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Overview of the 1989 Wind Tunnel Calibration Workshop

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OVERVIEW OF THE 1989 WIND TUNNEL CALIBRATION WORKSHOP

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Introduction

The purpose of the Workshop, held at Langley Research Center, Hampton, Virginia, April 19 - 20, 1989, was to explore wind tunnel calibration requirements as they relate to test quality and data accuracy, with the ultimate goal of developing wind tunnel calibration requirements for the major NASA wind tunnels at Ames, Langley and Lewis Research Centers.

There were two plenary sessions. The first addressed "What Constitutes a Properly Calibrated Wind Tunnel from Your Perspective and Why?" with industry, Air Force and NASA presenters. The second was "Status of Calibration of NASA's Major Wind Tunnels," with NASA presenters only.

These were followed by two working sessions which attempted to synthesize those portions of the presentations which were relevant to bringing the goal of the Workshop into focus. The first of these working sessions split into two groups, one dealing with subsonic/transonic facilities, and the other with supersonic/hypersonic facilities. The guidelines and recommendations they generated were presented to, and discussed by, the Workshop Attendees at the second working session.

This Overview attempts to capture the essence of the most significant contributions to the stated goal, and to present the consensus of the Workshop's conclusions and recommendations regarding formulation and implementation of that goal.

Background

Historically, the first calibration in a NASA wind tunnel is performed during tunnel shakedown following completion of construction. This is a key element in the process of determining whether the facility meets design specifications. The parameters selected for measurement, their distribution throughout the test volume, and their accuracy should be consistent with the types of testing to be performed, and the state of the art of the instrumentation used.

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With a new facility, there are always very compelling pressures to get to the business of turning out data to support the research and development programs for which the facility was built. Some facility managers resist these pressures and take the time to do a commendable first calibration; others succumb to them and wind up with calibrations which are minimal. In these latter cases, the calibrations are generally not published in the open literature, but wind up in a drawer someplace for the personal use of the facility staff. And even when the calibrations are extensive, there is no guarantee that they will be published.

Over the life of a facility, there will always be need for additional calibrations -- after changes have been made to the facility, when meeting a need for greater calibration accuracy is enabled by significant advances in instrumentation capability, when new types of testing are to be undertaken, etc. And the same pressures to minimize the amount of calibration data taken are always present. Extensive calibrations are time consuming, and all the major NASA facilities have large testing backlogs -- calibration time encroaches on testing time. As with initial calibrations, there is a wide variation in quality, extent, and availability of currently applicable calibrations among NASA's major wind tunnels. Concern for the magnitude of this variation led the Office of Aeronautics and Space Technology (OAST) -- now the Office of Aeronautics (OA) -- to convene the Workshop with the ultimate goal of developing wind tunnel calibration requirements.

A thorough calibration accurately measures all the pertinent flow variables for all wind tunnel operating conditions with sufficient density throughout the test volume that quality of flow in all three axes can be evaluated with precision under any test conditions. The task of the facility manager is to perform the calibrations in such a way that there will be enough information to do a reasonably accurate flow field evaluation without being overwhelmed by more data than is absolutely essential. This requires experience, flexibility, and sound engineering judgment. It is hoped that the material presented at the Workshop, and the recommendations developed by the Working Groups will be valuable catalysts for bringing the quality and availability of the calibrations of the NASA wind tunnels to a uniformly high state.

Overview of Presentations

Session I -- What Constitutes a Properly Calibrated Wind Tunnel from Your Perspective and Why?

A review of the first session's papers indicates a range of interpretations of what constitutes a calibration, from the conventional one that it is a set of measurements which define the characteristics and quality of the flow in the wind tunnel's test section, to a broader one that it also includes what will enhance getting the "right" answer to the aerodynamic or aerothermodynamic problem being simulated. The following overview is faithful to the view taken by the writer of each paper.

Reference 1: J. R. Cornelius - Boeing Commercial Airplanes

Wind tunnel calibrations are conducted in order to:

- Verify and document flow qualities and uniformities within the test volume
- Provide correction factors or adjustments to be applied to measured aerodynamic data

The reference discusses low speed and transonic wind tunnel calibrations as influenced by data quality and precision requirements for **commercial transport** development. The accuracy with which flow parameters are measured and how their distributions are determined will ultimately influence the aerodynamicist's ability to assess and predict aircraft performance, stability and control characteristics. If less than desirable flow characteristics are indicated, every effort should be made to track down the cause, and to rectify the situation. In today's competitive environment, it is crucial that these calibration flow parameters be documented and carefully monitored through initial and periodic evaluations.

The calibration parameters of concern are indicated in Figure 1. The primary considerations are the measurement of flow speed and flow angularity. Flow angularity distribution indicates the extent of secondary flows in the test volume, giving insight into flow symmetry and gradients that can influence wing twist distribution effects, stability derivatives, nacelle orientation, etc. The distribution of local speed and angularity throughout the test volume should be such that a representative value of each can be calculated for the model reference point -- the value may be an average over the test volume most models are expected to traverse during typical tests. In addition, the individual calibration measurements throughout the volume should be available in a form that will allow those unfamiliar with the facility to judge whether the flow characteristics are uniform enough for their requirements, to check how the reference values were determined, or to calculate their own reference value over a different space if desired.

Any increment between the test section wall static pressure measurement location and the model reference point must also be accounted for. Static pressure, being the most difficult parameter to measure, requires that great attention be paid to probe design. Temperature distribution is another indication of test volume flow qualities. Both temperature stratification and large gradients will influence model drag measurements. Turbulence and acoustic measurements are also becoming more important as the development of laminar flow techniques advance.

Since dynamic pressure accuracy directly affects aerodynamic coefficients, the precision of its calibration is of great importance. Providing aircraft customers landing and takeoff guarantees prior to acquiring flight test data is normal in the commercial business. Errors introduced in model test data do not surface until flight validation tests. An error in maximum lift coefficient of 0.1 is equivalent to 3.0 knots in approach speed. Errors in lift or L/D can influence takeoff field length or payload on a percentage basis. Boeing strives for a precision of better than +/- 0.25 percent for each dynamic pressure measurement with a variation throughout the test volume of less than +/- 0.50 percent.

Earlier calibrations indicated larger than desirable disturbances in the vertical plane at the lateral centerline of the test section of the University of Washington Aeronautical Laboratory (UWAL) Low Speed Wind Tunnel (see Figure 2). The anomaly caused discontinuities and misleading directional stability data. "Fine tuning" the 4th corner turning vanes and the anti-swirl vanes downstream of the fans made a significant improvement in both the flow angularity and the lateral distribution of longitudinal turbulence level (see Figures 3 and 4).

Whereas the primary calibration parameter in low speed flow is velocity, in transonic flow it is Mach number (M). A 0.001 error in M at the drag divergence M is worth one count in model drag. The same concerns for accuracy and distribution apply to M as for flow speed so that a representative value can be determined for the model reference point.

The calibration should allow accurate longitudinal pressure (or M) gradients to be determined. Even a small gradient, such as 0.0006 in M over the length of the model can yield one count of buoyancy drag, as indicated in the Boeing Transonic Wind Tunnel (BTWT) data in Figure 5.

Tunnel flow angularity distribution should be mapped to provide a qualitative understanding of working section flow quality -- as illustrated in Figure 6 -- even though corrections are not usually made to the data from this tunnel for these flow angle variations. It is the integrated upflow that is most frequently measured, tracked and corrected for in the data; a calibration model with a typical transport planform should be tested upright and inverted to establish the integrated upflow/downflow values. Both wing-body upflow and upflow at the horizontal tail should be determined. At a lift coefficient of 0.5, an upflow shift of +/- 0.01 degrees will cause a lift offset and polar rotation worth one count of drag coefficient.

Note that the practice of testing a calibration model upright and inverted in order to establish the tunnel's integrated upflow/downflow values is common in facilities with sting supported models (if the support strut is not symmetric, it must be made so by a dummy addition to the strut system when the measurements are made). This is not a reasonable practice in large tunnels with external balances and tripod supports; here the approach discussed earlier is used.

Upflow is a function of tunnel configuration and cleanliness. Values should be measured periodically and whenever work has been done to the tunnel circuit. As can be seen in Figure 7, tunnel modifications in September 1985 had a marked effect on test section upflow in the BTWT. In addition to periodic measurement of upflow with the calibration model, the upstream flow angle in the BTWT is measured pre- and post-test with a quick look probe. Monitoring of upsteam flow angle in this manner provides a good indication of flow angularity shifts and the need to recalibrate with the calibration model.

Reference 2: J. R. Strong - Douglas Aircraft Company

A properly calibrated wind tunnel requires an intimate knowledge and understanding in four basic areas:

- Flow quality throughout the test volume with the tunnel empty.
- Flow conditions throughout this same test volume with the model present.
- Model installation requirements.
- Data integrity requirements.

The most significant elements of each of these basic areas are defined as follows:

- Test section empty flow quality
  - Pressure and temperature measurements should be sufficiently accurate that Mach number can be determined to +/- 0.001, total temperature to +/- 10 degrees F, and turbulence level to +/- 1 percent root mean square (RMS) pressure coefficient.
  - Air dew-point temperature must always be maintained less than free stream static temperature to avoid local condensation shocks, with their consequent perturbation of the local flow quality.
  - It is important that the model support system be in place when making the static pressure measurements from which the longitudinal buoyancy corrections will be determined.

- Test Section/Model Flow Conditions
  - Determine tunnel flow angularity.
    - Get integrated flow angularity for each model by testing it rightside up and upside down at zero normal force. The value determined is a function of both the tunnel empty flow characteristics and the surface contours of the model being tested -- each model distorts the local flow field differently.
  - Determine model support interference.
    - The interference effects result from interactions between the support system and the model, and vary with changes in model attitude and model configuration.
    - For tunnels with external balances and strut supported models, experimental determination of interference effects requires use of a mirror image of the strut support system, and multiple tests.
    - While in concept, interference effects should be determined for every model attitude and control surface setting, actual practice generally ranges between the following two approaches:
      - determine the effects for a few conditions, including extremes; then, based on experience, estimate interference effects for intermediate conditions.
      - as first approximation, determine tare correction for loads on support strut(s) alone, but make no corrections for model/support interference effects. The saving grace to this approach is that the primary

concern is usually the incremental change in aerodynamic characteristics caused by configurational changes, rather than absolute values.
    - Intensify efforts to develop Computational Fluid Dynamics (CFD) codes for accurate estimation of support interference corrections.
  - Evaluate wall interference effects.
    - Neglect of these effects is not uncommon.
      - May be acceptable when goal is change in aerodynamic characteristics due to incremental change in configuration.
    - Concentrated effort to develop appropriate CFD codes and integrate their use into wall effect determination programs is required.

- Installation Effects on Model
  - Be aware of any installation requirements which wind tunnels under consideration for testing a model may have and how they may impact model design requirements. Will design requirements force some model contour integrity to be sacrificed? If so, what measurements will be required to correct for the distortion? Be sure these measurements will be made available.
  - Accuracy of +/- 0.01 degree required in model attitude setting.
  - Instrumentation calibration accuracy requirements are:
    - Internal balance -- +/- 0.25 percent maximum anticipated load
    - Pressure transducer -- +/- 0.25 percent maximum load capability
    - Thermocouple -- +/- 10 degrees F

- Wind Tunnel Data
  - Force and Moment
    - For sting supported models, proper balance selection is driven by customer requirements.
    - Data fidelity must be monitored constantly, and in real time.
      - Display data in coefficient form as it is being obtained, with provision to compare this data to similar data base when questions of fidelity arise.
      - Provision to switch from stability to body axis should be an option to aid diagnostic capability.

- Flow Visualization
    - Supplement data on local flow conditions and transition/shock wave location with:
        - Oil flow
        - Tuft studies
        - Pressure sensitive paint
            - While still in its infancy, this technique offers great promise, and its continued development should be vigorously pursued.

- Recommendations
    - Tunnel Calibration History
        - Documented, up-dated, and readily available -- NASA wind tunnel calibrations should be published in documents which can be referenced.
        - Calibrations should be checked/updated annually.
            - Use calibration models to check integrated effects.
        - Periodically check flow at various similar facilities with common calibration model.
    - Emphasize use of CFD in our continual efforts to learn how to relate wind tunnel test results to flight.

Reference 3: L. A. Wood - McDonnell Aircraft Company, McDonnell Douglas Corporation

The need for periodic calibrations throughout the entire test volume is Illustrated. Deviations from flow uniformity can occur unexpectedly, will probably not be picked up without a calibration, and will not always be detected by centerline calibrations only. Two experiences with excessive flow deviations off the tunnel centerline are described.

The first example is from the McDonnell 8.5' X 12' Low Speed Tunnel. That the tunnel's flow characteristics had changed was discovered fortuitously when test results on a particular model showed large differences in data compared to earlier tests. A dynamic pressure survey was then made across the test section which showed significant differences from an earlier calibration.

Tests earlier in the year which used smoke for flow visualization had left a slight residue on the screens in the settling chamber. Previous experience indicated that this would not cause a problem, and thus was of no concern.

However, a subsequent test had been run using an acoustic material. It was eventually found that extremely small acoustic fibers from this test had stuck to the smoke residue on the screens, thus reducing their porosity nonuniformly. Cleaning the screens corrected the dynamic pressure variation, as indicated on Figure 8. Note that both pre- and post-cleaning surveys show good agreement right on the centerline.

The second example is from the Douglas 4'X4' Trisonic Wind Tunnel at El Segundo (dismantled in 1984). Figure 9 shows the limits of a vertical traverse run at constant angle of attack to investigate the effect of model vertical position in the test section. Tests covered the Mach number range of 0.85 to 1.97. Results are shown in Figures 10a and 10b. There were significant variations in lift and drag coefficient, with the greatest at transonic Mach numbers. The variations were attributed to flow non-uniformity and wall effects. The situation was resolved, and subsequent vertical traverses at constant angle of attack were conducted successfully. It then became Standard Operating Procedure to perform these constant angle of attack vertical traverses periodically.

Reference 4: F.W. Steinle, Jr. - Ames Research Center, NASA

The primary goal of wind tunnel calibrations is to so characterize the state of the flow that the derived data can be used with confidence for:

- Code validation
- Configuration development decisions
- Prediction of flight performance
- Developing facility modifications

The author summed up in Figure 11 what he feels is a general representation of the situation at the Ames Research Center concerning wind tunnel calibrations in general -- excepting the National Full-Scale Aerodynamic Complex (NFAC) Facilities, 40'X80' and 80'X120', which have recently been thoroughly calibrated. Most calibrations are done to satisfy a specifically identified need in as short a period of time as possible because of great pressures to get on with putting the facilities into service supporting research and development activities. The usual result is that calibrations are minimal, pay little attention to off-centerline data, and are generally not published.

Important questions for which guidance should be established are:

- How extensive should a wind tunnel calibration be?
    - Tailored to purpose
- How should calibrations be used?
    - State of art limited -- needs much work

Today there is little pressure to obtain much beyond basic stream angle and M (or dynamic pressure) calibrations, with a mild interest in turbulence and acoustic levels. Interest in CFD validation seems to be pointing toward measurements in the outer flow field and calibrating for wall interference effects. One of the goals of CFD is to be able to combine it with detailed flow field calibration measurements to enhance the interpretation of the data measured on the model in the wind tunnel.

One component of a current Construction of Facilities (CoF) project at Ames is designed to improve the flow quality in the 11-Foot Transonic Wind Tunnel. Previous calibrations revealed the need for flow improvement. Additional calibrations, coupled with CFD analysis, tracked down the sources of the irregularities in the flow, and guided the redesign. Figure 12 indicates the four main flow quality specifications the upgraded facility is to meet. These requirements are quite stringent, and will require state of the art instrumentation. It is expected that flow field calibrations consistent with these types of improvements will become the norm as research and development interests sharpen in the future.

Reference 5: Rick Burrows - Rockwell International, Space Systems Division

Rockwell's experience testing the Space Shuttle in a wide variety of wind tunnels, including most of the major wind tunnels in the U.S, is drawn upon. The tests covered a broad range of test disciplines over a Mach number range of 0.2 to18, used both full and partial configuration models in various mounting locations in the various tunnels, and pushed or exceeded the limits of the calibration data in many of the tunnels used. Models encompassed the full test rhombus of many of the tunnels, traversing angle of attack ranges of -10 to + 45 degrees, and occasionally to +90 degrees. During separation tests in some facilities, where the model traversed a portion of the test rhombus at constant angle of attack, force and moment data varied, indicating flow nonuniformities. Occasionally Rockwell found it advisable to perform calibrations using their own hardware, particularly for flow angularity. In one facility, a complete calibration was done after it was ascertained that tests gave incorrect pitching moments.

A program like this, which requires the use of many different facilities, encounters a wide range of management attitudes towards the importance of thorough calibrations, and emphasizes the value that generally accepted wind tunnel calibration guidelines would have to all facility users, and to outside users in particular. Based on the Space Shuttle wind tunnel testing experience, Rockwell encourages widespread adoption of such an approach.

With the primary goal of reducing uncertainties in wind tunnel test data, future tunnel calibration efforts should include not only a higher density of static (RMS) measurements throughout the test volume than is currently common, but also dynamic characteristics of the flow field with spectra of the measured parameters as well. The requirements Rockwell proposes for uniformly calibrating all industry and government wind tunnels are as follows:

- Tunnel flow field survey with sufficiently high density of data throughout the effective test rhombus that gradients of flow characteristics can be determined with confidence
    - Static data
        - Total pressure
        - Static pressure
        - Total temperature
        - Density
        - Flow angularity
    - Dynamic data
        - Spectrum analysis for each of above parameters
        - Particle distribution in flow field
            - Size and number
            - Velocity distribution versus size

A 3-tiered approach is suggested for achieving these wind tunnel calibration requirements, with the approximate time-phasing indicated:

- A near term (current) effort to obtain RMS levels of all calibration parameters with 1% to 2% uncertainty in absolute values.

- Long term (3 to 5 years) goals to include more detailed mapping of the RMS values of the calibration parameters throughout the tunnel test volumes, and to reduce calibration data uncertainties to 0.5% to 1%, assuming measurement equipment and instrumentation is sufficiently improved beyond current state of the art capability.

- Far term (5 to 10 years) goals to obtain spectra information on as many of the selected parameters as possible, and to fill in what gaps experience may show to exist in the near/long term calibration effort, such as continued emphases on reducing uncertainty in absolute levels of RMS calibration parameters, extending the tunnel calibration volumes, increasing the density of measurements throughout the test volume to improve flow parameter gradient determinations, etc.

Recalibration is required when modifications are made to a facility, and may be required for changes in operational procedures.

Because there is currently no universally accepted method for calculating individual and combined calibration parameter uncertainties, the relative merits of data from different wind tunnels with the same capability are often difficult to judge based solely on the stated uncertainty of the parameters of interest. Rockwell therefore recommends that a process be established that will lead to the adoption of uniform methods for calculating parameter uncertainties throughout the U.S. wind tunnel operating community.

Reference 6: N. E. Scaggs - Wright Research Development Center

Calibration requirements for high supersonic and for hypersonic M regimes are discussed. The flow field parameters of concern, and the associated instrumentation requirements in the supersonic and lower hypersonic regimes are similar to those required for subsonic and transonic flows. But at the higher hypersonic Mach numbers, where the energy levels drive the state of the gas beyond the ideal, more exotic parameter and instrumentation requirements prevail. The parameters of concern are indicated in Figure 13.

Wright Research and Development Center (WRDC) strives to obtain the highest quality calibration data possible. The steps they take to do this are focused on both **instrumentation** and **measurement** requirements as follows:

- **Instrumentation** requirements
  - Instrumentation quality -- high priority is placed on maintaining an inventory of state of the art instrumentation
    - high resolution of measured quantities
    - high overall frequency response in dynamic range of concern
    - high signal/noise ratio
  - Instrument calibration -- although the research staff does not calibrate the instrumentation used, they take an active role in defining and monitoring the calibration procedures.
  - Frequency of instrument calibration -- all instrumentation used to measure wind tunnel flow properties is calibrated/recalibrated just prior to use.
  - Documentation -- calibration procedures, and quality and uncertainty of measurements are fully documented for each instrument used every time it is calibrated/recalibrated.

- **Measurement** requirements
  - Redundancy -- all calibration flow parameters in WRDC wind tunnels are determined by a primary method, and then spot-checked throughout the calibration volume by at least one independent technique. Where possible, non-invasive techniques are used for spot checking. To be acceptable, the independent measurements at the same point must not differ by more than 0.5% of the primary measurement.
  - Repeatability -- data at given points must be duplicated under identical conditions on different days (sequential runs are not acceptable).
  - Data acquisition and reduction -- calibration procedures and methods of analysis must be fully documented in a form suitable for publication. Documentation will include whether data has been "corrected" or "smoothed" and indicate how and why if it has.

Definition of the dynamic flow properties in the free stream of the M=3 and M=6 High Reynolds number Wind Tunnels is of particular concern because of the viscous dominated nature of the research carried out in these facilities. Dynamic free stream disturbance characteristics have been obtained with both laser doppler velocimetry and single- and double-wire hot wire probes -- agreement falls within the acceptable range.

WRDC has high confidence in their ability to measure the state of the gas in hypersonic wind tunnels up to M of about 8 to 10. As M increases much above this, the difficulty of obtaining accurate flow field calibrations increases significantly. The higher the energy levels become, the greater the deviation from the ideal state and the farther the flow process departs from isentropic. The flow properties of the resulting real gas must then be determined solely from measurements made locally at the points of concern in the flow. Real gas CFD codes can contribute to the calibration process only after their validity has been verified by experimental measurements. WRDC's policy of verifying calibration measurements by at least two independent methods is being severely challenged in the real gas flow regimes.

WRDC is attempting to improve their hypersonic real gas flow research capability by focusing a portion of their resources into a closely coordinated research program with three elements: design of real gas facilities, the required calibration instrumentation, and the most appropriate CFD codes.

Session II -- Status of Calibration for NASA's Major Wind Tunnels

The status of calibration of the major wind tunnels at Ames, Langley and Lewis Research Centers were presented at this session. A summary of the parameters measured, distribution through the test volume and publication status is indicated in Figures 14a through 14c.

Session III and IV -- Working Group Activity

Two Working Groups were appointed and given the task of drafting recommendations for wind tunnel calibration requirements for NASA's major wind tunnels. In their deliberations the members were to consider their own background and experience, and the material and discussions of the preceding two sessions. They reported their findings and recommendations back to the Workshop for comment and discussion.

One Working Group, chaired by Frank W. Steinle, Jr., of Ames, dealt with **Subsonic/Transonic** wind tunnels; the other, chaired by Aubrey M. Cary, Jr. of Langley, dealt with **Supersonic/Hypersonic** wind tunnels.

The reason for dividing the responsibilities of the Working Groups into these two categories is because of the natural consequences of the different field of influence of disturbances in their flow fields. In **subsonic** flow -- including **transonic** flow at Mach numbers below 1.0 -- every point in the flow field is influenced by disturbances from every other point. In

supersonic/hypersonic flow, the field of influence of disturbances is confined to the region behind the shock wave generated by strong disturbances, or behind Mach waves generated by weak disturbances; the free stream flow ahead of the model and its fore shock wave system is not influenced by the presence of the model .

On the other hand, all the characteristics of the flow in a **subsonic** wind tunnel change everywhere when a model is introduced into it. The changes are greatest close to the model, and diminish with distance upstream and to the sides. The shape assumed by the streamlines about the model are influenced by the presence of the wind tunnel walls. If the ratio of model to test section size is small enough, the change in streamline shape will be slight, and the inviscid flow characteristics about the model will closely approximate what would occur in free flight in the atmosphere. But since Reynolds number is such an important parameter, experimenters usually test as large a model as possible, which exacerbates the effect of the presence of the wall. The measurements made on the model, like forces, moments, pressure distributions, etc. will then differ from those that would have been made if the test had been done in the atmosphere. Corrections to the measured data must then be made to account for the proximity of the tunnel walls -- a requirement with no counterpart in **supersonic/ hypersonic** wind tunnel testing.

Subsonic/Transonic Working Group Report:

The following three agenda topics were considered by the Working Group:

- Identification of calibration items
- Observations pertinent to overall calibration status and need
- Recommendations to promote implementation of Workshop goals

A ground rule agreed to for the first agenda topic was that the resulting list of calibration items should be all-inclusive -- that is, while no one facility would require all the items to be indicated, no additional items should be required to cover the full spectrum of all OAST facility needs.

The major portion of the Working Group meeting was absorbed in discussing and reaching consensus on the list of **calibration items**, on identifying the range of occasions, or time intervals, for when the items should be done, the desired Precision/Accuracy of measurements, and the purpose for which the calibrations should be performed. This product of the

Working Group's efforts is shown in Figure 15.

Observations which could help guide the process of formulating what kinds of calibration guidelines would be of greatest value to the Agency were solicited from the Working Group members. The following observations are felt to be the most significant:

- High angle of attack testing is on the increase
  - The magnitude of required corrections to the data for wall effects increases with angle of attack, which for the highest angles, can be massive. Nonetheless, wall corrections are not done routinely, primarily because of great uncertainty in how to determine what they should be.
    - Wall correction techniques are more an art than a science today, and will require much concentrated effort to develop reliable data correction methods.
    - A requirement for developing such techniques is accurate, detailed definition of flow conditions over the surface of a large volume surrounding the test model -- knowledge of these requirements drive high angle of attack calibration requirements.
  - The most immediate incentive for developing reliable wall correction techniques is the requirement for experimental CFD code validation.

- Complexity of calibration requirements is a function of facility type -- i.e. whether subsonic or transonic, or whether continuous or blowdown.
  - It is not the number of calibration parameters which is impacted by facility type -- it is the number of variables which can influence each calibration parameter. For instance:
    - The calibration of a transonic wind tunnel with variable wall slot, or hole size, must indicate the variation of each calibration parameter as hole or slot size varies.
    - The variation of parameters with percent air exchange mass flow in a closed subsonic wind tunnel must be indicated.

- There are big differences between the results of past calibration practices and today's results because of advances in instrumentation technology.
  - Accuracy of both static and dynamic instrumentation has improved dramatically.

- New approaches, such as miniaturization of instrument components and non-intrusive instrumentation offer capabilities unmatched in the early days of NACA/NASA.

- A significant proportion of the Agency's basic calibration data has never been documented and is, for all practical purposes, unavailable to any but the wind tunnel staff.

- There is probably not a single well established major wind tunnel within NASA which has not been used for purposes well beyond its initial design objectives. Facility Managers need to be sensitive to the fact that this happens, and will continue to happen -- its the nature of research -- and assure that calibrations are tailored to address the added capabilities.

- No authority within NASA has established minimum acceptable standards for basic calibrations.

- No organization represented on the Working Group has established plans to do routine, periodic calibrations.

- Performing calibrations requires upper management commitment of resources and priorities.

- Most everyone seems to be in the same situation -- calibrations are old and minimal.

- The vast majority of wind tunnel users never ask to see the calibrations -- and of those who do, the majority do not understand them.

The Working Group then drew up the following set of **Recommendations**:

- Each organization should establish -- and utilize -- a comprehensive calibration policy.

- Each Wind Tunnel should have its current calibration status documented in a form which can be referenced.

- Standard calibration verification models should be acquired for each facility.
  - Test after change to any component of wind tunnel circuit.

- Test periodically to check consistency of flow quality and procedures.

- Where applicable, the state of calibration relative to CFD validation requirements should be assessed for each facility.
    - Tailor levels of calibration to application
        - e.g., some wall correction procedures require calibrations which extend to the outer boundaries of the wind tunnel
    - Procedures for using CFD to correct wind tunnel test results should be developed

- Standard instrumentation packages and techniques should be defined and recognized throughout the wind tunnel testing community for commonly measured calibration parameters.
    - Put comparison of flow qualities between different facilities on common measurement basis.

Each member of the Working Group was asked to identify the single most important **Recommendation.** The vote was evenly divided between the first two recommendations -- those preceded by the enlarged dots.

Supersonic/Hypersonic Working Group Report

The agenda adapted by the Working Group consisted of the following four "basic" elements required for supersonic and hypersonic calibrations:

- Mean flow
- Dynamic flow
- Measurement fidelity
- Calibration frequency

During discussion of the agenda items, two **observations** made were felt to be of sufficient importance that they are identified below:

- Cleanliness is an all pervasive concern because of the negative impact that high velocity foreign particles can have on the validity of the measured data and the integrity of the model.
    - All wind tunnels have airborne micron size dust particles which enter the tunnel circuit every time it is opened to the artmosphere. While these are generally of no consequence, micron sized particles have been found to be responsible for premature tripping

of the wall boundary layer in the Langley Research Center's M=3.5 Pilot Quiet Tunnel.

- Grit has a way of getting into wind tunnels. If welding is done anywhere in the circuit, the welds will be ground, and grit created. Although every effort is always made to clean it up, some residual grit will remain and be carried by the stream when the facility is operated.
- When maintenance programs fail to place sufficient emphasis on preserving the integrity of the interior surfaces of the tunnel circuit, rust can form and contribute to the grit problem.
- If the source of thermal energy in a hypersonic wind tunnel is a pebble bed heater, extraordinary efforts must be made to keep the grit size in the tunnel stream to acceptable levels. If these efforts are inadequate, the density of grit particles per unit of flow volume, and their size, will be of concern.
- The consequences of having high velocity particulate matter in the test stream are a function of particle size, as indicated below:

  • Large particles
    - Their momentum is such that they will not follow the streamlines, but will strike the surface of the model and bounce back into the oncoming flow. The most severe case is for blunt nosed bodies. The rebounding particles will perturb the shock structure, with a resulting quasi-turbulence effect on the model's skin friction and heating rate -- even though the quality of the oncoming flow may otherwise be very high. The magnitude of the effect will be a function of the frequency of the particle impacts. In addition, particle impacts degrade surface finish, causing premature boundary layer transition, and, in severe cases, distorting the model's shape.

  • Intermediate sized particles
    - Momentum low enough that it will not strike the model, but will turn, crossing streamlines while doing so. The relative velocities of the particle and the local flow it is traversing are such that the particle will generate small moving shock waves which will react with the body surface, causing increases in expected surface pressure and local heating rates.

- Small (micron sized) particles
  - Generally of no consequence.

- When the quality of flow in two or more facilities of similar capabilities are to be assessed, it is important that measurements and measurement techniques be comparable, if not identical.
  - Standard instrumentation packages and techniques should be agreed to throughout the NASA wind tunnel testing community.

The four "basic" elements of calibration were defined as follows:

- Mean flow — Derived parameters: $M, p, \rho, T, u, v, w, C_i$
  - Pitot pressure
  - Static pressure
    - Wedge
    - Cone
    - Tube
    - Wall
  - Flow angle -- all three axes
    - Generally not a problem with symmetric nozzles in high speed flow because axial component of velocity is so much greater than transverse deviations from machining inaccuracies. An exception is two-dimensional nozzles where Mach number variation is achieved with sliding non-symmetric nozzle blocks.
  - Total temperature
  - Dewpoint
    - To avoid condensation of moisture, which will affect mean flow characteristics.
  - Particle contamination -- size and distribution
  - Gas composition/state
  - Reservoir conditions
  - Flowfield wave strength and locations
  - Direct measurements of desired parameters as advanced techniques become available (e.g., optical measurements).

- Dynamic flow — Derived Parameters: $p', u', v', w', \rho', T', C_i'$, Particles
  - Fluctuating pitot pressure
  - Fluctuating total temperature
  - Fluctuating mass flow

- Direct measurements of desired parameters as advanced techniques become available (e.g., optical measurements).
- Mean stagnation point heat transfer on a hemisphere
  - Empirical method of pre-qualifying flow quality for obtaining valid heat transfer measurements.
    - Problems are indicated if measurement exceeds laminar prediction -- e.g. stream turbulence, or larger than acceptable particulate matter size.

- Measurement fidelity
  - Use state of the art instruments.
  - Give accuracy of measured and derived quantities.
    - Reservoir conditions
      - measurement can be challenging at high enthalpy levels.
    - Test section
      - Determine **mean** flow parameters throughout entire anticipated model test volume with sufficient density that flow gradients, Mach waves and viscous edge of test core can be determined with precision.
      - Density of **dynamic** measurements can be reduced to 1/5 that of **mean.**

- Calibration frequency
  - Each facility should periodically revalidate its calibration
    - Periodic interval determined by experience
    - Revalidate after modification to any component of tunnel circuit.
      - Special purpose standard models are excellent, rapid revalidation tools. They must be dedicated solely to calibration revalidation -- no changes can be made to it.
        - Model gives integrated effect of status of flow
        - If results differ from previous revalidation test, a full recalibration is required.

- **Recommendations**

  - Document and publish calibrations
  - Document and publish upgrades

Concluding Remarks

The purpose of the Wind Tunnel Calibration Workshop was to explore wind tunnel calibration requirements as they relate to test quality and data accuracy, with the ultimate goal of developing wind tunnel calibration requirements for NASA's major wind tunnels.

The purpose of the Workshop has been achieved, and is represented by the overviews of the selected papers and the reports of the two Working Groups. Although the ultimate goal of developing the detailed wind tunnel calibration requirements for each of NASA's major wind tunnels was beyond the scope of responsibility of the Workshop, the foundation upon which those requirements can be built is encompassed by the first two recommendations of the Subsonic/Transonic Working Group:

- Each organization should establish -- and utilize -- a comprehensive calibration policy.
- Each wind tunnel in the organization should have its current calibration status documented in a form which can be referenced.

After this foundation has been established, the contents of the Overview can be used to assess the current calibration status of each wind tunnel, and implement up-to-date calibration requirements -- if needed -- in order to bring the calibrations up to the high standards required in today's highly competitive aeronautical environment.

Experience with existing and developing technologies for non-intrusive optical measurement techniques offers great promise for directly and accurately measuring all the parameters required for calibrations across the speed range -- including real gas flows (e.g., laser velocimetry, raman scattering, laser induced fluorescence, and other hybrids and combinations). As these techniques are developed, validated, and become state-of-the-art, they should be used to help satisfy the high calibration standards envisioned by the Workshop.

Symbols

C_D	drag coefficient
C_L	lift coefficient

C_p	pressure coefficient
C_i	gas species
D	drag
L	lift
M	Mach number
p	pressure
p_t	total pressure
p	static pressure
q	dynamic pressure
R_{EX}	Reynolds number in streamwise direction
T	temperature
T_t	total temperature
U	mean freestream velocity
u,v,w	components of velocity in tunnel x,y,z axes directions, respectively
ρ	density
( )'	indicates dynamic measurements

References

1. J. R. Cornelius - Boeing Commercial Airplanes; Wind Tunnel Calibration Requirements from the Commercial Transport Viewpoint

2. J. C. Strong - Douglas Aircraft Company; What Constitutes a Properly Calibrated Wind Tunnel and Why? April 18 - 20, 1989

3. Lloyd A. Wood - McDonnell Aircraft Company, McDonnell Douglas Corporation; Off - Centerline Flow Deviations and an Approach to Off - Centerline Transonic Flow Calibrations

4. F. W. Steinle, Jr. - NASA Ames Research Center; Calibration Perspective. 4/19/89

5, Rick Burrows - Rockwell International, Space Systems Division; Wind Tunnel Calibration Requirements

6. Norman E. Scaggs - Wright Research Development Center; What Constitutes a Properly Calibrated Wind Tunnel?

Wind Tunnel Calibration

What Parameters are Measured?

<u>For Commercial Transport Aerodynamic Testing:</u>

- Primary
  - Pressure: Total Pressure, Static Pressure, Dynamic Pressure
  - Flow Angularity: Upflow (Wing & Horizontal Tail Region), Crossflow (Vertical Tail Region)
- Secondary
  - Temperature: Total Temperature (Velocity Calc.)
  - Turbulence: Velocity Turbulence (Flow Quality)
- Tertiary
  - Acoustics

Figure 1

93-1081

University of Washington Wind Tunnel UWAL

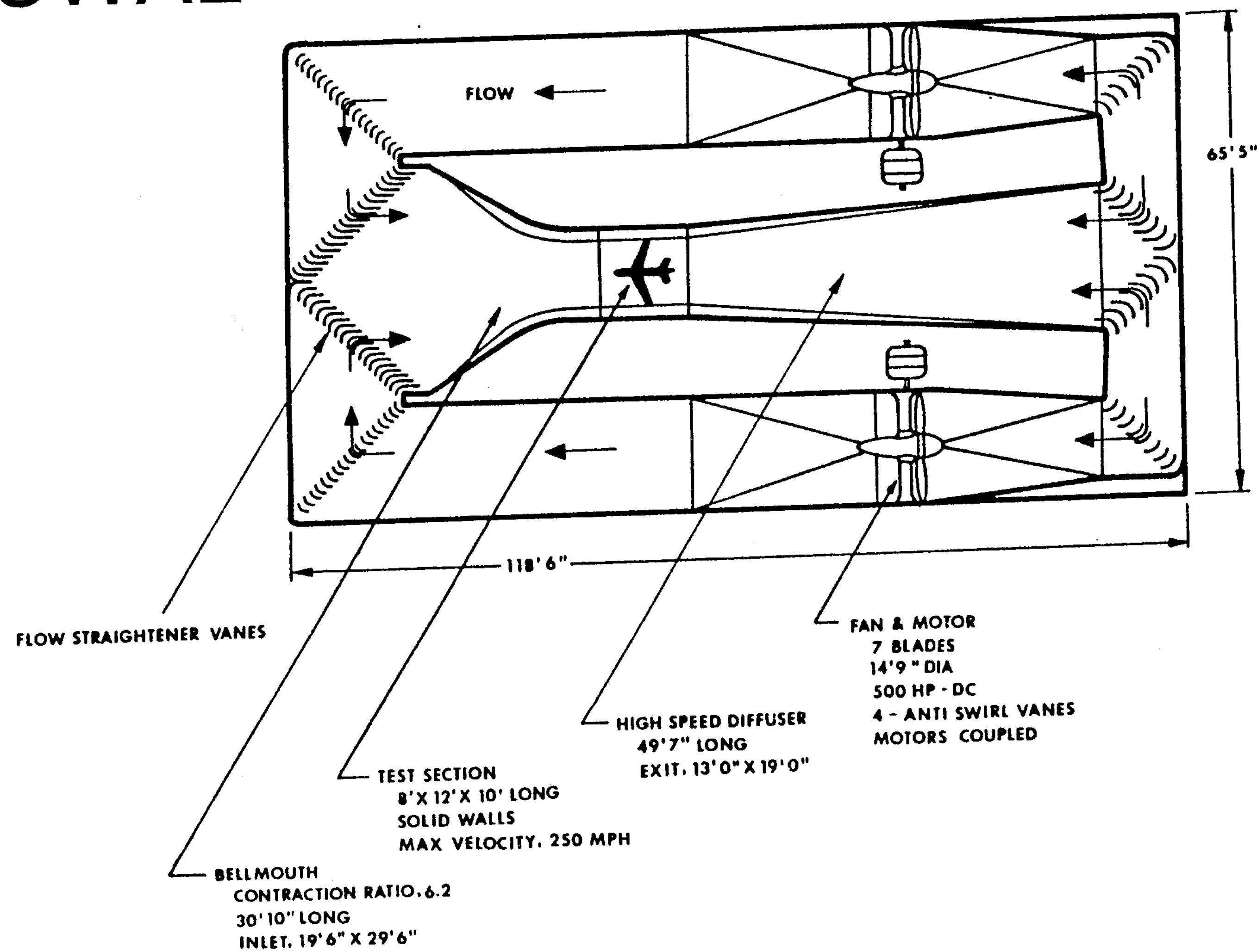
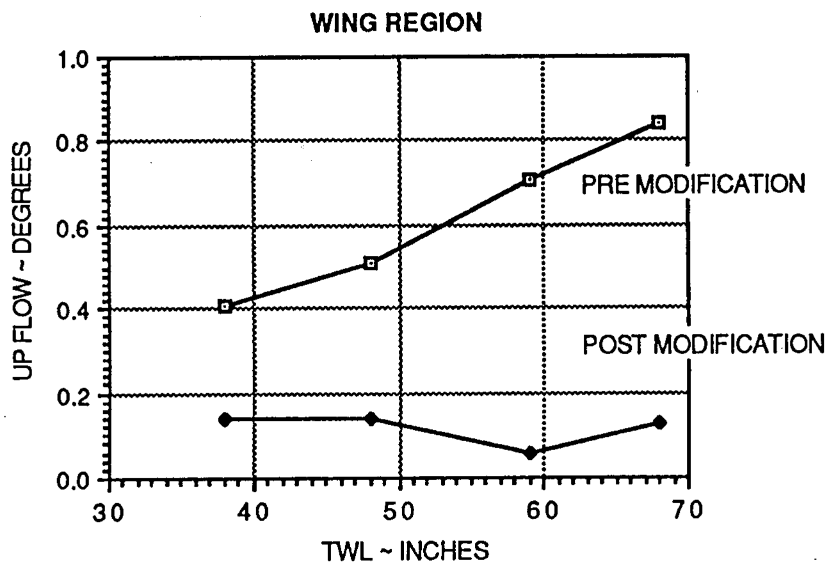


Figure 2

UWAL Flow Angularity Improvement



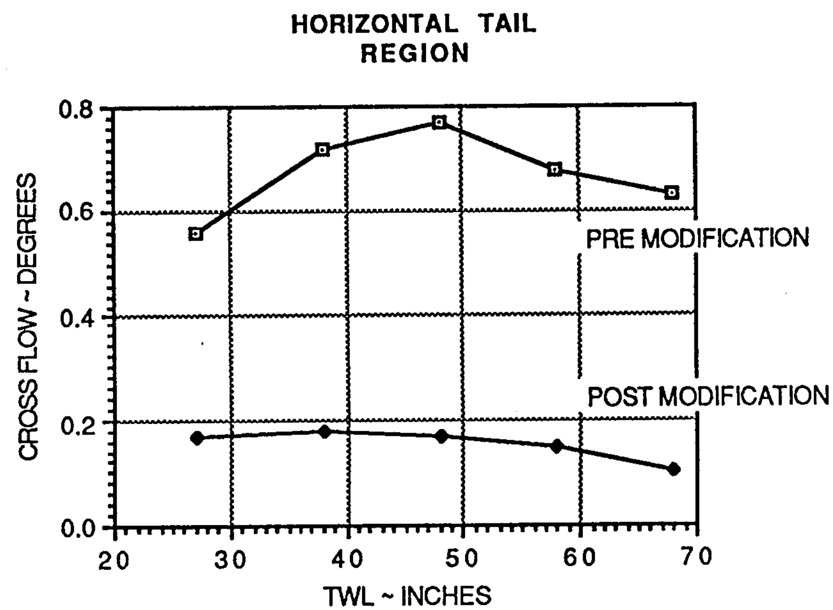


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Figure 3

UWAL Flow Quality Improvement

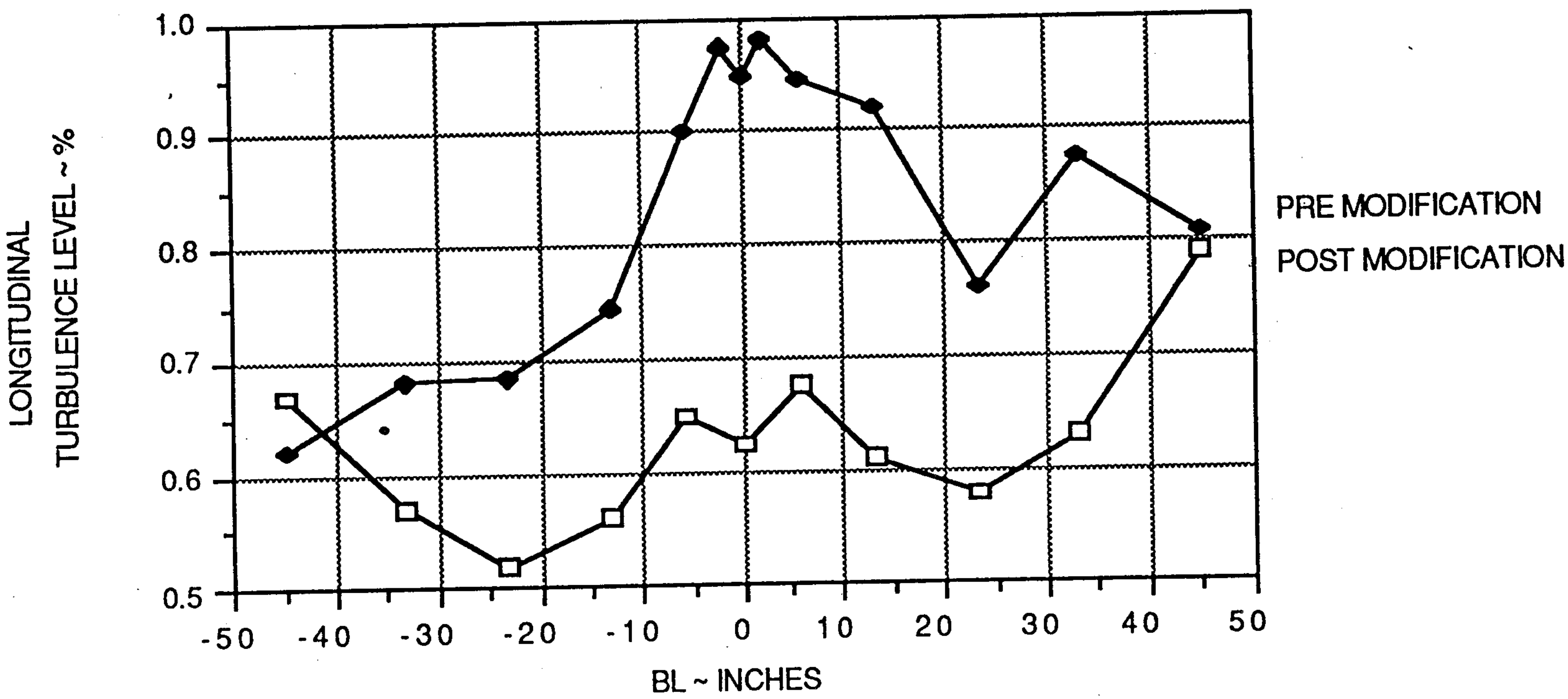
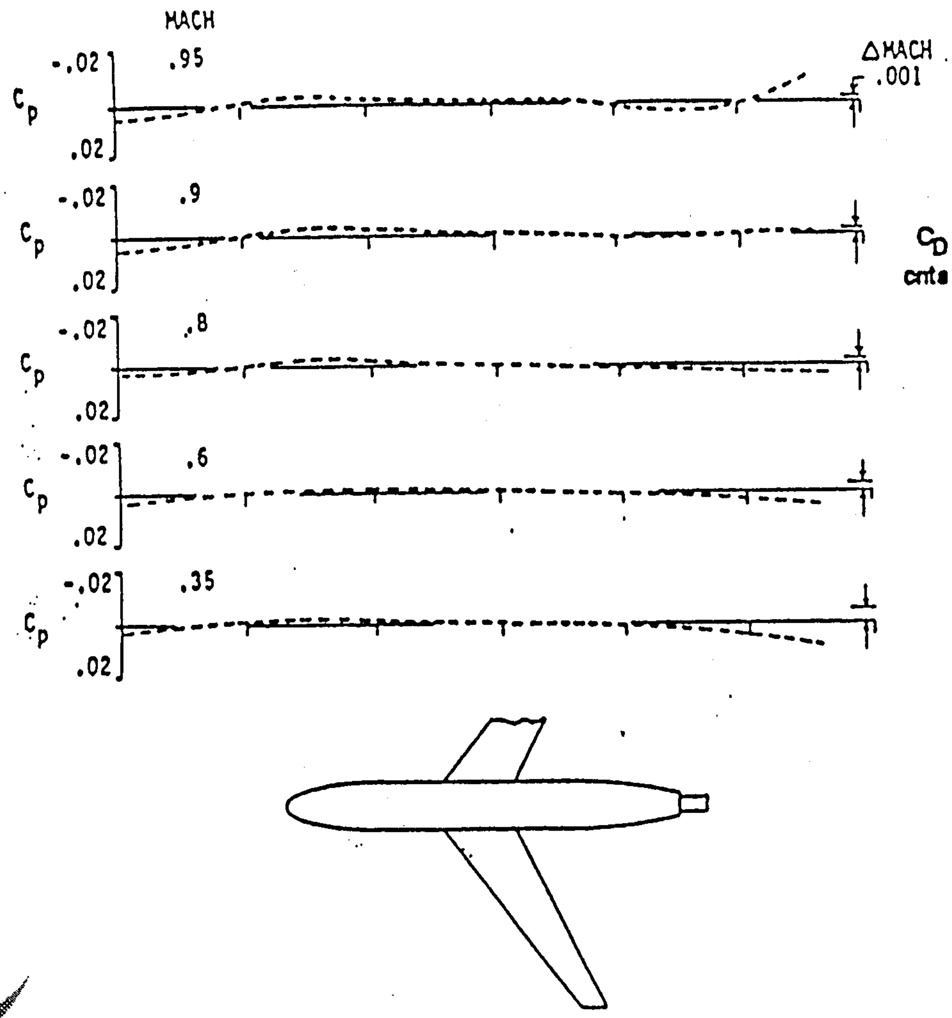


Figure 4

Longitudinal Pressure Distribution BTWT Centerline



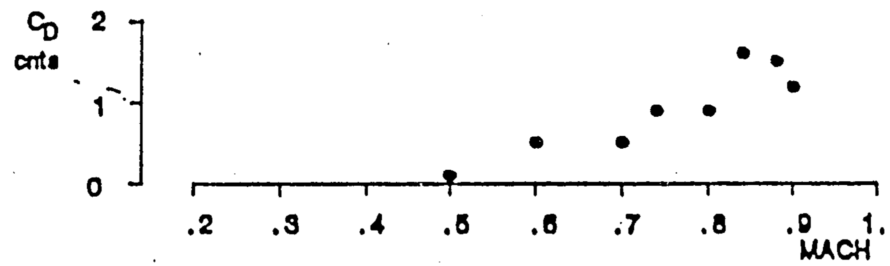
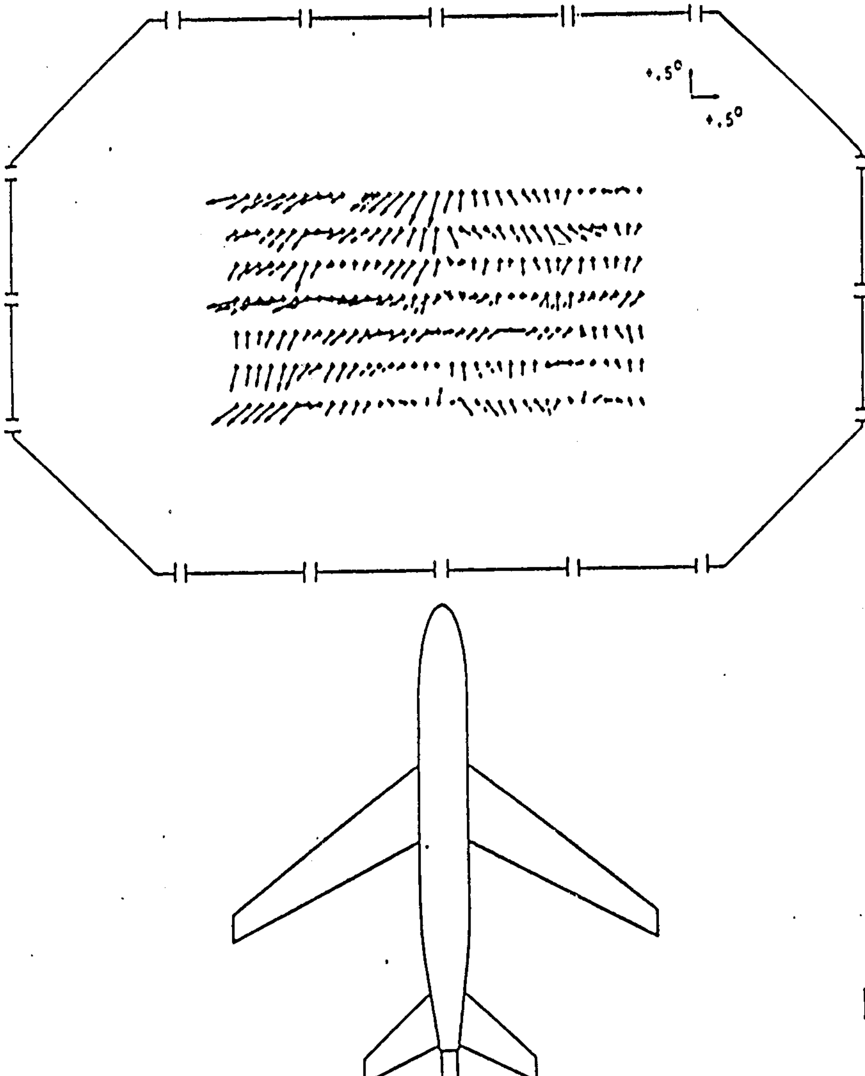
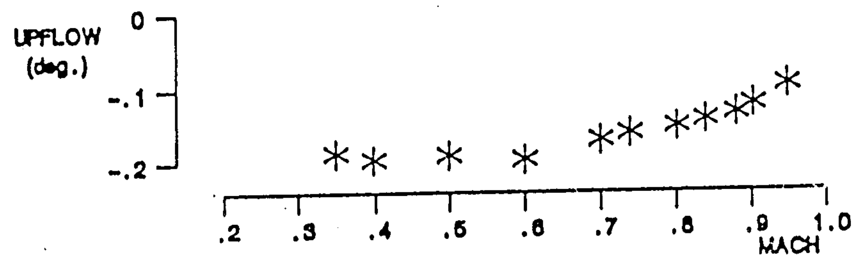


Figure 5

BTWT Flow Angularity





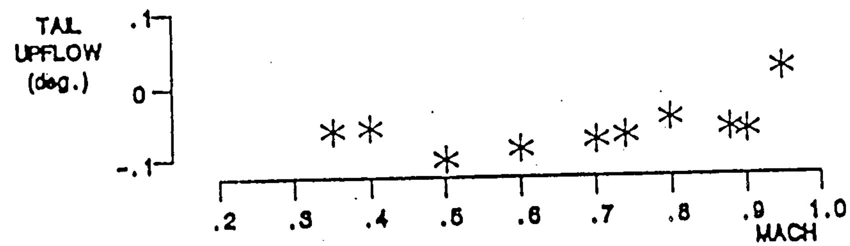


Figure 6

BTWT Upflow History

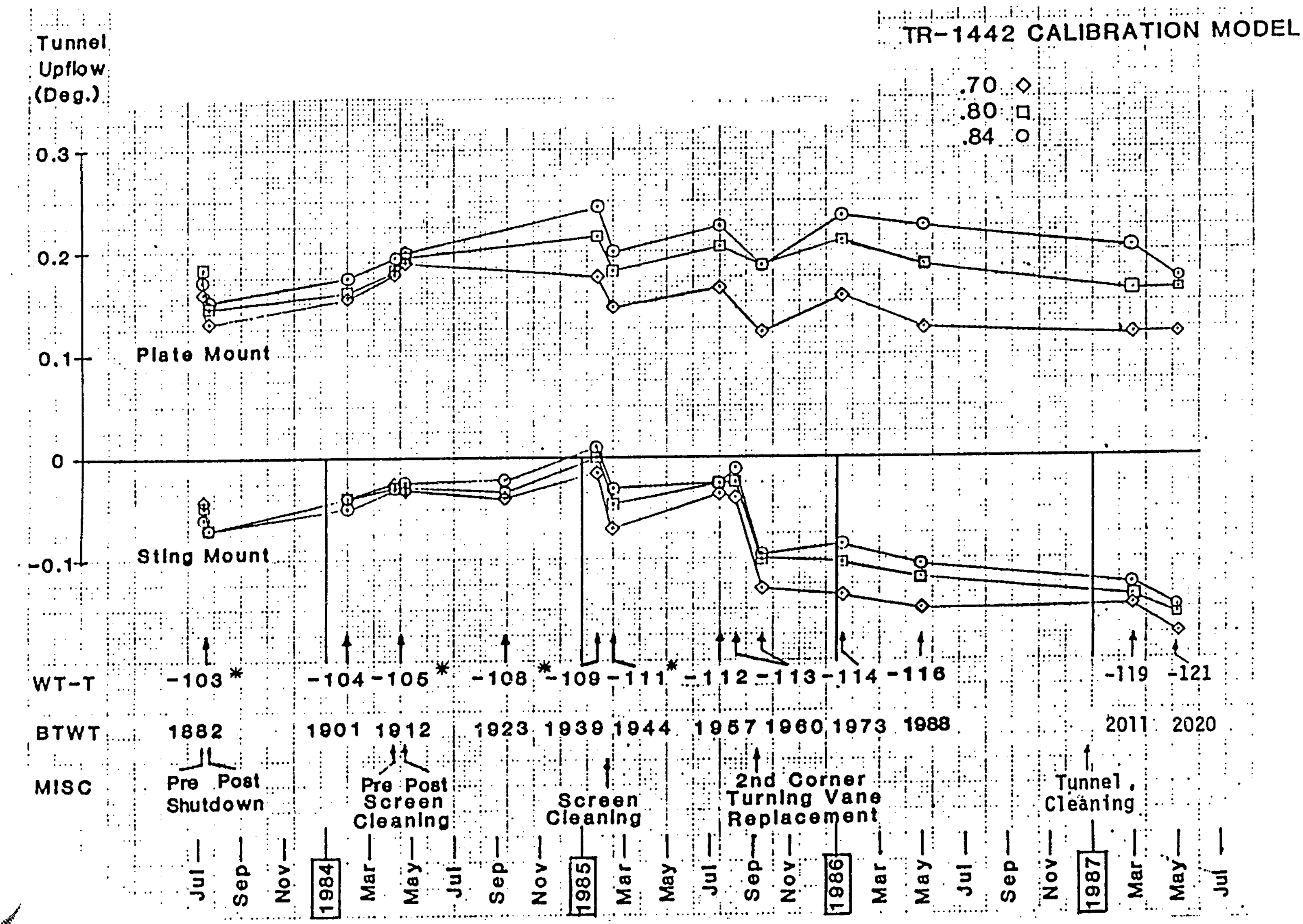


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Figure 7

McDonnell 8.5' X 12' Low Speed Wind Tunnel

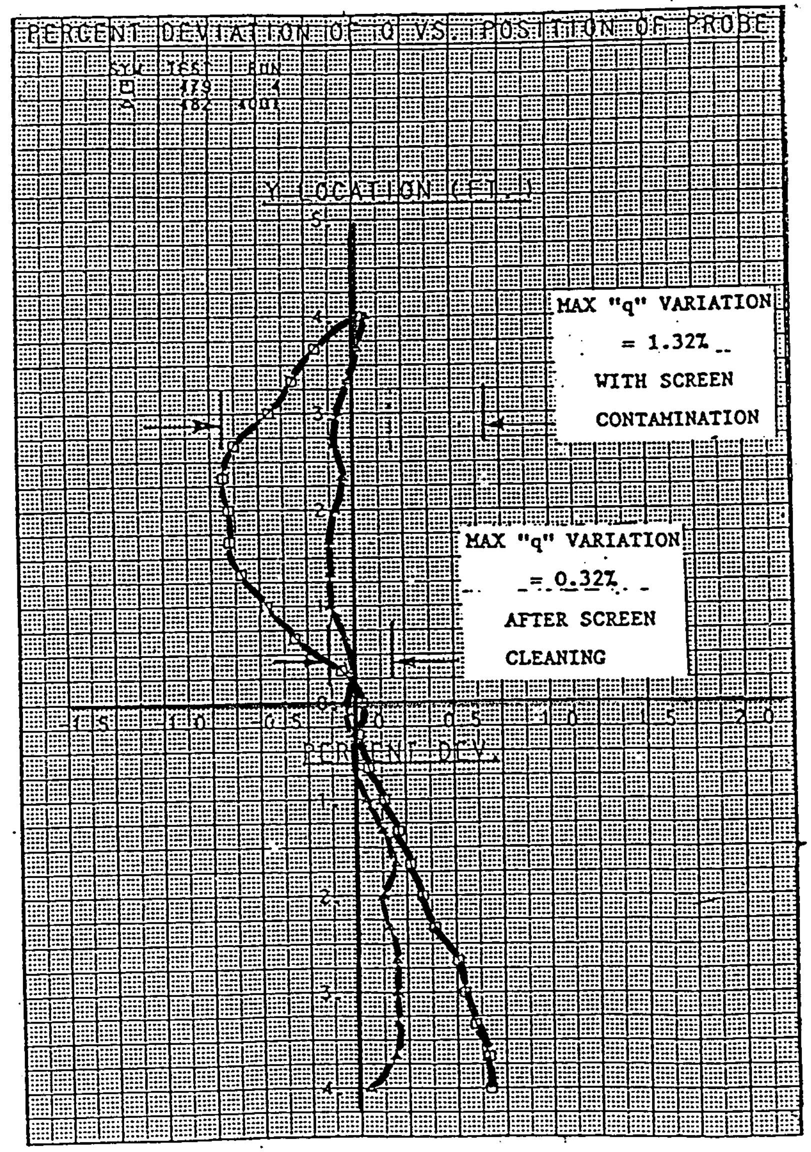

Figure 8

Douglas 4' X 4' Trisonic Wind Tunnel

Vertical Traverse

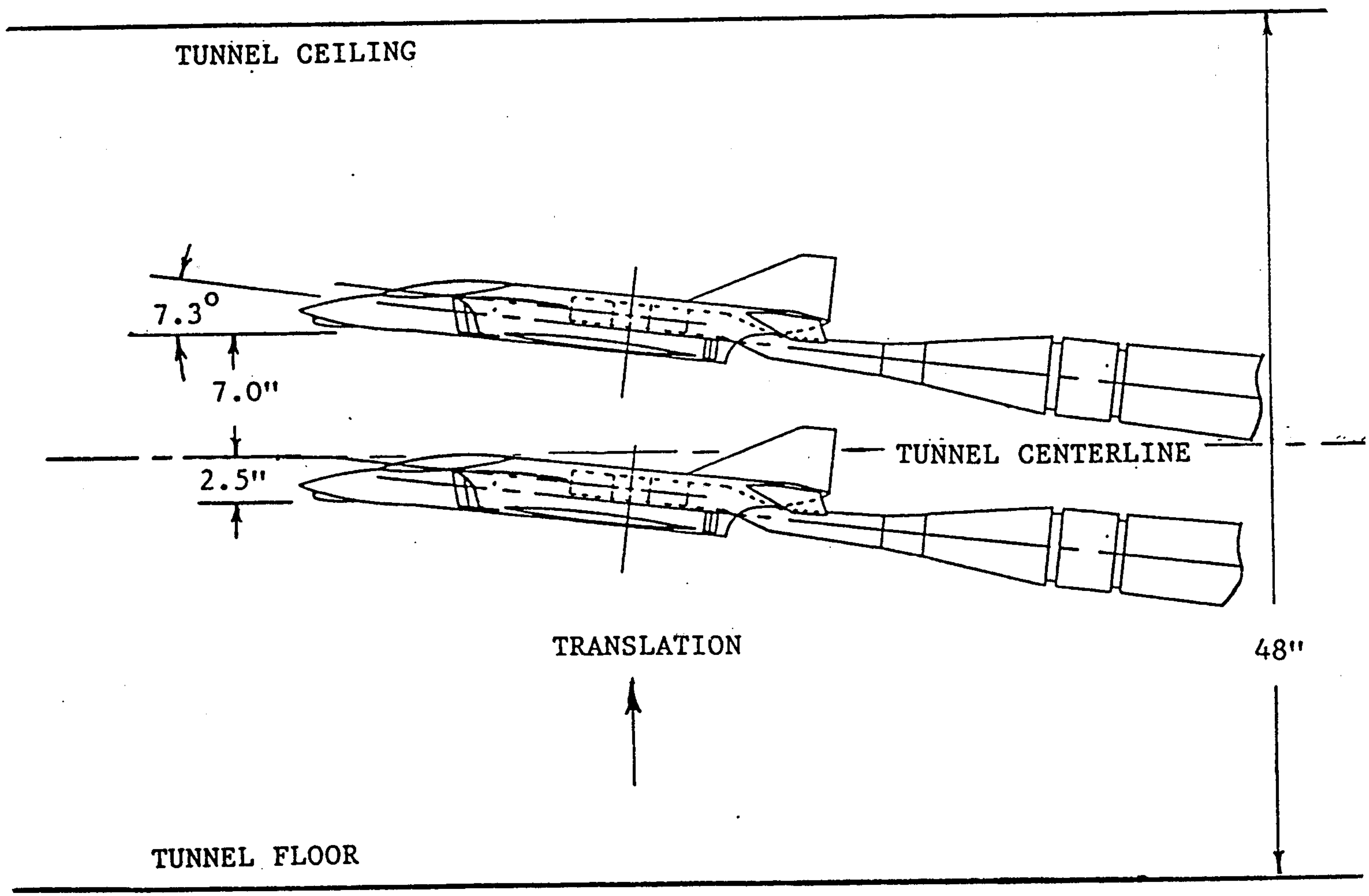

Figure 9

Douglas 4' X 4' Trisonic Wind Tunnel

Vertical Traverse

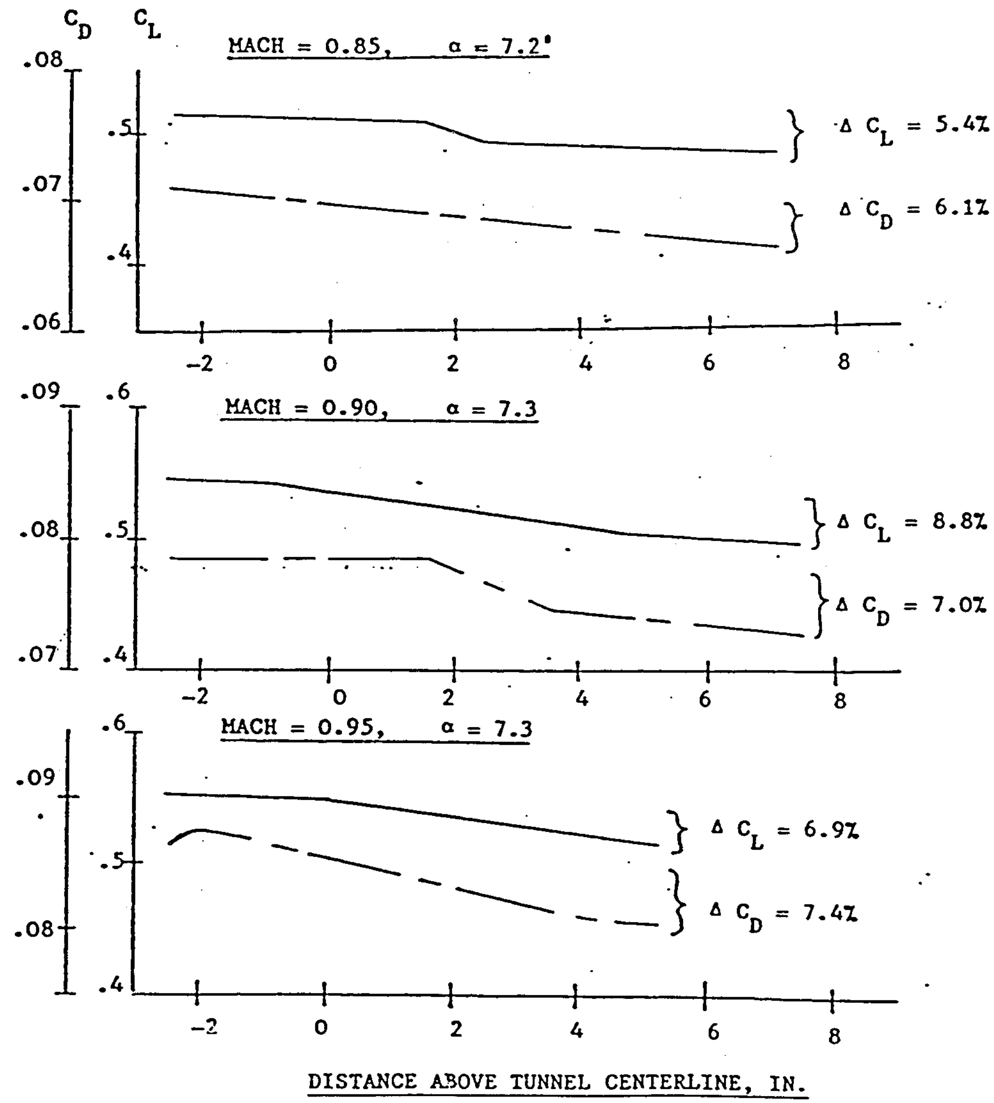

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Figure 10a

Douglas 4' X 4' Trisonic Wind Tunnel

Vertical Traverse

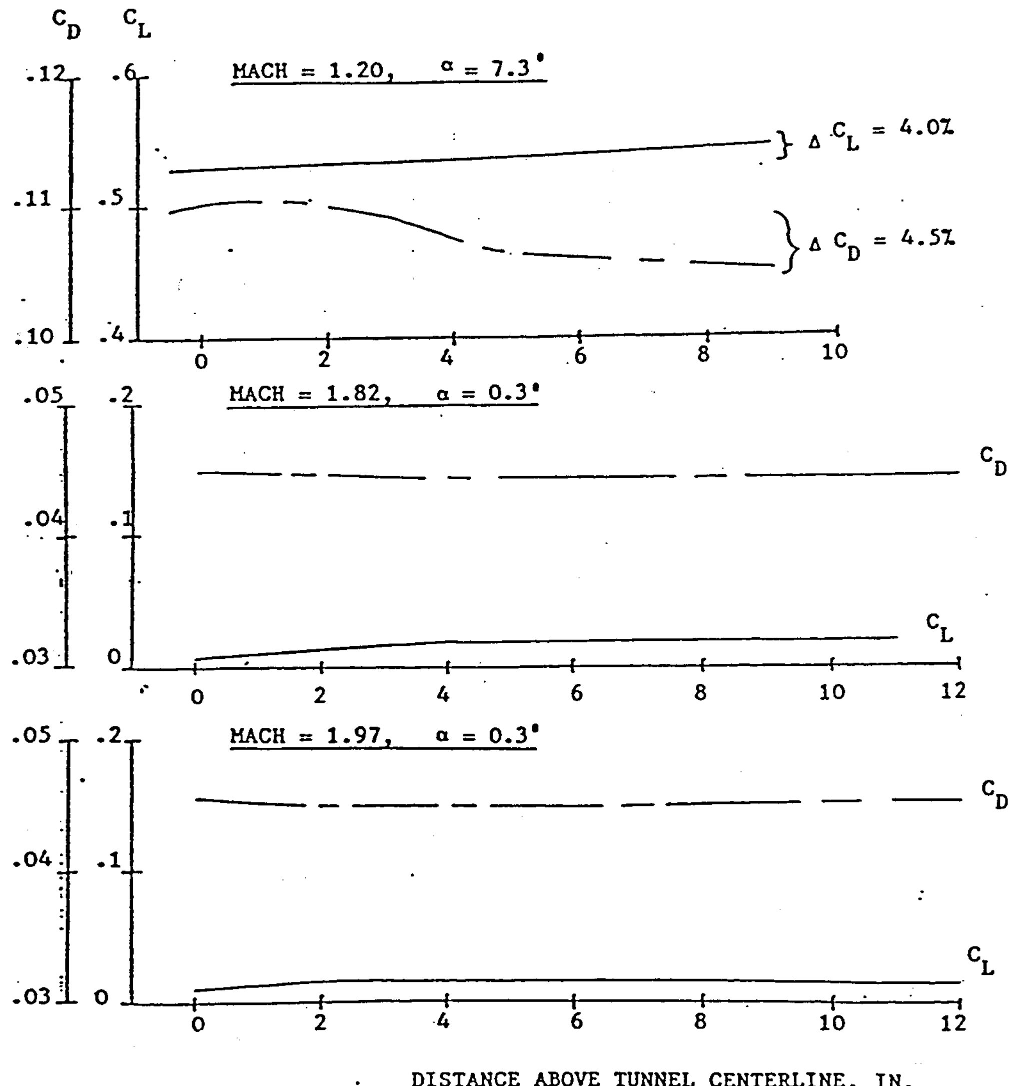

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Figure 10b

Perspectives on Calibration

- Diagnose Flow Problems
- Basic Tunnel-Empty Calibration
- Little Attention to Off-Centerline
- Techniques Differed
- Generally State-of-the-Art at the Time
- Generally Not Reported
- Instrumentation Deteriorated
- Identifiable Needs Lead to Minimal Calibrations
- Fine Details of Flow are Transparent to User
- Methodology to Utilize Modern Calibrations is Lacking

Figure 11

Flow Quality Improvement in 11ft. TWT and Impacts

- Reduce u'/U to 0.02% at M=0.8
  - Meet Drag Coefficient Accuracy of 0.0001
  - Measure Boundary Layer Properties Optically
  - Simulate Buffet Onset with Reliability
  - Double Accuracy of Force and Moment Measurements
  - Increase Productivity during Data Acquisition
  - Support Natural Laminar Flow Research
- Reduce Flow Angularities to less than 0.05 degrees
  - Meet Drag Coefficient Accuracy of 0.0001
  - Support CFD Validation
- Reduce Test Section T Variation to less than -4 degrees F.
  - Meet Drag Coefficient Accuracy of 0.0001
  - Support Correct Development of Boundary Layer
- Reduce Test Section Acoustic Noise caused by Wall-Slots
  - Measure Aero-Noise Effects Accurately
  - Support Research into Boundary Layer Transition

Figure 12

Calibration or Flowfield Parameters Needed

PARAMETERS	Supersonic and Low Hypersonic (Ideal Gas)		High Hypersonic (Real Gas)	
	Essential	Desirable	Essential	Desirable
Velocity (3 Components --u, v, w)	* (u)	*(v, w)	* (u)	*(v,w)
Pitot Pressure	*		*	
Static Pressure	*		*	
Reservoir or Stagnation Pressure	*		*	
Reservoir or Stagnation Temperature	*		*	
Static Temperature		*		*
Mach number	*		*	
Reynolds number		*		*
Flow Angularity	*		*	
Disturbances (Amplitude and Spectra)		*		*
State of Gas (Frozen, non-Equilibrium, Equilibrium)			*	
Enthalpy			*	
Gas Species			*	
Gas Species Concentration			*	

Figure 13

Wind Tunnel Calibration Status

Center Ames

● = ℄ Only
O = Test Volume

	PARAMETERS										
	Steady State						Unsteady				
Facility	M	∢	P_t	T_t	q	P_∞	U	V	W	P	Publication
40x80	O	O	O	O	O	O	O	O	O	O	TM 101065
80x120	O	O	O	O	O	O	O	O	O	O	TM 103920
11x11	O	O	O	O	O	O	●		●	●	
9x7	O	O	●	O	O	O				●	
8x7	O	O	●	O	O	O				●	
3.5 Foot	●	●	●	●							

Figure 14a

Wind Tunnel Calibration Status

● = ℄ Only
O = Test Volume

Center LaRC

Facility	PARAMETERS: Steady State: M	α	P_t	T_t	q	P_∞	Unsteady: U	V	W	P	Publication
14x22	●	O	●				●	●	●		NASA TP-3008, 9/90
LTPT	O	O	O		O		O			O	NASA TP-2328 AIAA 84-0621
30x60		O			O	●	O	O	O		NACA REP. 459, 3/33 NACA REP. 478, 5/33 NACA REP. 558, 2/36 BBN REP. 2100, 1/71 HAM. STD. NAS1 14753, 2/78 EAGLE REP. 88 - 2, 9/88
7X10	●	●			●	●					NOTE: α FROM MODEL UPRIGHT & INVERTED-REPORT IN REVIEW NASA TM-74207
16 FT. TT	O	O	O	O	O	O	●	●		O	NASA TM-X 909, 1964 NASA TM-X 1454, 1967 NASA TN-D 4135, 1967 NASA TN-D 7331, 1973 NASA TR-R 423, 1974 AIAA 74-627
TDT	O						●			●	NASA LWP-799, 1969
UPWT	O	O	O	O							NASA TP-1905, 1981
NTF	●		O	O		●				O	REPORT IN REVIEW
8 FT. TPT	●	●		O	●	●	O	●		O	NASA TP-1737 NASA CR-158983 AIAA 80-0434

Figure 14b

Wind Tunnel Calibration Status

Center LeRC

● = ℄ Only
O = Test Volume

	PARAMETERS										
	Steady State						Unsteady				
Facility	M	∡	P_t	T_t	q	P_∞	U	V	W	P′	Publication
8x6	O	O	O	O	O	O	●			●	NASA TMX - 1655, 1968; Aero flow field mods in process -- publication of new calibration expected in 1995
9x15	O	O	O	O	O	O	O				NASA TM 100883, 1989; Aero flow field mods in process -- pubication of new calibration expected in 1995
10x10	O	O	O	O	O	O				O	Unpublished Calibration Manual, 1964 -- Calibrations in process; NASA Report expected 1994

Figure 14c

Wind Tunnel Calibration Recommendations

Calibration Item	Occasion: Initial Operation	Change to Facility	Special Need	To Detect Changes	New Technology	3-5 Year Interval	> 5 Year Interval	Precision/ Accuracy	Purpose
Total Temperature	X	X					X	State-of-the-Art ↓	Stream & Core Flow ↓
Static Pressure	X	X	X		X	X	X		
Total Pressure	X	X	X	X					
Dynamic Pressure	X	X	X	X				.1-.2% Subsonic	
Mach Number	X	X	X	X				.001 Transonic	
Stream Angle	X	X		X				.01° Transonic	Test Each Model Upright & Inverted
Humidity Effects	X							1° C	Find Operational Limits on Dew Point
10° Cone Boundary Layer Transition	X	X						ΔR_{EX} = 50,000 ↓	Integrating Parameter for Environment
Flat Plate B.L. Transition			X						No Standard Identified
Measure Simultaneously: Mass Flux Fluct'n	X ↓	X ↓	X ↓					0.01% ↓	B.L. Research; Turbulence Factor; Buffet Onset; Vortex Formation
Temp Fluct'n									
Tot. Pres.Fluct'n									
Acoustic Noise									
Modulation Transfer Function			X						Optical Transmissibility

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Figure 15

93-1090

Wind Tunnel Calibration Recommendations

Calibration Item	Occasion: Initial Operation	Occasion: Change to Facility	Occasion: Special Need	Occasion: To Detect Changes	Occasion: New Technology	Occasion: 3-5 Year Interval	Occasion: > 5 Year Interval	Precision/ Accuracy	Purpose
<u>Standard Models</u>								State-of-the-Art ↓	
• 3-Dimensional	X	X	X	X					Periodic Flow Quality Check & Compare Facilities
• Semi-Span			X						Periodic Flow Quality Check
• Axisymmetric			X						Assess Buoyancy Corrections
• 2-Dimensional			X						Assess Corrections
• Flat Plate			X						Transition Research
• 10-Degree Cone	X	X							Flow Quality Monitor ↓
<u>Dynamic Flow</u>									
• T', p', $(\rho u)'$	X	X	X						
<u>Wall Boundary Conditions</u>									
• Wall(or Near Wall) Pressure	Continuously								** WIAC Procedure
• Upstream Flow	Continuously								
• Boundary Layer Displacement Thickness	X		X						Semi-Span Tests
• * υ_n vs. Δp_w	X		X						Wall Interference

* Normal wall velocity versus pressure drop across ventilated wall

** Wall Interference Assessment/Correction

Figure 15 (cont)

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13. ABSTRACT (maximum 200 words)

An overview of the 1989 Wind Tunnel Calibration Workshop held at Langley Research Center in Hampton, VA on April 19 and 20, 1989 is presented. The purpose of the Workshop was to explore wind tunnel calibration requirements as they relate to test quality and data accuracy, with the ultimate goal of developing wind tunnel calibration requirements for the major NASA wind tunnels at Ames, Langley, and Lewis Research Centers. The two sessions addressed 1) what constitutes a properly calibrated wind tunnel, and 2) the status of calibration of NASA's major wind tunnels. The most significant contributions to the stated goal are highlighted and the consensus of the Workshop's conclusions and recommendations regarding formulation and implementation of that goal are presented.

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