NATIONAL TRANSONIC FACILITY STATUS

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ABSTRACT

The National Transonic Facility (NTF) has been operational in a combined checkout and test mode for about 3 years. During this time there have been many challenges associated with movement of mechanical components, operation of instrumentation systems, and drying of insulation in the cryogenic environment. Most of these challenges have been met to date along with completion of a basic flow calibration and aerodynamic tests of a number of configurations. This paper reviews some of the major challenges resulting from the cryogenic environment with regard to hardware systems and data quality. Reynolds number effects on several configurations are also discussed.

INTRODUCTION

The National Transonic Facility (NTF), which was constructed by NASA with a goal of meeting the national needs for High Reynolds Number Testing, has been operational in a checkout and test mode for about 3 years. The order of magnitude increase in Reynolds number over existing transonic wind tunnels provided by the NTF, figure 1, is the result of operating at cryogenic temperature and stagnation pressures to 8.8 atmospheres. Although the cryogenic temperatures provide some significant and well documented benefits from a Reynolds number standpoint, the harsh environment also provides equally significant challenges for reliable operation of large mechanical systems and instrumentation.

The approach followed during the 3 years of operating in a combined checkout and test mode had some obvious advantages for a facility like the NTF where there is not a significant experience base. Known problems can be solved while identifying and solving those problems that will only show up by using the tunnel in a testing mode. The end result is a fully operational facility at an earlier date. However, there are also some disadvantages. Most significant among them is that testing during this time period is at a much reduced level of efficiency. For a facility like NTF where a very high level of efficiency is important, it is difficult for both operators and observers to maintain perspective during this test period.

Over the past 3 years a host of operating problems resulting from the cryogenic environment have been identified and solved. These ranged from making mechanical/electrical systems functional to eliminating temperature-induced vibration, to minimizing the effect of moisture outgassing from the thermal insulation. Additionally, a preliminary flow calibration has been completed, and a series of aerodynamic tests has demonstrated data quality and provided Reynolds number effects on several configurations. Currently, a major effort is under way, through the summer of 1988, which is devoted to improving operating efficiency with a goal of being ready to efficiently support both research and development testing requirements by the fall.

This paper will review some of the more significant efforts during this time period and summarize the NTF status concerning hardware and instrumentation systems, operating constraints imposed by the cryogenic environment, data quality, and some Reynolds number data.

SYMBOLS

c	wing chord, ft.
C_L	lift coefficient
C_l	rolling moment coefficient
C_{l_β}	rolling moment coefficient due to sideslip
C_N	normal force coefficient
C_n	yawing moment coefficient
C_{n_β}	yawing moment coefficient due to sideslip
C_p	pressure coefficient
°F	degrees Fahrenheit
GPM	gallons per minute
HP	horsepower
LN_2	liquid nitrogen
M	Mach number
mv	milivolts
P_T	total pressure
P_∞	free-stream static pressure
$\tilde{p}$	root mean square (rms) value of fluctuating component of static pressure
q	dynamic pressure
RN	Reynolds number
T	stagnation temperature
U	mean velocity streamwise
$\tilde{U}$	rms value of mean velocity streamwise
$\frac{x}{c}$	fraction of chord
$\frac{dM}{dx}$	partial derivative of Mach number with respect to test section length
α	model angle of attack

β model sideslip angle

ΔW test section floor and ceiling angle relative to the horizontal

TESTING AND CHECKOUT EXPERIENCE

The testing and checkout experience is summarized in figure 2. The initial start-up experience (prior to 1985) is reported in references 1 to 3. As stated previously, the testing that has been accomplished to date has a two-fold purpose of providing aerodynamic data and exposing testing problems associated with the tunnel and instrumentation systems. Nine of the configurations tested are shown in figure 3 which collectively utilized the maximum capability of the NTF at both ambient and cryogenic conditions over the Mach number range. Two other aircraft configurations have also been tested but will not be discussed here. The primary model used for checkout of both tunnel and instrumentation systems was the Pathfinder I which has a high aspect ratio wing with a supercritical airfoil (reference 4). This model was first installed in the tunnel during the first quarter of 1985.

The major areas receiving attention during the checkout are listed at the bottom of figure 2 and include model access, process controls, moisture in the tunnel, model vibration, and tunnel/test instrumentation. All of these problems were worked simultaneously as indicated by the figure and were phased in with the testing schedule as appropriate. The tunnel was unavailable for cryogenic operation during most of the first half of 1987 due to a failure of an expansion joint in the liquid nitrogen supply system.

Model Access. - Access to the model requires the movement of large components within the tunnel, (figures 4, 5, and 6), over the temperature range from ambient to fully cryogenic. The details of this system are defined in references 3 and 5. The test section plenum is isolated from the rest of the tunnel circuit by large isolation valves. The process of putting these valves in place involves unlocking and translating a large section of the contraction cone and the high speed diffuser away from the plenum; this process uses dual electrical driven actuators with a seven-foot stroke which must operate in phase on each component. Additionally, the ability to make up limit switches or components to fairly close tolerance where the components may be exposed to large temperature excursions is required. With the plenum vented to atmospheric pressure, the 9- by 12-foot doors in the pressure shell are opened and the test section sidewalls are dropped so that access housings may be inserted to encapsulate the model as shown in figures 5 and 6. The reliable movement of these large components at cryogenic temperatures has required several modifications to the basic actuation concept. These modifications have resulted from operational experience and were implemented over the past 3 years. A final series of modifications to these components is being made during the current enhancement period which should make it a fully operational system.

Process Controls. - The primary controls for the tunnel are closed loop and provide fast response interactive control of pressure, temperature, and Mach number and control of model attitude (see figure 7). The controls for the test section variables (tunnel walls and re-entry flaps) are also closed loop but have slower response requirements.

A detailed description of the process controls is provided in reference 6 and only a brief summary will be presented here. The approach used in design of the pressure, temperature, and Mach number controls involved using a mathematical model of the process to determine circuit response characteristics in order to establish the design criteria for the control hardware and the initial control laws. This approach as indicated in figure 8 required measurement of actual tunnel response characteristics for verification of the control laws and update of the math model. This effort was a first priority in the early tunnel operation and indicated that the accuracy required could not be obtained due to insufficient system resolution and excessive instrumentation noise. To correct this problem the microprocessors, servo control valves, and instrumention were upgraded. The upgraded stagnation pressure and Mach number control systems were completed in the first half of last year. The Mach number system provides a rapid response and will control around set point to within ±0.001. The last system to become fully operational was the temperature control. Initially, this system was based on a measurement of the liquid nitrogen flow rate entering the tunnel. Minimal success was obtained in making this measurement and an alternative approach which calculates the flow rate has been recently implemented and provides adequate performance.

Moisture Contamination. - During the early operation of the NTF at Cryogenic temperatures, a coating was observed on several models that had a frost-like appearance. Quantifiable measurements of the extent of the coating were not obtainable. However, it was clear that frost-like crystals were forming and that reflected light was making it visible with a television system. An extensive study was undertaken to determine the contaminating substance and its source as well as its possible effect on the aerodynamic data. This study identified the contaminant to be water.

Further evaluation of the incoming liquid nitrogen, various tunnel purge technique, and samples of the thermal insulation system identified the insulation as the water source. The closed-cell polyisocyanhrate foam used for the thermal insulation has been shown to have approximately 1.5 percent water by weight. (As a reference, dry wood has approximately 6-percent water by weight.) The problem, as shown in figure 9, is that at the cryogenic temperatures only a very small quantity of water is required to saturate the free-stream gas. For example, at -70°F only about 0.2 pounds of water is required to saturate all of the gas in the tunnel at atmospheric pressure, while at +70°F about 200 lbs of water is required. Two questions naturally arise at this point. How to eliminate the moisture, and what is its effect on the aerodynamic data measurements? Extensive investigations have been conducted in both areas. With regard to the question of eliminating the moisture, the studies have indicated that the simplest solution appears to be drying the tunnel and then maintaining a dry environment. Drying has been accomplished in the past by maintaining the tunnel at the maximum warm temperature (approximately 150°F) for several hours in dry nitrogen gas with a periodic purge. The diffusion of water from the insulation in the NTF is a maximum at this condition as indicated in figure 10. The figure also illustrates the reduction in diffusion with decreasing temperature which is, of course, a favorable effect. Since in the nitrogen operating mode the tunnel is continuously vented, i.e., purged to maintain constant stagnation pressure, test conditions with very small amounts of condensation can be obtained. Aerodynamic studies conducted under these conditions, which will be discussed later, have indicated that the resulting effects on the aerodynamic data are not measurable.

Therefore, the plannned approach when the tunnel is brought back into operation at the conclusion of the current enhancement period will be to dry it for several days and keep it closed to atmospheric air. It should be pointed out that the drying process takes place in static as well as operating conditions; therefore, it continues to dry over weekends and nonworking shifts.

The two cryogenic tunnels in Europe with internal insulation, KKK at Köln and T2 at Toulouse, have experienced similar moisture concerns and have also reached the conclusion that they can achieve conditions of dryness where effects on the aerodynamic data are not measurable. We are convinced from experience to date, with the NTF and other studies, that procedures can be followed that will eliminate moisture contamination as a concern regarding aerodynamic data quality.

Model Vibration. - Significant vibration of the model/balance combination in the lateral plane has been encountered at some conditions since the initial operation of the NTF. After some period of operation the vibration was found to be more severe when the structure was cold. The model pitch system is illustrated in figure 11 and is composed of an arc sector driven by a hydraulic cylinder. Restraint is provided by a series of bearing pads located at both the top and bottom of the sector. The loads are transmitted through the pads to the internal tunnel structure. There is also a fairing on the downstream part of the sector that is fixed to the tunnel structure and provides a cavity for instrumentation leads. The attachment of the fixed fairing to the arc sector is a slip joint which allows the sector to move independently of the fairing. The bearing pads, while providing restraint, also have clearance to allow for thermally induced movement of the internal structure.

The vibration problem has been investigated both experimentally and analytically. In the experimental investigation, the Pathfinder model was used as a test vehicle. Both it and the model support system were extensively instrumented as follows:

a. Six component force balance and 3-axis accelerometer package in the Pathfinder model

b. Pressure tranducers in the fixed fairing and test section walls

c. Accelerometers on the fixed fairing, bearing pads, and the surrounding tunnel support structure

d. Strain gages and thermocouples on the tunnel support structure

The analytical investigation involved detailed calculations of the dynamic structural respose and of the unsteady aerodynamic characteristics of the model support system.

Experimental observations were made of the dynamic structural response characteristics, Mach number, dynamic pressure, test temperature, and coldsoak time. The installation of vortex generators and splitter plate on the fixed fairing afterbody helped to identify unsteady flow at the rear of the arc sector as one of the sources of dynamic excitation. Eventually, the primary factor governing the dynamic response of the model was found to be the clearance tolerance between the bearing pads and the surface of the arc sector. A procedure was evolved for setting the clearance adjustment which reduced the model dynamic response to acceptably low levels independent of temperature cycling. Some of the test results are illustrated in figure 12 which shows the dynamic yawing moment as a function of stagnation temperature for several of the test configurations of the arc sector. Although the low level shown in the figure for the last case is completely satisfactory, it may be sensitive to adjustment with time due to temperature cycling.

Instrumentation. - For several years prior to initial operation of the NTF an extensive research and development program was undertaken by the Instrument Research Division at Langley to develop instrumentation systems for basic measurements of forces and moments, pressures, and angle of attack that would function with both reliability and accuracy in the cryogenic environment. The results of this program were the development of strain gage balances that were not temperature controlled and heated instrument packages for pressure and angle of attack measurements. These instrument systems were developed in cryogenic chambers and verified to the extent possible, in the 0.3-Meter Transonic Cryogenic Tunnel and indicated good performance and soundness of the basic concepts. Upon application of these instruments to models in the NTF, there were several system problems that had to be resolved. The most significant of these were the effect of leads required to support the pressure instrumentation system on the balance axial force component, and the calibration system for the electronic scanning pressure (ESP) system. Recent tests, both in the NTF and in the cryogenic checkout chamber, have indicated satisfactory resoultion of both of these problems.

As will be discussed in a later section, a strong concern from the outset has been data quality. In this regard, an extensive effort has been carried out to eliminate data scatter due to electrical noise and extraneous signals. Care was taken from the beginning to provide a "clean" instrumentation ground, but as is often the case, extraneous signals can creep into the system. A significant effort has been made over the past year to track down and eliminate noise sources that were infiltrating the data system. The results of this effort are indicated in figure 13. The figure illustrates a reduction in data scatter by a factor of 5 to a level less than 10 microvolts. This level corresponds to a balance error of less than 0.1 percent of full scale.

OPERATING CONSTRAINTS

The NTF has the general appearance of, and is often talked about, as a typical continuous operating fan driven wind tunnel that has the potential to mass produce data on a continuous basis. Although in principle the potential exists, it is somewhat misleading to think about a large cryogenic tunnel in this context. In reality the operation must be viewed much as a blow-down tunnel with efforts directed toward minimizing run time and maximizing data gathering rates. The two main constraints with regard to run time are liquid nitrogen logistics and costs, and model access. It was shown in the early 1970's that the application of cryogenics to wind tunnel testing provided the most cost effective approach to high Reynolds number testing. This does not mean, however, that testing at high Reynolds numbers will carry the same cost and degree of complexity as testing in the many ambient temperature and pressure tunnels around the country. This is illustrated in figure 14 where the energy cost ratio (liquid nitrogen is a form of energy) is shown as a function of Reynolds number ratio for the NTF compared to the Langley 16-Foot Transonic Tunnel. An order of magnitude increase in Reynolds number has an energy cost ratio of approximatley 44. In the cases where high Reynolds number is required for research or development testing, the cost is cheap compared to flight test. But because of this cost difference, test programs and objectives must be carefully defined and supported by adequate precursor studies at low Reynolds numbers. Therefore, it is not well suited for researchers to exercise broad freedom or for indiscriminate development programs.

LN_2 Supply System. - Liquid nitrogen is supplied to the NTF by a commercial air separation plant located adjacent to the Langley property and connected to the NTF site by a pipeline. The capability of this system is shown in figure 15. The challenge is to optimize the interface of the plant which operates continuously 24 hours per day at a 300 ton per day rate with the intermittent operation of the NTF, which can use LN_2 to a maximum rate of 30 tons per minute. This requires, of course, storage tanks to serve as a buffer. The current system has a 2100 ton storage tank at the plant and a 700 ton tank located at the NTF with capability to transfer approximately one tank per 24 hour day. The system can sustain a use rate of 2100 tons per week and if the tunnel has not been using nitrogen for a while, can build up to a maximum quantity available of 4800 tons for a week. This tends to optimize on two week test programs using liquid nitrogen assuming all tanks are full at the start. The maximum transfer rate of the pipeline is 656 tons or approximately one NTF tankful per day; therefore, the maximum use rate is one tankful per day. As shown in figure 16, if operation is started on Monday morning with the equivalent of four NTF tankfuls available and used at a rate of 1 tank per day, with 0.5 tanks being resupplied by the plant, and no use over the weekend, the total supply is exhausted by the end of the second week. The options at that point are either to operate on one-half tank per day (the plant output) which is not practical, or to allow 8 days for the nitrogen supply to be replenished and use the tunnel in the air mode or some other capacity during this period. This use scenario can be changed, of course, by increasing the plant capacity and/or storage and transfer rate. A decision to increase the plant capacity must take into consideration long term use rates. The most immediate benefit will be provided by an increase in storage capacity and associated transfer rates. Current plans are to triple the NTF onsite storage capacity in FY 1990. This will tend to optimize at about a three week test program in nitrogen.

The most important aspect of the tunnel operation from cost considerations is the speed of changing test conditions and data acquisition. This is driven primarily by the degree and quality of automation. Figure 17 illustrates the impact of time per data point for a typical test condition of $M = 0.8$ and temperature = -250°F. This illustration includes time to change angle of attack and Mach number and adjust temperature and pressure. When the NTF was first brought on-line and manual control was used, times averaged greater than 45 seconds per point. After the current enhancement period it is expected to be under 30 seconds per point with a goal of 7 to 10 seconds per point with further refinements in the control and operating system. The reduction in electrical signal noise discussed earlier has a direct impact on this in that it reduces the number of data samples required to be averaged to obtain high quality data.

DATA QUALITY

In this section the status of flow calibrations and efforts to assess data quality will be discussed. The discussion will include both steady and dynamic aspects of the flow calibration, the ability to measure Mach numbers and angle of attack, importance of wall boundary effects, and the effect of moisture contamination or "frost" on the data.

Flow Calibration. - As reported previously, references 3 to 10, the NTF has been operated throughout the operating envelope as shown in the upper left of figure 18. The initial calibration looked at the distributions of temperature, pressure, Mach number, and flow angularity on the tunnel centerline as measured by the model upright and inverted. More recent efforts concerned the details of the Mach number calibration and the effect of temperature on flow angle.

The ability to vary the test section wall angle provides the capability to maintain zero Mach number gradient through the test section, thus eliminating model buoyancy effects in the empty tunnel for all test conditions. A typical variation of wall angle with Mach number is shown in the left of figure 19. This particular case is for a warm temperature of 100°F and varies from approximately 0.2° convergence at M = 0.2 to 0.4° divergence at M = 1.15. A typical correction to Mach number as calculated from the plenum static or reference pressure is also shown. In general the quality of the steady flow appears to be excellent and sufficient adjustments are available on the test section geometry, i.e., wall angle and re-entry flap settings, to eliminate the existence of any Mach number gradients in the empty tunnel.

In order to investigate the effect of tunnel structural deformation due to temperature gradients in the structure on flow angle with temperature, frequent measurements of flow angle have been made during the last several test programs. The data presented in figure 20 are typical of results obtained from these measurements. With the exception of one point the effective flow angle is always equal to or less than 0.02° which is approaching the measurement accuracy. This effect will continue to be monitored until sufficient history is developed to have a firm basis for determining the required frequency of flow angle measurements.

NTF Dynamic Flow Quality. - In 1980 while the NTF was still under construction, the plans for flow quality measurement were described extensively in reference 11. The measurements were to consist primarily of fluctuating pressure and velocity measurements. Since that time, hot-film probes and fluctuating pressure gages have been operated in the test section at the locations indicated in figure 21, and further tests are planned as also shown.

Some results of the measurements made to date are shown in figures 22 and 23. These results have been excerpted from work by W. B. Igoe on a proposed doctoral dissertation to be submitted to the George Washington University. Figure 22 shows the root-mean-square fluctuating static pressure measured in the NTF as a function of Mach number for a unit Reynolds number of 6 million per foot. The fluctuating pressures were measured in air on the test section sidewall and have been divided by free-stream static pressure. Fluctuating static pressures have been measured in the free stream in a number of other large transonic wind tunnels using a 10° cone on the centerline (see reference 12 for example). Some of these results have been included for comparison in figure 22 for a Reynolds number range of 1.3 to 5 million per foot.

The results of hot-film probe measurements at low Mach number in the test section are shown in figure 23. These measurements were made in the free stream in air with the slots closed. Results are shown for the streamwise measurements at total pressures of 1 and 8 atm. Although there is considerable scatter at a pressure of 1 atm, the measurement levels are about 0.1 percent, which was the target level for the NTF. Streamwise hot-wire probe measurements made in the Langley Low Turbulence Pressure Tunnel (LTPT) at total pressures of 1 and 10 atm (reference 13) are shown for comparison.

Further measurements in the NTF are planned using fluctuating static pressure probes in the test section free stream, and hot-film probes in the test section, settling chamber, and in the vicinity of the cooling coil and screens. The measurements will be made over the full operating range of the NTF. By the time the measurements are completed, the dynamic flow quality of the NTF will have been fully documented.

Mach Number and Angle of Attack Sensitivities. - Prior to looking at either Reynolds number effects or the effects of frost on data quality, it was desirable to obtain an assessment of the sensitivity of the model to the basic test parameters, Mach number and angle of attack, and some qualitative assessment of our ability to measure them. As stated in the introduction, the primary model used for assessing data quality was the Pathfinder I Model. This model was built early in the program for the purpose of developing model design and fabrication technology as well as providing a research model. It has an aspect ratio 10 wing with a supercritical airfoil section typical of supercritical airfoil design technology of the mid 1970's. As a result, shock movement is very sensitive to small changes around the design point in Mach number and angle of attack. This made it a good model for use in assessing our ability to measure Mach number and angle of attack in the NTF. Figures 24 to 26 illustrate the results obtained from this assessment. The figures show pressure distributions for an inboard and an outboard wing station at a Mach number around 0.82 with transition fixed at 10 percent of chord. The data of figure 24 shows that a Mach number increment of 0.0038 results in a shock movement of about 6 percent of chord for the outboard wing station. In light of the high degree of sensitivity to Mach number, a series of runs were compared where all variables except Mach number were held constant and Mach number varied in very small increments of 0.0001 to 0.0006. Wing pressure distributions for these cases are shown in figure 25. The data show an orderly progression of shock movement and the well defined curves suggest that both wing pressures and Mach number are being measured with a high degree of accuracy.

The sensitivity of this model to angle of attack is illustrated in figure 26. In this case, the angle of attack increment was 0.054° with a Mach number difference of 0.0013. Again, the shock movement is about 5 to 6 percent. However, about one half of the movement can be attributed to Mach number effects. These data support the point that the highest quality instrumentation is an absolute requirement for using the NTF to understand incremental effects of Reynolds number and compressibility. Further they support the conclusion that a high degree of accuracy is currently available in the Mach number, angle of attack, and model pressure measuring systems. The data also underscore the importance of being able to accurately assess wall boundary effects. Recent research on this subject by W. B. Kemp (ref. 14), P. A. Newman and associates (ref. 15), is described by Dr. Newman in a separate session of this symposium. Sophisticated techniques have been developed which utilize measured tunnel wall static pressures to calculate model induced variations of Mach number and upwash through the test section. Figure 27 shows typical contours, in the region of the model, of wall induced Mach number corrections. For this size model at the conditions illustrated the corrections are relatively small, $\Delta M = 0.001$, but as illustrated in the previous figures, corrections of this magnitude are significant if high quality data are to be obtained.

Moisture Contamination "Frost" Effects. - Having established confidence that small incremental effects of the basic test parameters, Mach number, and angle of attack could be both controlled and measured, an investigation to assess the possible effects of frost on the data was undertaken. Care was also taken to insure that comparable test parameters were obtained where the only significant variable was that in one case frost was visible on the model and in the other case it was not visible. Wing pressure distributions from these two cases are compared in figure 28. Although care was exercised in setting the test parameters it should be noted that the Mach number is different by 0.0004 and the angle of attack by 0.01°. These differences are believed, based on previous discussion, to account for the small difference in shock location shown in the data of figure 28 for the outboard wing station. After accounting for the difference in shock location, there is a small difference in pressure level ahead of the shock that may be a small effect of frost. In general the two cases are in very close agreement and provide confidence that when planned tunnel drying procedures are used and the inside of the tunnel kept closed to atmospheric air, frost on the models will not be a problem with regard to data quality.

REYNOLDS NUMBER EFFECTS

During this initial checkout and testing phase several Reynolds number sensitivity studies have been conducted using both the conventional air mode and the cryogenic capability

Air Operation. - The operating envelope in air is shown in figure 29. It is restricted above a Mach number of 0.4 by the drive power in the variable speed motors. A maximum Reynolds number capability of about 20 million per foot at a Mach number of 0.38 is available. This Reynolds number is the maximum available in this speed range and tunnel size in the United States. One of the attractive features of this capability is that a constant dynamic pressure line tends to be close to the maximum drive power boundary. Therefore, models designed for testing at high subsonic or transonic speeds at 1 to 2 atmospheres can also be tested at high Reynolds numbers at the lower Mach numbers at the same dynamic pressure and model loads. One case where this was done was the EA-6B wing modification program. The objectives and overall results from this program are described in reference 16. In summary, it involved modifying the wing leading-edge slat and trailing-edge flap airfoil sections with a major goal of improving maximum lift at loiter and maneuver conditions. A photograph of the EA-6B configuration mounted in the NTF is shown in figure 30. The effect of Reynolds number on the lift characteristics at a Mach number of 0.30 for the basic and modified configuration are shown in figure 31. The 1.4 million Reynolds number case corresponds to testing at 1 atmosphere stagnation pressure. Two points are significant. First, as would be expected, Reynolds number effects on $C_{L_{max}}$ are large for all configurations. Second, modifications to the leading-edge slat showed no benefit at the low Reynolds number condition; however, at the higher Reynolds number the slat benefit was approximately equal to that of the flap. These data are an example of the potential pitfalls of relying on low Reynolds number data for configuration refinement. The effect of Reynolds number on lateral and directional stability as measured by C_{l_β} and C_{n_β} are shown in figures 32 and 33. The effects are not as dramatic as those shown for $C_{L_{max}}$, but in general a stabilizing increment in lateral stability was obtained with increasing Reynolds number. The exception to this was the basic configuration above $\alpha = 16°$ and the modified wing configuration with glove and vertical tail extension above α equal about 14°. A more stabilizing effect in C_{n_β} was obtained for all configurations with increasing Reynolds number.

Cryogenic Operations. - Results from three of the configurations tested during this period will be briefly discussed here. They include the Pathfinder I, a Lockheed high-wing transport which was a Lockheed wing tested on the Pathfinder I fuselage, and a rather large submarine model.

The Pathfinder I (figure 34) was tested over a range of conditions; however, most of the test was aimed at evaluating instrumentation and moisture concerns. Most of the high Reynolds number data was obtained in the early test program and in retrospect may have been contaminated with moisture effects and instrumentation errors. Therefore, the data shown in figure 35 are for more intermediate Reynolds numbers (RN = 5 and 18 million) which were known to be free of instrumentation errors. These data are for a Mach number of 0.82, a constant angle of attack and essentially constant lift coefficient with transition fixed at approximately 10-percent chord. These conditions are the design point for the wing. The natural transition point of the 18 million Reynolds number case was estimated to be essentially at the trip location. The effects of Reynolds number are relatively small with only a slight aft movement of the shock indicated at the outboard wing station.

The data for the Lockheed configuration shown in figure 36 show a much more pronounced effect of Reynolds number. A photograph of the model is presented in figure 37. For the case with transition fixed, the strip was located at a constant 1-inch aft of the wing leading edge. The difference in shock location between transition fixed and free at a Reynolds number of 5 million is about 18 percent of chord. A significant difference was obtained by increasing the Reynolds number to 30 million. A further increase to 40 million produced a negligible effect. These data clearly support the well-known need to be able to monitor transition location as a function of Reynolds number if effects at Reynolds numbers less than full scale are to be interpreted.

The submarine test in NTF was unique in that full scale Reynolds number was obtained in a wind tunnel for the first time. A photograph of the model and Reynolds number velocity envelope is presentd in figure 38. Details of the test and data have been omitted for classified security reasons. In the test both static and dynamic measurements of pressures were obtained through the boundary layer in the plane of the propeller for evaluation and development of scaling laws. As can be seen on the right of figure 38, data in the past using a 6 percent scale model have been obtained at Reynolds numbers about an order of magnitude below full scale. The test in the NTF extended these data well into the region of full-scale submarine operation.

SUMMARY

The National Transonic Facility has been operational in a checkout and test mode for the past 3 years. During this time there have been many challenges associated with testing in a large cryogenic wind tunnel. For the most part they centered around the effect of large temperature excursions on the mechanical movement of large components, the reliable performance of instrumentation systems, and an unexpected moisture problem with dry insulation. Most of these challenges have been met, and it is expected that the rest of them will be met during a major effort that is ongoing through the summer of 1988 to improve operational efficiency. Also, during the past 3 years a preliminary flow calibration has been completed and a data quality evaluation conducted along with high Reynolds number aerodynamic tests of several configurations. Tests were also conducted that provided major inputs to several programs that were not discussed for classification reasons. There is still a requirement for a major effort to develop and implement flow visualization and diagnostic techniques for maximum utilization of the facility. The current NASA facility revitalization program includes funding for these activities in FY'89 and 90. However, from a basic facility standpoint, we believe that it will be ready to efficiently support research and development requirements by the fall of 1988.

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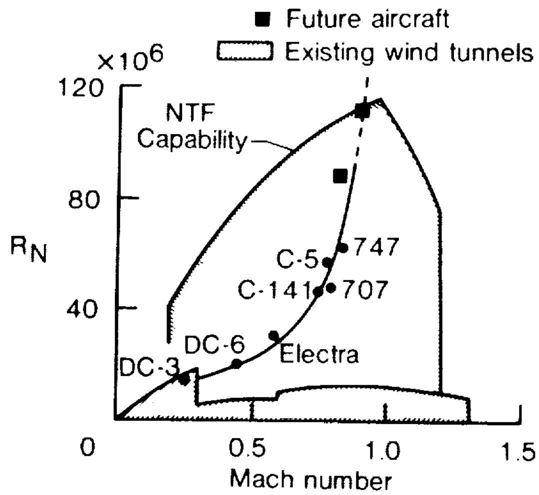
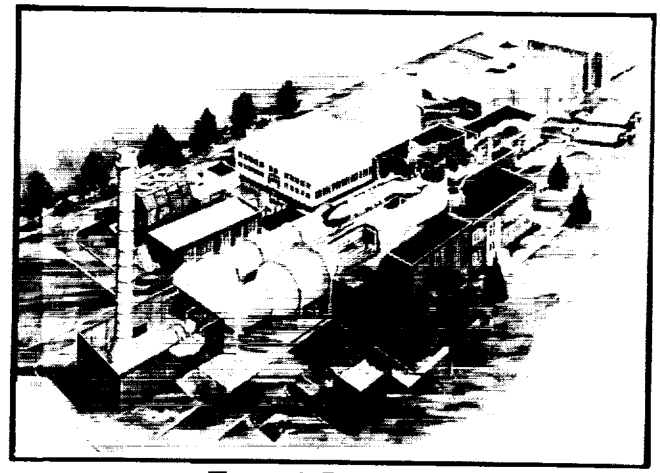




Tunnel Complex

Figure 1. National Transonic Facility perspective and Reynolds number operating envelope.

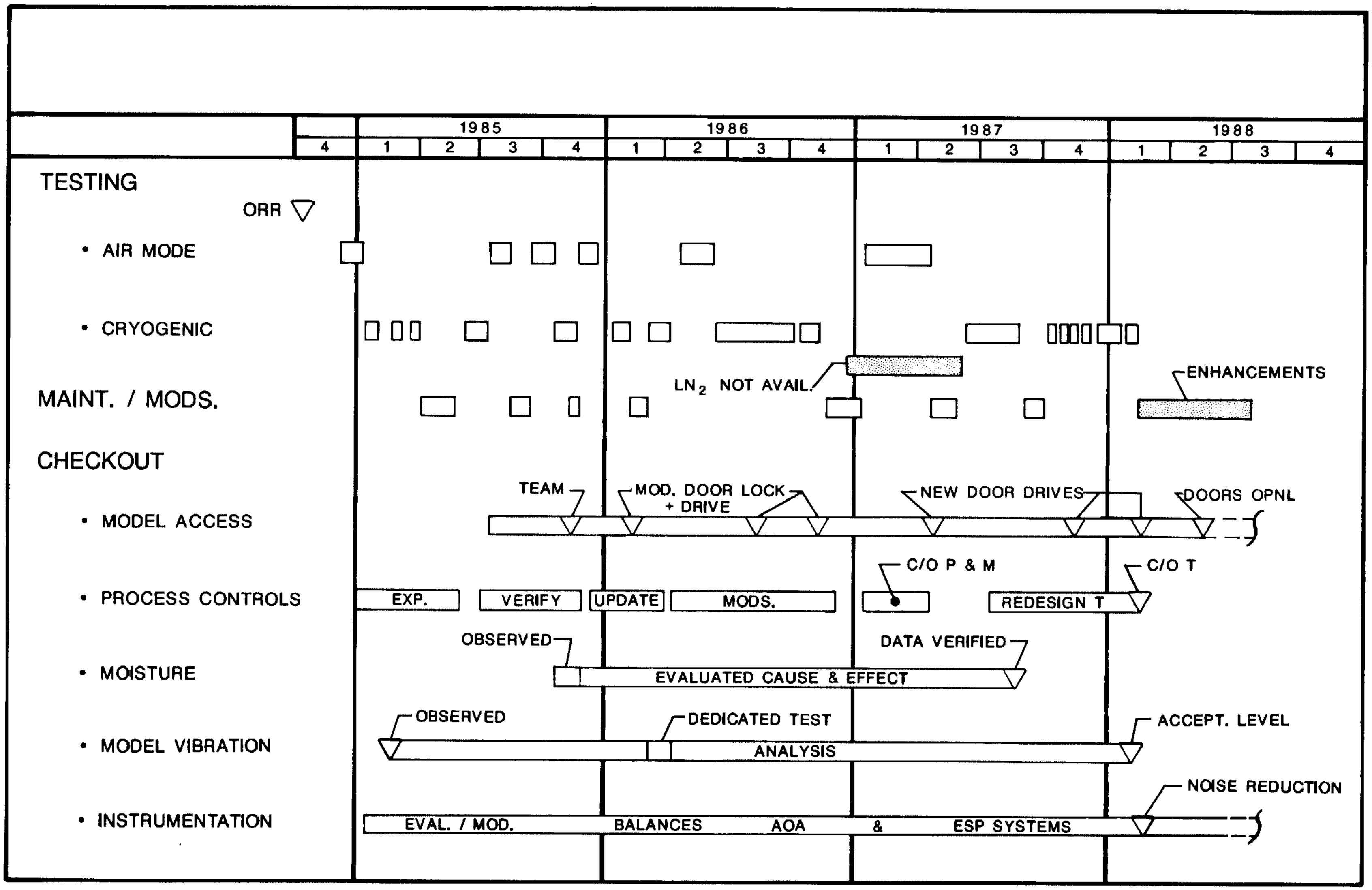


Figure 2. Summary of the NTF testing and checkout experience.

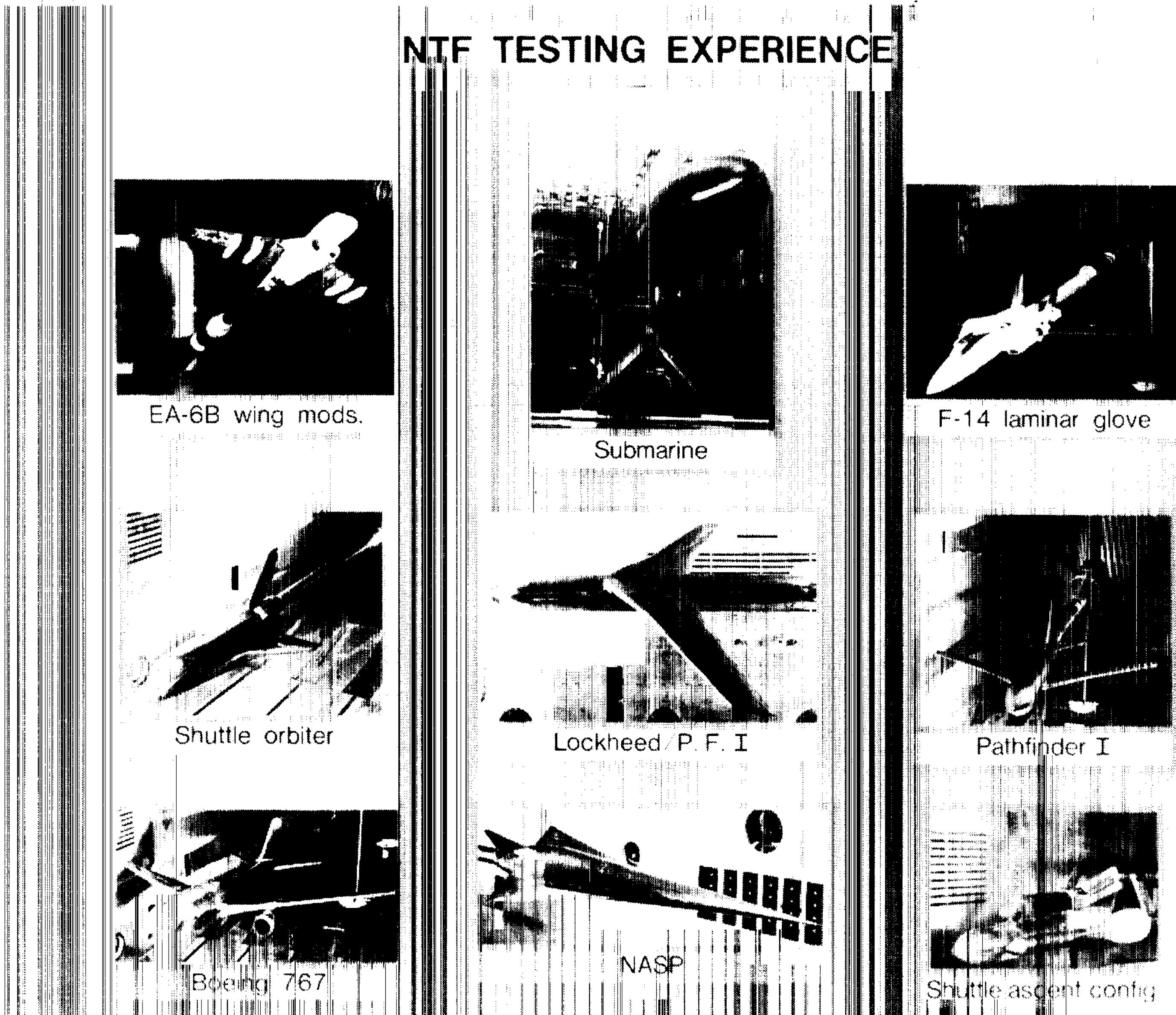


Figure 3. Photographs of models tested in the NTF.

NATIONAL TRANSONIC FACILITY

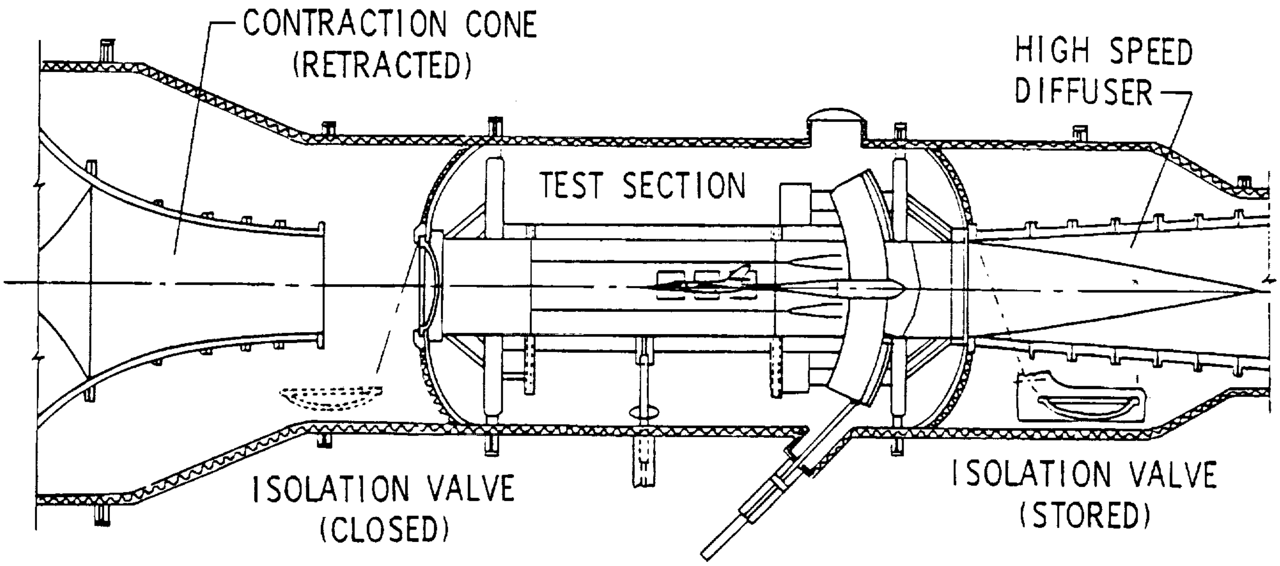


Figure 4. Test section and plenum isolation system.

NATIONAL TRANSONIC FACILITY

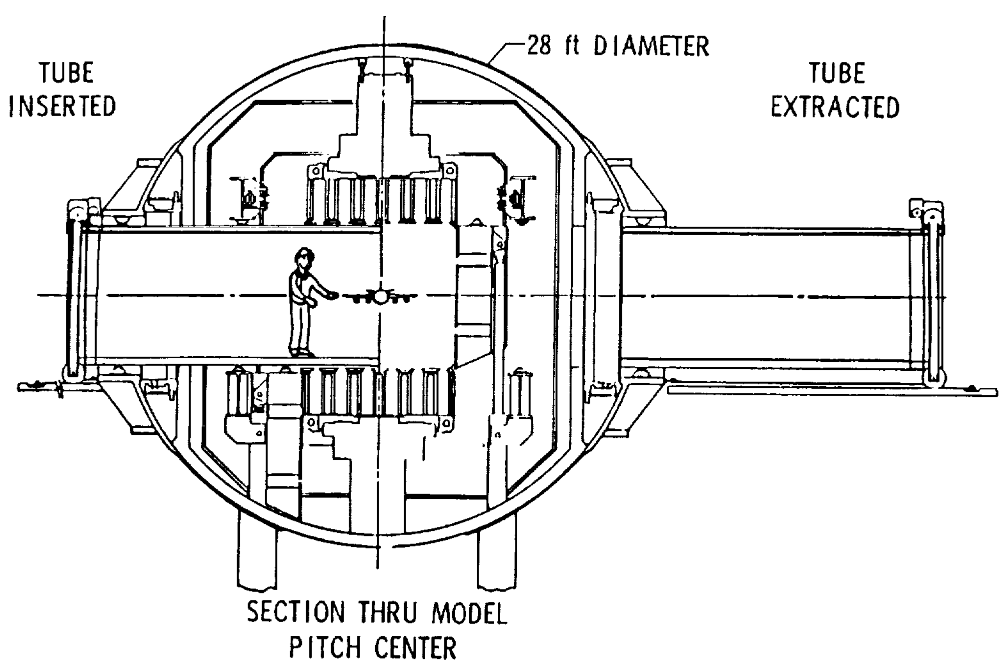


Figure 5. Schematic of model access system illustrating access tubes in the inserted and retracted positions.

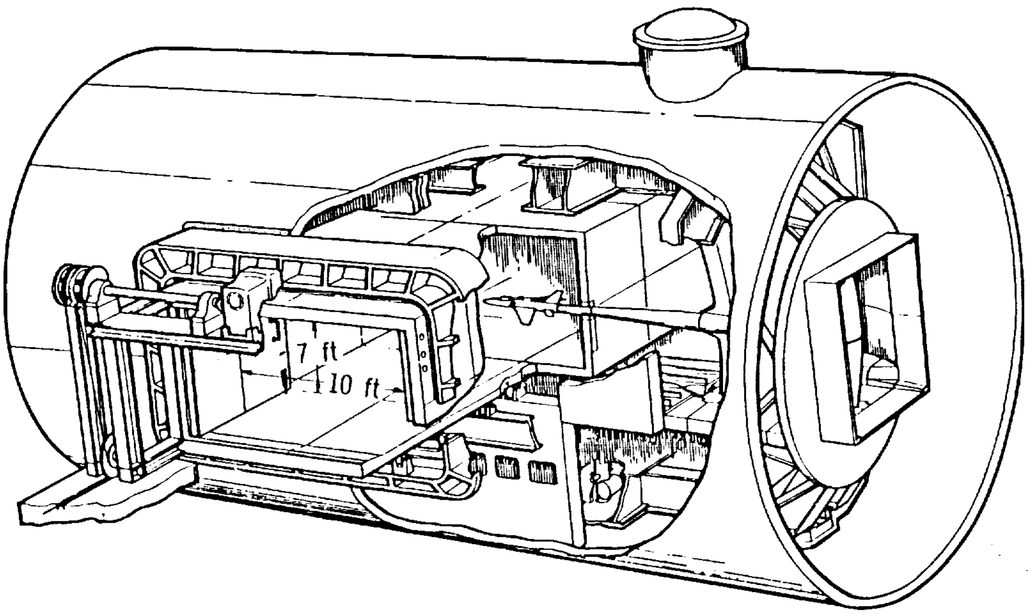


Figure 6. Model access system concept with tubes installed for model entry.

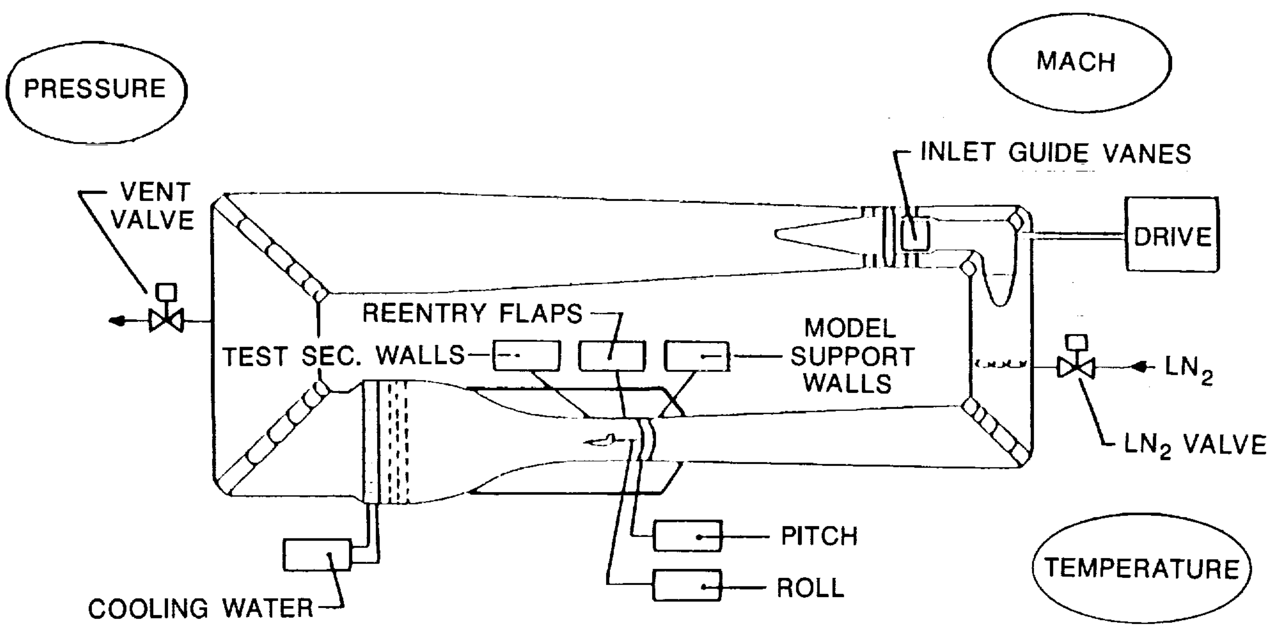


Figure 7. Schematic of NTF process controls.

PRESSURE, MACH NO. & TEMPERATURE CONTROL SYSTEMS

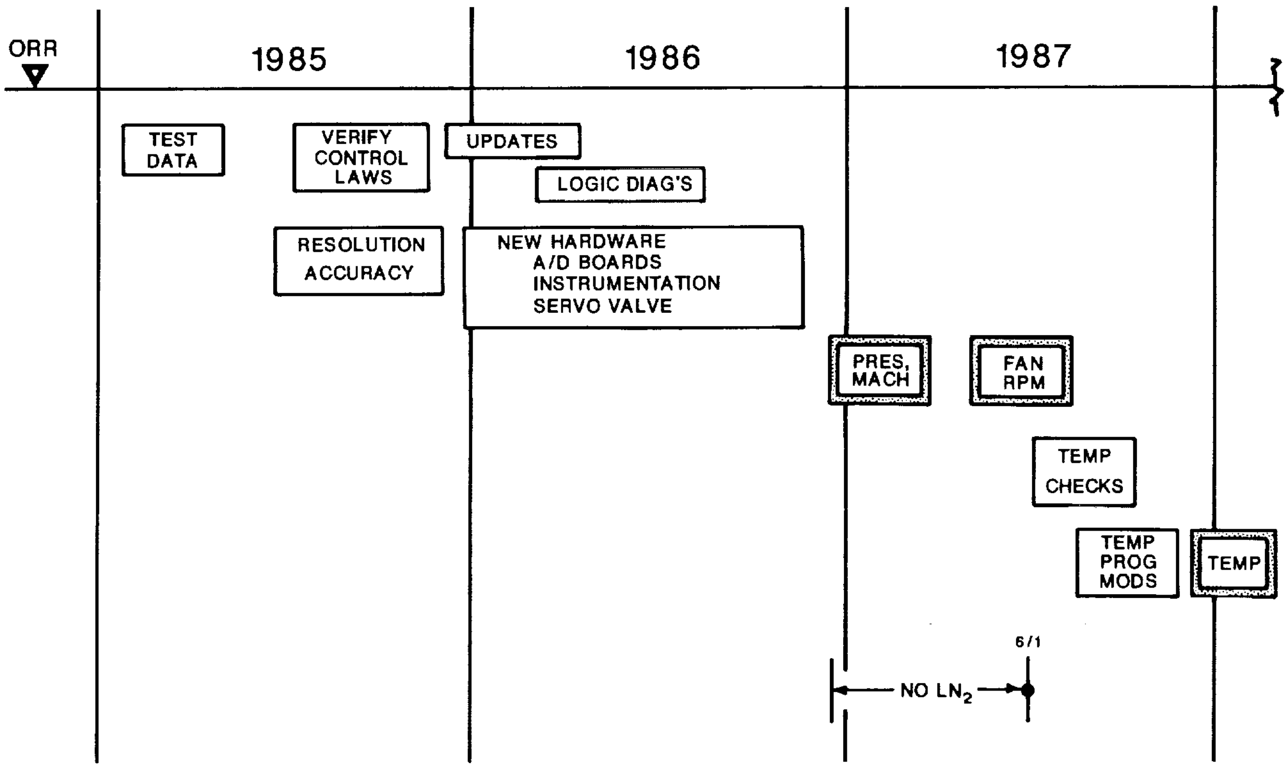


Figure 8. Chronology of events for control system checkout and upgrade.

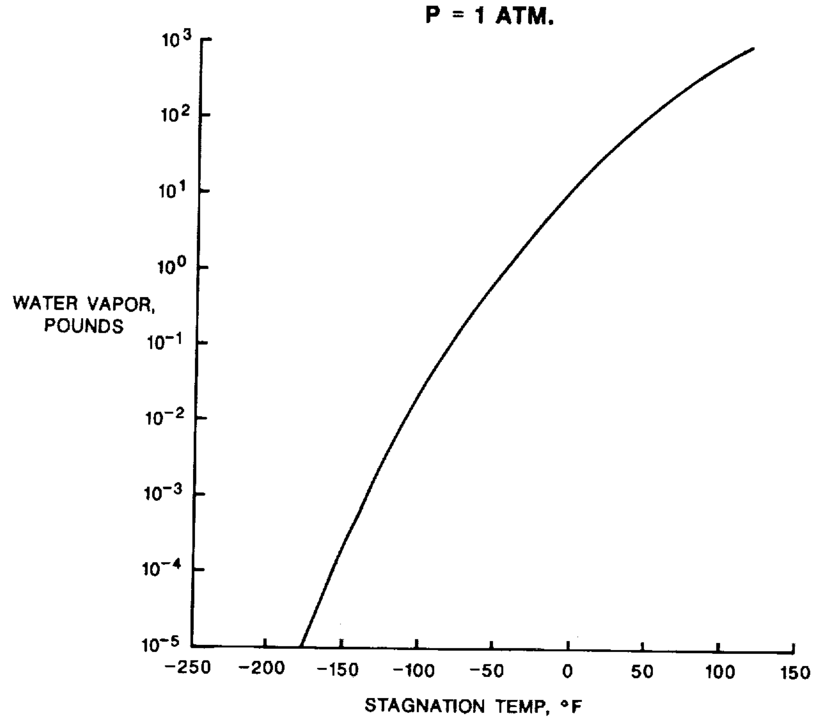


Figure 9. Water vapor required to saturate free-stream gas as a function of stagnation temperature.

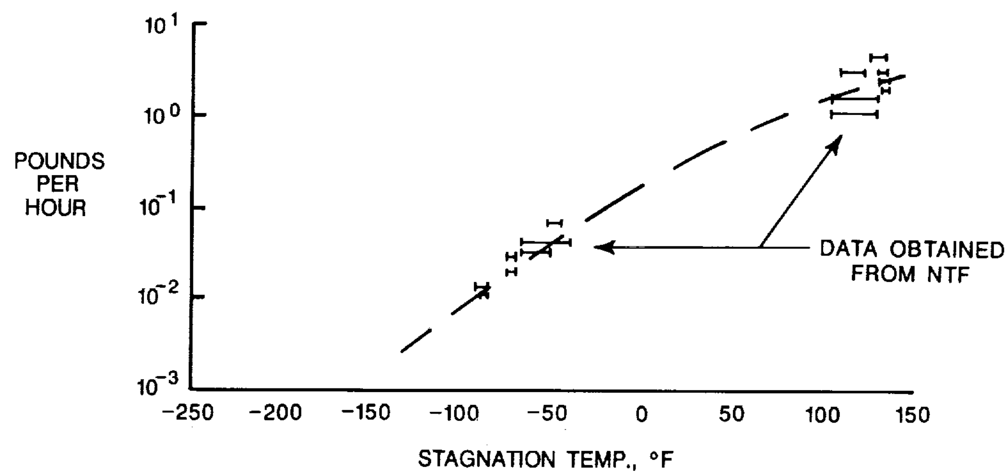


Figure 10. Rate of water transfer from insulation to free-stream gas as a function of stagnation temperature.

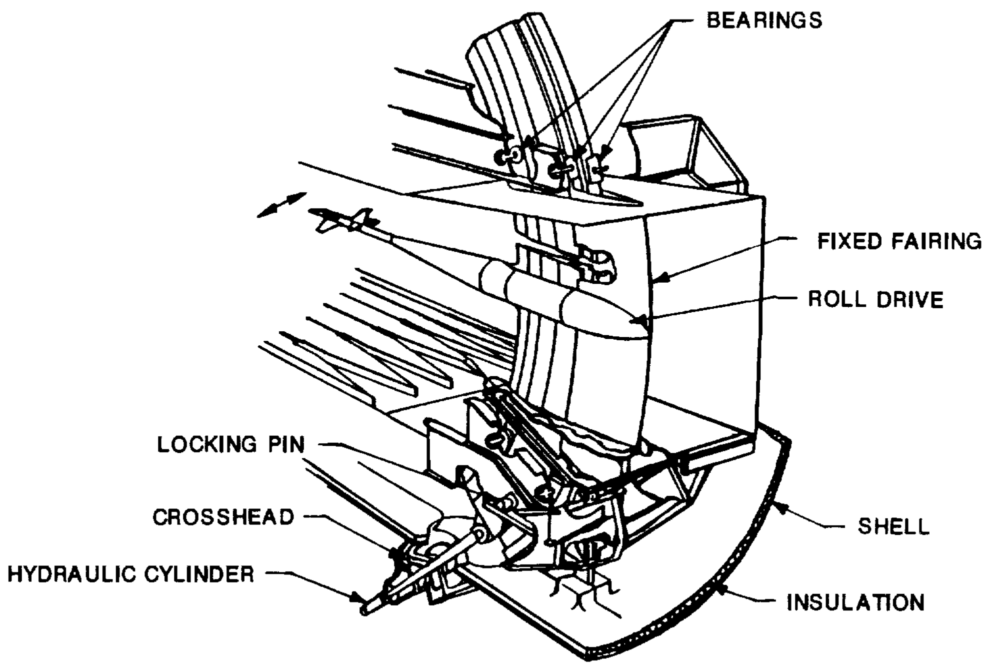


Figure 11. Model sting-support and arc-sector system.

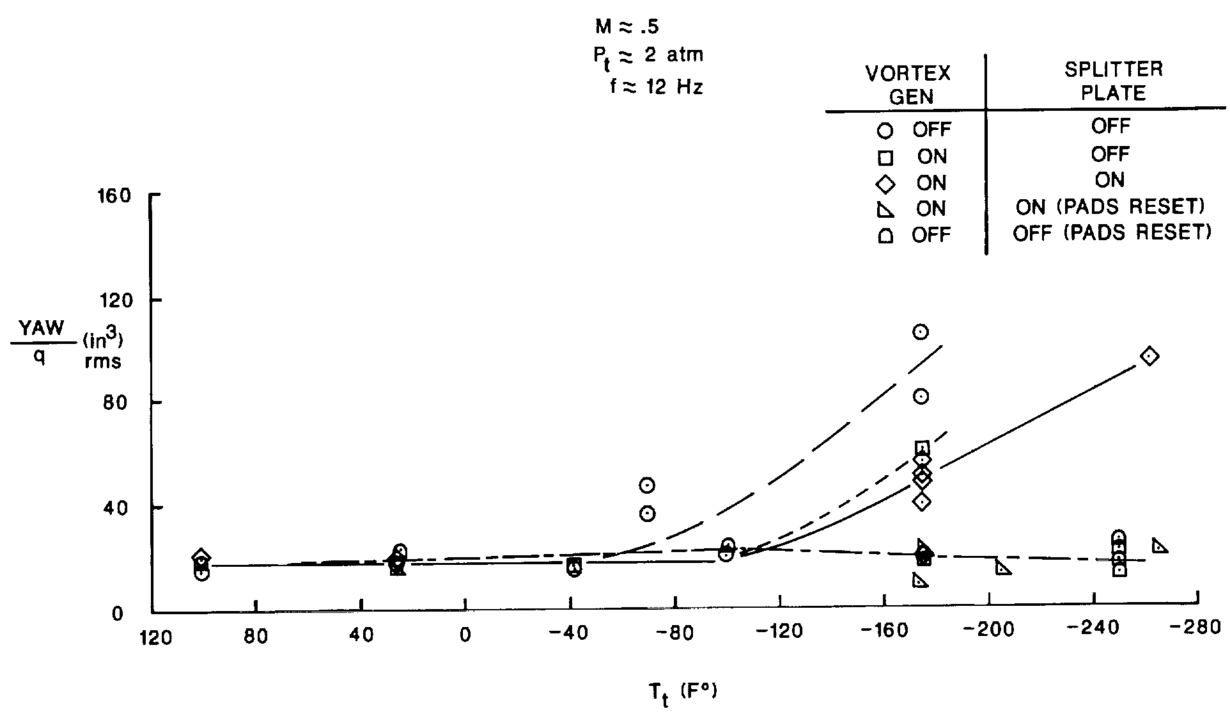


Figure 12. Yawing moment response of the NTF-104 balance with the Pathfinder I Model installed to sting and arc sector dynamics. M = 0.50; P_T = 2 atmos.; f = 12 hz.

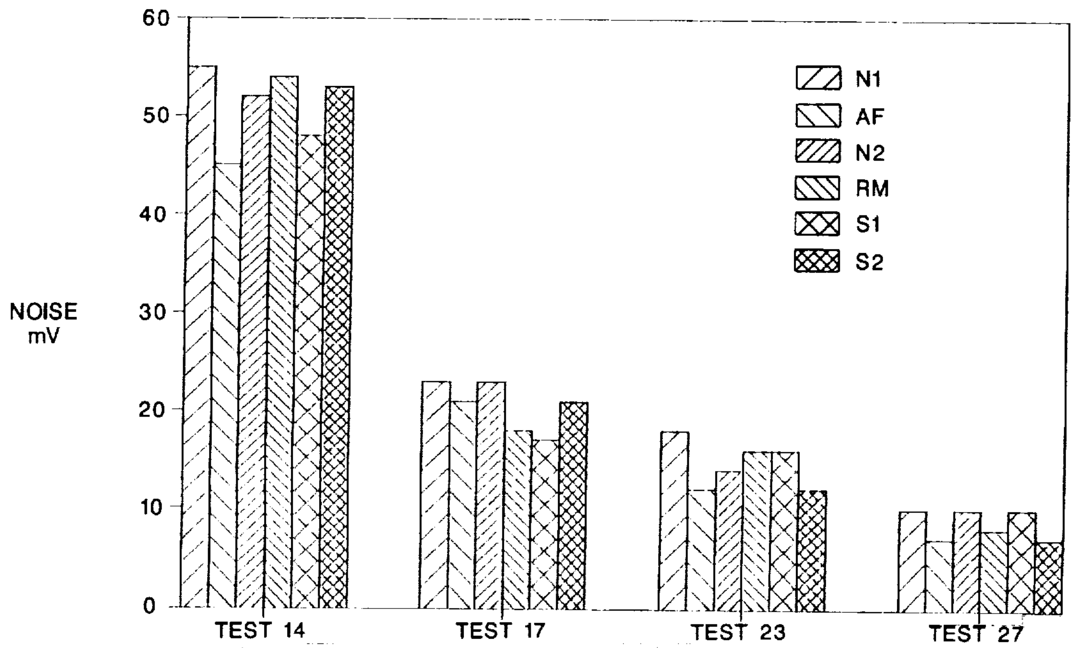


Figure 13. Reduction in electrical noise in the strain gage balance data channels.

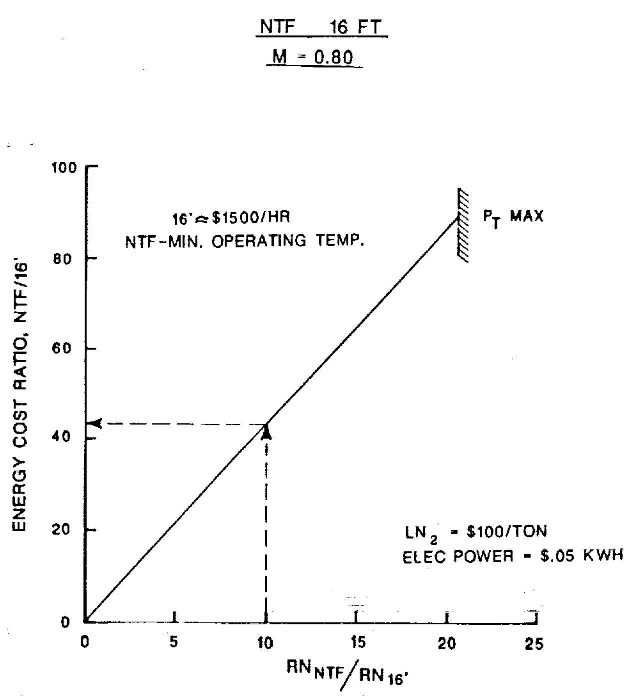
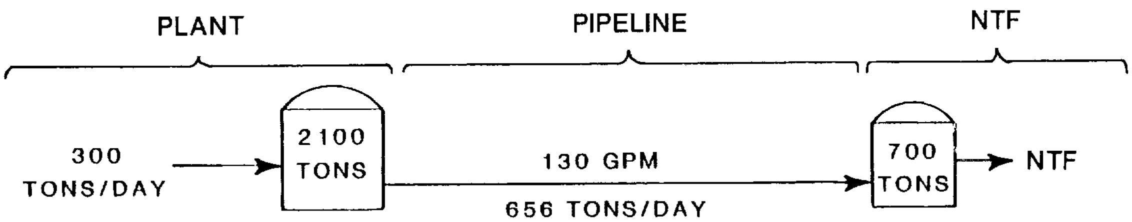


Figure 14. Comparison of operating energy cost between the NTF and the Langley 16-Foot Transonic Tunnel.

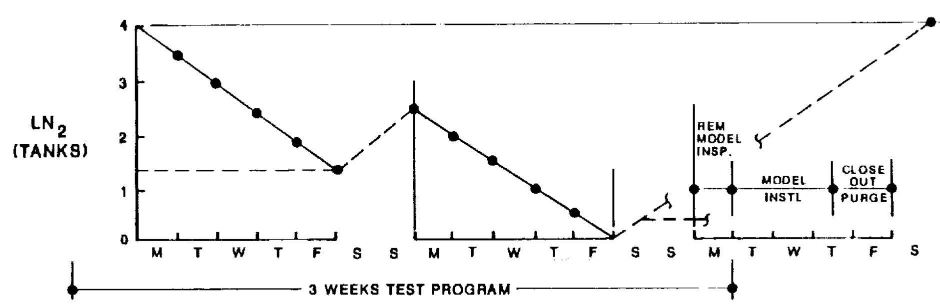


MAX SUSTAINED RATE = 2100 TONS/WK

MAX AVAIL. FOR A WK = 4800 TONS

40 WKS/YEAR = 84,000 TONS

Figure 15. Characteristics of the liquid nitrogen supply system.



FOR TWO WEEKS OF TESTING

		TONS LN_2
LN_2 AVAILABLE (MAX.)	BULK STORAGE - 2900 TONS PLANT OUTPUT - 3360 TONS	6300
COOLDOWNS	2 LARGE ΔT's (300 TO 350°F) 8 SMALLER ΔT's (100°F)	945
PRESSURIZATIONS – 1 PER DAY (AVE)		86
AVAILABLE FOR TESTING		5269

Figure 16. NTF maximum utilization based on LN_2 supply system.

(M = 0.80, T_t = −250° F)

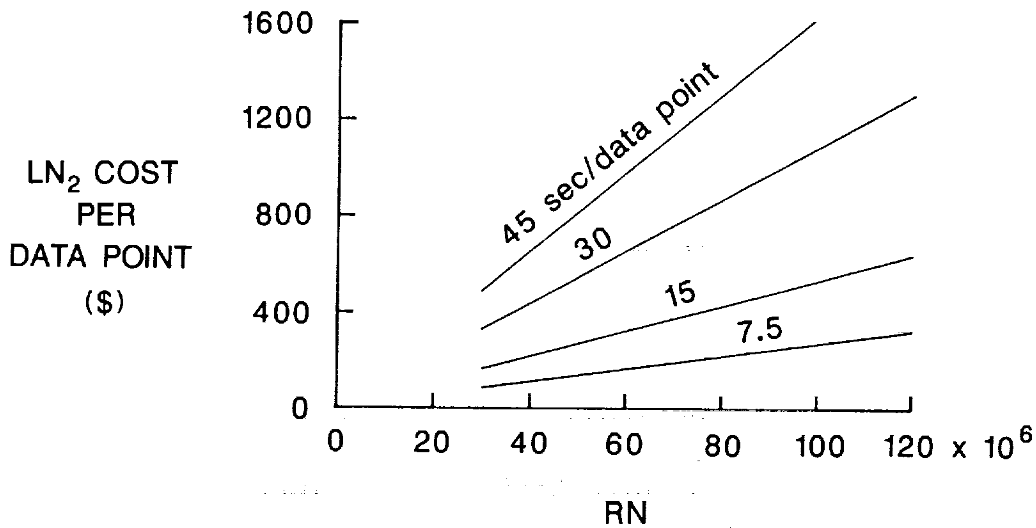


Figure 17. The effect of data sampling rate on liquid nitrogen costs.

NTF

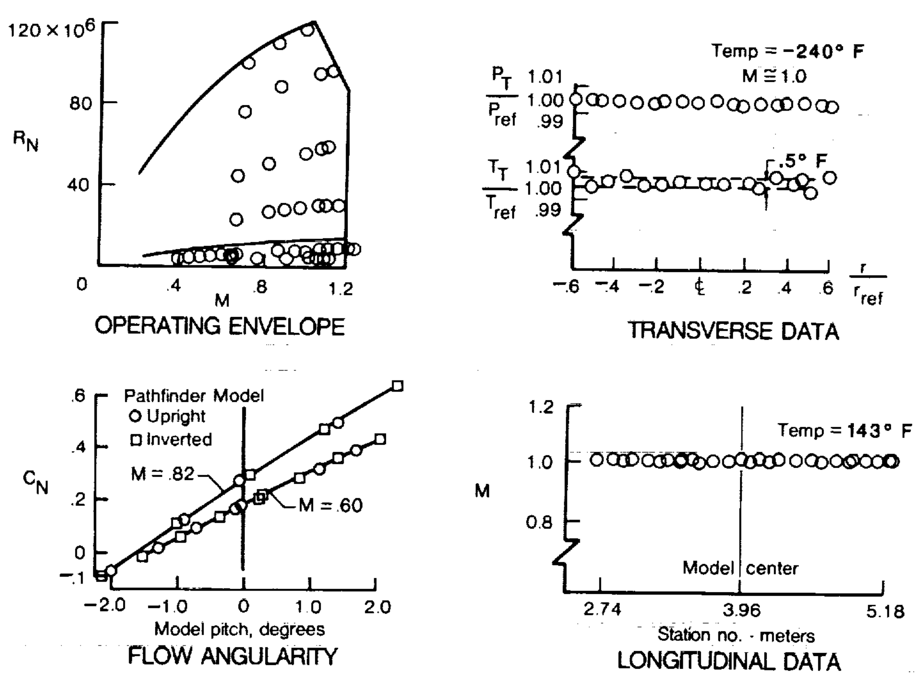


Figure 18. Typical calibration results.

NTF CALIBRATION RESULTS
T = 100°F

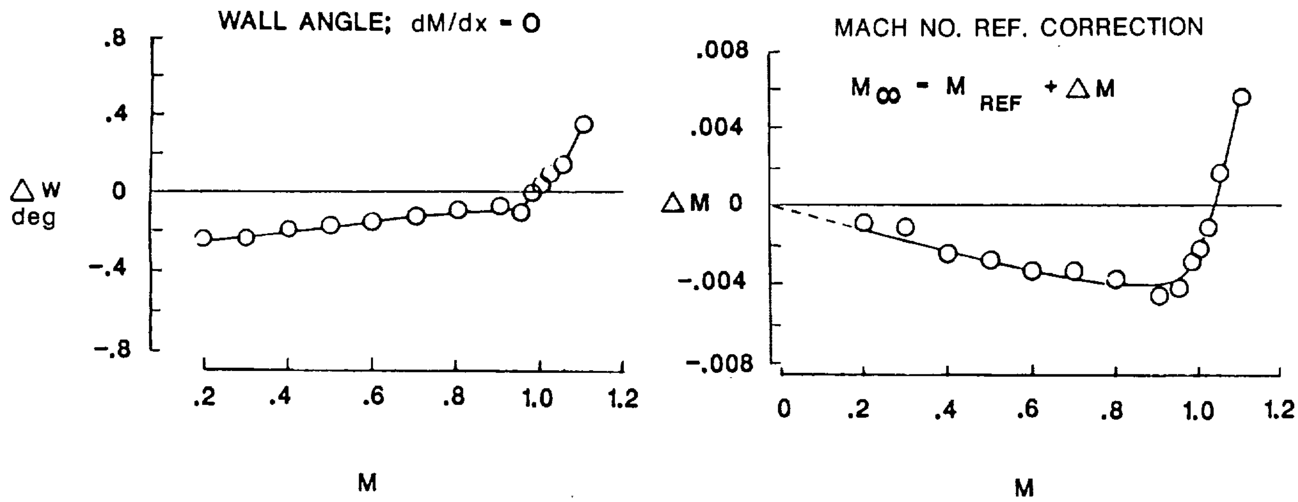


Figure 19. Variations of test section wall angle required for zero Mach number gradient at the model location and correction to reference Mach number with Mach number. Stagnation temperature = 100°F.

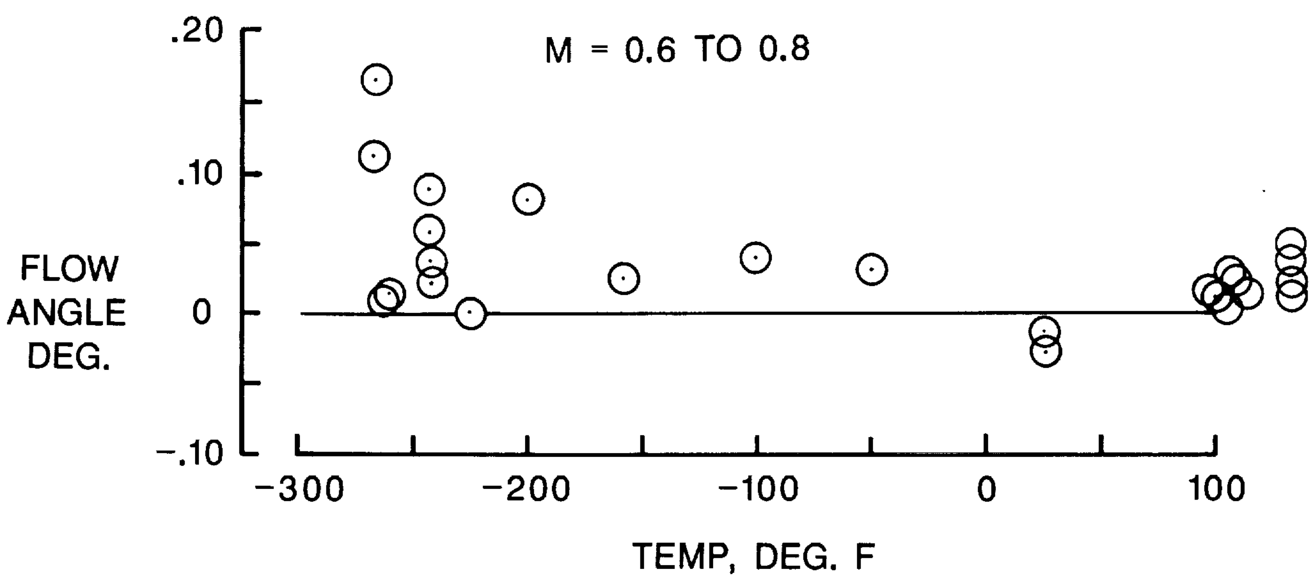


Figure 20. Typical variation of tunnel flow angle with temperature as measured by model upright and inverted. M = 0.82.

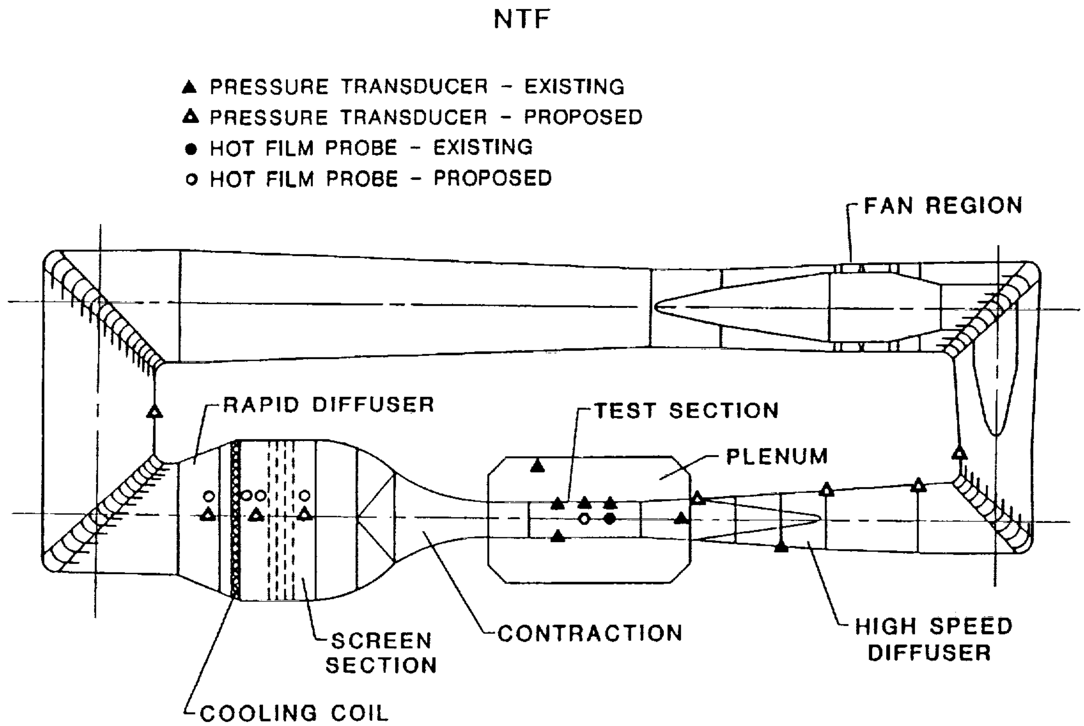


Figure 21. Location of dynamic flow quality measurements.

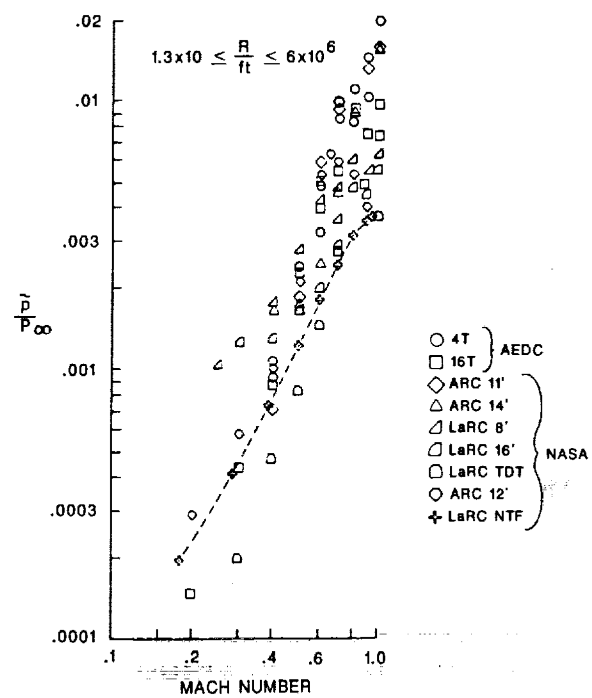


Figure 22. Variation of fluctuating static pressure in the test section with Mach number for several major wind tunnels.

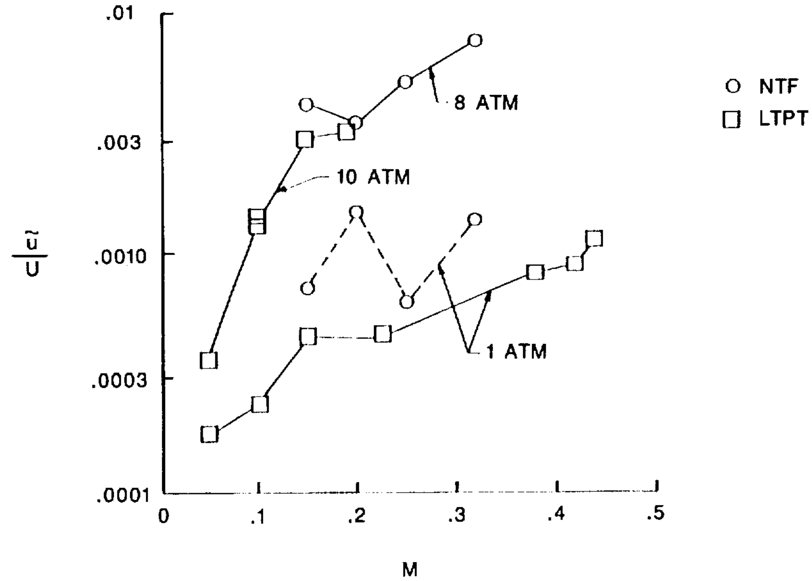


Figure 23. Comparison of turbulence measurements in the test section for the NTF and LTPT.

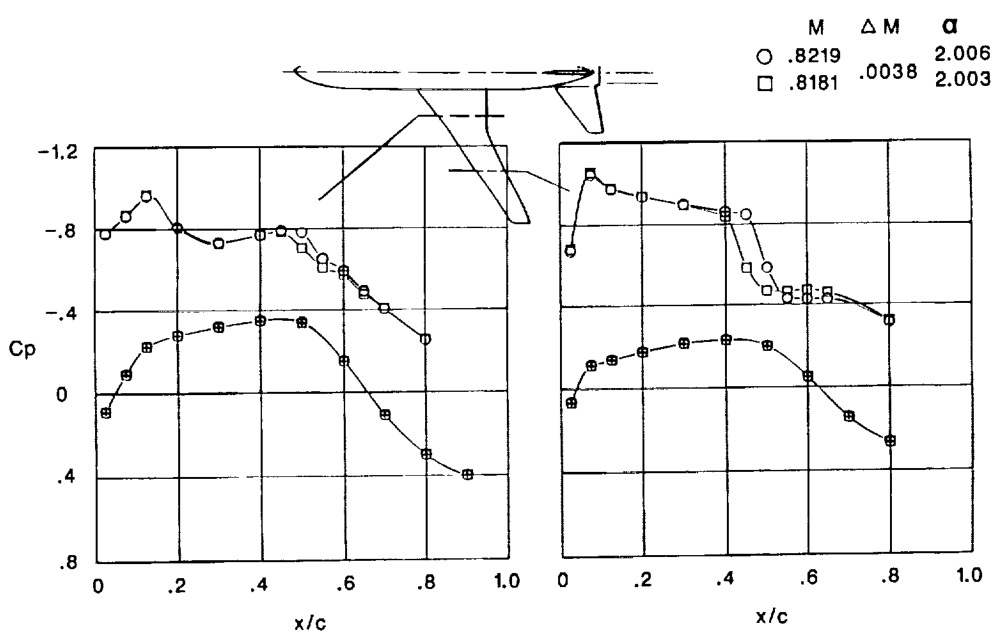


Figure 24. The effect of Mach number on wing pressure distributions for the Pathfinder I model. RN = 6.5×10^6; transition fixed at 0.10c.

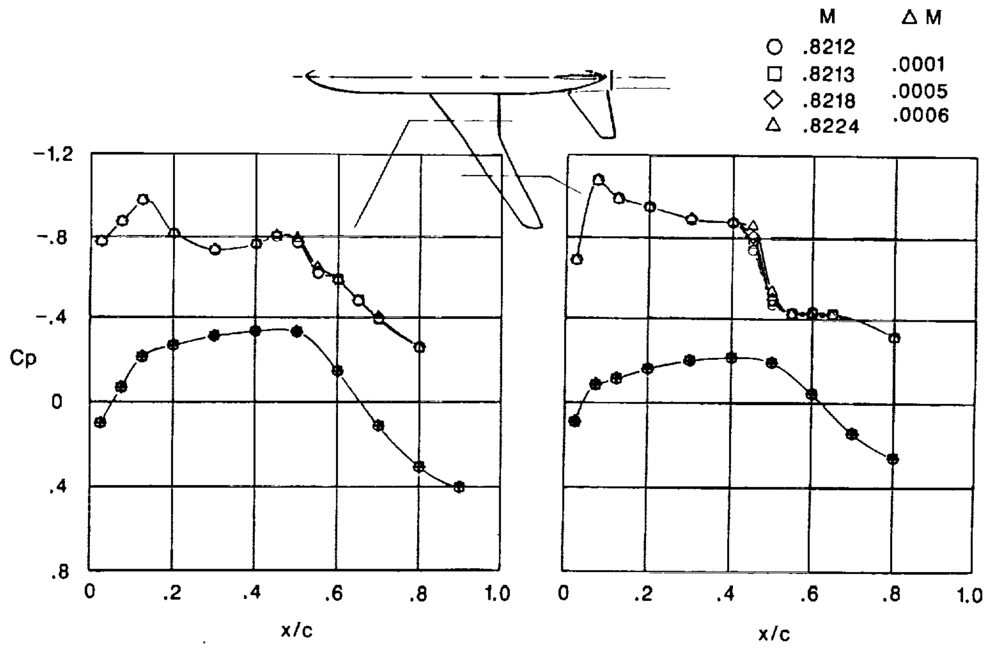


Figure 25. The effect of Mach number on wing pressure distributions for the Pathfinder I model. RN = 8.9 x 10^6; transition fixed at 0.10c.

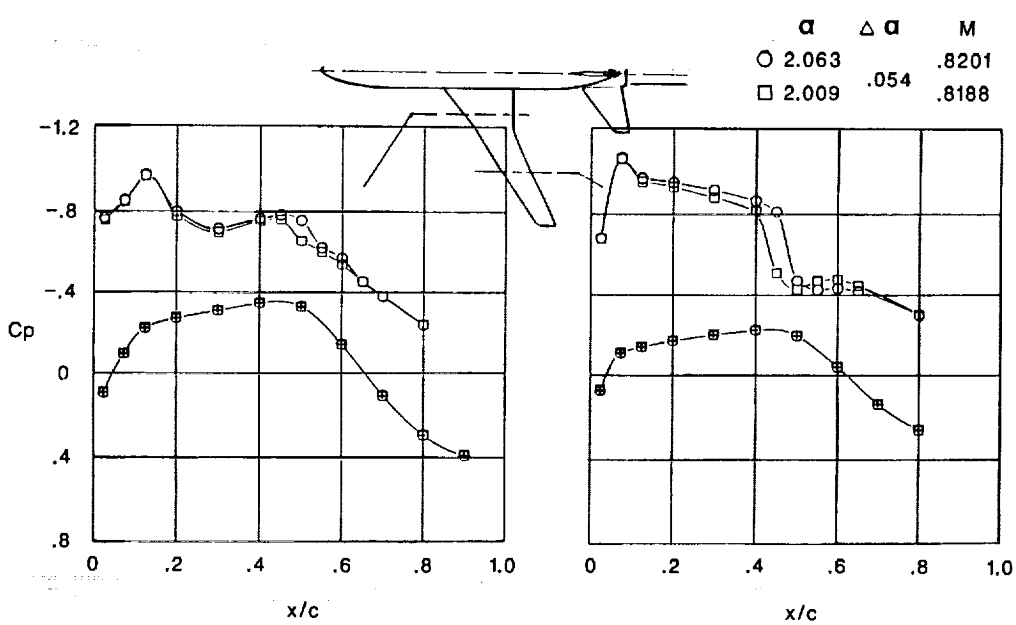


Figure 26. The effect of angle of attack on wing pressure distributions for the Pathfinder I model. RN = 6.0 x 10^6; transition fixed at 0.10c.

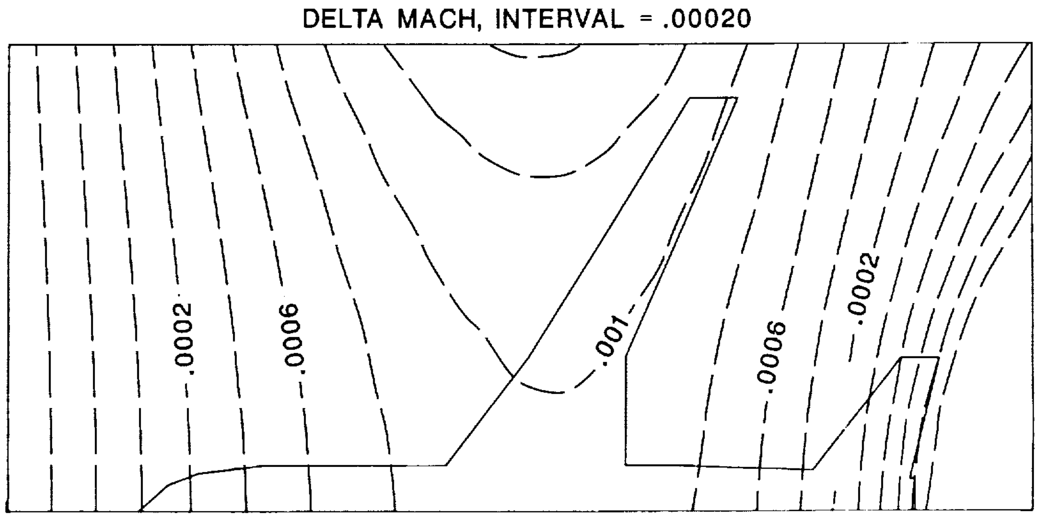


Figure 27. Typical example of calculated wall boundary induced Mach number contours.

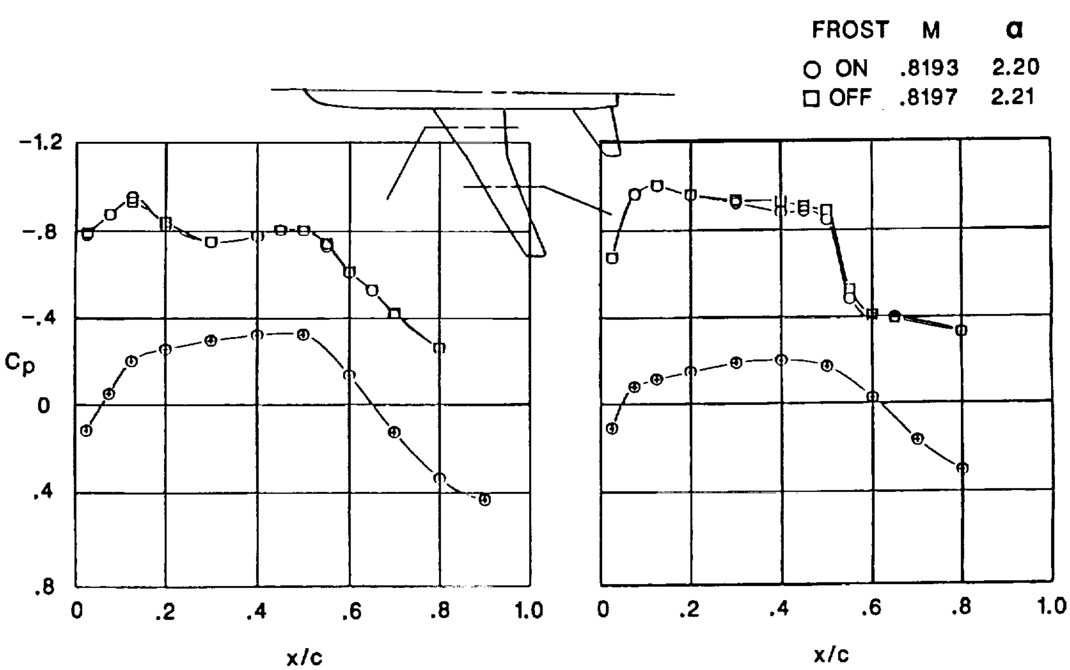


Figure 28. Comparison of pressure distribution for the Pathfinder I model with and without frost on the wing. RN = 23.0 x 10^6.

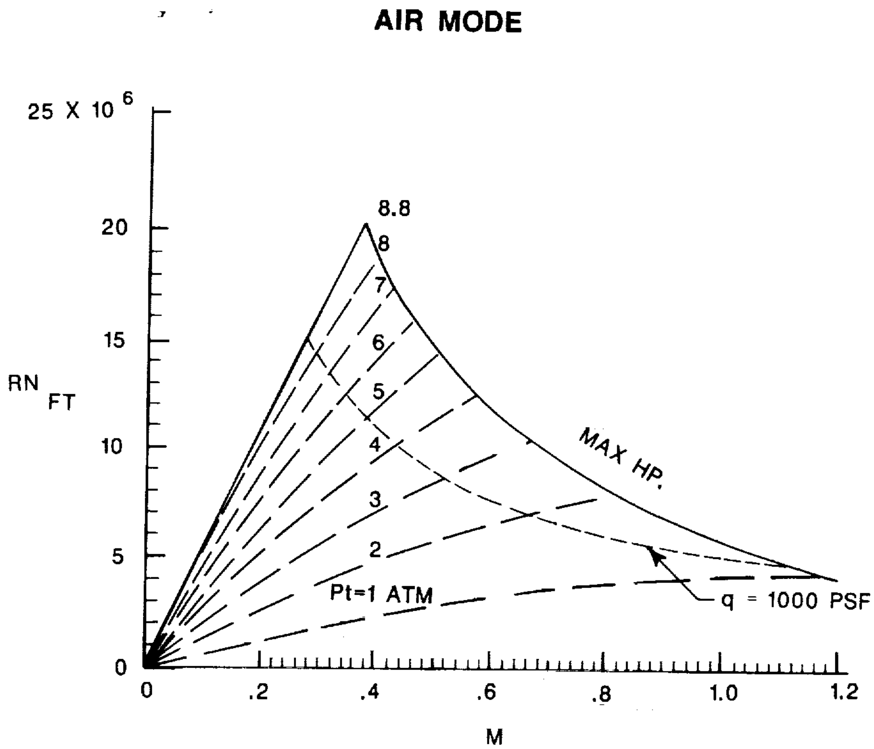


Figure 29. NTF operating envelope at ambient temperature.

Figure 30. EA-6B model mounted in NTF.

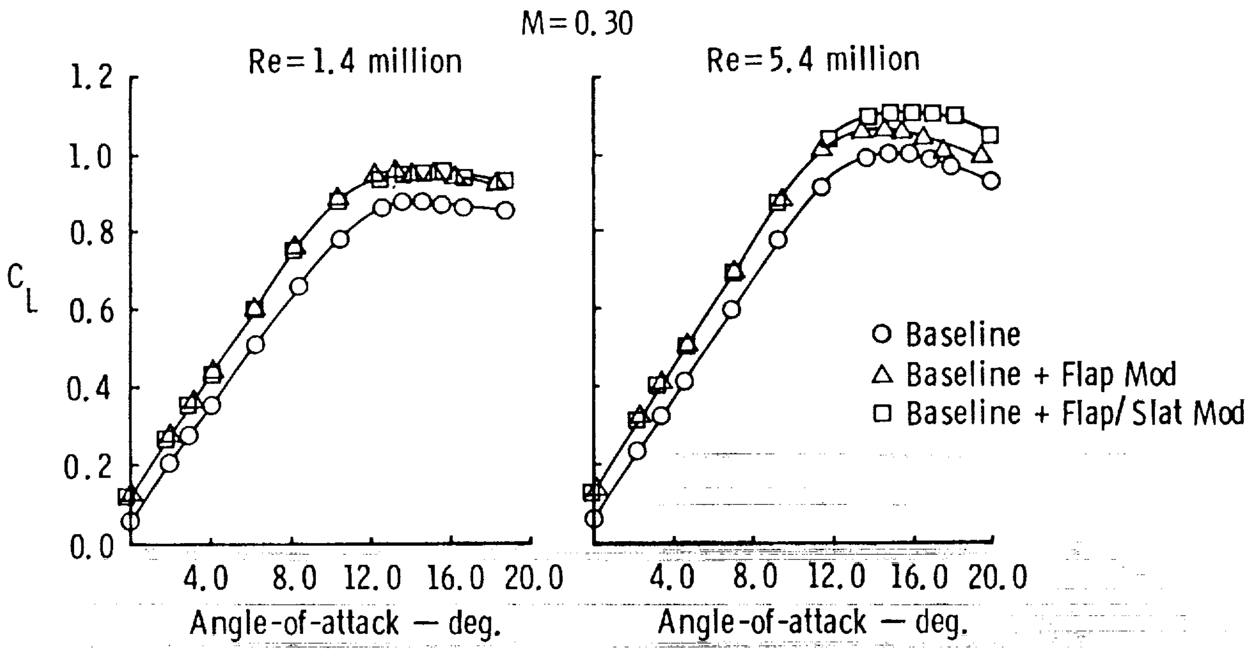


Figure 31. The effect of flap/slat modifications on the low speed lift characteristics for the EA-6B aircraft model. M = 0.30.

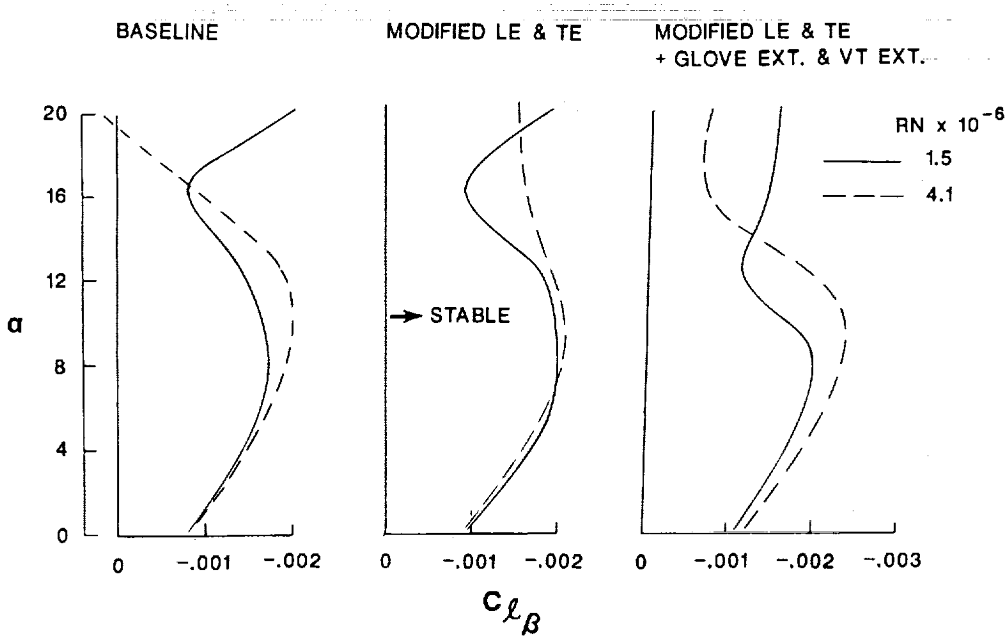


Figure 32. The effect of Reynolds number on rolling moment due to sideslip for the EA-6B. M = 0.30.

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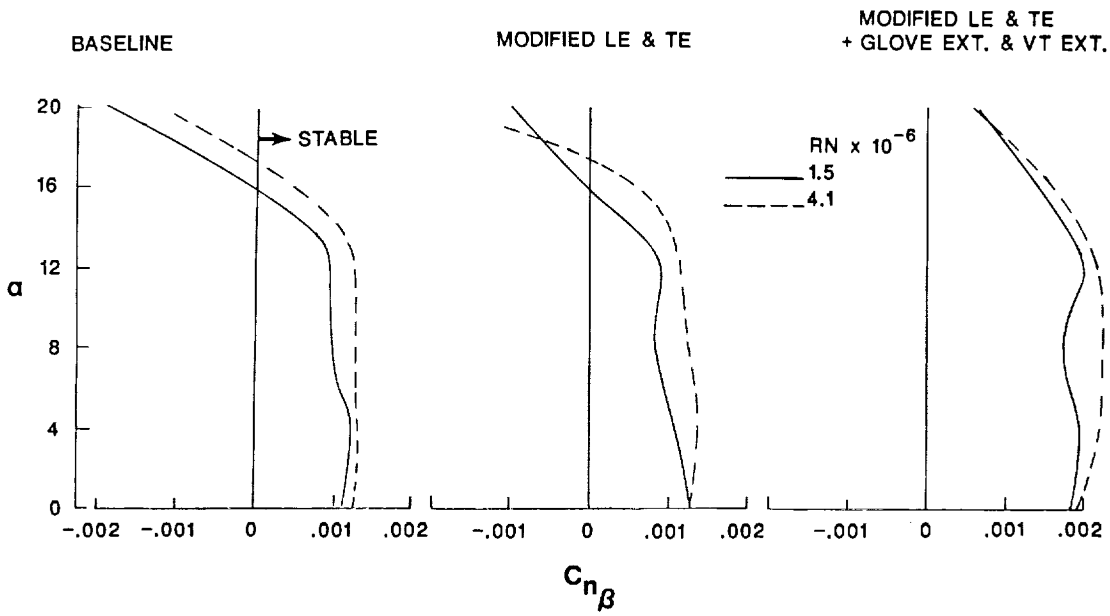

Figure 33. The effect of Reynolds number on yawing moment due to sideslip for the EA-6B. M = 0.30.

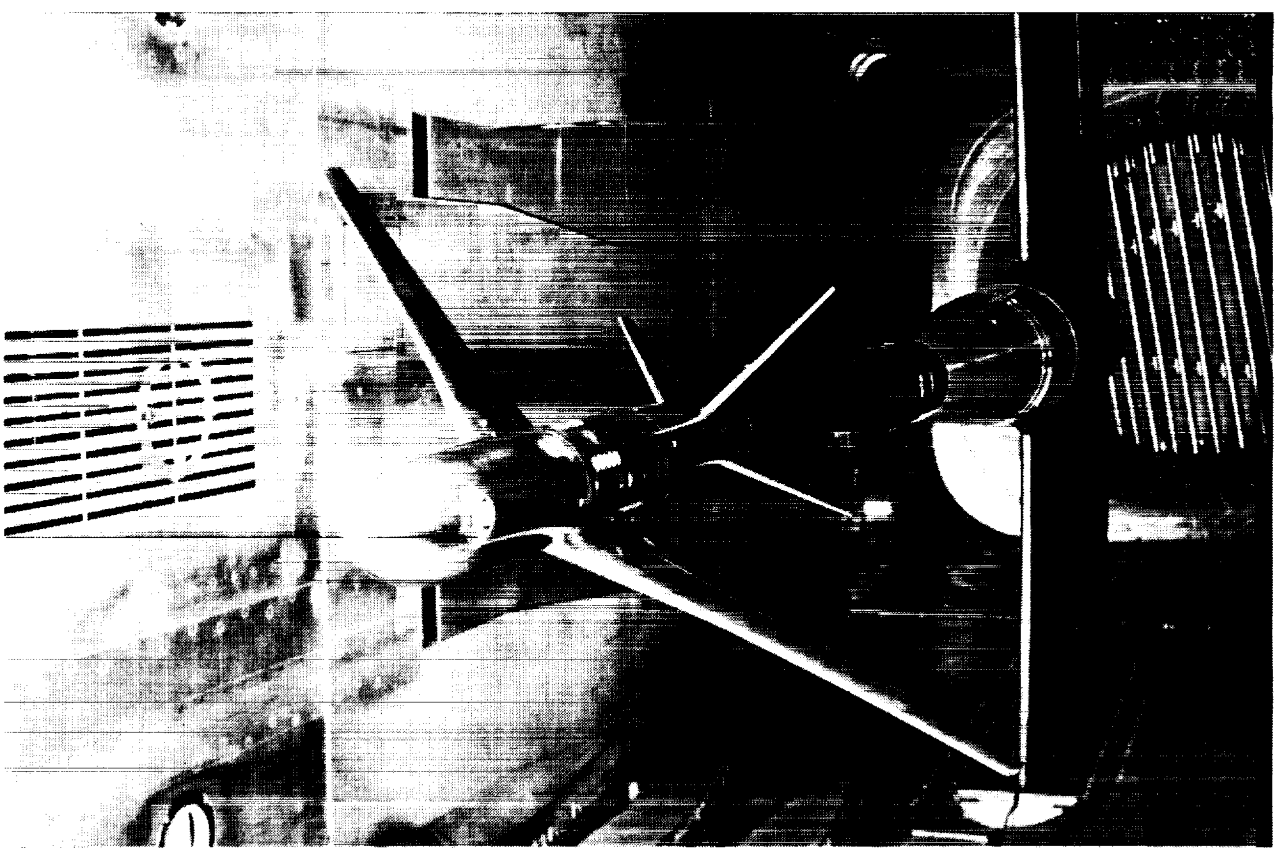

Figure 34. Photograph of the Pathfinder I model mounted in the NTF.

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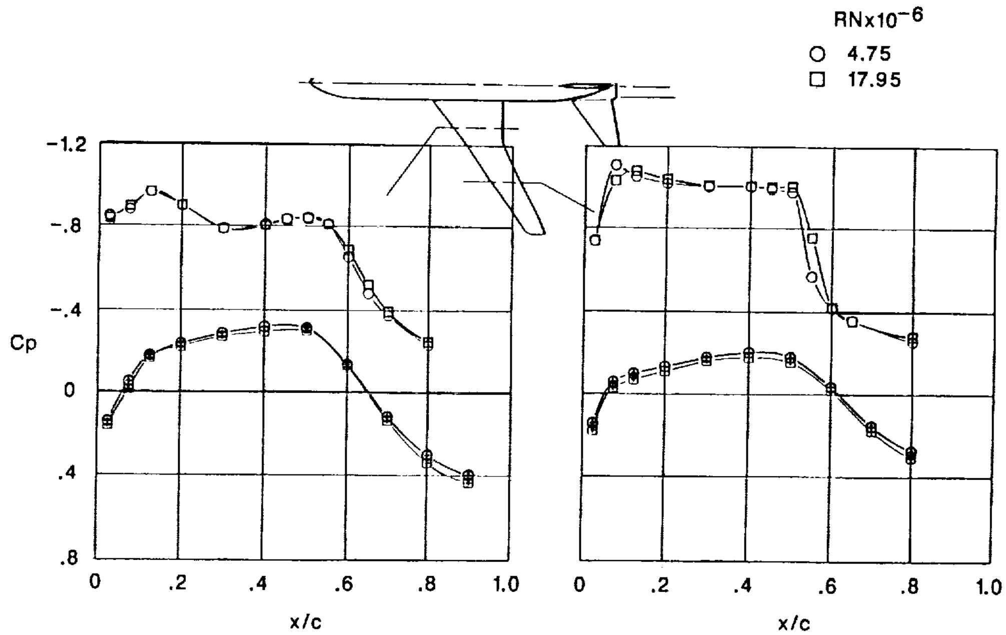

Figure 35. Effect of Reynolds number on wing pressure distributions for the Pathfinder I model. $M = 0.82$; $\alpha = 2.57°$; transition fixed at 0.10c.

LOCKHEED HIGH WING TRANSPORT CONFIGURATION

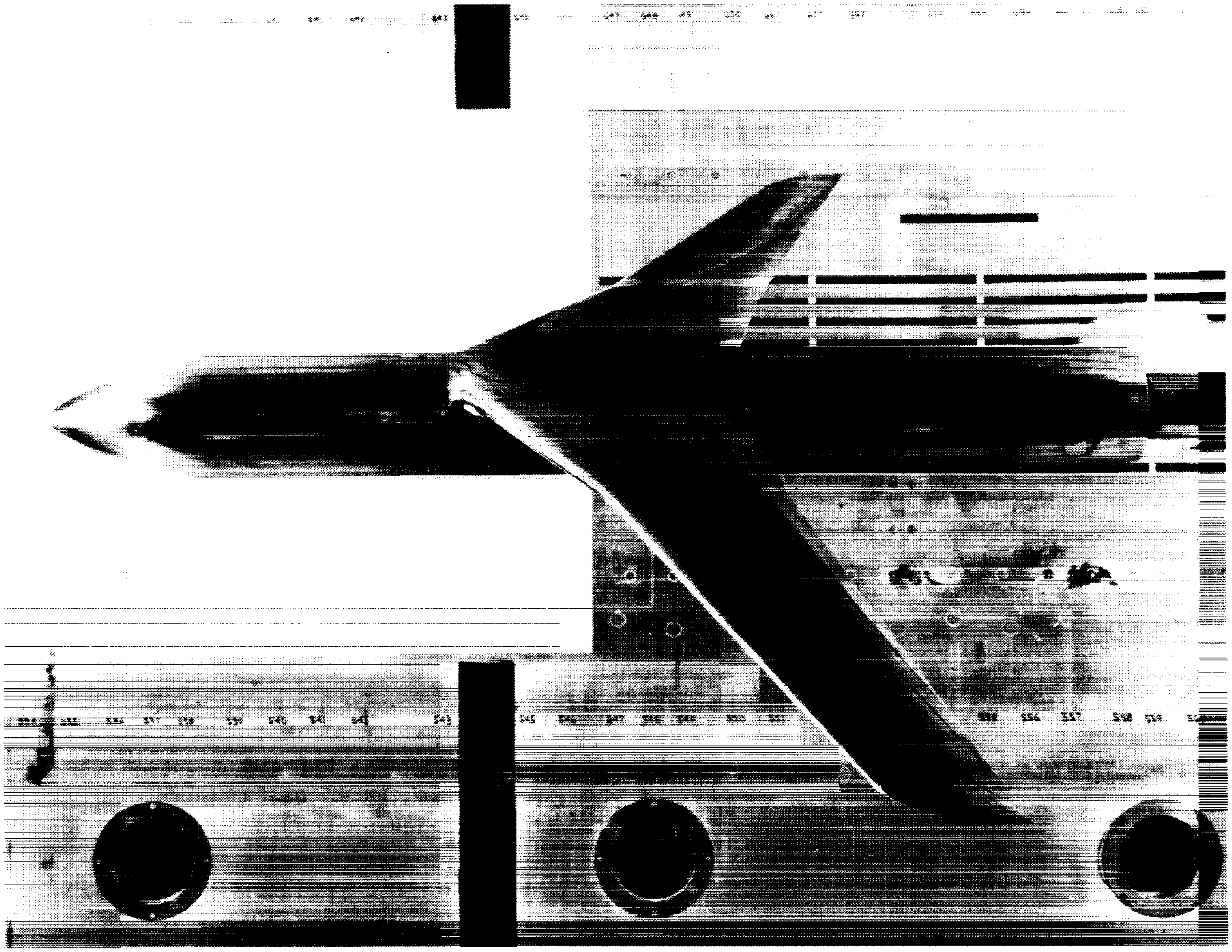

Figure 36. Photograph of Pathfinder I fuselage with the Lockheed transport wind installed in the NTF.

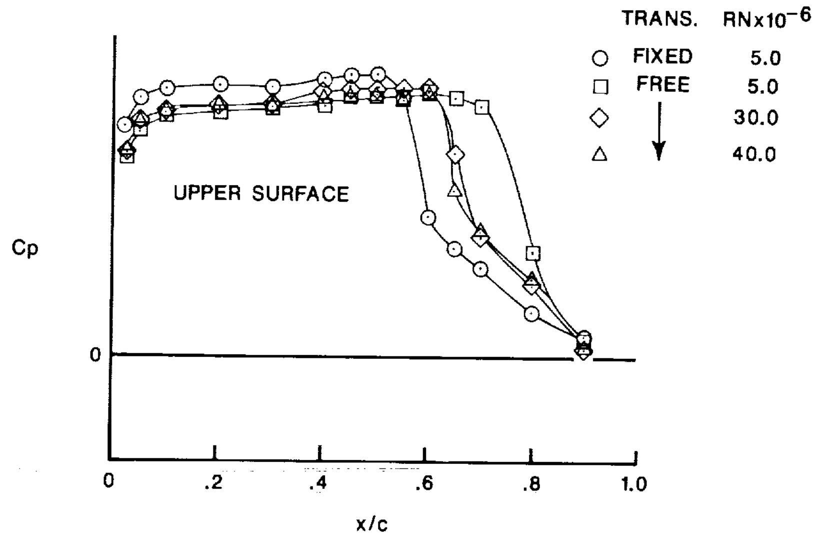

Figure 37. Effect of Reynolds number on wing pressure distributions for the Lockheed high wing transport configuration. $M = 0.80$; C_N = Constant.

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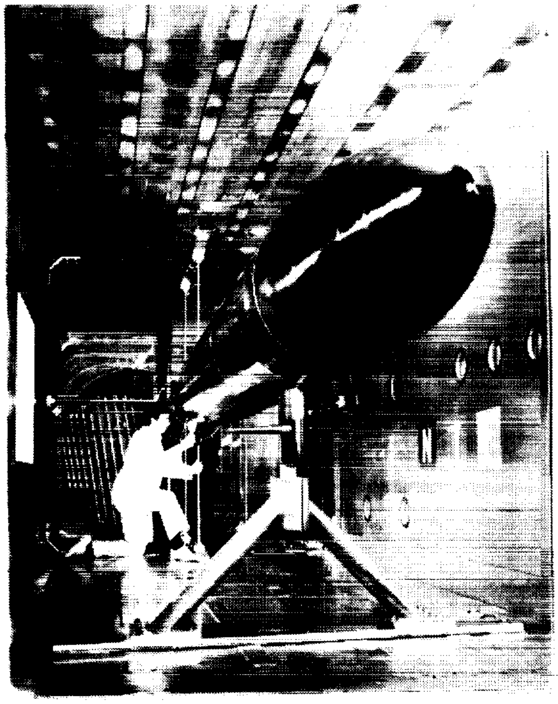

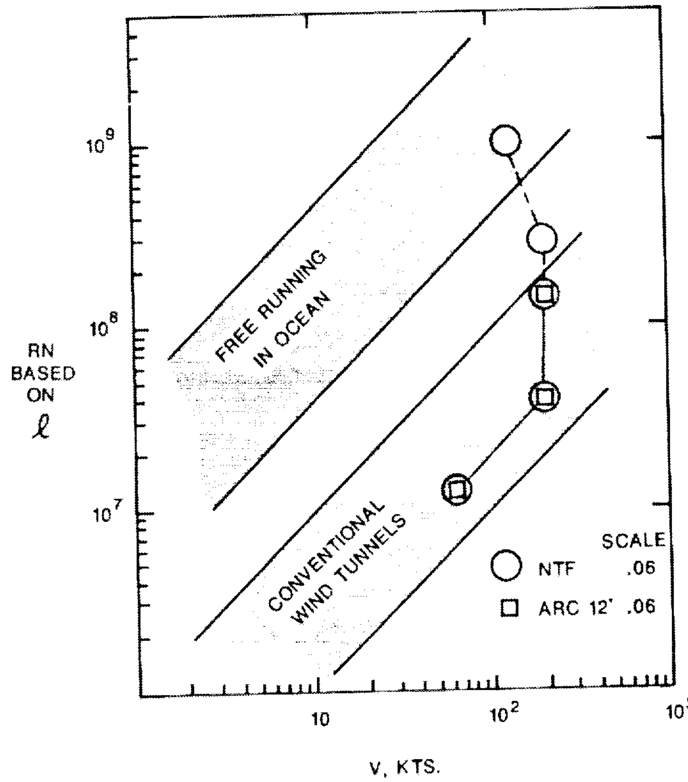

Figure 38. Photograph of submarine model mounted in the NTF and Reynolds number envelope.

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