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F. Kmak
NASA Ames Research Center
Moffett Field, CA

M. Hudgins, and D. Hergert
The Boeing Company
Seattle, WA

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REVALIDATION OF THE NASA AMES 11-BY 11-FOOT TRANSONIC WIND TUNNEL WITH A COMMERCIAL AIRPLANE MODEL (INVITED)

By
Frank J. Kmak *
NASA Ames Research Center
Moffett Field, CA

Mark S. Hudgins †, and Dennis W. Hergert ‡
The Boeing Company
Seattle, WA

ABSTRACT

The 11-By 11-Foot Transonic leg of the Unitary Plan Wind Tunnel (UPWT) was modernized to improve tunnel performance, capability, productivity, and reliability. Wind tunnel tests to demonstrate the readiness of the tunnel for a return to production operations included an Integrated Systems Test (IST), calibration tests, and airplane validation tests. One of the two validation tests was a 0.037-scale Boeing 777 model that was previously tested in the 11-By 11-Foot tunnel in 1991. The objective of the validation tests was to compare pre-modernization and post-modernization results from the same airplane model in order to substantiate the operational readiness of the facility. Evaluation of within-test, test-to-test, and tunnel-to-tunnel data repeatability were made to study the effects of the tunnel modifications. Tunnel productivity was also evaluated to determine the readiness of the facility for production operations. The operation of the facility, including model installation, tunnel operations, and the performance of tunnel systems, was observed and facility deficiency findings generated. The data repeatability studies and tunnel-to-tunnel comparisons demonstrated outstanding data repeatability and a high overall level of data quality. Despite some operational and facility problems, the validation test was successful in demonstrating the readiness of the facility to perform production airplane wind tunnel tests.

* Chief, Wind Tunnel Engineering Branch, Member AIAA
† Engineer, Member AIAA
‡ Associate Technical Fellow, Member AIAA

1. INTRODUCTION

The Ames UPWT facility has been the most heavily used wind tunnel in all of NASA. The UPWT was completed in 1956 under the Unitary Plan Act of 1949. Every major commercial transport and almost every military jet built in the United States over the last 45 years has been tested in this facility. Also tested in this tunnel complex were models of the Space Shuttle, as well as models of the Mercury, Gemini, and Apollo capsules.

The UPWT Modernization Project was started in 1988 and consisted of a variety of equipment upgrade, refurbishment, and replacement work packages managed by NASA Ames. The 11-By 11-Foot tunnel was removed from service in April 1995, for modernization construction activities. After the completion of construction activities at the 11-By 11-Foot tunnel, a series of reactivation tests were conducted to bring the facility back into operation. The progression of testing involved a tunnel startup IST, calibration tests, and airplane model validation tests before resuming production testing. The IST was the first wind-on test that progressively demonstrated tunnel operations and evaluated the aerodynamic and structural performance of the modernized tunnel.[1] The focus of the IST was to bring the Facility Control System (FCS) to a mature state and to checkout all FCS features throughout the entire tunnel envelope. Two calibration tests were performed after successful completion of the IST. A standard Mach number calibration of the test section was performed using a static pipe apparatus. A subsonic calibration model was the first airplane test and involved checkout of the Sting Model Support System (SMSS).

Two airplane model validation tests were completed to allow comparisons of airplane aerodynamic performance data for models previously tested in the 11-By 11-Foot tunnel. A typical commercial transport model and a military fighter were selected to test tunnel procedures and processes. A 0.037-scale Boeing 777 model and a 0.08-scale Boeing F/A-18E model were tested to validate the readiness of the 11-By 11-Foot Transonic Wind Tunnel for production testing.

The Boeing 777 test (Ames test number 11-0053, AT0053) was performed during two tunnel entries. The first entry was installed after the subsonic calibration model test, and the test was stopped due to undamped model vibrations caused by the model support control system. The model was removed and problems with the SMSS were addressed for two weeks before the next validation test. The Boeing F/A-18E validation test was then installed and the test successfully completed. The second Boeing 777 entry, phase 2, was then installed and completed successfully. The phase 2 Boeing 777 validation test is the focus of this paper.

2. FACILITY

2.1 FACILITY DESCRIPTION

The UPWT consists of three tunnel legs and an Auxiliaries facility: the 11-By 11-Foot Transonic leg, the 9-By 7-Foot Supersonic leg, and the 8-By 7-Foot Supersonic leg, Figure 1. The supersonic legs share a common eleven-stage axial-flow compressor and aftercooler drive leg, and use diversion valves at the ends of the common leg. A three-stage axial-flow compressor drives the 11-By 11-Foot leg. A common drive motor system can be coupled to either the three-stage or eleven-stage compressors. One tunnel can therefore be run while the other two are in the process of installing or removing test articles.

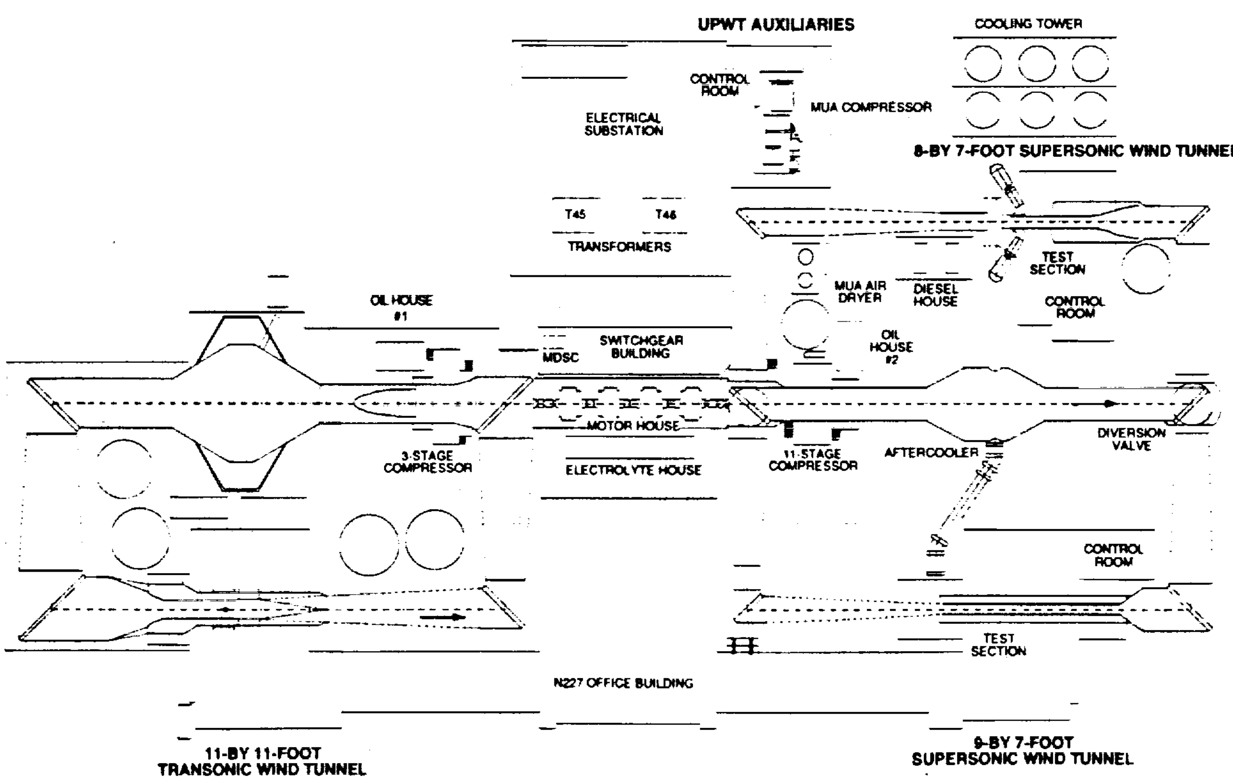

Figure 1. Unitary Plan Wind Tunnel Site Plan

The 11-By 11-Foot Transonic leg is a closed-circuit variable-pressure continuous-operation wind tunnel, Figure 2. Subsonic Mach number control is accomplished by setting the compressor drive speed to one of ten setpoints and using variable camber Inlet Guide Vanes (IGV) for fine Mach number control. Supersonic Mach number control involves setting the flexible wall nozzle upstream of the test section to achieve the proper area ratio in addition to setting the compressor drive speed and the Inlet Guide Vanes. A tandem diffuser system with an annular diffuser followed by a wide-angle diffuser is upstream of a 70-foot diameter aftercooler section in the drive leg. The settling chamber upstream of the contraction is 38 feet in diameter after the installation of a liner fairing that is 6 inches thick to accommodate flow conditioning element support hardware. The contraction provides a transition from the circular cross-section of the settling chamber to the square cross-section of the test section. The contraction ratio is 9.4. The test section is 11-by-11 feet in cross section and 22 feet in length. Slots in all four walls run the full length of the test section and include baffles that provide a porosity of 6% into the plenum. Ejector flaps on all four walls at the exit of the test section can be remotely set to control the plenum flow bypassed from the test section. A Plenum Evacuation System (PES) provides an active method of removing air from the test section plenum using the Make-Up Air (MUA) compressor system in the Auxiliaries facility. The MUA compressor drive motor is located in the Auxiliaries equipment building on the UPWT site. The 15,000-horsepower motor drives a four-stage low-pressure centrifugal compressor and a seven-stage high-pressure centrifugal compressor mounted in tandem.

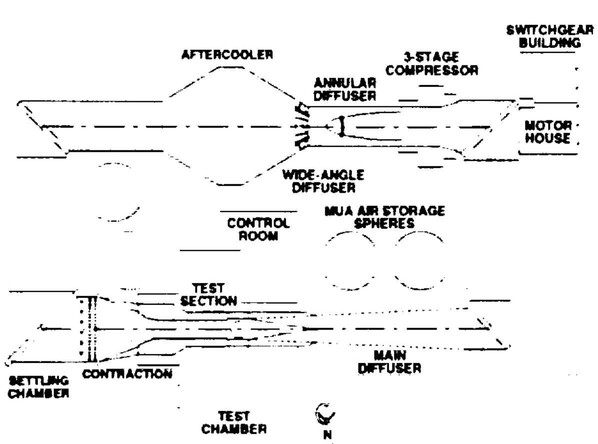

Figure 2. 11-By 11-Foot Transonic Wind Tunnel

2.2 FACILITY IMPROVEMENTS

The 11-By 11-Foot Transonic leg was taken out of service in April 1995, and wind-on startup testing began in November 1998. Automation systems were installed in all three UPWT tunnel legs and the Auxiliaries facility. Major improvements were made to the four control rooms, model support systems, main drive motors, and main drive speed control. Pressure vessel repairs and refurbishment to the electrical distribution system were also completed. Significant changes were made to improve test section flow quality in the 11-By 11-Foot transonic leg. After the completion of the construction phase of the project, acceptance and checkout testing was performed to demonstrate the capabilities of the modernized facility. A pneumatic test of the tunnel circuit was performed to verify the structural integrity of the pressure vessel before wind-on operations. Test section turbulence, flow angularity, and acoustic parameters were measured throughout the tunnel envelope to determine the effects of the tunnel flow quality improvements. The new control system processes were thoroughly checked during wind-off and wind-on operations. Manual subsystem modes and automated supervisory modes of tunnel operation were validated. The aerodynamic and structural performance of both the new composite compressor rotor blades and the old aluminum rotor blades was measured. The entire subsonic and supersonic envelope of the 11-By 11-Foot transonic leg was defined up to the maximum total pressure.

The primary objective of the Facility Control System upgrade was to automate the operation of the tunnel legs of the UPWT and the associated Auxiliaries support facility. Automation of the tunnel operation allows test operators to enter a series of test conditions and model angle schedules into run schedule tables prior to a run series. The processes of moving the model through a move-pause or continuous sweep polar, taking data at each point, maintaining the tunnel total pressure, and maintaining the tunnel Mach number, have been fully automated. The operator interacts with the control system to monitor the processes and step the system to the next tunnel condition or model polar.

The twenty-year-old Main Drive Speed Controller (MDSC) electronics were replaced with a programmable, microprocessor-based control system to regulate the four main drive wound-rotor induction motors and liquid rheostat systems.

The scope of work for control room modernization included remodeling and enlarging the three tunnel control rooms and the Auxiliaries facility control room. The old control rooms contained the original facility control consoles and were not large enough to accommodate both the operating staff and the customer staff. The new rooms feature a modern control console that houses the automation operating workstations. Each new tunnel control room has approximately two thousand square feet and accommodates data acquisition and control systems as well as facility and customer staff. A small instrumentation repair room is also included in each tunnel control room to facilitate on-site repair of model and data system electronics.

The objective of the flow quality improvements was to reduce the turbulence, flow angularity and low frequency Mach number fluctuations in the test section of the 11-By 11-Foot transonic leg. A Turbulence Reduction System (TRS) consisting of a honeycomb and two screens was installed in the settling chamber of the tunnel. The honeycomb is composed of one-inch hexagon cells twenty inches deep (25 mm by 500 mm). The structure is fixed at the tunnel shell and is self-supporting. The two turbulence reduction screens are located downstream of the honeycomb and are spring-tensioned, six-mesh, 304 stainless steel screens using 0.041-inch diameter wire.[2]

Test section upflow and crossflow data across a variety of test conditions were obtained simultaneously with a five-hole cone probe. Pre-modernization flow field survey data with the test section in a solid floor configuration showed indications of a flow perturbation near the lateral centerline, 40 inches above the floor, with a crossflow gradient of up to 0.6 degrees. IST data taken with the same tunnel configuration show that this phenomenon has been eliminated. Preliminary crossflow data show that the variations are within ± 0.08 degrees.

Test section turbulence data measured during the IST show that at a Mach number of 0.80, the baseline turbulence level has been reduced from 0.32% to 0.25% at a nominal total pressure of one atmosphere. With all test section slots covered, the turbulence is further reduced to 0.12%. The turbulence gradient throughout the test section was also noted to be much more uniform than the pre-modernization levels. Amaya and Murthy describe the instrumentation and methods and report the flow angularity and turbulence results from this phase of the IST in detail.[3]

The Wide-Angle Diffuser (WAD) is located in the 11-By 11-Foot Tunnel drive leg, downstream of the compressor and annular diffuser and directly upstream of the tunnel aftercooler. The WAD has a 60-degree included angle. The flow in the WAD region was studied extensively before modernization and exhibited a highly separated jet flow characteristic. Unsteady separated flow in the annular diffuser coupled with WAD jet flow was identified as one of the sources of test section low frequency Mach number fluctuations. In order to eliminate this flow unsteadiness and improve the WAD diffusion process, passive flow enhancement structures, consisting of turning vanes and wall flaps, were introduced into the annular diffuser and the WAD.

The flexible wall (flexwall) nozzle upstream of the test section provides the converging-diverging nozzle that creates supersonic flow in the slotted-wall test section. The flexible wall nozzle was replaced to increase dynamic stability and to improve control of the nozzle contour during supersonic operations. The original flexwall had problems with dynamic stability during transition through certain tunnel conditions and was found to have cracks in several critical structural welds. The two-dimensional nozzle side walls are eleven feet high by approximately twenty feet long with a variable thickness along the length of the wall.

The test section turntable was replaced to provide a higher capacity model support system to accommodate large semi-span models. The approach included providing a commercial rotary indexing table with modifications to fit the wind tunnel requirements.

The original redwood cooling tower was replaced with a modern six-cell Fiberglass Reinforced Plastic tower of similar capacity. The original tencell redwood tower was demolished and removed, except for the concrete water basin.

The pressure vessel weld repair portion of the project arose out of a centerwide effort to recertify all major pressure vessels. Initial assessments of the welds and the pressure vessel material demonstrated that the UPWT pressure vessel system could be repaired rather than replacing the entire shell as was done to the 12-Foot Pressure Wind Tunnel at Ames. The existing Make-Up Air (MUA) system piping was found to have many defective welds. For this reason, it was decided to replace all of the piping "in kind", as well as to replace all of the system control valves and instruments.

A variety of electrical upgrades were also part of the UPWT Modernization Project. The four main drive motors were rewound to provide long-term reliability and to increase their power capability. The original motors were rated at 45,000-horsepower, for 60-cycle, 6,900-volt, 3-phase power. The rewound motors are capable of producing 65,000 horsepower at 695 rpm. Switchgear modernization involved refurbishment of the original facility breakers to provide long term service. These circuit breakers are used to supply power to the main drive motors, the power factor correction capacitors, and the transformers. The two main transformers (T45 and T46) that feed the entire UPWT facility, were rewound and their cores replaced. The refurbished transformers were upgraded to a 115 Kv primary voltage, a 7.2 Kv secondary voltage, and a 97,160 Kva rating.

2.3 FACILITY ACTIVATION RESULTS

The primary objective of the Integrated Systems Test was to safely demonstrate and document the post-modernization capabilities of the 11-By 11-Foot Tunnel. Other objectives were to verify the safe operation of the tunnel, to verify the performance of tunnel systems, to verify the Standard Operating Procedures (SOP), and to define the operating envelope, Figure 3.

The IST was divided into distinct phases that demonstrated different capabilities of the facility. The first phase of the IST involved the functional checkout of the mechanical and automation systems of the MUA system. The second phase of the IST focused on the wind-off performance of the tunnel, primarily safety systems and pumping and evacuation times. Subsequent phases which focused on enlarging the operational envelope were named Subsonic Operation (Phase 3), Subsonic Performance (Phase 4), Flow Quality Performance (Phase 5), Supersonic Operation (Phase 6), and Supersonic Performance (Phase 7).

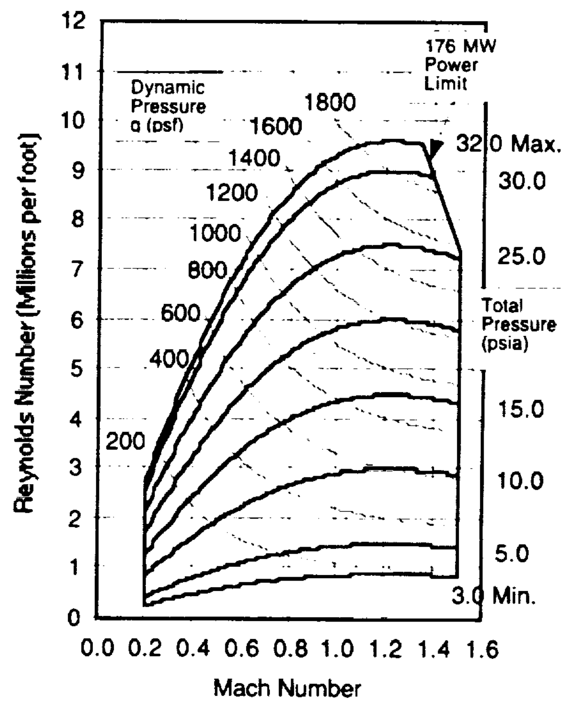

Figure 3. Operating Characteristics of the 11-By 11-Foot Transonic Wind Tunnel

2.4 FACILITY CALIBRATION RESULTS

Two calibration tests and two validation tests were completed before the first production test. The first calibration test was the Mach number calibration of the test section using a static pipe apparatus. A new static pipe apparatus had been made prior to the tunnel shutdown and one of the final pre-modernization tests in 1995 was a tunnel calibration with the new static pipe. The calibration pipe remained in the test section after the Supersonic Performance Phase of the IST, Figure 4. The tunnel was calibrated on centerline throughout the entire subsonic and supersonic regime at four total pressures, nominally 0.5, 1.0, 1.5, and 2.2 atmospheres. The pipe was then lowered to midway between tunnel centerline and the floor and the slots on the floor sealed to calibrate the tunnel for semi-span model configurations. The complete tunnel Mach number envelope was again calibrated in this configuration.

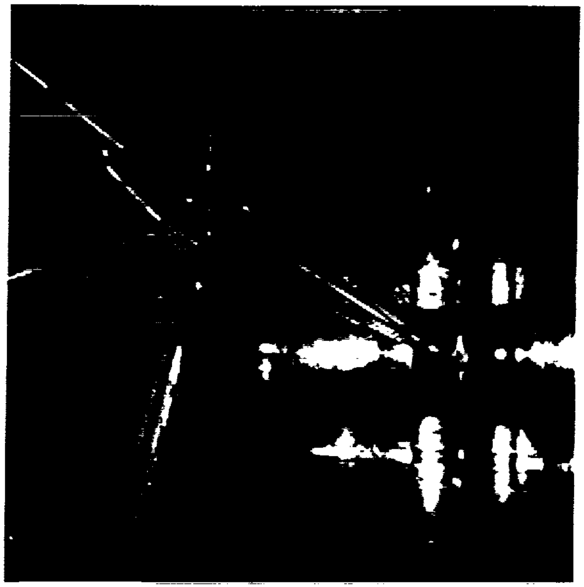

Figure 4. Static Pipe Calibration Apparatus in the 11-By 11-Foot Tunnel (View looking downstream from contraction)

The pipe was supported by cables at the upstream end in the contraction and tensioned on the downstream end by a hydraulic cylinder mounted on the model support strut. The pipe is instrumented with static pressure orifii spaced three inches apart through the length of the test section. Data were acquired during multiple runs at the same conditions to provide a statistical average for the calibration, and the data were fit with a smoothing algorithm to account for orifice error. Comparison of the post-modernization to pre-modernization static pipe data showed little change in the character of the data for both subsonic and supersonic Mach numbers. However, the quality of the post-modernization data in terms of repeatability was significantly improved due to two factors. First, the standard deviation of the multiple pressure samples was reduced due to the use of Digital Temperature Compensation (DTC) Electronically Scanned Pressure (ESP) modules that provide superior temperature stability. Second, the new data acquisition system, the Standard Data System (SDS), acquires tunnel conditions and model pressure data at the same time rather than sequentially, as the old data acquisition system had done. Calibration data taken with the MUA compressor in the PES mode showed that there is little effect on the centerline calibration data with the PES removing air from the test section through the test section slots.

The Ames subsonic calibration model, identified as the LB-435 model, was then installed and tested to measure the integrated flow angularity, to compare aerodynamic performance results with pre-modernization data, and to validate the model support system operation with an airplane model. This test also successfully demonstrated the automated coordination between the test conditions controller and model support controller.

A significant portion of the LB-435 test was dedicated to a sampling study to determine the optimum strain-gage balance data filtering and overall sampling strategy to acquire accurate and repeatable data. After analyzing the sampling study data, it was determined that a 10 Hertz balance amplifier filter with a one second sampling duration provided the optimum data acquisition strategy. Overall drag coefficient repeatability was determined to be better than ±1 drag count at a Mach number of 0.80 and maximum total pressure. The integrated flow angularity was also evaluated during the test and compared with the pre-modernization flow angularity results. The post-modernization upflow for this model was determined to be less that 0.05 degrees in the transonic regime, which is about one-half of the typical pre-modernization upflow.

3. TEST

3.1 TEST BACKGROUND

Wind tunnel test AT0053 was a test of the Boeing Commercial Airplanes 0.037-scale 777 model, WT-T-1867-10A, in the 11-By 11-Foot Transonic Wind Tunnel. Figure 5 shows the model installed in the test section. The test was conducted in two different entries, both in early 2000. The purpose of the test was to validate the modernized Ames 11-By 11-Foot facility.

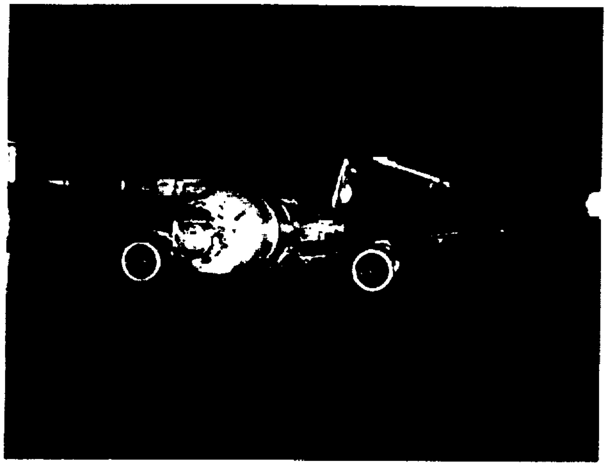

Figure 5. 0.037-Scale 777 Model Installed in the Ames 11-By 11-Foot Wind Tunnel

3.2 TEST OBJECTIVES

The primary purpose of the wind tunnel test from the Boeing perspective was to validate the Ames 11-By 11-Foot facility for conducting commercial airplane product development and research full-model tests. The specific test objectives were:

1. To compare force, moment, and pressure data at one atmosphere total pressure with those obtained at the BTWT, the AEDC 16T, and Ames pre-modernized 11-By 11-Foot.
2. To compare force, moment, and pressure data at two atmospheres total pressure with those obtained at Ames prior to the facility shutdown.
3. To obtain measures of the data repeatability.
4. To evaluate productivity for a full-model test.
5. To evaluate the capabilities of the facility and Ames personnel for conducting typical commercial airplane product development tests.
6. To better understand the correlation between wind tunnel data from this facility and flight test data. The results from this objective are not reported in this paper.

All of the specific test objectives were met.

3.3 MODEL INFORMATION

The model designation as tested was WT-T-1867-10A. This model is a 0.037-scale model of the 777 airplane. The model consisted of a fuselage, wings, nacelles, flap track fairings, a wing-tip fairing, and the horizontal tail. The model was mounted on an upper swept strut sting. The Boeing 6262B internal balance was used to measure forces and moments. Sundstrand QA2000 accelerometers were used to measure model angle with respect to gravity. DTC ESP modules were used to measure model pressures. Notable characteristics of the model include:

1. The wing was always flown with the wing body fairing and the wing-to-body strakelet. The wing reference area is 6.304 ft^2, aspect ratio 8.42, span 87.431 inches, and the MAC is 10.305 inches. 297 pressure taps are installed in the wing, located in 9 rows of 33 ports each.

2. The body represents the 777-200 production configuration. The body is 91.446 inches long, and has a constant section diameter of 9.028 inches. 10 cavity pressures and 12 body pressures were recorded during this test.

3. The horizontal tail was flown at two different incidence angle settings, -1° and +1°. The tail was set using fixed angle blocks. The horizontal strakelet was always flown with the tail. The reference area of the tail is 1.492 ft^2, aspect ratio 4.50, span 31.095 inches and the MAC is 7.444 inches.

4. The model was flown both with and without the 777 flap track fairings.

5. The fan cowl represents the PW4084 nacelle. The left-hand nacelle includes six internal pressures for internal drag calculations. This cowl was flown with the 777 strut and the engine core cowl sized to achieve the design inlet capture ratio. The nacelle chine was always flown with this cowl.

6. The model was flown both with and without the 777 wing tip fairing.

7. Two model transition trip strips were used for the wind tunnel validation portion of the test. Both were forward trips at different heights. One height was used for 1.0 atmosphere total pressure testing, while the other height was used for 2.2 atmosphere total pressure testing. Both of these trip strips were made from vinyl stick-on dots.

Ser #	CONFIGURATION	Φ deg.	Pt atm.	MACH # / No. of Runs														Notes
				.40	.60	.70	.75	.78	.80	.82	.83	.84	.85	.87	.90	.94	.97	
1	Body only	0	1.0	6	1	3	1		1		3	3		1	2			1
2	√	√	√	6	1	3	1		1		3	3		1	2			2
2	√	√	2.2	6	1	3	1		1		3	3		1	2			√
3	K1	180	1.0								3				3			3
4	√	√	√								3				3			√
5	√	√	√								3				3			√
6	√	√	√								3				3			√
7	√	√	√												3			√
8	√	√	1.0	1	1	3	1	1	1	1	3	3	1	1	1	1	1	4
9	√	√	2.2	1	1	3	1	1	1	1	3	3	1	1	1	1	1	√
10	√	0	√	1	1	3	1	1	1	1	3	3	1	1	1	1	1	5
11	√	√	1.0	1	1	3	1	1	1	1	3	3	1	1	1	1	1	√
12	K1 + Wing Tip Fairing	√	√			3					3	3						6
13	K2	√	√	1	1	3	1		1		3	3		1	1	1		7
14	√	√	2.2	1	1	3	1		1		3	3		1	1	1		√
15	K2 - Flap Track Fairings	√	√	1	1	3	1	1	1	1	3	3	1	1	1	1	1	8
16	√ (load comp on)	√	√	1	1	1	1		1		1	1		1				9
17	√	√	1.0	1	1	3	1	1	1	1	3	3	1	1	1	1	1	8
18	K1 + Nacelles	√	√	1	1	3	1		1		1	3		1				10
19	√	√	√			1						1						11
20	√	√	2.2	1	1	1	1		1		1	1		1				10
21	K2	√	√			3					3	3						12
22	√	√	1.0			3					3	3						√
23	K3 (tail angle = -1 deg)	√	√	1	1	1	1		1		1	1		1	1	1		13
24	√ (tail angle = 1 deg)	√	√	1	1	1	1		1		1	1		1	1	1		√
25	√ (tail angle = 1 deg)	√	2.2	1	1	1	1		1		1	1		1	1	1		√
26	√ (tail angle = -1 deg)	√	√	1	1	1	1		1		1	1		1	1	1		√
27	K1	√	√			3					3	3						12
28	√	√	1.0			3					3	3						√

Configurations:

K1 = wing + body

K2 = wing + body + nacelles + flap track fairings + wing tip fairing

K3 = wing + body + nacelles + flap track fairings + horizontal tail + strakelet

Forward vinyl trip strip used, all configurations - Height depending on PT

Notes:

1. Mach Tolerance Study
2. SBIB Determination
3. Acquisition Studies
4. Upflow Determination
5. Baseline Configuration
6. Comparison w/AEDC series
7. Full-Up Configuration
8. Small Increment
9. Load Compensator Effects
10. Small Increment #2
11. IR Visualization
12. Near Term Repeatability
13. Horizontal Tail

PT units, atmospheres

Mach number tolerance, .001 through M=.85, .002 for higher Mach numbers

Table 1. Initial Plan of Test for Wind Tunnel Validation Phase of AT0053

3.4 PLAN OF TEST

The plan of test for the wind tunnel validation phase of AT0053 is presented in Table 1. Not shown in the plan of test are several additional validation run series aimed to further understand the correlation between wind tunnel data acquired in the facility and flight test data. Note also that the plan of test presented is of the planned test, and not the test as was actually run. The test as run was very similar to that which was planned, except for several additional series required because of problems encountered during the first entry, and some duplicate runs acquired in order to make entry-to-entry comparisons.

From the plan of test, note that data were acquired at two different total pressures. Data were acquired at 1.0 and 2.2 atmospheres total pressure. The 1.0 atmosphere total pressure data matches data from the BTWT and typical Boeing tests at AEDC. The 2.2 atmospheres total pressure data provides data at the highest practical Reynolds number for the facility.

3.5 TEST STATISTICS

This test was run as two different model installations. The first entry was tested in January and February 2000, and the second entry was tested in April and May 2000. The first entry faced many difficulties, including various facility deficiencies, and a Boeing labor dispute. The first entry was finally abandoned when the pitch strut feedback frequency changed such that it excited unacceptable model dynamics. A total of three useful Mach series were acquired during the first entry. The body only series were acquired during the first entry, and thus were not repeated during the second entry. The remainder of the test plan was acquired during the second entry. Some test statistics are presented in Table 2.

Metric	Value
Entries	2
Occupancy for Entry 1	239 hours
Occupancy for Entry 2	330 hours
Total Useful Mach Series	35
Total Runs	761
Total Useful Data Runs	486
Useful Data Runs, Entry 1	54
Useful Data Runs, Entry 2	432
Entry 1 Calendar Time	Jan 31 to Feb 28, 2000
Entry 2 Calendar Time	Apr 24 to May 19, 2000

Table 2. Test Statistics

Some notes regarding test statistics and the as-run test matrix follow:

1. Very little of the plan of test was completed during the first entry.
2. Many of the valid runs acquired during the first entry were used for troubleshooting purposes. Just 54 runs out of 151 wind-on runs acquired during the first entry were used for subsequent analysis. Many runs acquired during the first entry were suspect due to excessive scatter, unexplained level shifts, etc.
3. The following useful run series were acquired during the first entry: body alone series at both PT levels, one low-PT series, and the acquisition parameter studies.
4. All of the runs acquired during the second entry were judged to be useful data. Data shifts, excessive scatter, and other typical wind tunnel enigmas were absent during this entry of the test.
5. The requested Mach number tolerance was 0.001. The tolerance achieved during the first entry was typically 0.002. The tolerance achieved during the second entry was less than 0.001, typically 0.0005.

3.6 COMPARISON TEST INFORMATION

The same model and support system was previously tested in the BTWT to obtain direct comparison data. Additionally, less direct comparison data exists from the AEDC 16T wind tunnel and the pre-modernization Ames 11-By 11-Foot tunnel. Note that none of the comparison tests contained all of the tunnel conditions and model configurations tested during AT0053. However, each comparison test contained at least several tunnel conditions and model configurations that were run during this validation test. Additional comparison test information is presented in Table 3.

Facility	Test	Year	Balance	Notes
Ames 11-By 11-Foot	AT0053	2000	6262	(1)
BTWT	BT2233	1999	6262	
AEDC 16T	TF0912	1996	6226	(2)
Ames 11-By 11-Foot	ARC151	1991	6257	(1) (2)
(1) Data acquired at both 1 and 2.2 atmospheres total pressure (2) These tests used a different wing body fairing and a different wing strakelet. It is believed that effects from this configuration change are negligible				

Table 3. Comparison Test Information

3.7 DATA CORRECTIONS

Appropriate tunnel parameter corrections and balance related corrections were applied to the data from AT0053 as well as the comparison tests. Additional data corrections are typically applied to model attitude and to model forces and moments. Table 4 lists these additional corrections for the subject test and the comparison tests.

Corrections to model attitude (angle of attack) are:

1. Upflow
2. Wall Interference

Corrections to model forces and moments are:

1. Clear Tunnel Buoyancy (affects drag)
2. Solid Blockage Induced Buoyancy (affects drag)
3. Cavity Pressure Effects (affects drag, lift, and pitching moment)
4. Nacelle Internal Drag (affects drag, lift, and pitching moment)
5. Skin Friction normalized to standard BTWT operating curve for one atmosphere data only (affects drag, lift, and pitching moment)

Correction	AT0053	ARC151	BT2233	TF0912
Upflow	Lift curve method	Polar Rotation method (3)	Lift Curve method	Polar Rotation method (3)
Wall Interference	Same as ARC151	777 Derived δ_0 values	Current WT δ_0 values	WT δ_0 value (4)
Solid Mach Number Blockage	Same as ARC151	777 Derived	No	No
Clear Tunnel Buoyancy	Yes	Yes	Yes	Yes (2)
Solid Blockage Induced Buoyancy	Yes	Yes (2)	Yes	Yes (2)
Tare and Interference	Applied to derive SBIB	Applied to derive SBIB	Applied to derive SBIB	Applied to derive SBIB
Cavity Pressures	Yes	No (1)	Yes	Yes (2)
Nacelle Internal Drag	Yes	Yes	Yes	Yes
Normalized Skin Friction to standard curve	Yes, applied only to 1 atmosphere data	Yes, applied only to 1 atmosphere data	Yes	N/A ran standard BTWT curve

(1) These pressures not available in the archived data
(2) This data correction applied by wind tunnel staff for tunnel to tunnel comparisons. Original test did not apply this correction, or applied different corrections
(3) Upflow calculated from Polar Rotation Method agrees well with that calculated from Lift Curve Method
(4) Preliminary value, wall interference corrections still being determined for this facility

Table 4. Data Corrections used for AT0053 and Comparison Tests

Figure 6 shows the upflow angle α_{u} versus Mach number as calculated for AT0053 and the comparison tests. The upflow angle correction is model specific. The corrected angle of attack is found by adding the upflow angle correction to the uncorrected angle of attack. Only upflow at one atmosphere total pressure is plotted for the two Ames 11-By 11-Foot tests. However, there was good agreement between the upflow calculated at 1.0 and 2.2 atmospheres total pressure for both these tests. Figure 6 shows that the upflow angle present at the Ames 11-By 11-Foot is smaller in magnitude than upflow found in either the BTWT, or the AEDC 16T. Also note that the upflow from the current test is smaller than what was found in 1991 during ARC151. This is due to the effectiveness of the flow conditioning devices installed during the modernization of the facility.

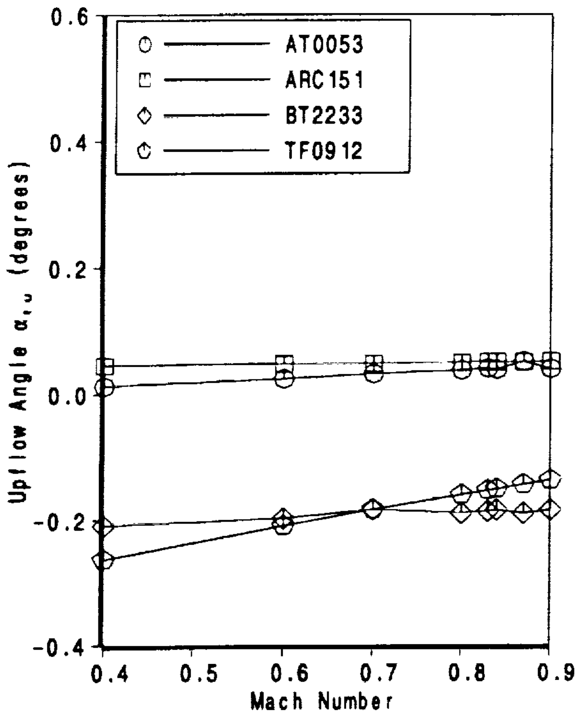

Figure 6. Upflow Angle Corrections for AT0053 and Comparison Tests

Figure 7 shows the wall effects term δ_0 versus Mach number for both of the Ames 11-By 11-Foot tests and the BTWT test. δ_0 at a Mach number of 0.83 is shown for the AEDC 16T comparison test. Wall effects corrections at other Mach numbers are still being determined for the 16T facility. The δ_0 term is used to determine the lift interference correction angle α_{LI} from the equation:

$$\alpha_{LI} = \frac{180}{\pi} * \delta_0 * CL * \frac{S_{ref}}{A_{tun}}$$

The corrected angle of attack is found by adding the lift interference correction angle to the uncorrected angle of attack as is done with the upflow correction angle. Note that the wall effects term δ_0 is not model specific; however, the lift interference angle is model specific, since the angle is a function of the model reference area.

Figure 8 shows the Clear Tunnel Buoyancy correction coefficient DCDCTB versus Mach number for both of the Ames tests, the BTWT test, and the AEDC test. The clear tunnel buoyancy correction is model specific for each tunnel. The corrected drag coefficient is found by subtracting the DCDCTB term from the uncorrected drag coefficient.

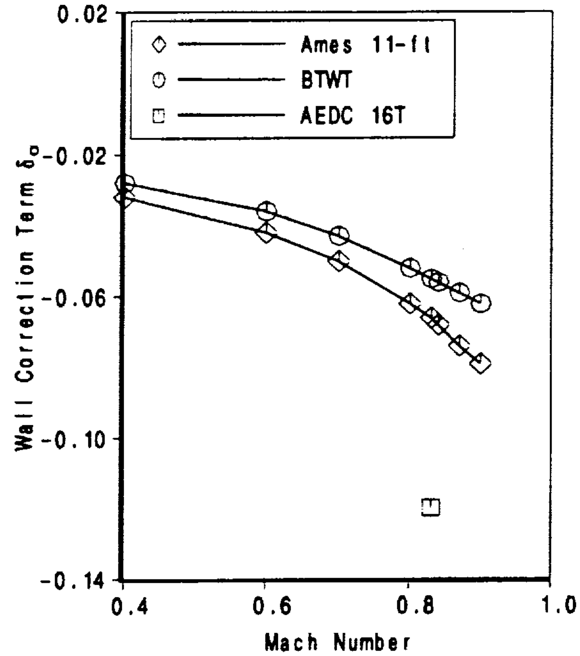

Figure 7. Wall Effects Term δ_0 for AT0053 and Comparison Tests

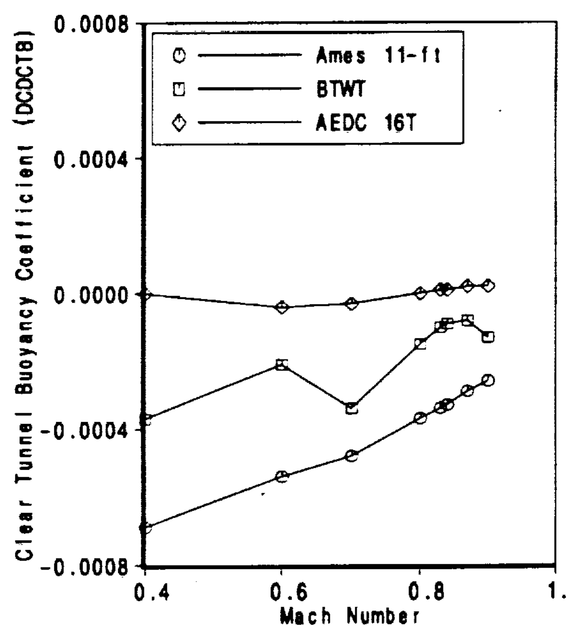

Figure 8. Clear Tunnel Buoyancy Coefficient (DCDCTB) for AT0053 and Comparison Tests

Figure 9 shows the Solid Blockage Induced Buoyancy correction coefficient (DCDSBIB) for the Ames AT0053 test, as well as the pre-modernization Ames ARC151 test, and the BTWT and AEDC 16T comparison tests. As with clear tunnel buoyancy, the solid blockage induced buoyancy term is model specific for each tunnel. The corrected drag coefficient is found by subtracting the DCDSBIB term from the uncorrected drag coefficient. Note the relative magnitude of the correction.

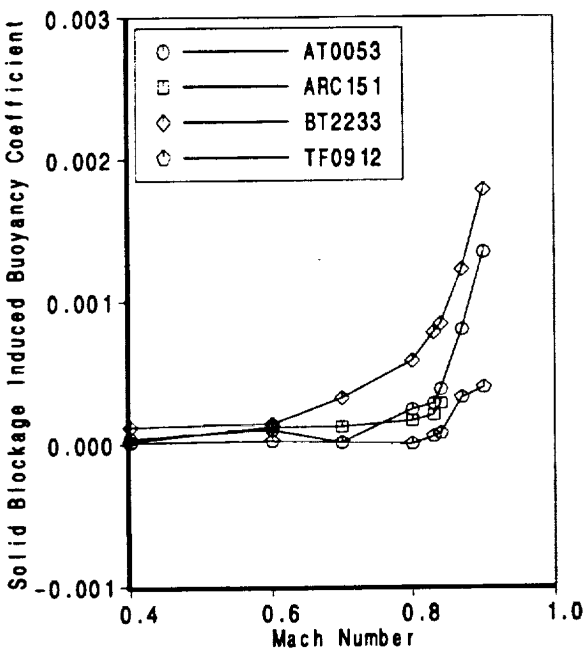

Figure 9. Solid Blockage Induced Buoyancy Coefficient (DCDSBIB) for all tests

4. TEST RESULTS

The overall quality of the data was evaluated by examining comparisons of key performance parameters. Data repeatability was evaluated by comparing within-series, within-test, and test-to-test drag performance at transonic cruise conditions. Comparisons of the pre-modernization to post-modernization Ames tests show dramatic improvements in repeatability. The smoothness of curve fits to drag polars is used to evaluate overall data quality. Other evaluations of the test results include comparisons of the levels and shapes of lift curves and drag polars. The drag rise characteristics from test-to-test are also used as a measure of data quality. In addition, drag increments due to the addition of flap track fairings are used as a typical indicator of the ability to evaluate the data quality during incremental studies. Finally, productivity is evaluated using the metrics Runs per Occupancy-hour and Runs per Air-on-hour to understand the tunnel efficiency.

4.1 DATA REPEATABILITY

The repeatability of data acquired during the AT0053 test was excellent. Drag coefficient repeatability is presented in this report. Repeatability of the other aerodynamic coefficients was also excellent.

Figure 10 shows the level of drag coefficient repeatability demonstrated within a Mach number series of runs. The three runs plotted on this figure were not acquired back to back, but rather well spaced within the twenty runs making up the Mach number series. Within-series repeat runs were scheduled at Mach numbers of 0.70, 0.83, and 0.84. Figure 10 shows the repeat runs at a Mach number of 0.83. Repeatability at the other two Mach numbers was comparable to that at a Mach number of 0.83. The data presented were acquired at one atmosphere total pressure. As with Mach number, repeatability was found to be equally good at both total pressure conditions. The model configuration for the data presented was wing+body. However, repeatability was found to be independent of model configuration throughout the test.

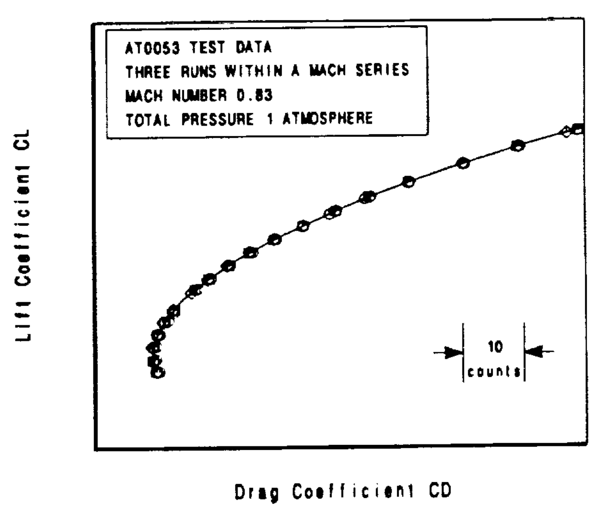

Figure 10. Drag Coefficient Repeatability Demonstrated during the AT0053 Test

Note that the drag coefficient versus lift coefficient from the three runs appears identical on the magnified scale of Figure 10. Offsets and scatter between the polars are absent. This level of excellent data repeatability was demonstrated throughout the entire test.

Figure 11 shows the level of drag coefficient repeatability within a Mach number series from the pre-modernization ARC151 comparison test. Data in Figure 11 also included three runs at a Mach number of 0.83, one atmosphere total pressure, and wing + body model configuration.

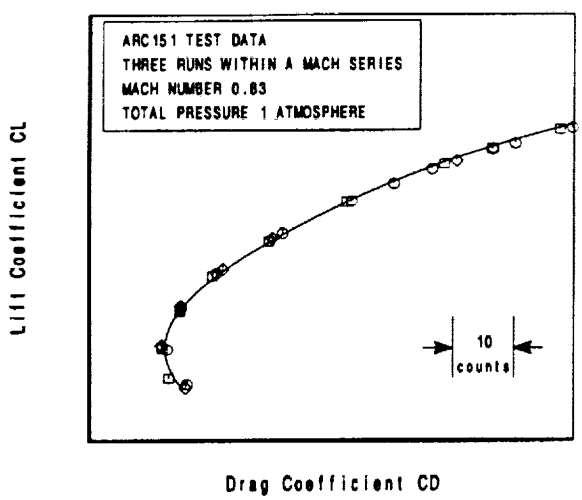

Figure 11. Drag Coefficient Repeatability Demonstrated during the ARC151 Test

The scale of Figure 11 is identical to the scale of Figure 10. Note however that the repeatability demonstrated during the 1991 test is significantly worse than that currently demonstrated. Both offsets and random scatter are evident between the three runs plotted. The level of the scatter evident during ARC151 is almost twice that of the scatter evident during the AT0053 test.

Note that the data presented in Figure 11 were acquired with a different internal balance and a different physical wing body fairing and wing strakelet, as shown in Table 3. It has been determined from past tests that the level of repeatability that can be achieved with both balances is similar. Repeatability effects due to model configuration changes are thought to be negligible.

Figure 12 shows the level of scatter presented as residuals from the curve representing the polar from both Figures 10 and 11 on a greatly expanded scale. In addition to the residuals, both the 95% confidence intervals, and the 95% prediction intervals are also shown. The prediction interval is a better measure of data scatter than the confidence interval since the confidence interval is an inverse function of the number of data points within the sample. As seen on Figure 12, the 95% prediction interval for the current Ames test is 1.2 counts total bandwidth, or ±0.6 counts. This compares to the 1991 ARC151 test where the 95% prediction interval was 2.2 counts total bandwidth, or ±1.1 counts. This improvement in data repeatability is dramatic.[4]

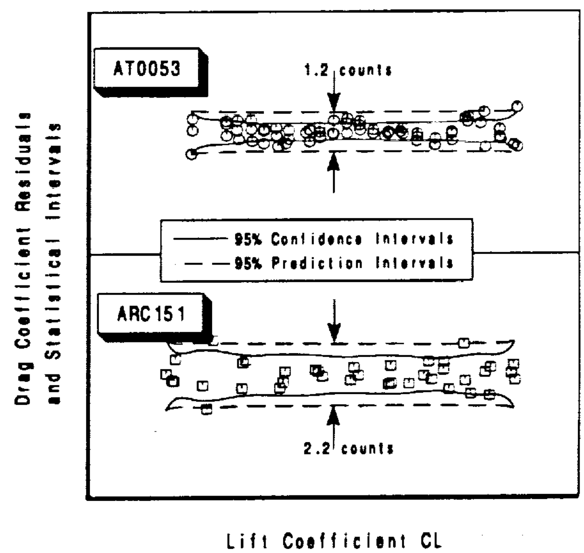

Figure 12. Drag Coefficient Residuals and Statistical Intervals for both the current and past Ames Tests

Figure 13 shows the level of near term drag coefficient repeatability from the current AT0053 test. Data from two repeat model configurations acquired 15 days apart are presented. The data represented by circles on the figure are the same data presented in Figure 10. The data represented by squares are from the repeat entry. In addition to the time element, the model configuration had been changed 26 times between these two Mach series. Figure 13 shows that there are essentially no differences between the two data sets. Near-term repeatability was as good as within-series repeatability throughout the test.

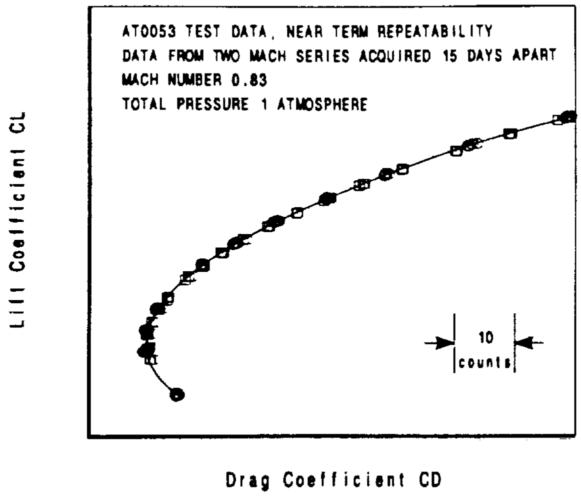

Figure 13. Near Term Drag Coefficient Repeatability during the AT0053 Test

Data repeatability is a function of Mach number tolerance, uniformity of tunnel conditions, and temperature stability during and between Mach number series. The Mach number tolerance of data collected during AT0053 was about 0.0005, versus about 0.001 for the 1991 comparison test ARC151. This improvement in Mach number tolerance, coupled with improved flow quality and temperature uniformity in the test section, are believed responsible for the tighter data repeatability noted in the modernized tunnel. Data repeatability at the Ames 11-By 11-Foot is now on par with that demonstrated at the very best tunnels ever used by Boeing Commercial Airplanes.

4.2 DATA QUALITY

In addition to repeatability, smoothness of the acquired data is a measure of overall data quality. Smooth data results in more accurate curve fit representations that lead to more accurate interpolated data and increments between data sets. Figures 14 and 15 show drag polars at a Mach number of 0.97, one atmosphere total pressure. Figure 14 presents data acquired at the Ames 11-By 11-Foot during AT0053. A Conditional Sampling scheme resulted in a Mach number tolerance of less than 0.001 for the entire second entry. Figure 15 presents data from the BTWT with a Mach number tolerance of 0.002.

A Mach number of 0.97 is well up in the drag rise of the 777 airplane. The effects of Mach number tolerance are easily seen. Note how the drag polar from the AT0053 test is very smooth, while the polar from the BT2233 test is more ragged.

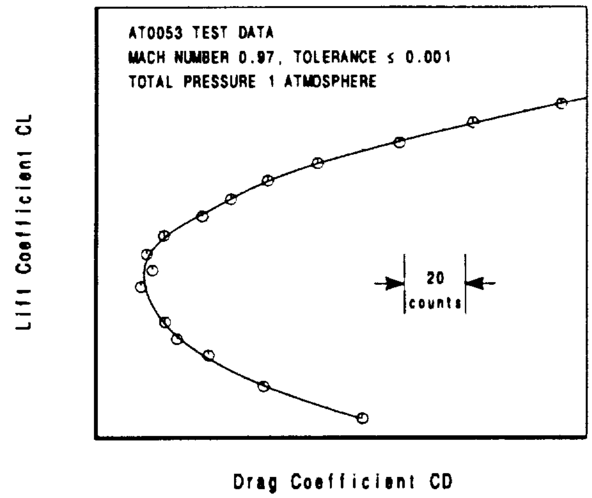

Figure 14. Smoothness of Drag Polar Acquired during the AT0053 Test

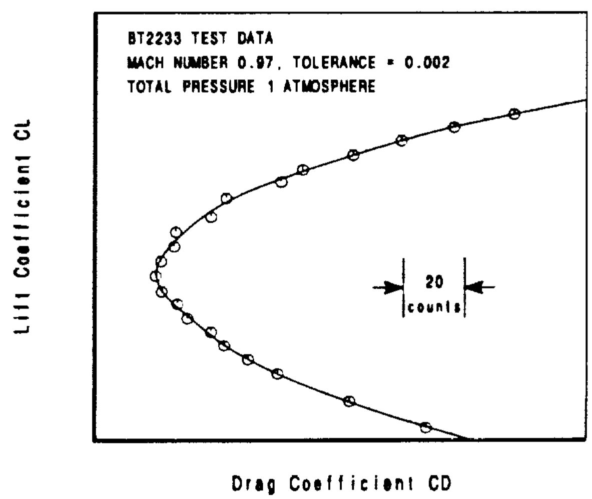

Figure 15. Smoothness of Drag Polar Acquired during the BT2233 Test

4.3 COMPARISON OF LIFT CURVE SLOPES

A comparison of pre-modernization (ARC151) and post-modernization (AT0053) model lift curve slopes is presented in Figure 16. Data at a Mach number of 0.83 for both one and two atmospheres total pressure are presented.

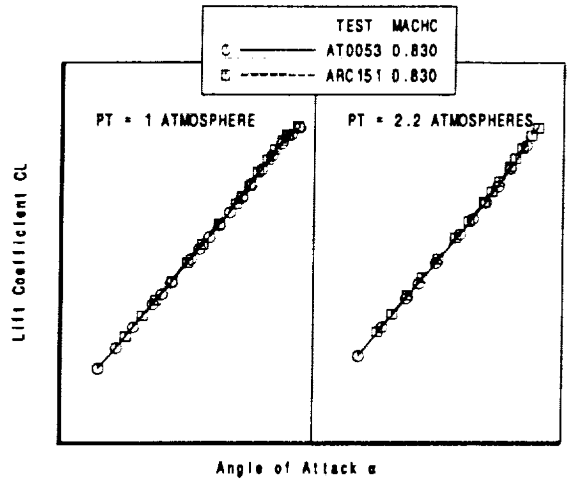

Figure 16. Comparison of Lift Curve Slopes Before and After Modernization

The agreement in lift curve slopes between the two tests is very good as shown in Figure 16. This is not unexpected, as the upflow corrections were calculated within each test, and the same wall corrections were used for both tests. However, this agreement does show that tunnel wall effects have not changed as a result of the tunnel modernization effort.

Figure 17 shows the model lift curve slope as measured during the AT0053 test compared with those measured from the BT2233 and TF0912 comparison tests. Again, data are presented at a Mach number of 0.83.

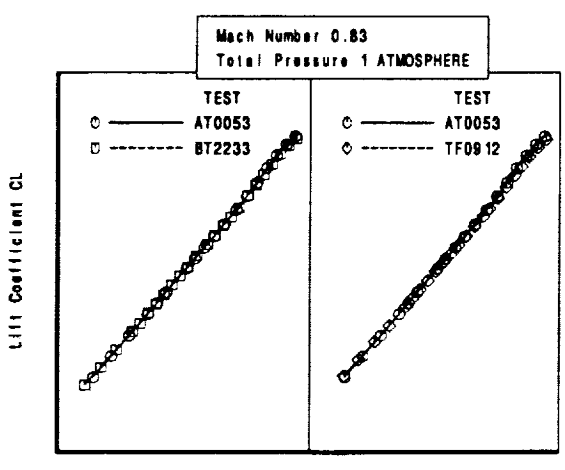

Figure 17. Comparison of Lift Curve Slopes between the Ames 11-By 11-Foot, BTWT, and AEDC 16T

Again, the agreement between the data is considered good. This indicates that throughout the linear portion of the curve, which extends to lift coefficients above cruise, the wall corrections between the three tunnels all result in comparable final data. There is some divergence at higher lift coefficients that indicates that the δ_0 value may not be independent of lift coefficient, as is presumed in the model. This has been consistently noted in past tunnel-to-tunnel comparisons.

4.4 COMPARISON OF DRAG POLARS

In general, drag from the current Ames validation test, AT0053, compared well with drag from the Ames test in 1991, (ARC151), as well as with drag from the BTWT test BT2233 and the AEDC 16T test TF0912. All data presented are at a Mach number of 0.83. Agreement at other Mach numbers is comparable to that which is presented here. Drag levels typically compared within about 4 to 5 counts in the worst case, but were more often within about 2 counts. This level of agreement is considered good for test-to-test comparisons, and very good for tunnel-to-tunnel comparisons.

Figures 18 and 19 show the comparison between the current Ames validation test AT0053 and the 1991 test ARC151 for 1.0 and 2.2 atmospheres total pressure. The configuration of the model for both plots is wing and body. Note the expanded scale on both figures.

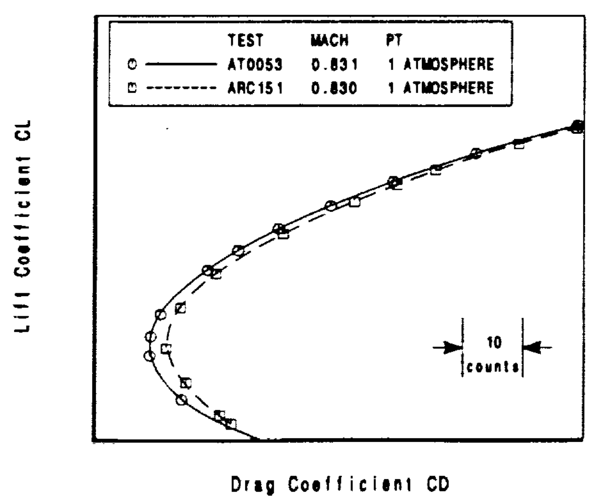

Figure 18. Drag Comparison between AT0053 and ARC151 at 1.0 Atmosphere Total Pressure

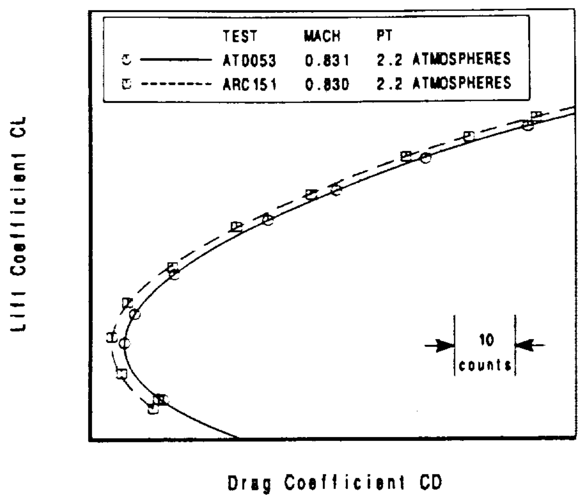

Figure 19. Drag Comparison between AT0053 and ARC151 at 2.2 Atmospheres Total Pressure

Figure 18 shows that the current drag level is about 2.5 counts less than that measured during ARC151 at the minimum drag coefficient. However, Figure 19 shows that the current drag level is about 2 counts higher than that measured during ARC151 at the minimum drag coefficient. The agreement at both total pressures is approximately within a historical 2 count ability to repeat drag data. However, it is interesting that the data from the current test results in less drag at one atmosphere, and more drag at two atmospheres than the 1991 comparison test. Figures 18 and 19 indicate a 4.5 drag count difference between the two tests at one and two atmospheres total pressure.

The expected drag difference due to Reynolds number effects was examined in an attempt to determine which data set, AT0053 or ARC151, resulted in drag increments which better agreed with theory. Skin friction correction methodology shows that the Reynolds number effect should lie between that calculated for each test. Specifically, it appears that the effect as measured during AT0053 is about 2 counts less than calculations suggest, while the effect as measured during ARC151 is about 2.5 counts greater than the calculated effect.

Figure 20 compares drag from the Ames validation test AT0053 with the BTWT comparison test BT2233. These data represent the full-up model configuration. Note that the data from the BTWT is about 2 counts higher than the data from the Ames 11-By 11-Foot at minimum drag coefficient. Again this agreement is considered very good for tunnel-to-tunnel comparisons.

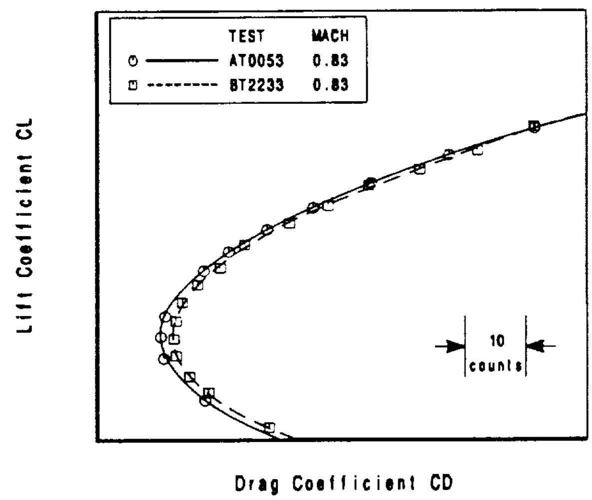

Figure 20. Drag Comparison between AT0053 and BT2233

Figure 21 compares drag from the Ames validation test AT0053 and the AEDC 16T comparison test TF0912. These data also represent the full up model configuration. Here the two data sets agree at minimum drag coefficient, but diverge to a fairly constant 2 count difference at higher lift coefficients. From the figure, it appears as if there is a slight polar rotation and a small shape change between the two curves. These differences between the two tunnels are visible because of the greatly expanded scale used on the plot. Again, this level of agreement is considered very good for tunnel-to-tunnel comparisons. It is believed that agreement within 2 counts is generally within our test-to-test repeatability level.

Figure 22 shows the comparison between polar shapes from the Ames 11-By 11-Foot, the BTWT, and the AEDC 16T. This figure shows the full drag polars for the three tests at a Mach number of 0.83. The three curves have been normalized such that they collapse at the minimum drag coefficient. As seen on the figure, the polar shape agreement between the three facilities is quite good. Neither polar rotations or shape changes are visible. In summary, the drag polar shape from the three different facilities all agree well.

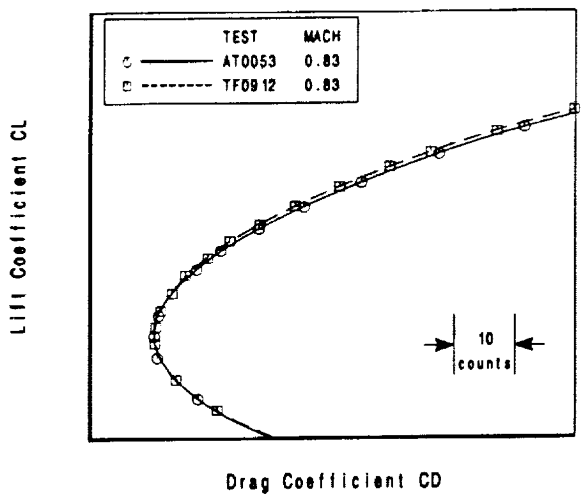

Figure 21. Drag Comparison between AT0053 and TF0912

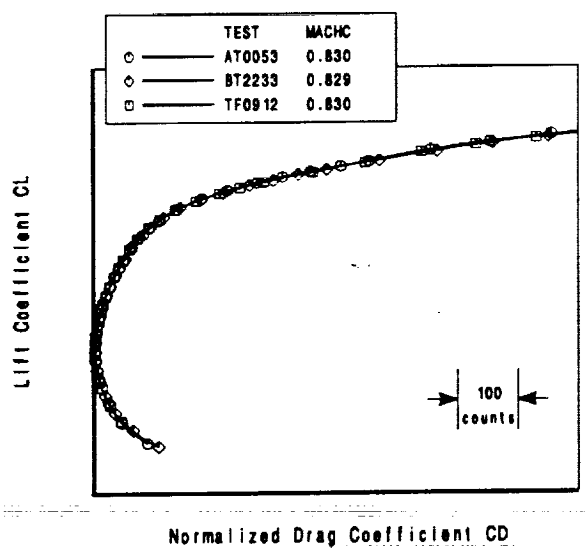

Figure 22. Drag Polar Shape Comparison between Ames 11-By 11-Foot, BTWT, and AEDC 16T

4.5 COMPARISON OF DRAG RISE

A drag rise comparison with respect to Mach number for the Ames 11-By 11-Foot AT0053, the BTWT BT2233, and the AEDC 16T TF0912 tests is presented in Figure 23. The data presented are at one atmosphere total pressure. The model is in the full up configuration. The lift coefficient for this data is approximately representative of the cruise condition for the airplane. As can be seen from the figure, the drag agreement for the three tests is good. The shape of both the drag rise and the Mach number where the curve breaks are in good agreement among the three tests. This level of agreement for drag rise between different facilities is considered good. The drag rise agreement presented is typical of that which was noted throughout the test.

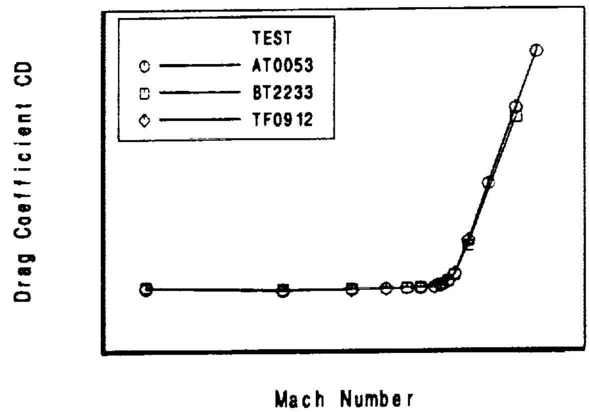

Figure 23. Drag Rise Comparison between Ames 11-By 11-Foot, BTWT, and AEDC 16T

4.6 COMPARISON OF DRAG INCREMENTS

A comparison of drag increments between two model configurations for the AT0053, BT2233, and TF0912 tests is presented in Figure 24. The drag increment presented is for the flap track fairings, that is, drag level of the model with flap track fairings on minus the drag level of the model with flap track fairings off. The data presented are at a Mach number of 0.83 and one atmosphere total pressure.

The agreement of the drag increment, ΔCD, between the three facilities is within about 1 count throughout much of the lift coefficient range. The disagreement between the increments is about 2 counts in the worst case. Note that with drag increments, as with many other comparisons, the data from AT0053 tend to be in between the data from BT2233 and TF0912. This agreement presented in Figure 24 is typical of the agreement in increments for other configuration changes. Again, the level of agreement in drag increments for the three different tests conducted in three different facilities is considered good. In general, this statement about good data agreement can be expanded to include all data comparisons between the Ames validation test AT0053, the 1991 Ames comparison test ARC151, the 1999 BTWT comparison test BT2233, and the 1996 AEDC 16T comparison test TF0912.

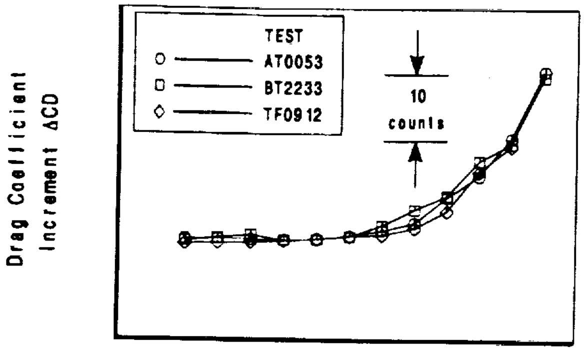

Figure 24. Comparison of Flap Track Fairing Drag Increment at Mach number 0.83

4.7 PRODUCTIVITY

Test productivity during the second entry of the AT0053 validation test was generally acceptable, and very good if installation and facility problems were excluded. The productivity metrics showed dramatic improvement when the 11-By 11-Foot pre-modernization and post-modernization tests are compared. The validation nature of the test also skewed the productivity metrics lower than a typical production test.

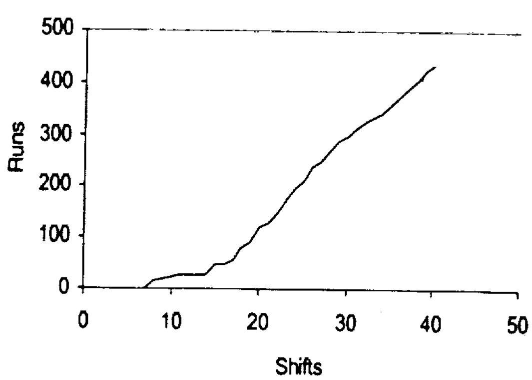

Figure 25. Cumulative Good Data Runs versus Shifts for AT0053, Second Entry

Figure 25 shows cumulative good data runs versus shifts. The installation took seven shifts in part due to the validation nature of the test. Problems encountered during the installation are described in the Facility Findings section. Future installations will require less time due to the lessons learned during this test. After installation, there was good productivity for one shift and then facility problems consumed the next six shifts. After these facility problems were fixed, there were no significant periods of facility downtime for the remainder of the test. Facility downtime would not be charged during a typical production test. Facility downtime would also not be included when calculating the typical accounting terms Runs per Occupancy-hour and Runs per Air-on-hour during a production test.

Figure 26 presents the accounting terms Runs per Occupancy-hour and Runs per Air-on-hour versus cumulative shifts, also for the second entry of the Ames validation test AT0053. By the end of the test, 5.4 cumulative Runs per Air-on-hour were the norm. This many runs per hour for a typical polar density is considered good. A typical run, or polar, contained around 30 test points, with some variation depending on Mach number. Note that there is essentially no slope to the Runs per Air-on-hour curve by the end of the test. This is more indicative of what would be achievable for a typical production test, but is very dependent on the angle schedules and run matrix for a specific test.

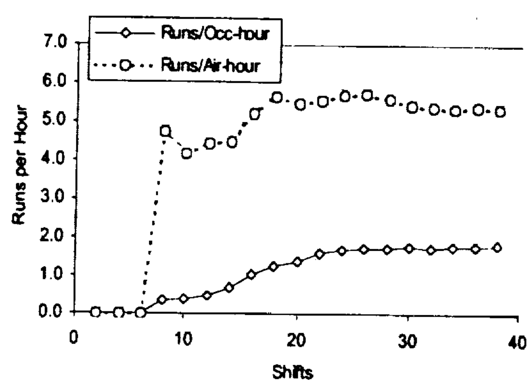

Figure 26. Cumulative Runs per Occupancy Hour and Runs per Air-On Hour for At0053 Entry

Figure 26 shows that 1.8 cumulative Runs per Occupancy-hour were completed by the end of the test. This metric was strongly affected by the long installation. Note that the slope of this curve is still positive at the end of the test. The long installation dilutes the Runs per Occupancy-Hour metric. In addition to the long installation, this metric was also affected by the decision to run this evaluation test with a minimum Boeing support crew. Model changes in particular required more time than is typical for a Boeing Commercial Airplanes production wind tunnel test.

Figure 27 presents cumulative Runs per Air-on-hour and Runs per Occupancy-hour for the subject test compared with the 1991 Ames 11-By 11-Foot test ARC151. Note the improved productivity compared to that demonstrated in 1991. The improvement in Runs per Occupancy-hour is about 40%. The improvement in Runs per Air-on-hour is 116%. The magnitude of these improvements is dramatic. Overall, the test productivity that was demonstrated during the second entry of the validation test is considered good. The productivity demonstrated during this test is comparable to that from other world class facilities where Boeing Commercial Airplanes has tested. Nonetheless, the Facility Findings section describes efforts that were completed and some still underway to increase productivity and data quality.

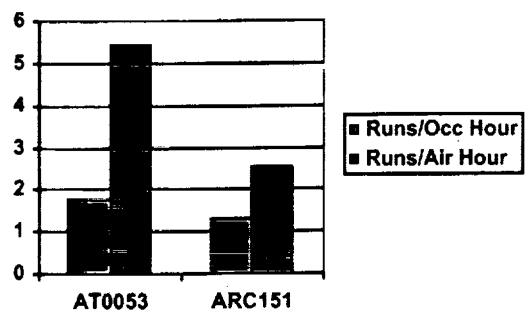

Figure 27. Productivity Comparison Between the Ames 11-By 11-Foot Tests AT0053 and ARC151

5. FACILITY FINDINGS

5.1 PROBLEMS ENCOUNTERED DURING THE TEST

5.1.1 TEST SECTION MACH NUMBER TOLERANCE VARIANCE

Test section Mach number control in the 11-By 11-Foot tunnel is accomplished by setting the compressor drive speed to achieve a "coarse" Mach number and varying the compressor Inlet Guide Vanes to set the "fine" Mach number. The Mach number variance at a Mach number of 0.82 is approximately ± 0.002. This variance increases slightly with Mach number and as the model is pitched, and was slightly outside the Boeing 777 test required Mach number tolerances of ±0.001 up to a Mach number of 0.85 and ±0.002 at Mach numbers from 0.85 up to 0.97.

Model data acquisition at the UPWT is performed using the Standard Data System (SDS) that consists of a variety of Functional Subsystem Processors that acquire different types of data. Typical data acquisition acquires model force and moment data and tunnel conditions data during a period set as the sampling duration, typically one second.

A Conditional Sampling (CS) strategy was developed during validation tests to acquire force and moment data with a tighter Mach number tolerance. Conditional Sampling is an acquisition strategy that breaks a data point into many smaller time slices. The data point is collected in 125 millisecond time slices. Each time slice is then used to compute whether or not the raw data is to be considered as "good". If a time slice is "good," it is added to the aggregate raw data for the point being acquired. Raw data determined to be "not good" is discarded. The total time duration of the aggregate raw data is determined by the user specified point duration. Conditional Sampling will take up to five times the specified point duration in its attempt to obtain a one duration aggregate raw data buffer. If the aggregate has not been acquired in the five times duration interval then all data is discarded and the process repeats. The maximum number of repeat attempts is five. If the maximum number of repeat attempts fail then the point fails.

The Computer Systems Technician entered the Mach number setpoint and the tolerance before a given run. The deviation of the actual Mach number from the Mach number setpoint was used as the "goodness" criterion for each of the time slices. Accurate data were taken using the Conditional Sampling strategy to meet the Boeing Mach number tolerance requirements.

5.1.2 DIFFERENCES IN AMES AND BOEING DATA PROCESING

A variety of minor differences in the data processing computations were identified during both test entries. None of the following differences resulted in significant differences in the final aerodynamic coefficients, but are representative of differences in approach in computations. Some of the differences include; 1) Constraints of the Boeing portable data system that require that wind-off zero points be acquired within a run series, whereas Ames handles initial conditions scans differently, 2) Ames uses a shunt system to transfer the balance calibration constants to the tunnel data system, Boeing uses a voltage standard method, 3) Ames corrects for drift in the CAL signal taken after each zero and corrects the prime balance sensitivities automatically, whereas Boeing monitors bridge voltage and adjusts the sensitivity if the excitation changes exceed a tolerance, 4) The balance zero load output is handled differently by each system, 5) Standard engineering units in SDS are foot-pounds and psfa, whereas Boeing uses inch-pounds and psia, and 6) Both systems use different naming conventions for a variety of computations. None of the above differences necessarily cause a difference in the final coefficients, but are differences in approach that caused confusion during the test.

5.1.3 INLET GUIDE VANE PROBLEMS

The 54 IGV's are located at the inlet of the three-stage compressor that drives the 11-By 11-Foot tunnel. The vanes are positioned by a single motor, driving two trains of vanes through a series of external gearboxes and u-joints. The direct current electric motor is mounted on a platform on the north side of the compressor, external to the wind tunnel. At one time during the test the IGV's were "frozen" and would not move when commanded from the control room.

An inspection of the motor revealed that the coupling to the motor tachometer had broken. The motor tachometer is used in the motor speed feedback logic and its loss would not allow movement of the IGV system. The small coupling was replaced and the IGV's returned to operation within several hours. The flexure coupling appeared to fail in shear due to fatigue. Additional spare couplings were ordered.

5.1.4 FAILED COMMUNICATIONS LINK BETWEEN THE FCS AND MDSC

The communications link between the 11-By 11-Foot Facility Control System and the Main Drive Speed Control failed during the test. The problem prevented the FCS from "receiving" MDSC data. The "send" portion of the link was still functioning properly, but proper control of the tunnel conditions was not possible without the "receive" channels.

The hardware and software related to the fiber optic link were tested and found to be good. The FCS database had previously caused similar problems, so it was restored to sort out the link problem, but this had no effect. The serial bus communications card was replaced without effect. A bad analog input card that was totally independent of the link was finally found to be the cause of the problem. An analog FCS card probably had a failure in the address logic that caused interference with the link communications card. The card was replaced and the system performed normally. Spare FCS boards are available at the UPWT site, however, the health monitoring capability of the boards is limited.

5.1.5 SLOW MODEL INSTALLATION

A typical test in the 11-By 11-Foot tunnel involves setup and checkout in a Model Preparation Room (MPR) for two weeks prior to test installation in the test section. Tests perform balance checkloading and model buildup and checkout on the sting assembly before transport to the test section. The Boeing 777 test installation was accomplished in seven shifts. The goal for installation of moderately complex production tests is two to four shifts.

The model installation went slowly due to several factors. Typical model installations, such as the F/A-18E model test preceding the Boeing 777 entry, spend two weeks in the MPR performing checkout of all critical instrumentation and model hardware. The focus in the 11-By 11-Foot during the week preceding the Boeing 777 second entry was to validate an incremental upgrade to SDS data acquisition software, particularly Conditional Sampling software. The 777 model was installed directly into the test section due to the validation nature of the test, and the MPR was not used for the second entry.

The problems encountered during the model installation for the second entry included difficulties unique to the test and some process problems that were addressed after the test. The balance cable was determined to be bad and replaced early in the installation period. A taper pin connection on the balance axial gage was loose and required additional time to troubleshoot and repair. Setup and checkout of the QA2000 angle accelerometers required almost an entire shift to complete. Checkout and repair of bad model pressures also took about a shift to complete. Also, the A/B hardwired limit switches on the strut blade were difficult to set and one of the switch wires broke, requiring repair.

5.1.6 STING MODEL SUPPORT SYSTEM PROBLEMS

The Sting Model Support System (SMSS) in the 11-By 11-Foot tunnel was automated as part of the UPWT Modernization Project. This system uses a pair of rotating bent arms called the 'Knuckle' and 'Sleeve' to obtain taper pitch angle (A) and taper yaw angle (B) anywhere within ±15 degrees. The Knuckle-Sleeve taper is supported by an 8-inch thick vertical blade strut that translates vertically to keep the test article pitch center on tunnel centerline during pitch polars. Drive power is provided to the Knuckle and Sleeve by hydraulic motors through a series of roller-link chains that extend through the center of the strut blade down to the pallet-mounted drive system. A hydraulic motor-driven ball-screw jack provides the power to translate the strut vertically. The Knuckle-Sleeve (K-S) mechanical assembly was not redesigned as part of this project; however, it was refurbished and rebuilt during the tunnel down time. This resulted in a significantly tighter mechanical system due to refitting of all bearings and races.

Testing of the SMSS with an airplane model was not performed until the calibration and validation tests. The majority of SMSS checkout was done in a wind-off condition, without the effect of dynamic loads or model/sting frequency response. The first wind-on test with a model on the SMSS occurred during the LB-435 subsonic calibration test. No severe model vibration problems were encountered with either the LB-435 or the F/A-18E validation tests due to these models having relatively higher natural frequencies.

During the first Boeing 777 entry the model exhibited severe undamped vibrations that prevented the test from achieving its primary objectives. The test was stopped and the problem with the SMSS addressed during a two-week shutdown period. The second Boeing 777 test entry was performed after the successful Boeing F/A-18E validation test.

The Boeing 777 model exhibited dynamic instability during the second entry under certain loading conditions. The vibration problem was not as severe as that encountered during the first entry and the test made good progress by avoiding certain angles in the pitch schedule. The primary SMSS problem involved the damping in the control system and the interaction of the model natural frequency with the SMSS controller that has a limited frequency response. The existing SMSS hydraulic drive system response frequency was found to be limited to about four hertz, which is very close to the natural frequencies of large model and sting configurations like the Boeing 777. Adding a low-pass electronic filter to the low-level SMSS controller solved this problem. This approach worked well except at the point where the pitching moment on the strut reaches zero due to the model aerodynamic lift load equaling the model and sting weight. At this point the restraining moment reaches zero and the natural frequency of the model and sting system drops to a low value. This initiated another system instability that was solved by introducing a small amount of derivative gain into the controller.

Another SMSS problem encountered during the test involved the non-linearity in the angle solution for K-S positions at zero A and B setpoints. Small changes in the A or B setpoints when they are near zero can result in large K-S rotational velocities and coordination problems that result in the yaw angle wandering off setpoint during a pitch sweep. Software changes that provide precise movement control near the zero A and B region eliminated this problem. Another minor problem that was discovered involved and angle setpoint anomaly related to slight differences in the Knuckle and Sleeve bend angles. The original fabrication of the Knuckle and Sleeve resulted in slightly different bend angles that prevent the SMSS from achieving setpoints within ± 0.025 degrees of zero A and B. Angles in the pitch schedule that fell within this small zone were removed from the schedule during the test and the problem was eliminated after the test by a software change. Overall, these SMSS challenges were addressed by the tunnel engineering staff in a timely and effective manner that allowed the test to proceed successfully in the midst of troubleshooting efforts.

5.1.6 RUPTURE DISK FAILURES

The tunnel rupture disk failed five times during the test. The Maximum Allowable Working Pressure of the 11-By 11-Foot circuit is 18 psig. The maximum operating pressure is 17 psig, or approximately 4600 psfa. The two tunnel relief valves are calibrated to open at 18 psig. The 24-inch diameter rupture disks that failed were nominally rated at 24 psig. The tunnel pressure did not exceed 18 psig during operations, so the disk ratings were not exceeded during operations. The rupture disks were replaced during the test to keep the test running and the problem investigated after the test.

5.1.7 INFRARED CAMERA MALFUNCTION

An Infrared (IR) camera system is mounted in the ceiling of the test section to evaluate model boundary layer transition. The IR camera was initially used in the first Boeing 777 test entry until a failure occurred and it was then shipped to the manufacturer for repairs. A processor chip and cooling system failure were found and repaired. The camera was re-installed during the second test entry; however, a similar failure occurred immediately. Another failure in the cooling system controller was found along with problems in the digital output board. These were fixed at the manufacturer; the unit tested, returned, and installed several days before the end of the test. The camera system operated for about 7 hours near the end of the test. Once setup parameters were adjusted properly, the resulting images showed great detail of the flow field over the model upper wing surface. At higher angles of attack, vortices from the vortex generators could easily be seen passing over the wing and bursting on the flap region. A distinct change in the surface condition (perhaps a shock) was noted near the mid to aft portion of the wing as well. These results were obtained without imposing a thermal gradient that was thought to be needed for transition detection, giving the impression that the camera can easily detect flow field details. Upon starting the system on the following day, the system image was poor, indicating another failure in the camera.

5.2 FACILITY MODIFICATIONS MADE AFTER THE TEST

5.2.1 TEST SECTION MACH NUMBER TOLERANCE VARIANCE

The Conditional Sampling feature of SDS has been used extensively since the Boeing 777 validation test and several enhancements have improved its effectiveness. Instead of having a technician enter the Mach number setpoint and tolerance into SDS before a run, this process has been automated. The Mach number setpoint is now downloaded from the FCS to the SDS continuously and eliminates the need for technician interaction. The Mach number tolerance is determined by the use of a SDS look-up table with the Mach number tolerance a function of the Mach number setpoint. This automatically generates the Mach number setpoint and tolerance and increases data entry accuracy and productivity by eliminating the technician in the loop.

5.2.2 DIFFERENCES IN AMES AND BOEING DATA PROCESING

The Boeing 777 test requirements identified test dependent computations that were implemented in the setup of the SDS data acquisition system before the test entry. The changes during the test were minor in scope and involved differences in computational approach. A thorough review of the required equations before a test entry will identify the differences in computational approach, and this will be done before future entries. In addition, Ames and Boeing computations staff will meet to discuss the differences in approach. Ames will then be able to implement some of the Boeing preferred computations as standard computations in the Ames SDS.

5.2.3 SLOW MODEL INSTALLATION

Installation problems that were addressed included the process of leak checking model pressures, performing the angle checks of angle sensors, and setting the A/B limit switches. The A/B limit switches are located on the primary taper and prevent movement of the model outside preset angles in the A (vertical) and B (horizontal) planes. A modified switch installation design and a new type of switch have eliminated the problem in setting the test angle limits. These modifications to the A/B limit switches have proven to significantly reduce the time needed to set the switches and increase the reliability of the system. The model leak check process has been modified to allow parallel checking of multiple pressures at one time. The Boeing 777 test crew checked each port individually. The Angle Measurement System (AMS) is an angle standard (accelerometer) which is used to check test dependent model angle sensors during the installation checkout period and before daily operations. The AMS is being modified so that the angle measurement signal will be fed directly into the SDS to automate the checkout process.

An intensive five-week training period was implemented during the time after the validation tests. The training addressed many of the issues related to the slow model installation process. The training focused on certification of test engineers and tunnel operators. Tunnel operators went through extensive training in tunnel operations and the features of the tunnel systems and the FCS. Test engineers attended courses related to instrumentation, data acquisition hardware and software, data reduction software, and data corrections as well as the courses related to tunnel operation certification. Instrumentation engineers, instrumentation technicians, and Computer System Technicians also went through extensive course work related to the details of wind tunnel model instrumentation and data acquisition.

Three multidisciplinary process development teams were also formed to work together through the process of model checkout and installation. Each team performed the entire process, from balance installation and checkout in a Model Preparation Room to model transport and installation into the test section. The goal of the process development was to promote proficiency and consistency throughout the model checkout and installation phase of a wind tunnel test. Operators and test engineers went through on-the-job training after the five-week classroom training period to compete their certification training. Tests conducted since the completion of the training have reaped the benefits of a more proficient and effective operating staff. This training addressed the problem of slow model installations encountered with the Boeing 777 validation test by promoting consistency throughout the installation process.

5.2.4 STING MODEL SUPPORT SYSTEM PROBLEMS

Wind-off tuning of the SMSS was performed after the Boeing 777 test to further tune the system. This involved simulating the structural characteristics of the Boeing 777 model with a sting and lead weights to replace the model weight. After having been tuned down to 2 degrees per second during the test entry, the Knuckle and Sleeve rotational speeds were doubled to 4 degrees per second without any adverse effect on the coordination errors. The derivative gain in the SMSS position controller was also further tuned to optimize system response without initiating model vibration at the zero A or B positions. The problem with the slight difference in K-S bend angles was addressed with a software change. Setpoints within 0.026 degrees of zero A and B are now "pushed" outside of the zone to the nearest possible setpoint. These changes have addressed the SMSS problems encountered during the Boeing 777 validation test and have allowed the facility to move forward successfully with production testing.

5.2.5 RUPTURE DISK FAILURES

The rupture disk holder consists of two rings that were removed and measured after the validation test. The sealing face of the outer ring was warped by 0.044 inches and the inner ring surface by 0.012 inches. This problem was most likely caused by improper installation technique, and over time the rings warped due to differential tightening of the holder bolts. The installation of rupture disks in the warped holder most likely induced stresses in the disks that caused premature failure. As a short-term solution, the outer ring was machined to improve the flatness after the B777 test entry, and another rupture disk was installed to continue with 11-By 11-Foot testing. More recently, a new set of holder rings from the manufacturer was installed and should prevent a reoccurrence of this problem.

5.2.6 IR CAMERA MALFUNCTION

The IR camera was again shipped back to the manufacturer for repair after the Boeing 777 test. The cooling pump for the focal plane array was determined to have failed, and was replaced. Recent wind tunnel tests using the system have demonstrated continuous operation without any failures.

5.2.7 PRODUCTIVITY

The focus on productivity improvements since the validation tests has been to reduce the time between data points during a pitch-pause data polar. The initial SMSS operator's screen used during the validation tests was designed to allow the operator to monitor the system as it automatically stepped to each angle setpoint. The SMSS process included moving the model to a new angle setpoint, determining whether the tunnel is on conditions, initiating a data point by communicating with the SDS, receiving the "data point taken" signal from SDS, and then moving to the next angle setpoint. The operator screen tracked each step of the process, and delay timers had been introduced at each step to allow the operator to follow the progression of the process. This was also done to allow troubleshooting of the automated process during activation and validation testing and to help the SMSS operator become more familiar with the steps involved in the process. However, it did have a negative effect on productivity.

The average time between data points during a standard wind-off polar performed during the Boeing 777 validation test was 13 seconds. After eliminating the delays in the SMSS operator screen software, a similar polar was run recently and achieved an average time between data points of 6 seconds. Both the Boeing 777 validation runs and recent productivity runs include one second for actual data acquisition. These recent changes since the validation tests have therefore resulted in a two-fold decrease in the time required for data acquisition during a run. This does not equate to a doubling of the Runs per Occupancy-Hour metric; however, it does increase the Runs per Air-On Hour productivity metric.

Other factors, such as the number of data points near the A and B origin, have a significant impact on the actual SMSS productivity. In addition to the changes in the SMSS software, productivity has been improved due to the extensive operator training that was described earlier.

6. CONCLUSION

The UPWT Modernization Project successfully completed a significant upgrade in capability and reliability of an aging UPWT facility. After completion of construction activities, activation tests were performed to progressively demonstrate the performance of the facility. The 11-By 11-Foot Integrated Systems Test and two Calibration tests prepared the 11-By 11-Foot tunnel for the two airplane validation tests that followed.

The Boeing 777 validation test in the 11-By 11-Foot Transonic Wind Tunnel successfully demonstrated the readiness of the tunnel to proceed with production wind tunnel tests by meeting the objectives of the test entry. Tunnel-to-tunnel comparisons showed that the validation test drag was lower than the BTWT entry, but higher than the pre-modernization Ames test and the AEDC entry and that the total spread between the four tests was less than ten drag counts. Comparisons of pre-modernization to post-modernization force and moment data and pressure data were also very reasonable. Data repeatability within run series for the validation test was excellent and reflected a high level of data quality. The productivity was better than the pre-modernization test at Ames and reasonable for a validation test where test processes were still being modified and refined. The Ames operations staff also demonstrated their proficiency at testing and their ability to conduct commercial airplane tests.

7. NOMENCLATURE AND ABBREVIATIONS

7.1 NOMENCLATURE

α_{LI}	Lift interference correction angle, degrees
α_{tu}	Upflow angle, degrees
δ_0	Wall correction term
Δ	Delta or increment
ϕ	Model roll angle, degrees
A	SMSS taper pitch angle, degrees
A_{tun}	Tunnel cross-sectional area, ft^2
B	SMSS taper yaw angle, degrees
CD	Drag coefficient
CL	Lift coefficient
PT	Tunnel total pressure
S_{ref}	Model reference area, ft^2

7.2 ABBREVIATIONS

AEDC	Arnold Engineering Development Center
Ames	NASA Ames Research Center
AMS	Angle Measurement System
AT0053	Ames Test 11-0053
Boeing	Boeing Commercial Airplanes
BTWT	Boeing Transonic Wind Tunnel
CS	Conditional Sampling
DCDCTB	Clear Tunnel Buoyancy Correction coefficient
DCDSBIB	Solid Blockage Induced Buoyancy correction coefficient
DTC	Digital Temperature Compensation
ESP	Electronically Scanned Pressure
FCS	Facility Control System
Flexwall	Flexible Wall Nozzle
IGV	Inlet Guide Vane
IR	Infrared
IST	Integrated Systems Test
K-S	Knuckle-Sleeve system
Kv	Kilovolt
Kva	Apparent power, Kilovolt-Amperes
MAC	Mean Aerodynamic Chord
MDSC	Main Drive Speed Control system
MPR	Model Preparation Room
MUA	Make-Up Air system
PES	Plenum Evacuation System
RPM	Revolutions per Minute
SBIB	Solid Blockage Induced Buoyancy
SDS	Standard Data System
SMSS	Sting Model Support System
SOP	Safe Operating Procedures
UPWT	Unitary Plan Wind Tunnel
WAD	Wide-Angle Diffuser

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