AIAA-2001-0754
The National Transonic Facility: A Research Retrospective (Invited)

R. A. Wahls
NASA Langley Research Center
Hampton, Virginia

39th AIAA Aerospace Sciences Meeting & Exhibit
8-11 January 2001
Reno, Nevada

THE NATIONAL TRANSONIC FACILITY: A RESEARCH RETROSPECTIVE

R. A. Wahls*
Aerodynamics, Aerothermodynamics, and Acoustics Competency
NASA Langley Research Center
Hampton, Virginia

ABSTRACT

An overview of the National Transonic Facility (NTF) from a research utilization perspective is provided. The facility was born in the 1970s from an internationally recognized need for a high Reynolds number test capability based on previous experiences with preflight predictions of aerodynamic characteristics and an anticipated need in support of research and development for future aerospace vehicle systems. Selection of the cryogenic concept to meet the need, unique capabilities of the facility, and the eventual research utilization of the facility are discussed. The primary purpose of the paper is to expose the range of investigations that have used the NTF since being declared operational in late 1984; limited research results are included, though many more can be found in the references.

INTRODUCTION

The National Transonic Facility (NTF) at the NASA Langley Research Center (LaRC) is a unique national facility, the first of its kind in the world, and yet relatively few research results have been published or even discussed in open forums. Most open discussions have focused on facility capabilities, upgrades, test techniques and the like, rather than research results or even the types of investigations that have used the NTF. While much research data and specific model detail still remain proprietary, thus limiting its disclosure and discussion, another government-imposed restriction, "For Early Domestic Dissemination Only," was recently removed (1998). The existence of a comparable facility outside the US, specifically the European Transonic Windtunnel (ETW), was key to this decision. As a result, more open presentation and discussion of the use of the NTF, including research results and specific test challenges, has begun to occur. The primary purpose of the paper is to expose the range of investigations that have used the NTF since being declared operational in late 1984; limited research results are included, though many more can be found in the references.

*Assistant Head, Configuration Aerodynamics Branch, Associate Fellow, AIAA

TERMS, ABBREVIATIONS, & ACRONYMS

AACB	Aeronautics & Astronautics Coordinating Board
AGARD	Advisory Group for Aerospace Research and Development
AEDC	Arnold Engineering & Development Center
AST	Advanced Subsonic Technology, or Advanced Supersonic Technology (program)
CFD	computational fluid dynamics
C_D	drag coefficient
C_M	pitching-moment coefficient
C_P	pressure coefficient
DoD	Department of Defense
ETW	European Transonic Windtunnel
HIRT	High Reynolds Number Tunnel
HSR	High Speed Research (program)
LaRC	Langley Research Center
M	Mach number
NATO	North Atlantic Treaty Organization
NTF	National Transonic Facility
P_T	Total Pressure
T_t	Total Temperature
Rn	Reynolds number
TRT	Transonic Research Tunnel
USAF	United States Air Force
α	angle of attack
β	angle of sideslip

NTF ORIGIN AND EVOLUTION

The origin and evolution of the NTF can be summarized in four phases as follows: 1) internationally recognized need for high Reynolds number test capability, 2) down select to the cryogenic nitrogen concept, 3) detailed design, construction, and research utilization planning, and 4) facility operations, continual improvement, and research application. Figure 1 provides an overview of several key activities and milestones during the evolution of the NTF.

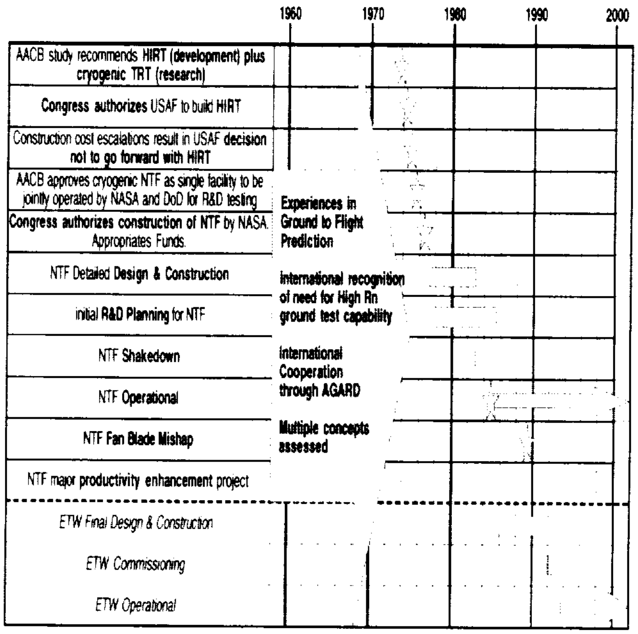

Figure 1. Key activites and milestones during the evolution of the NTF.

Original Motivation

An internationally acknowledged need for a flight (or near flight) Reynolds number ground test facility emerged during the 1960s as noted in the foreword to reference 1 which states:

"...AGARD held a Specialists' Meeting in Paris on 'Transonic Aerodynamics' in recognition of the fact that the absence of adequate theoretical methods and wind tunnels of high enough Reynolds number had already led to costly shortcomings in the transonic performance of certain combat and transport aircraft."

Preflight prediction of flight characteristics is a necessary process for the developer of any aerospace vehicle, and may introduce significant risk to the success of the vehicle. Whether the customer of the vehicle is commercial or governmental, the final full-scale vehicle must meet certain requirements to be certified as safe, and certain performance requirements to be economically successful. The aircraft designer and his company strive to know the performance of their vehicle with high confidence prior to flight, thus enabling optimal design trades prior to flight and elimination of costly modifications, if possible, to the aircraft after initial flight testing. The problems of predicting flight characteristics across the full flight envelope prior to flight have been and continue to be challenging as evidenced by experiences with past configurations publicly documented (refs. 2-10, for example) or otherwise. Examples have been shown in which flight performance was better than anticipated, while in other cases worse than predicted. Several examples are: 1) the significantly higher loading on the wing of the C-141 in flight, 2) the higher than expected interference drag for nacelle-pylon-wing integration on the Convair 990, 3) the increased cruise speed of the C-5A due to delayed drag rise in flight, 4) the higher than expected nacelle-pylon-wing interference drag on a prototype DC-8 long duct nacelle, 5) the high drag and resulting fuel burn required for the XB-70 to accelerate through Mach 1, 6) the higher than expected interference drag for the F-111 airframe, 7) the lack of performance benefit for the DC-10 using a drooped aileron, 8) the pitch characteristics of the B-2, and 9) the ascent loads and pitch characteristics of the space shuttle. This is only a partial list; more examples can be found in the literature, and one would suspect further examples exist that have not been disclosed publicly. Figures 2-5 reproduce results previously published demonstrating several of these discrepancies.

A number of the past discrepancies between preflight estimates and flight results can be traced with significant confidence to design, test, and evaluation at sub-scale, low Reynolds numbers. This is not meant to imply that Reynolds number scaling is the only issue with regards to flight prediction, as there are many other influences such as wall and model support interference and wind tunnel flow quality (ref. 7). The Reynolds number is the ratio of inertial to viscous forces, and is the primary aerodynamic scaling parameter used to relate sub-scale wind tunnel models to full-scale aircraft in flight. The challenge of Reynolds number scaling increases with the size of the full-scale aircraft, and the degree to which aerodynamic technology is pushed, as the Reynolds number increment

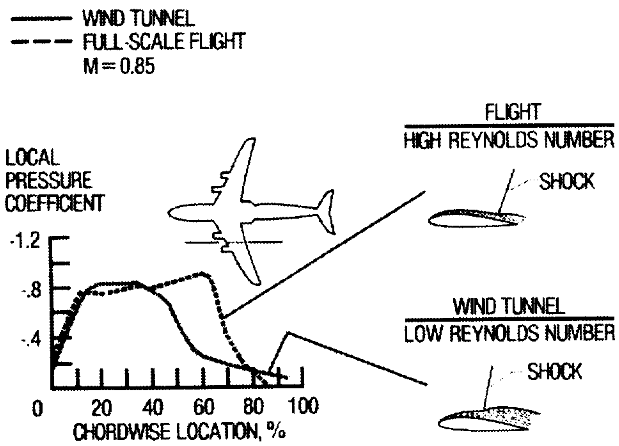

Figure 2. C-141 wing loading discrepancy from wind tunnel to flight (ref. 3).

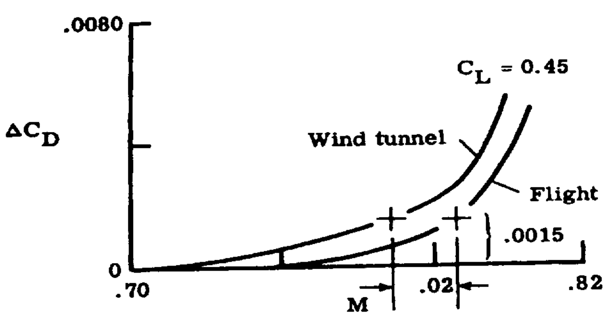

Figure 3. C-5A drag-rise discrepancy from wind tunnel to flight (ref. 3).

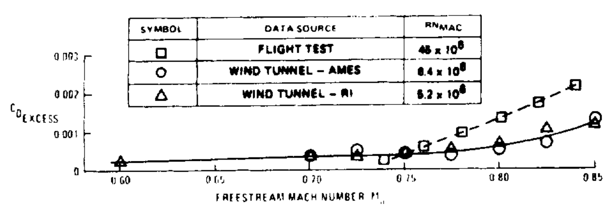

Figure 4. DC-8 prototype long duct nacelle interference drag discrepancy from wind tunnel to flight (ref. 6).

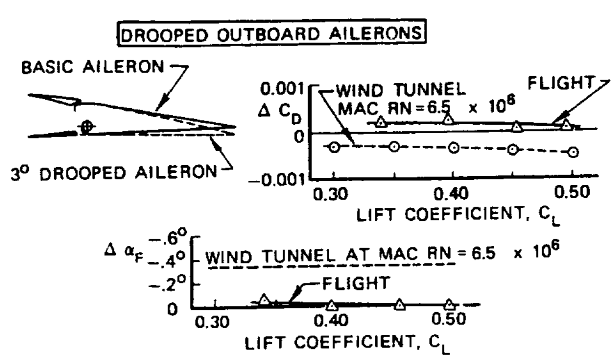

Figure 5. DC-10 drooped aileron performance discrepancy from wind tunnel to flight (ref. 6).

between that obtainable in conventional wind tunnels and flight conditions expands. Additionally, the challenge for both wind tunnel and computational approaches increases as flow features become dominated by viscous-sensitive phenomena such as those listed in table 1 (ref. 3). Clearly, there are numerous flow phenomena that impact vehicle design. Though some situations involve attached flow where boundary-layer displacement effects are important, most relate to separation onset and progression in some manner. Also, while much early focus was placed on scaling problems for transonic conditions, low-speed high-lift conditions are also known to be problematic (refs. 8, 11, 12).

NASA CP-2009, 1977	Vehicle Type				
	maneuver	subsonic transport & cruise	supersonic transport	hypersonic	launch vehicles
boundary-layer growth & separation	x	x	x	x	x
boundary-layer transition		x	x	x	
turbulent boundary layers	x	x	x	x	x
boundary layer/shock interaction	x	x	x	x	x
separated flows	x			x	x
viscous cross flow	x	x	x	x	x
viscous corner flow	x				
viscous mixing effects	x	x	x	x	x
base flow & wake dynamics	x	x	x	x	x
base recirculation				x	x
base drag				x	x
skin friction drag	x	x	x		
roughness, protuberance drag	x	x	x	x	x
pressure fluctuation	x				x
vortex flows	x	x	x	x	x
interference flow fields	x	x	x	x	x
jet plume interference	x	x	x	x	x
bluff body aerodynamics				x	x
heat transfer				x	x

Table 1. Reynolds number sensitive phenomena (ref. 3).

Specific approaches for ground to flight scaling, and Reynolds number scaling in particular, have been documented over the years for a variety of vehicles and specific parameters (ref. 13, for example). Reynolds number scaling can be addressed in several ways. First, and very commonly employed, is the reliance on similar vehicles with existing ground and flight databases; one learns from past experience and applies residual increments to the new configuration and "hopes for the best." This approach has its highest risk when evaluating novel/revolutionary configurations.

A second approach, and one becoming more common, is the use of Computational Fluid Dynamics (CFD) to extrapolate results to flight conditions, or compute at flight conditions. The approach has been useful for attached flow conditions where boundary-layer displacement effects are most important. However, CFD independent of wind tunnel data has not advanced to the point of confident (willing to bet the company), routine industrial use for a broad range of separated flow conditions, which constitute most of a vehicles off-design flight envelope. This is not meant to imply that the evolution of CFD has not impacted today's aircraft designs. In fact, the use of CFD has both improved attached flow designs and reduced wind tunnel requirements by providing a better, smaller set of designs prior to wind tunnel testing. The advances in design for a wing in presence of a pylon/nacelle installation are particularly noteworthy. Figure 6 shows the historical trend of wind tunnel requirements for various aircraft. Though there is variability, as one should expect, a general flattening trend begins in the 1960/70s range, which overlaps with the emergence of computers and modern CFD.

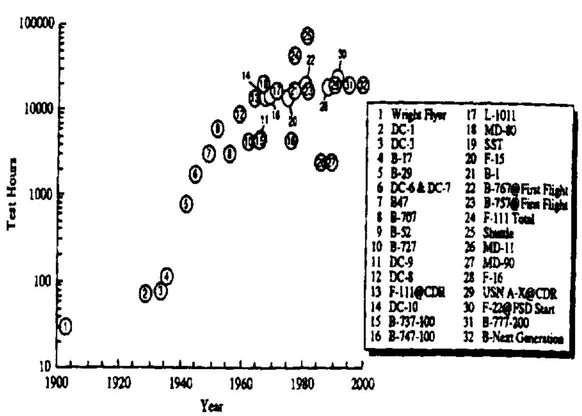

Figure 6. Historical trend of wind tunnel test requirements, (ref. 14).

A third approach for scaling is the use of large-scale prototypes and flight tests. This approach is most likely to occur for the relatively small, high performance military vehicles, but is prohibitive for large airframes for a number of reasons including cost, time, and risk. Additionally, scaling efforts must still take place to reduce the risk of the prototype in flight.

Another approach is the use of high Reynolds number wind tunnels such as the NTF and its counterpart, the ETW; these facilities provide flight, or near flight conditions including Reynolds number for sub-scale models. These facilities provide a link from conventional wind tunnel to flight conditions, enable verification of CFD methods at flight conditions, and allow assessment of flight characteristics across the flight envelope, thus providing increased confidence in a final design prior to flight.

Down Select to a Cryogenic Wind Tunnel

Coincident with the recognition of the need for a high Reynolds number ground test capability in the 1960s, many ideas on how to meet the need were generated and reviewed in great detail both domestically and internationally (ref. 3, 15). Considerable technology exchange between the US and Europe occurred under the auspices of NATO's Advisory Group for Aerospace Research and Development (AGARD), with regards to test requirements and approach.

From the definition of the Reynolds number, several options present themselves: 1) large model/test section size, 2) high pressure, and 3) low temperature. In the US, the decision came down to a high pressure Ludwieg tube concept and a cryogenic nitrogen concept to reduce the temperature of the test gas. Beginning in 1966, the USAF pursued the design of a Ludwieg tube facility in which transonic flow is established by sudden expansion of air in a long, pressurized charge tube resulting in high Reynolds number with a useful run time of a few seconds. NASA had studied both intermittent and continuous flow facilities, and down selected to a continuous flow, cryogenic nitrogen facility known as the Transonic Research Tunnel (TRT). In 1971, the NASA/DoD Aeronautics and Astronautics Coordinating Board (AACB) approved a Ludwieg tube facility known as the High Reynolds number Tunnel (HIRT) to formally propose as the national facility, though its characteristic short run time and very high dynamic pressures prompted continued consideration of alternatives. In 1973, the AACB recommended the HIRT to meet the nations development needs, and the TRT, due to advances in cryogenic test technology, to meet the nations research needs. Due to construction cost escalations in 1974, the USAF made the decision not to go forward with the HIRT. As a result in 1975, the AACB recommended a single cryogenic facility that would be jointly operated by NASA and DoD to meet research and development needs. In 1976, Congress authorized the construction of a continuous-flow, pressurized wind tunnel using cryogenic nitrogen as the test gas; this facility became known as the NTF. In Europe, a similar decision followed shortly thereafter and led to the ETW of today (ref. 16).

Several key issues enabled the selection of the cryogenic nitrogen concept for implementation. First and foremost is the high sensitivity of the Reynolds number to reduced temperature, as seen figure 7. Additionally, the speed of sound decreases with temperature, thus enabling lower speed and power requirements to achieve transonic conditions. Note that all of these benefits are achieved with a nearly constant dynamic pressure, and thus model load/deformation. The addition of tunnel pressurization serves to extend the Reynolds number capability. Secondly, it was demonstrated that a cold nitrogen test gas is more similar to ideal ambient, isentropic flight conditions than using very high pressure air or nitrogen as the test gas (figure 8). Finally, an independent control of total pressure, total temperature, and fan speed allow the isolation of pure Reynolds effects, pure static aeroelastic (dynamic pressure) effects, and pure compressibility (Mach) effects. Figure 9 shows a constant Mach envelope from a supersonic transport test in the NTF to demonstrate an application of this capability.

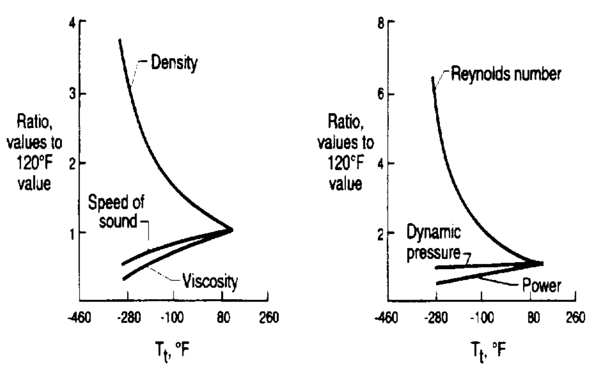

Figure 7. The key argument for cryogenic wind tunnels, shown for M = 1.0 with constant total pressure and test section size (ref. 3).

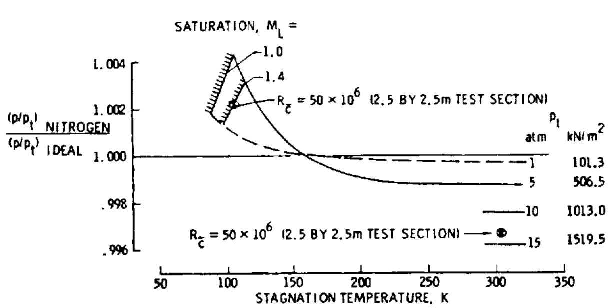

Figure 8. Real gas effect, isentropic expansion pressure ratio of nitrogen, M = 1.0 (ref. 3).

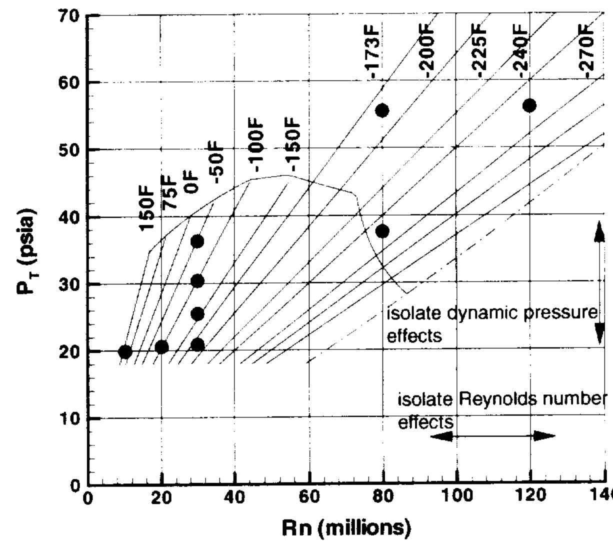

Figure 9. Unique capability of a variable pressure, cryogenic wind tunnel; M = 0.90 envelope, based on reference length of 1.8925 ft; symbols are test points from a typical test.

The National Transonic Facility

Construction of the NTF was initiated in 1979, and completed in 1982. The resulting facility (fig. 10) enables tests of aircraft configurations at conditions ranging from subsonic to low supersonic speeds at Reynolds numbers up to full-scale flight values, depending on the aircraft type and size. The facility (fig. 11) is a fan-driven, closed-circuit, continuous-flow, pressurized wind tunnel capable of operating either in dry air at warm temperatures or in nitrogen gas from warm to cryogenic temperatures. The test section is 8.2 ft by 8.2 ft in cross section and 25 ft in length. The test section floor and ceiling are slotted (6 percent open), and the sidewalls are solid. Freestream turbulence is damped by four screens and a 14.95:1 contraction ratio from the settling chamber to the test section. Fan-noise effects are minimized by an acoustic treatment both upstream and downstream of the fan. A detailed assessment of the dynamic flow quality in the NTF is reported in reference 17, and reconfirmed with more recent measurements shown in reference 18. The NTF is capable of an absolute pressure range from 15 psi to 125 psi, a temperature range from −320°F to 150°F, a Mach number range from 0.2 to 1.2, and a maximum Reynolds number of 146×10^6 per ft at Mach 1. Typical tests use a temperature range from −250°F to 120°F. The operating envelope for the NTF is shown in figure

12, as compared to the ETW, other US wind tunnels, and representative flight Reynolds numbers for several vehicles; a comparison of general characteristics with the ETW is shown in table 2. Further NTF details can be found in reference 19.

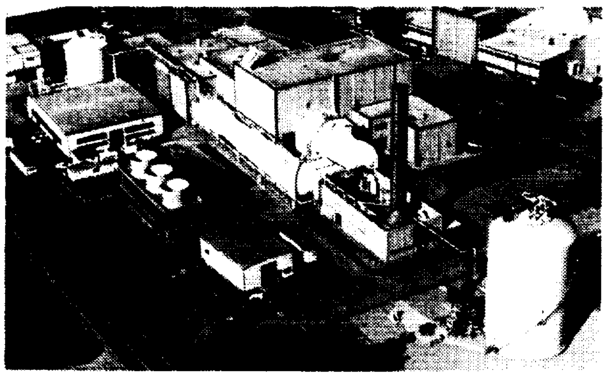

Figure 10. External view of the NTF.

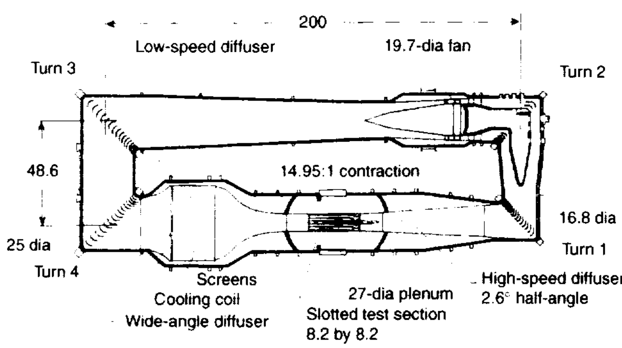

Figure 11. NTF circuit diagram (linear dimensions in ft).

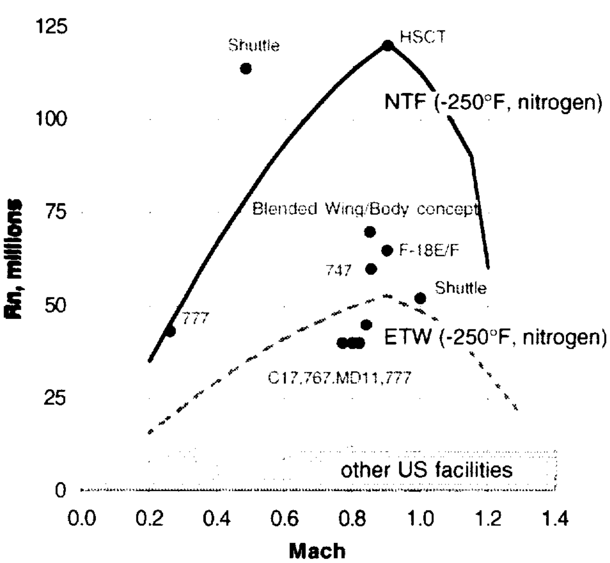

Figure 12. NTF operating envelope, wind tunnel reference length is 0.1 x square root of test section cross-sectional area.

Parameter	NTF	ETW
Test Section Dimensions (ft)	8.202 W x 8.202 H x 25.0 L minus corner fillets	7.874 W x 6.562 H x 29.528 L no corner fillets
Test Section Area (ft²)	66.774	51.667
Wall Configuration	6 slots in floor and ceiling 6% open solid sidewalls	6 slots in floor and ceiling 6.25% open solid sidewalls
Test Gas	Air or GN_2	GN_2
Maximum Power (MW)	100	50
Mach Range	0.20 to 1.20	0.15 to 1.30
Pressure Range (psi)	15 to 125	17 to 65
Temperature Range (deg F)	-320 to 150	-300 to 100
typical range	-250 to 120	-250 to 80
Contraction Ratio	14.95:1	12:1
anti-turb/flow straightening	screens & cooling coil	screens & honeycomb

Table 2. Comparison of NTF and ETW general characteristics.

Upon completion of construction, the NTF entered into a 27-month shakedown process. In December 1984, the NTF was declared operational and the research activities developed, discussed, and reviewed from 1976 to 1984 (refs. 3-5, 20) were initiated with the test of a subsonic transport configuration. Significant practical experience in the operation of the world's first large cryogenic wind tunnel was gained throughout the remainder of the 1980s. The unfortunate loss of several fan blades in 1989 had the positive benefit of wind-off time to implement many of the test and measurement technique lessons learned to date. The NTF emerged from the repairs in late 1989 a noticeably improved facility with respect to data quality at cryogenic conditions, and with a renewed emphasis on research applications and needs as opposed to facility systems engineering. Additionally, in response to research needs and further operational experience in general, a series of facility productivity enhancements were implemented in 1997 (ref. 21).

RESEARCH UTILIZATION OF THE NTF

A wide variety of research investigations have taken place in the NTF since the first test of the Pathfinder I low wing subsonic transport configuration in December 1984. Investigations have included fundamental fluid mechanic experiments, studies of advanced research configurations and components, ground-to-flight correlation studies, and several preflight risk reduction tests. Tests have been directed towards both military and commercial applications, and have included high performance fighter configurations, transport configurations, a bomber, and space access vehicles. There have been three classified tests and one non-aerospace test; one of the classified tests (B-2) has recently been acknowledged publicly, though the results remain closed (ref. 22).

Figures 13 and 14 summarize the distribution of research tests among vehicle class and research focus, respectively. A distinction not evident from the figures is that between research and facility time. Facility time, whether wind-on or wind-off, for maintenance, upgrade, repair, calibration, and the like is not included. Additionally, the percentages shown in the figures should be taken as approximate rather than precise as instances such as holidays or minor, within test maintenance/repair are attributed to the test in the tunnel at the time.

It is clear from figure 13 that most research has focused on transports. This should not be unexpected as the transports are typically much larger than the other vehicle classes, and thus must deal with the largest Reynolds number increment from conventional wind tunnel to flight conditions. It is, however, a little surprising how dominate transport research has been, given the motivation expressed during the planning of NTF for fighter and fundamental fluid mechanic research. Figure 14 shows that the majority of research has focused on relevant research configurations, where a research configuration is defined as one without a full-scale counterpart. These configurations have been tested to assess advanced aerodynamic concepts and technologies at flight Reynolds number, serve as CFD-based design tool verification, or simply to study scaling in the controlled environment of a wind tunnel for relevant, complex geometry. A significant portion of time has also been directed towards flight vehicle research, which has as its motivation either ground-to-flight correlation/scaling or preflight risk reduction. Again, it is clear that studies focused specifically at fundamental fluid mechanics have been lacking. This is due in large part to a lack of instrumentation to measure parameters typically sought by the fundamental fluids researcher in the high pressure, cryogenic temperature environment of the NTF.

The following sections will review the types of tests that have occurred in the NTF relative to fundamental fluid mechanics, transport/bomber vehicles, high performance military vehicles, access to space vehicles, and a non-aerospace configuraton.

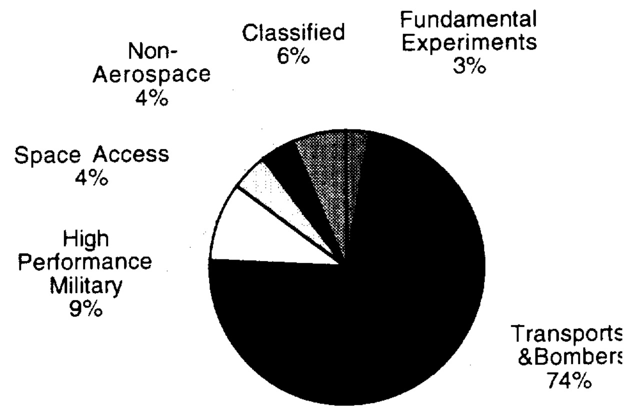

Figure 13. Research utilization of the NTF by vehicle class since 1985.

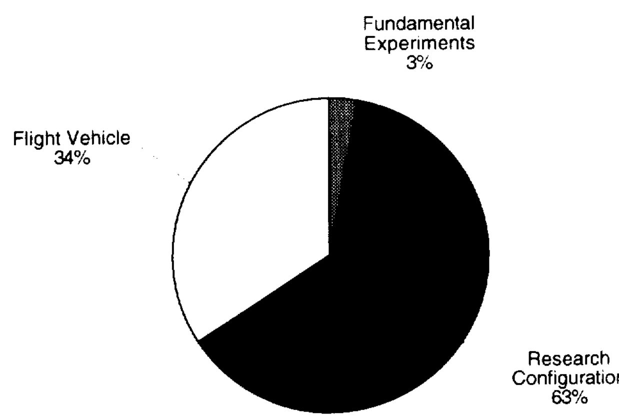

Figure 14. Research utilization of the NTF by investigation focus since 1985.

Fundamental Experiments

Several fundamental fluid mechanic experiments originally planned for the NTF are described in reference 20, including studies of flat-plate turbulent skin friction, leading-edge separation induced vortical flows, and separated flows at high angles of attack. Studies in these three areas have been executed, though in some cases not as originally envisioned. Although it was anticipated that additional fundamental experiments would be identified and implemented, these three experiments have been the only ones executed to date, and represent 3% of the research testing. It should be noted that some facility-related testing, such as measurement of tunnel flow quality and its affect could be considered as fundamental research, but is not included in this discussion.

Skin friction model. The study of zero pressure gradient turbulent skin friction was executed in 1996. Though originally intended to be implemented using a large, two-dimensional flat plate model, the investigation used the axisymmetric model shown in figure 15 due to expected problems with mounting and surface accuracy for the former in the high pressure, cold environment of the NTF. The three methods of determining the skin friction were: 1) Preston tubes, 2) velocity profiles from which skin friction was inferred with the Clauser method, and 3) direct measurement with a skin friction balance. Compressible and incompressible data was acquired for incompressible Reynolds numbers based on momentum thickness up to 619,800 using the van Driest transformation, and compared to a variety of existing theories. Results and detailed discussion of this experiment are provided in reference 23.

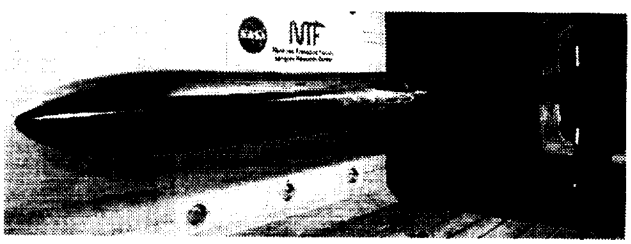

Figure 15. High Reynolds number skin friction model.

65 deg delta wing model. The study of leading-edge separation induced vortical flows was executed in 1991. This study was implemented very nearly as planned in the early 1980s employing a 65 deg delta wing model with interchangeable leading edges of various bluntness. The four leading edges included streamwise leading-edge radii, as normalized by the mean aerodynamic chord, of 0, 0.0005, 0.0015, and 0.0030. Force and surface pressure data were acquired for Mach numbers from 0.40 to 0.90, Reynolds numbers from 6 to 120 million based on the mean aerodynamic chord, and angles of attack from –2 to 28 deg. The specific purpose of the study was to isolate the effects of leading-edge radius, Mach number, and Reynolds number on leading-edge separation onset and progression. The model is shown in figure 16, and detailed data is reported in references 24-27. The results provide an excellent database for CFD verification, though relatively little detailed analysis of this data set has occurred to date. A typical result showing the impact of Reynolds number on leading-edge suction is given in figure 17 (ref. 28).

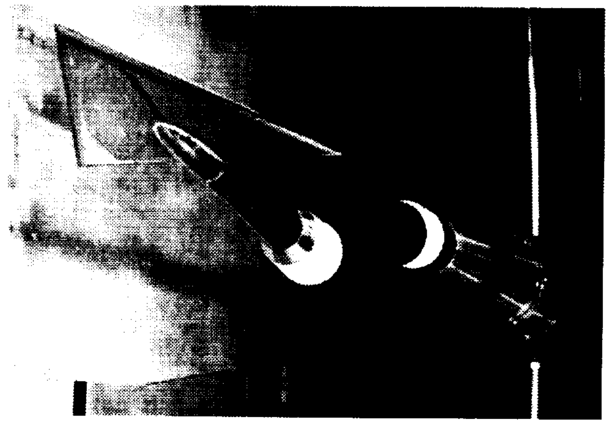

Figure 16. 65-deg delta wing model with interchangeable leading-edges.

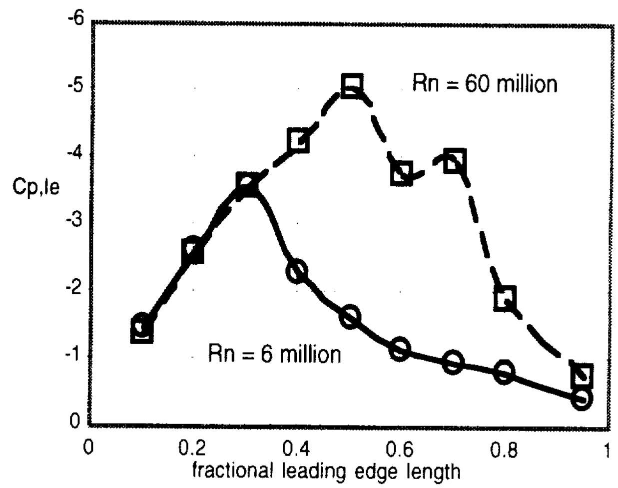

Figure 17. Reynolds number effect on leading-edge suction, 65-deg delta wing with medium leading edge radius at M = 0.40, α = 13 deg (ref. 28).

Forebody models. A study of separated flows at high angles of attack was originally envisioned to use an ogive-cylinder model (ref. 20) similar to a model tested in the NASA Ames Research Center 12-foot tunnel at Mach 0.3 and a Reynolds number of 4 million. The NTF test was to extend the data set to Mach 1.15 and a Reynolds number of 23 million. To date, this model has not been tested in the NTF. However, a similar study was conducted in 1990 on a series of conventional and advanced, faceted forebody shapes as shown in figure 18. These forebodies were tested at Mach 0.2 from Reynolds numbers based on diameter of 0.43 to 3.6 million at angles of attack from 0 to 27 deg. At selected pitch angles, data was collected for sideslip angles from –12 to 14 deg. The data set includes force, moment, and surface pressure data. The models were constructed for and previously tested in conventional facilities; as a result the models were not certified for cryogenic conditions and the test was limited to warm air. Results and discussion from the NTF test are found in reference 29. Though Reynolds number effects were observed on all shapes, the effects were largest on the conventional, smooth-sided bodies.

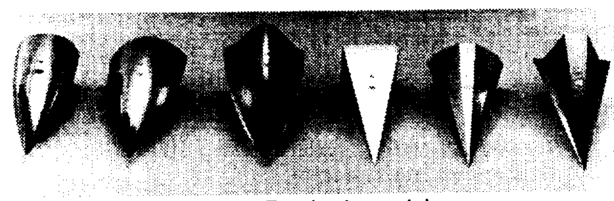

Figure 18. Forebody models.

Transport Aerodynamics

As noted previously, transport configurations have been utilized in the majority of the research tests in the NTF. Configurations falling in this category include subsonic commercial and military transports, supersonic transports, bombers, and business jets, though testing of the latter two has been very limited. As indicated in figure 19, subsonic transport configuration tests have been most prevalent, followed by supersonic transports. This should not be unexpected for several reasons. First, the larger vehicles suffer from a larger Reynolds number gap from conventional wind tunnels to flight. Second, more transports, particularly commercial transports, are developed either from scratch or through major derivative efforts than is the case for bombers, and prototype demonstrations are prohibitive due to cost, time, and risk. Finally, the 1990s saw two major NASA aeronautics programs implemented that focused on Advanced Subsonic Technology (AST – subsonic transports) and High Speed Research (HSR – supersonic transports).

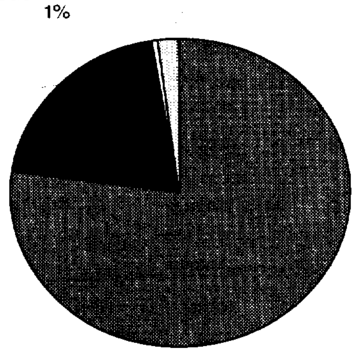

Figure 19. Distribution of transport configuration research utilization since 1985.

The one business jet test (1995) was limited to warm air conditions due to the use of an existing conventional model not certified for cryogenic conditions and focused on design tool verification. As mentioned previously, the one bomber test was of the B-2. This test was executed in 1986, was limited to warm air conditions due to the use of an existing conventional model (fig. 20) not certified for cryogenic conditions, though total pressure up to 115 psi was used. The test focused on Reynolds number effects for extremely high angle of attack aerodynamics, and served to update preflight stall characteristics, control effectiveness, and envelope limits associated with pitch-up. Test conditions included Mach numbers from 0.1 to 0.85, and Reynolds numbers from 2 to 15 million based on the mean aerodynamic chord. The majority of this data remains classified.

Figure 20. B-2 model on the high angle-of-attack sting.

Subsonic Transport Overview. Subsonic transport configurations have been utilized in approximately 57% of all the research investigations in the NTF since 1985. The configurations have included low and high wing configurations, commercial and military configurations, and advanced technology research and flight configurations. The investigations have had many different objectives, and have been executed as primarily NASA projects, NASA sponsored contract projects, and jointly executed cooperative projects between NASA and industry. Original thrusts for transport aerodynamics (ref. 20) research included high- and low-speed configuration aerodynamics, lateral/longitudinal control aerodynamics, propulsion-airframe integration, and verification of continually evolving CFD.

Considerable effort has been directed towards preflight prediction problem areas experienced by industry such as drag rise, interference effects, control surface effectiveness, and buffet onset/post-buffet pitch characteristics; figures 2-5 provide historical examples for some of these issues. Additionally, a semi-span test capability has been developed enabling flight Reynolds number investigations of complex high-lift system scaling issues (ref. 30). In general, drag rise characteristics have tended towards more favorable in flight, providing a delay in drag divergence resulting in a higher cruise speed, though the often associated change in load characteristics can present difficulties. This situation has been most prevalent when the wing uses aft-loaded airfoils, or when the boundary-layer tripping strategy used at low Reynolds numbers is not optimal. Interference effects, such as in nacelle-pylon-wing region, have generally been more adverse in flight when missed, and often result in expensive drag reduction or clean-up efforts to improve performance. Prediction of control surface effects has been mixed, sometimes providing higher than expected performance in flight, other times less. Data from the NTF on a variety of transport configurations generally follow these trends, thus implying a preflight high Reynolds number test in the NTF can prevent surprises upon flight test, particularly when pushing aerodynamic technology limits.

In addition to investigating the predictability of aerodynamic performance in the traditional problem areas, efforts have also been directed towards specific advanced aerodynamic concepts and design approach. The high Reynolds number aerodynamics and scale issues associated with concepts such as blunt or divergent trailing edges, aggressive airfoil shapes designed at high Reynolds number, and advanced nontraditional configurations such as a blended wing body configuration have been investigated. A natural outcome of the design studies has been the assessment and verification of the design methods at flight conditions, and an understanding of the consequences of designing and validating a flight vehicle at low Reynolds number conditions. An early advanced wing (McDonnell Douglas wing W44) was designed at low Reynolds number incorporating a divergent trailing edge and an aggressive design strategy that included an aft shock position and a steep pressure recovery gradient approaching the trailing edge. High Reynolds number results provided some surprises including a tendency for a double shock at cruise conditions and different shock/boundary layer separation and reattachment characteristics at higher angles of attack. Additionally, this design proved to have noticeably higher than expected nacelle-pylon-wing interference drag at flight Reynolds numbers, and displayed an adverse aileron (trailing-edge down) effectiveness trend as well. Finally, as with most other subsonic transport configurations tested in the NTF, the importance of isolating the generally similar sized but opposite direction effects of static aeroelasticity from Reynolds number effects was highlighted during the tests.

With all the progress that has been made, there has been one glaring disappointment to date with regards to subsonic transport testing. Testing near and beyond buffet onset for the transport configurations has generally been limited by a combination of facility and model dynamics. The specifics of the limitations (maximum angle of attack, lift, severity, dynamic modes, etc.) have been model dependent, but it is difficult to recall a subsonic transport model achieving the desired complete angle of attack range at transonic Mach numbers and flight Reynolds numbers. Understanding and elimination of this problem has received a constant but relatively low level of effort since the NTF became operational until a dedicated focused effort in recent years. The challenges in overcoming model vibrations on stings at high angles of attack are discussed in reference 31. The latest progress at the NTF is reported in reference 32. It is interesting to note that the ETW has had similar experiences, and has been addressing the problem as noted in references 33 and 34.

Subsonic Transport Research Configurations. As defined earlier, a research configuration is defined as one without a full-scale counterpart. The initial research configuration for the NTF is known as the Pathfinder I (ref. 20). The Pathfinder I model was designed during NTF's pre-operational period and incorporated a high aspect ratio, supercritical wing. In addition to serving as an aerodynamic research testbed, this model was also used for development of initial cryogenic model design and fabrication techniques. Additionally, the Pathfinder I has served as the NTF's formal check standard model for data quality assurance since 1997 (ref. 35). Several NASA baseline wings have been constructed: 1) a solid wing for force measurement, 2) a pressure wing for surface pressure measurement and load characterization, and 3) two controls wings with adjustable spoilers and ailerons. Additionally, the fuselage has been used with multiple industry-defined wings tested under both cooperative agreements and the NASA AST program. Figure 21 shows the Pathfinder I fuselage with the McDonnell Douglas advanced wing known as W44 without the pylon/nacelles installed. The W44, and its follow-on high Reynolds number multi-point design known as W50 from the NASA AST program, were tested at chord Reynolds numbers up to 30 million at transonic conditions. Reference 36 documents limited results for the W44 configuration. Reference 37 provides additional documentation of the aileron effectiveness study with W44, and focuses on the limitations of computational prediction of the experimental results. Results from a test of the Pathfinder I with the baseline NASA wing are given in reference 38, and results on aileron and spoiler effectiveness from the Pathfinder I controls wing are discussed in reference 39. Finally, though results have not been published, the Pathfinder I fuselage was also tested briefly in 1987 with a Lockheed-defined high wing design (fig. 22).

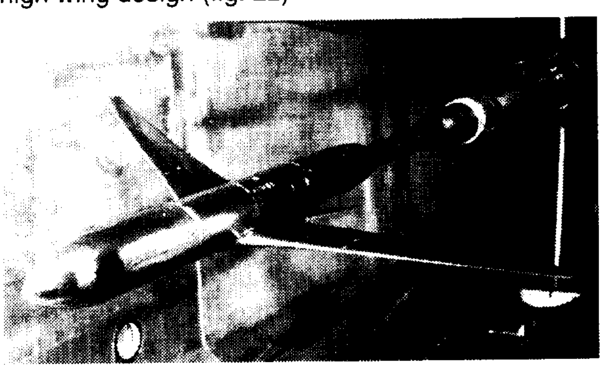

Figure 21. Pathfinder I fuselage with McDonnell Douglas wing W44, shown without pylon/nacelle.

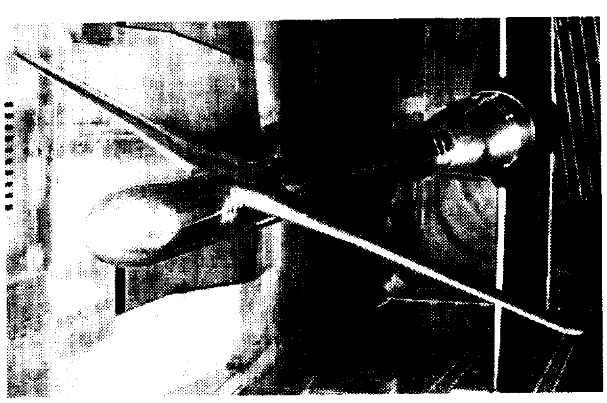

Figure 22. Pathfinder I fuselage with Lockheed high wing.

While McDonnell Douglas (now Boeing-Long Beach) has used the Pathfinder I fuselage to mount its advanced wing designs, Boeing (Seattle) studies have used the fuselage from its 767 cryogenic model. Unlike the Pathfinder I fuselage which mounts on a straight sting, the 767 fuselage is typically mounted with an upper swept strut as shown in figure 23. Here, the non-metric strut provides a flow field similar to that of a vertical tail (the strut is larger than a scaled vertical tail) and allows modeling of the aftbody boat tail. During the NASA AST program, this arrangement was used to verify high Reynolds number CFD design tools using a four-engine configuration (fig. 23). Two wing designs, known as AST models 2/5 and 4/5, were tested over a Reynolds number range of 3 to 36 million, based on the mean aerodynamic chord, at transonic conditions. The first provided a baseline multi-point design with the second design demonstrating aerodynamic and design capability enhancement. It is important to note that the high Reynolds number design capability verified during the NASA AST program were for wings in the presence of the twin- and quad-engine installations. Some results from the four-engine configuration studies are given in reference 40.

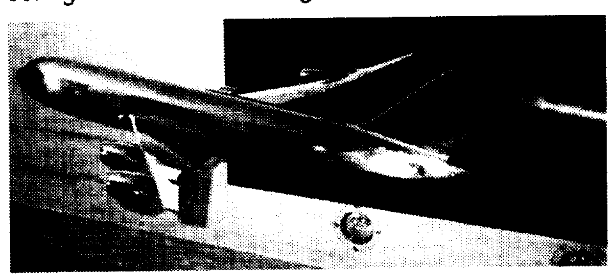

Figure 23. Four-engine, subsonic transport configuration on an upper swept strut mount.

The most unconventional transport tested in the NTF has been the blended-wing-body configuration shown in figure 24; this model did not include a nacelle installation. This configuration was tested at transonic conditions and Reynolds numbers approaching flight, though the expected full-scale size of this conceptual design is large enough that flight values were not achieved. This configuration was designed at a high Reynolds number, and served to verify CFD design capability for an unconventional configuration towards the end of the AST program. During the relatively short, focused test of this configuration, the model angle of attack was limited due to adverse model/facility dynamics, similar to that observed with the conventional transports. A model design and testing challenge associated with this configuration, applicable to conventional wind tunnels as well, is the model support and accompanying interference which, in this case, required localized geometric distortion in the aft region of the model to incorporate the sting mount. The challenge becomes even greater when model includes nacelles and/or control surfaces in the mid-aft body.

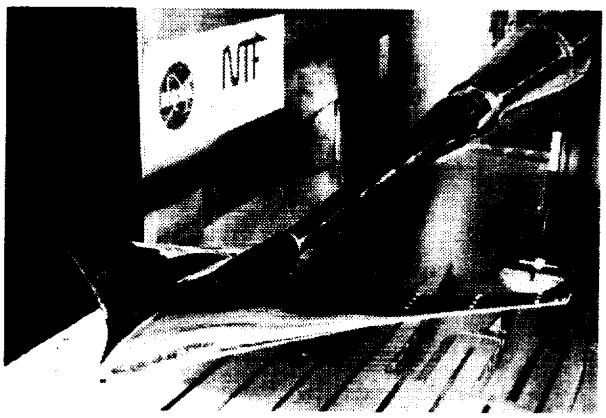

Figure 24. Blended-Wing-Body model.

Subsonic Transport Flight Vehicle Configurations. There have been five subsonic transport models tested that have a counterpart flight vehicle and enable comparison of ground results with flight. These models include full-span high-speed models of a Boeing 767, a Boeing 777, an MD-11 wing, and a High Wing Military Transport configuration, plus a low-speed semi-span model of the Boeing 777. In a similar manner to the Pathfinder I, the 767 model was intended to serve as a benchmark or facility assessment model.

The Boeing 767 model has been tested extensively to study many aspects of ground to flight correlation. The model has been tested in many different configurations and represents the most complete assessment of NTF to flight correlation to date. Typical testing has spanned a Reynolds number range from 4.45 to 40 million, where 40 million is the flight condition. The baseline configuration and model support is shown in figure 25. One of the required configurations used in a support tare and interference investigation is shown in figure 26, where the model is mounted on a lower strut and a dummy upper swept strut is included. Additional tests with only the lower strut, with and without a vertical tail, enable experimental assessment of interference effects, which can then be removed from the data enabling a better correlation with flight. Figure 27 shows an additional test arrangement, the fuselage alone case, which was used to assess solid blockage induced buoyancy effects, and to study turbulent skin friction drag scaling prior to the design and testing of the axisymmetric skin friction model discussed previously.

Limited results have been published relative to the 767 investigations. Reference 41 documents a data repeatability study in the NTF using the 767, and reference 42 provides aerodynamic results, prior to the tare and interference tests. Figure 28 reproduces the excellent comparison of pitching-moment increments due to wing vortex generators from measured data in the NTF at the full-scale Reynolds number with data measured in flight. The fact that small (0.023 inch high at model scale), geometrically scaled and positioned vortex generators produced the same result as in flight is compelling evidence that the full-scale flow physics is adequately simulated in the NTF. In addition, studies of vortex generator size and distribution can be confidently studied prior to flight at flight conditions, rather than relying exclusively on low Reynolds number studies. Reference 42 also shows that the presence of the vortex generators generally delayed the onset limiting model/facility dynamics. Though the angle of attack was limited, unpublished results have shown an excellent ground to flight correlation of the buffet boundary for the 767.

The McDonnell Douglas (Boeing-Long Beach) High Wing Military Transport model has also been extensively tested in the NTF (fig. 29). Investigations have focused on scaling issues and the verification of drag reduction concepts for potential derivatives. Good correlation between NTF at flight conditions (Rn = 40 million) and flight have been observed for aileron effectiveness, winglet installation, wing load characteristics, and nacelle-pylon-wing interference. This model, like others, was limited at high angles of attack due to adverse model/facility dynamics, which leaves scaling questions open in this regime. The High Wing Military Transport model is one of two models that has been tested in both the NTF and the ETW. In general, results between the two facilities agreed well and, interestingly, dynamics limited the pitch range to nearly the same angle in each facility.

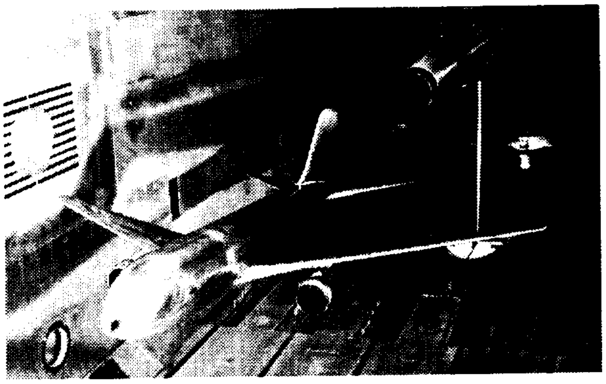

Figure 25. Boeing 767 model on upper swept strut.

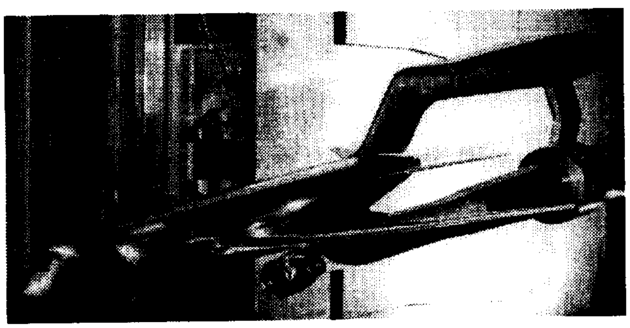

Figure 26. Boeing 767 support tare & interference investigation.

Figure 27. Boeing 767 fuselage alone.

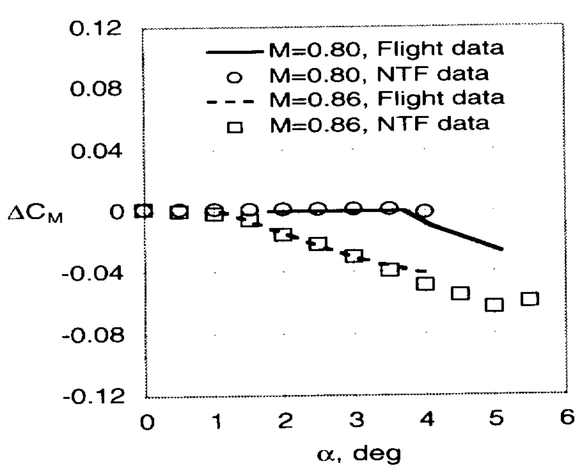

Figure 28. Comparison of flight and NTF vortex-generator (VG) effects on pitching moment at the flight Reynolds number, Δ = VG on – VG off (ref. 42).

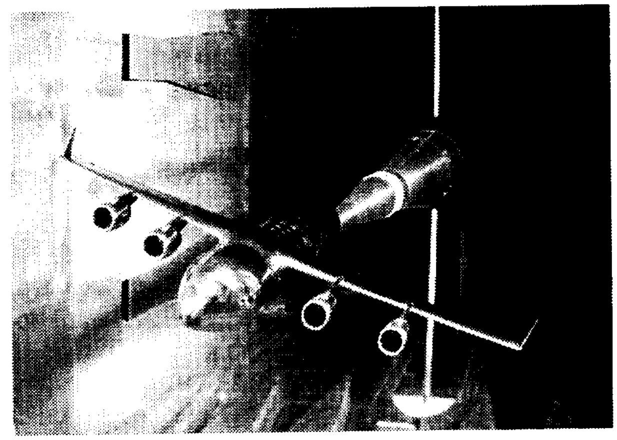

Figure 29. McDonnell Douglas (Boeing-Long Beach) High Wing Military Transport model.

In order to further assess, or at least attempt to assess, correlation with flight at higher angles of attack, an MD-11 wing complete with nacelle/pylon, winglet, and flap support fairings was built and mounted to the Pathfinder I fuselage (fig. 30). This relatively short test in 1997 included transonic conditions at flight Reynolds numbers. Unfortunately, this configuration was also limited by model/facility dynamics at the higher angles of attack, and did little to advance the understanding of scaling issues in this regime. Relatively little effort was focused on cruise-related correlation with flight with this model. Reference 43 provides some discussion of the test and results. It is anticipated that this model will be tested again upon elimination of the limiting dynamics.

Figure 30. MD-11 wing on the Pathfinder I fuselage.

The two newest transport models for the NTF are full-span high-speed and semi-span high-lift representations of the Boeing 777. The high-speed model is shown in figure 31 on an upper swept strut support. A series of investigations on this model similar to those on the older technology 767 model are anticipated. The semi-span model is shown in figure 32 mounted on the NTF sidewall. As mentioned previously, development of the semi-span capability in the NTF is reported in reference 30; aerodynamic analysis from the initial test of the 777 semi-span model are given in reference 44. As noted in reference 44, portions of the data were contaminated by the presence of frost on the model. As a result, many conclusions must wait until an anticipated re-test of the model, though some conclusions were made. Among the conclusions presented were that Reynolds number trends can be distorted if not decoupled from static aeroelastic effects. Additionally, the optimum outboard flap position for landing did not change with Reynolds number between conventional (pressure) wind tunnel and flight levels, though the relative performance benefit over the baseline did increase.

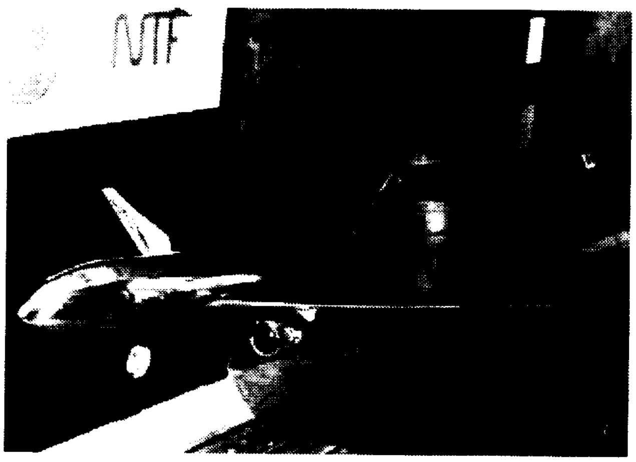

Figure 31. Boeing 777 high-speed model.

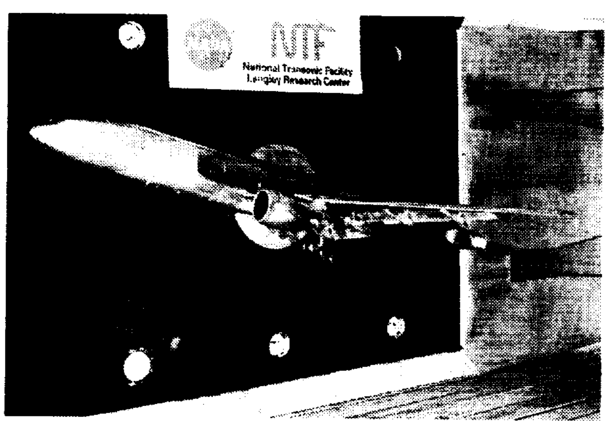

Figure 32. Boeing 777 high-lift semi-span model.

Supersonic Transports. Supersonic transport configurations have been utilized in approximately 15% of all the research investigations in the NTF since 1985. This is considerably less than the time devoted to subsonic transports, but more than any other vehicle class. The vast majority of this testing occurring during NASA's HSR program, phase II, beginning in 1993, and all tests were of research configurations without a flight vehicle counterpart.

Prior to the HSR program, a cooperative program with Boeing led to an investigation of a supersonic arrow-wing design that had its origins in the late 1970s as part of NASA's Advanced Supersonic Technology and Supersonic Cruise Research programs. The configuration, known as the AST-210 (fig. 33), represented a Mach 2.7 cruise design and had a small leading-edge radius. The model was one of the first constructed for the NTF, with construction completed in 1980. Prior to the eventual NTF tests in 1990 and 1991, additional inboard leading edges were constructed with a larger radius and parts to enable both deflected and undeflected flap configurations. The test focused on performance benefits associated with a blunter leading-edge radius, and on leading-edge separation at low speed (Mach 0.30) conditions representative of take-off and landing. At Mach 0.30, the maximum chord Reynolds number attained was 115 million, or approximately 60% of the flight condition. Results from this investigation are discussed in reference 45.

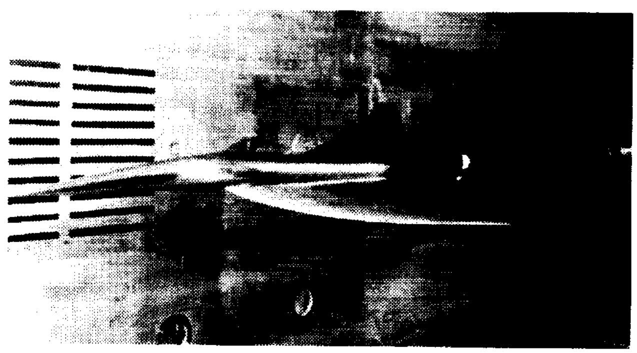

Figure 33. AST-210 supersonic transport model..

Beginning in 1993, a series of tests with the HSR baseline configuration known as Reference H began in the NTF. The configuration represents a Mach 2.4 cruise design capable of carrying 300 passengers over 5000 nautical miles. Several models of this configuration were built and tested in multiple facilities across the speed envelope. The purpose of the NTF model was to address Reynolds number scale effects and high Reynolds number aerodynamics at both low-speed high lift and transonic conditions. Low speed data was acquired at Mach 0.30, Reynolds numbers up to 90 million, and angles of attack up to approximately 24 deg. Transonic data was acquired up to Mach 1.1, with a focus in the cruise regime of Mach 0.90 to 0.95, and a maximum Reynolds number of 120 million with angles of attack up to approximately 12 deg. The model had flap settings representative of supersonic cruise (baseline, undeflected), transonic cruise, take-off, landing, and stall recovery, and incorporated variable horizontal stabilizer and rudder settings. Though not part of the original configuration, limited data with a canard was acquired to support configuration tests executed in conventional facilities. Additionally, the model was modified late in the HSR program to study leading-edge radius effects on the planform of a follow-on configuration. The configuration without the empennage is shown mounted on a straight sting in figure 34; the configuration with the empennage is shown in figure 35. Force, moment, and surface pressure data on the wing and forebody was acquired for various configurations; off-body pressures were measured with rakes for a limited number of configurations. In addition to an extensive study of longitudinal characteristics, the lateral/directional data set acquired remains the largest of any configuration tested in the NTF.

One interesting result from reference 46 is reproduced in figure 36 showing the senstivity of yawing moment to Reynolds number for the full Reference H configuration with a canard and 30 deg rudder deflection at low speed. Note the nonlinear behavior at sideslip angles near 2 deg at the lowest Reynolds numbers. This effect is attributed to hingeline separation on the rudder, and gradually goes away with increasing Reynolds number. Additional results from these tests are found in references 46-55. General observations include an increased sensitivity to Reynolds numbers above design conditions where separated flow dominates and pitch characteristics are more sensitive to Reynolds number changes than is lift. Drag characteristics appear scaleable with current theoretical methods near design points, and it is important to isolate static aeroelastic effects from Reynolds number effects to avoid misinterpretation of results, even for this low aspect ratio configuration.

Figure 34. HSR Reference H model in the wing/body/nacelle configuration on a straight sting.

Figure 35. HSR Reference H model, full configuration with empennage on a lower swept blade support.

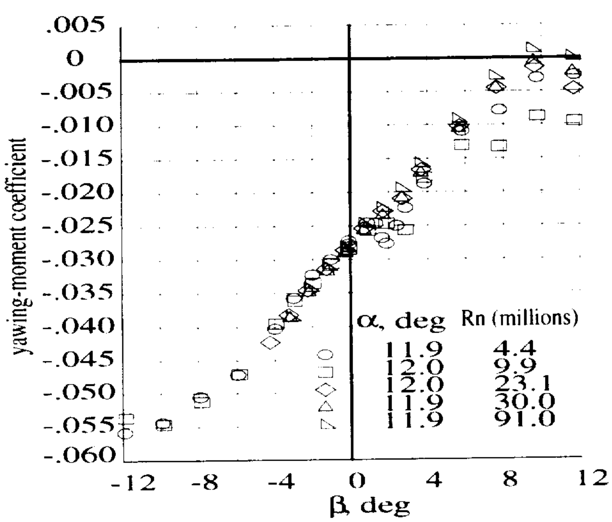

Figure 36. Effect of Reynolds number on the yawing-moment coefficient, HSR Reference H full configuration with canard and 30 deg rudder deflection, M = 0.30 (ref. 46).

High Performance Military Aircraft Aerodynamics

There have been seven high performance military models tested representing 9% of the research utilization time in the NTF since 1985. This figure does not include the high-wing transport tests, the B-2 bomber test, or the other two as yet undisclosed classified tests.

Additionally, this figure does not include the two fundamental experiments with direct military application previously discussed, namely the 65 deg delta wing and forebody investigations. Regardless, there has been less utilization of this national facility in support of the military than was envisioned in the 1970s and early 1980s; recall that as originally approved by the AACB in 1975, this single national facility was to be jointly operated by NASA and the DoD. Reference 20 provides a view of the research plans for high performance military aircraft aerodynamics just prior to NTF operational status. Reference 28 provides a summary of the high performance military aircraft utilization of the NTF to date, including an overview of the tests and some results. Additionally, reference 28 addresses the changing political environment over the years since 1985 and its resulting impact on the research utilization of the NTF. A brief discussion of the high performance military aircraft tests follows; the reader is encouraged to review reference 28 for further discussion.

Among the seven models are three research configurations and four configurations with full-scale aircraft counterparts. Investigations with these models have addressed cruise, maneuver, and low-speed high-lift aerodynamics. The first two tests occurred in 1985 and used existing, non-cryogenic models of an EA-6B and an F-14. The EA-6B test was executed to verify high Reynolds number computational wing design improvements on high-lift performance with different wing/flap/slat modifications. The F-14 test was executed to obtain flight certification data for natural laminar flow glove effects in support of the Variable Sweep Transition Flight Experiment.

The next series of tests did not occur until the 1992-95 timeframe, just prior to and in the early stages of NASA's AST and HSR programs. The high performance military aircraft tests in this timeframe included two research configurations in the Pathfinder II series of models, brief tests of the Grumman X-29 and the Dornier Alpha Jet flight vehicle configurations; all four models were designed for and tested in cryogenic conditions at high Reynolds numbers.

Similar to the Pathfinder I configurations for subsonic transports, a Pathfinder II series of relevant, yet generic fighter configurations were defined collaboratively with industry during the 1980s. The configurations associated with General Dynamics and McDonnell Douglas were tested, and are shown in figures 37 and 38, respectively. The General Dynamics configuration included a conventional forebody, an advanced moderately swept wing, and the capability for parametric variation of leading- and trailing-edge devices; test conditions included Mach numbers from 0.4 to 0.95, angles of attack up to 33 deg, and a maximum Reynolds number of 66 million. The McDonnell Douglas configuration included a conventional forebody, an advanced wing, and a variety of empennage components enabling investigation of singe- and twin-tail configurations. Test conditions included Mach numbers of 0.6, 0.8, and 0.9 at angles of attack up to 18 deg with chord Reynolds numbers up to 61 million. Additionally, the McDonnell Douglas Pathfinder II configuration was tested at sideslip angles up to 10 deg. Aside from the HSR Reference H configuration, this configuration has the most extensive lateral/directional database at high Reynolds numbers.

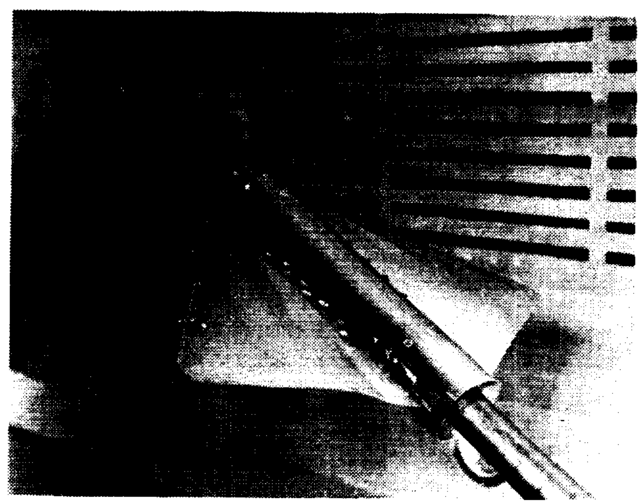

Figure 37. Pathfinder II – General Dynamics configuration.

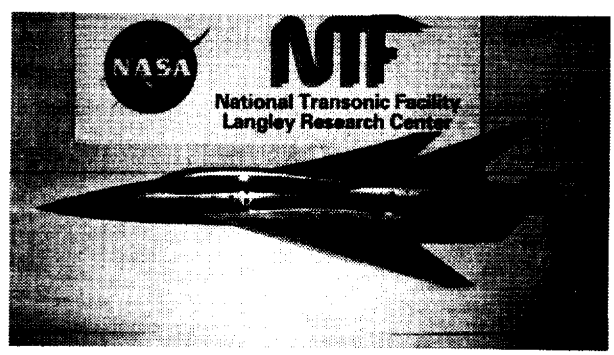

Figure 38. Pathfinder II – McDonnell Douglas configuration.

The X-29 model, a small part of the overall X-29 flight test demonstration program, was intended to provide an extensive database for detailed ground-to-flight correlation studies focused on Reynolds number effects. Unfortunately, very limited test time was allocated to the X-29, primarily due to changes in priority within NASA. The single, relatively brief test of the model focused on forebody pressure measurements at angles of attack from 30 to 66 deg at low-speed (Mach 0.22 – 0.25) conditions and Reynolds numbers up to flight values. The X-29 model mounted on the high angle-of-attack sting is shown in figure 39. Significant Reynolds number effects were observed; limited presentation and discussion of the results are included in reference 56.

Figure 39. X-29 model on the high angle-of-attack sting.

The Alpha Jet model (fig. 40) was tested in the NTF as part of a collaborative effort between the USAF and the German Ministry of Education and Science, Research, and Technology to study wind-tunnel-to-flight correlation beginning in 1986. Additionally, tunnel-to-tunnel correlation was examined as the model was tested in several US and German wind tunnels; the Alpha Jet model was the first of two models that has been tested in both the NTF and ETW to date. The primary objectives of the NTF test were to obtain baseline data for the tunnel-to-tunnel comparison, to determine trends from conventional wind tunnel to flight Reynolds numbers, and to obtain data at precise conditions matching existing flight test data. Similar to the X-29 experience, allocated test time decreased as NASA priorities shifted; the relatively short test in 1993 provided useful data, but left several issues open pending further tests. Reference 57 includes limited results from the NTF test.

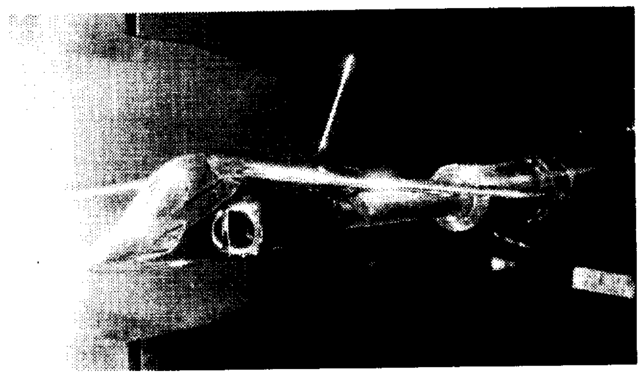

Figure 40. Alpha Jet model.

The most recent high performance military test in the NTF occurred in 1999, after the end of the AST and HSR programs. The NTF test of the Diamond-Wing semi-span model (fig. 41) was conducted under the auspices of the Technical Cooperation Program, a multi-national research collaboration, and included NASA, the US Navy, the USAF, and the United Kingdom Defense Evaluation and Research Agency. The primary objectives were an understanding of Reynolds number effects for slotted high-lift system flow physics and geometric rigging for an advanced, low-observable constrained wing planform suitable for carrier operations. Although the model was not qualified for cryogenic operations, low speed high Reynolds number conditions representative of flight were easily achieved using high-pressure air and the recently developed semi-span capability in the NTF (ref. 30). A large data set consisting of many high-lift system parametric variations was generated during this relatively long test; additionally, data was acquired with slotted and solid wall test sections enabling improved wall correction methods at low speeds in the NTF (ref. 18). Initial discussion of aerodynamic results is found in references 58 and 59. It is interesting to note that of the relatively small 9% research utilization of the NTF for high performance military configurations as a whole, almost 40% of this subtotal occurred during this single test of the Diamond-Wing configuration.

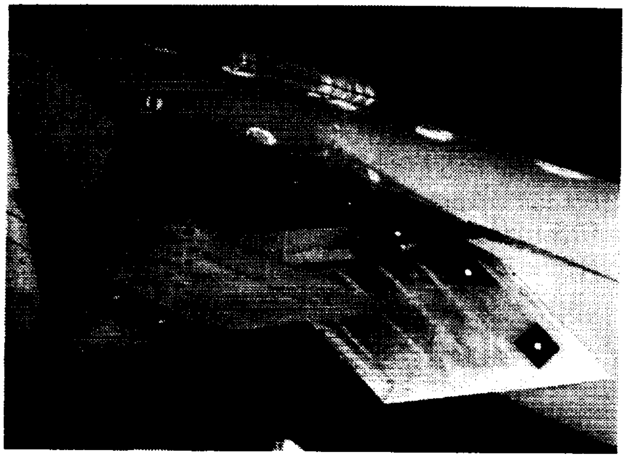

Figure 41. Diamond-Wing semi-span model.

Space Access

Space access or hypersonic configurations have been tested very little in the NTF, using approximately 4% of the research utilization time since 1985. Early tests were directed towards scale effects for the Space Shuttle system, and were followed by transonic, high Reynolds number tests in 1988 and 1991 of models in support of the National Aero-Space Plane program.

Early in 1985, the first of two Space Shuttle models was tested, followed immediately by a second, as scale issues identified during early flights of the Shuttle were eagerly addressed. The first model was a 1%-scale representation of the ascent configuration, shown in figure 42, and was intended to address scale effects on transonic load characteristics. Mach number was varied from 0.8 to 1.2. The second model was a 2%-scale representation of the Orbiter alone, and was intended to investigate stability and control issues during descent. Test Mach numbers ranged from 0.4 to 0.98. Both tests achieved near flight Reynolds number conditions. Unfortunately, the tests did not produce the enduring data set sought, due primarily to testing difficulties including data quality associated with the very early, initial operations of the new facility. It is still hoped that funding will be identified to re-test these configurations and establish a detailed database for ground-to-flight correlation relevant to this vehicle class. The complex flow fields resulting from the multi-body interactions, many geometric junctures, and rounded surfaces make this vehicle class very interesting from a Reynolds number scaling perspective. Recent X-vehicle programs have identified Reynolds number effects as an issue to address, particularly from a preflight risk reduction perspective, but higher priority tests and limited budgets have eliminated proposed tests from program plans thus far.

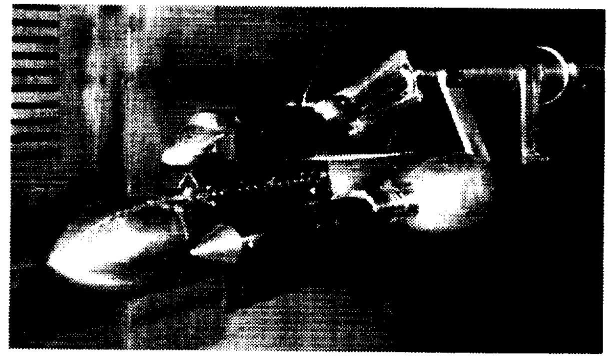

Figure 42. Space Shuttle ascent configuration.

Non-Aerospace

In addition to aerospace vehicles, large submersibles are another class of vehicles that can benefit from high Reynolds number testing. As shown in figure 13, 4% of the NTF's research utilization time has been directed towards this non-aerospace vehicle class. Specifically, a single test of a relevant submarine geometry was tested during 1986. This low-speed test used both warm air and nitrogen at cryogenic temperatures to attain the highest Reynolds number data possible short of a full-scale configuration in water. The test configuration is shown in figure 42; the model was mounted inverted in the test section to allow sufficient support, and the test section slots were covered. The primary focus of the test was the assessment of Reynolds numbers effects in the wake of the vehicle.

Test Techniques & Measurement Challenges

To close, though not the purpose of this paper, it should be acknowledged that all the research applications to date have relied on the development of test techniques, measurement techniques, and operational procedures suitable for high pressure, cryogenic conditions. Over the years, these topics have been discussed far more openly than the research utilization and results from the NTF. However, a few thoughts are offered here.

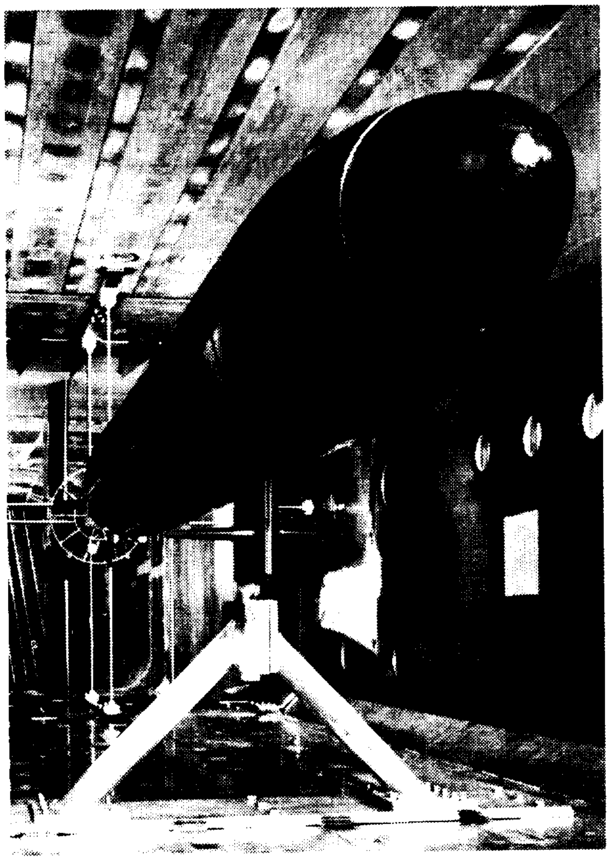

Figure 42. Submarine model with wake rake.

Challenges start with the hardware, both facility and model related, which must withstand high loads while maintaining sufficient fracture properties at cryogenic conditions. The challenge of model design in particular has continually increased as wings have become thinner while the requirement for surface pressure measurements is almost always "as much as I can get and maintain sufficient safety factors." Reference 60 provides a recent perspective on issues related to cryogenic model materials. Next are the measurement and resulting instrumentation requirements. Onboard electronically scanned pressure transducers and accelerometers are typically placed in heated enclosures, thus filling more space within the model than in a non-cryogenic facility; fortunately, the reality of a cryogenic capable pressure transducer is approaching. Force and moment measurements are made with unheated strain-gauge balances that require special attention to temperature compensation, and must be accurate over a large load range to cover typical test conditions from low to high Reynolds numbers within a given test. Reference 61 provides a recent perspective on the cryogenic balance technology used at the NTF. Beyond the standard measurements, off-body flow field diagnostics remain a key challenge. One would like to have available the off-body measurement capability available at some conventional tunnels to study high Reynolds number flows in the NTF. Much work remains in this area. From a qualitative perspective, implementation of a focusing Schlieren system in the NTF is anticipated in the near term. The development of a video model deformation measurement system (ref. 62, 63) was primarily driven by the research requirements of typical NTF tests, specifically to aid in understanding the separate effects of static aeroelasticity and Reynolds number for conditions covering a wide range of dynamic pressure. This system is routinely requested for NTF tests, and the capability has successfully transferred to many other facilities. A temperature sensitive paint system (ref. 53) was developed and demonstrated with the primary purpose of transition detection, though other flow features have been observed as well. This system, unlike the model deformation system, has not yet evolved into efficient, routine use at the NTF. Finally, several of the recent process improvements at the NTF, including Mach control, are discussed in reference 64.

CONCLUDING REMARKS

An overview of the NTF from a research utilization perspective has been provided. The original motivation for a high Reynolds number ground test facility, selection of the cryogenic concept to meet the need, unique capabilities of the facility, and the eventual research utilization of the facility have been discussed. The primary purpose of the paper is the exposure of the range of investigations that have utilized the NTF since late 1984. Few examples of research results are provided herein, though many can be found in the references and more open presentation is expected in the future. The following are offered as summary remarks:

1. It is important to remember that the NTF originated from an internationally acknowledged need, and that the original need still exists today as many traditional problems remain, and new revolutionary concepts are developed.
2. The use of high-pressure, cryogenic nitrogen to achieve high Reynolds numbers was a breakthrough test concept that is clearly useable, but still maturing. This is particularly

evident as it relates to advanced measurement capability and the elimination of test envelope limitations resulting from model/facility dynamics.

3. The majority of research testing in the NTF has been directed towards transport configurations, with 57% of the research time available utilized for subsonic transports and 15% for supersonic transports. This is not unexpected due to the typical size of full-scale transports and the resulting Reynolds number gap from conventional facilities to flight, in addition to the prohibitive cost, time, and risk associated with prototypes.
4. Results from subsonic transport investigations have demonstrated the advantage of flight Reynolds number tests, and provided verification of CFD methods. The glaring disappointment has been rather routine high angle of attack limitations due to the combination of model and facility dynamics. Efforts are in progress to eliminate this issue.
5. Very few fundamental fluid mechanic experiments have taken place in the NTF, most likely due to a lack of measurement capability. Those that have occurred provided basic insight into viscous fluid flow and Reynolds number scaling.
6. High performance military configurations have seen relatively little test time in the NTF, and the testing has not been continuous over the years. The lack of testing is due in part to changes in international politics, resulting in reduced military funding within both NASA and the DoD. These configurations, particularly at off-design conditions, remain of interest to study.
7. Space access vehicles have seen very little testing in the NTF, though the shapes and complexity of these vehicle systems would undoubtedly make for interesting Reynolds number effect studies. It is surprising that essentially equal research test time has been utilized for this vehicle class and submarines.

ACKNOWLEDGEMENTS

The author would like to thank all the people associated with the NTF during its advocacy, development, and operation. This paper was made possible by the efforts of this large group from within government and industry over the years. In particular, I would like to thank Blair Gloss and Frank Lynch for their personnel insight and discussion of high Reynolds number aerodynamics and testing during my 11-year association with the NTF.

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