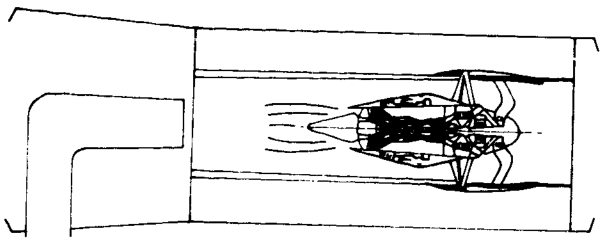
STOVL AIRCRAFT WITH F100 ENGINE IN AWT



- PERFORMANCE
- ICING

FIGURE 22

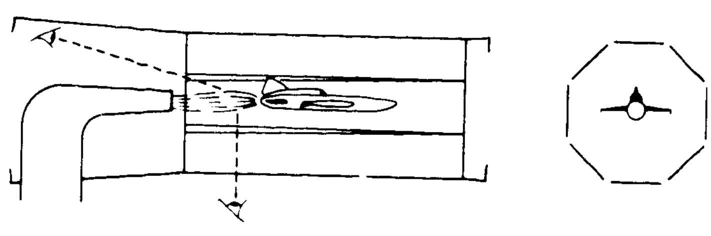
HIGH BYPASS RATIO TURBOFAN PROPULSION SYSTEMS



- PERFORMANCE
- ACOUSTICS
- AEROELASTICS
- ICING

FIGURE 23

SPECIAL PURPOSE VEHICLES



- SIGNATURES
- ICING
- PERFORMANCE

FIGURE 24

ORIGINAL PAGE IS
OF POOR QUALITY

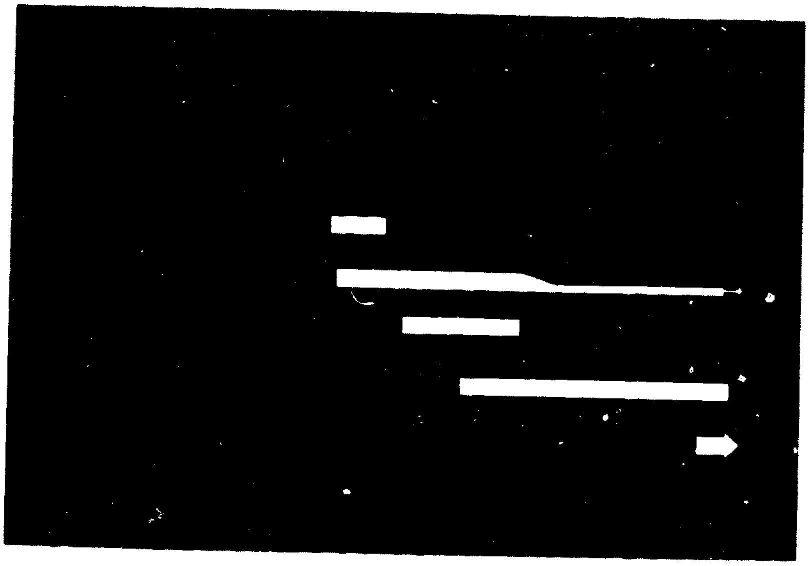
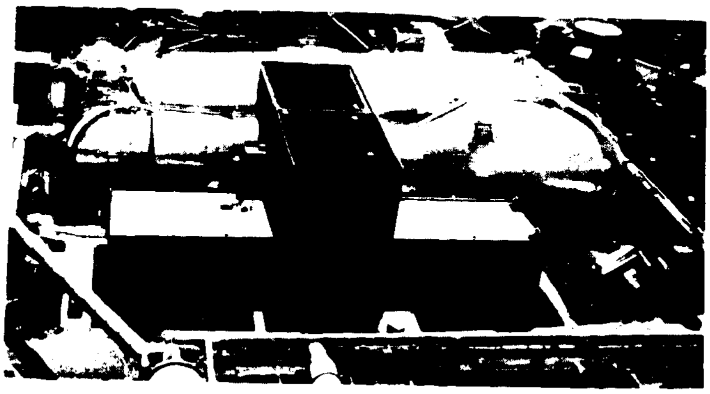


FIGURE 25

ALTITUDE WIND TUNNEL



PROVIDES NEW NATIONAL
AERONAUTICAL PROPULSION AND ICING R&D CAPABILITY

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Figure 26.