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Experimental Results of the 2.7% Reference H Nacelle Airframe Interference High Speed Civil Transport Model

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Experiments were conducted in the NASA Ames 9-Ft by 7-Ft Supersonic and 11-Ft by 11-Ft Transonic Wind Tunnels of a 2.7% Reference H (Ref. H) Nacelle Airframe Interference (NAI) High Speed Civil Transport (HSCT) model. NASA Ames did the experiment with the cooperation and assistance of Boeing and McDonnell Douglas. The Ref. H geometry was designed by Boeing. The model was built and tested by NASA under a license agreement with Boeing.

Detailed forces and pressures of individual components of the configuration were obtained to assess nacelle airframe interference through the transonic and supersonic flight regime. The test apparatus was capable of measuring forces and pressures of the wing body (WB) and nacelles. Axisymmetric and 2-D inlet nacelles were tested with the WB in both the in-proximity and captive mode. The in-proximity nacelles were mounted to a nacelle support system apparatus and were individually positioned. The right hand nacelles were force instrumented with flow through strain-gauged balances and the left hand nacelles were pressure instrumented. Mass flow ratio was varied to get steady state inlet unstart data. In addition, supersonic spillage data was taken by testing the 2-D inlet nacelles with ramps and the axisymmetric inlet nacelles with an inlet centerbody for the Mach condition of interest. The captive nacelles, both axisymmetric and 2-D, were attached to the WB via diverters. The captive 2-D inlet nacelle was also tested with ramps to get supersonic spillage data.

Boeing analyzed the data and showed a drag penalty of four drag counts for the 2-D compared with the axisymmetric inlet nacelle. Two of the four counts were attributable to the external bevel designed into the 2-D inlet contour. Boeing and McDonnell Douglas used these data for evaluating Computational Fluid Dynamic (CFD) codes and for evaluation of nacelle airframe integration problems and solutions.

- Objectives
  - Database for CFD Validation
  - Axisymmetric vs 2-D Inlet Nacelles
  - Nacelle Installation: Captive and In-Proximity
  - Supersonic Spillage Data
  - Steady-State Inlet Unstart Data

- Participants: NASA Ames, Boeing, and McDonnell Douglas

- Results of 2.7% Ref. H NAI Test
  - Measured 4.5 Drag Count Penalty for 2-D Inlet Nacelle
  - 2 Drag Counts Attributable to External Bevel Design
  - CFD and Wind Tunnel Tools Evaluated

An experiment was conducted from December 1993 to February 1994 in the NASA Ames 9-Ft by 7-Ft Supersonic Wind Tunnel and from March to May 1994 in the 11-Ft by 11-Ft Transonic Wind Tunnel of a 2.7% Reference H (Ref. H) Nacelle Airframe Interference (NAI) High Speed Civil Transport (HSCT) model. NASA Ames did the experiment with the cooperation and assistance of Boeing and McDonnell Douglas. The Ref. H geometry was designed by Boeing. The model was built and tested by NASA under a license agreement with Boeing.

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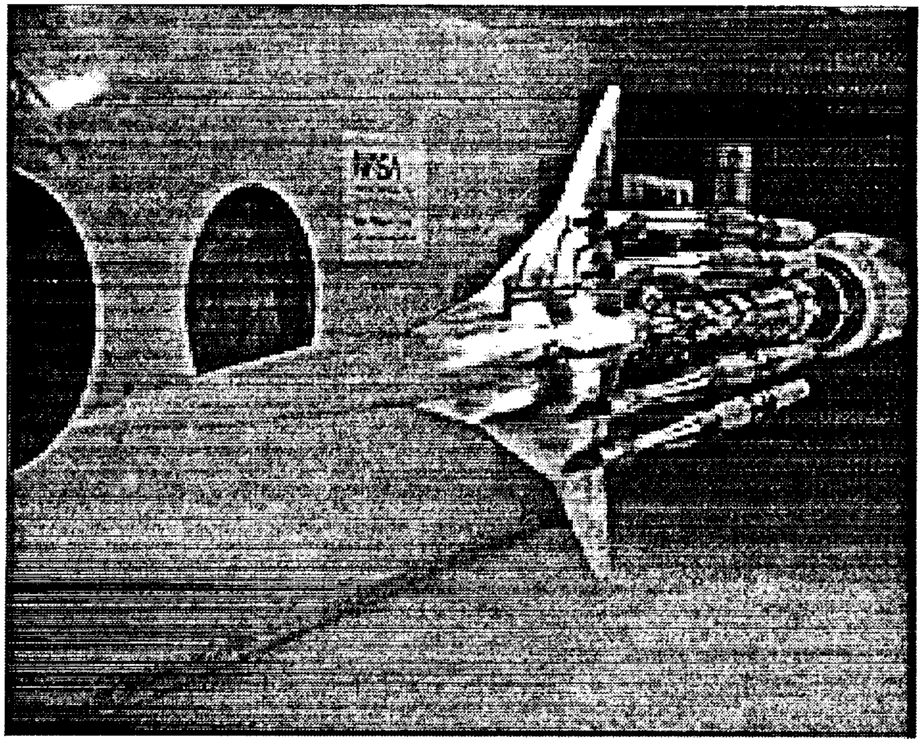

Figure 1. 2.7% Ref. H WB and MCTCB In-Proximity Nacelles in 9x7

The 2.7% Ref. H NAI model consists of a wing body (WB) and nacelles either attached using diverters or in-proximity using a Nacelle Support System (NSS). The WB represents Boeing's Ref. H geometry of an HSCT designed using linear theory. Figures 1 show the axisymmetric nacelles tested in-proximity to the WB using the NSS in the 9x7.

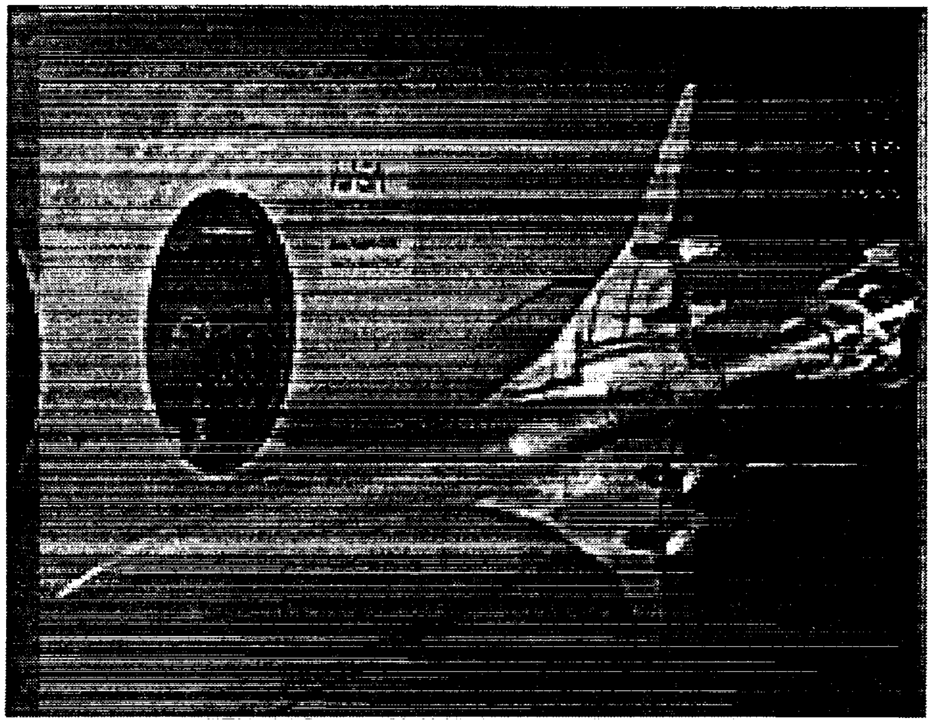

Figure 2. 2.7% Ref. H WB and BTSSI Captive Nacelles in 9x7

Figure 2 shows the BTSSI nacelles tested captively on the 2.7% Ref. H WB in the 9x7.

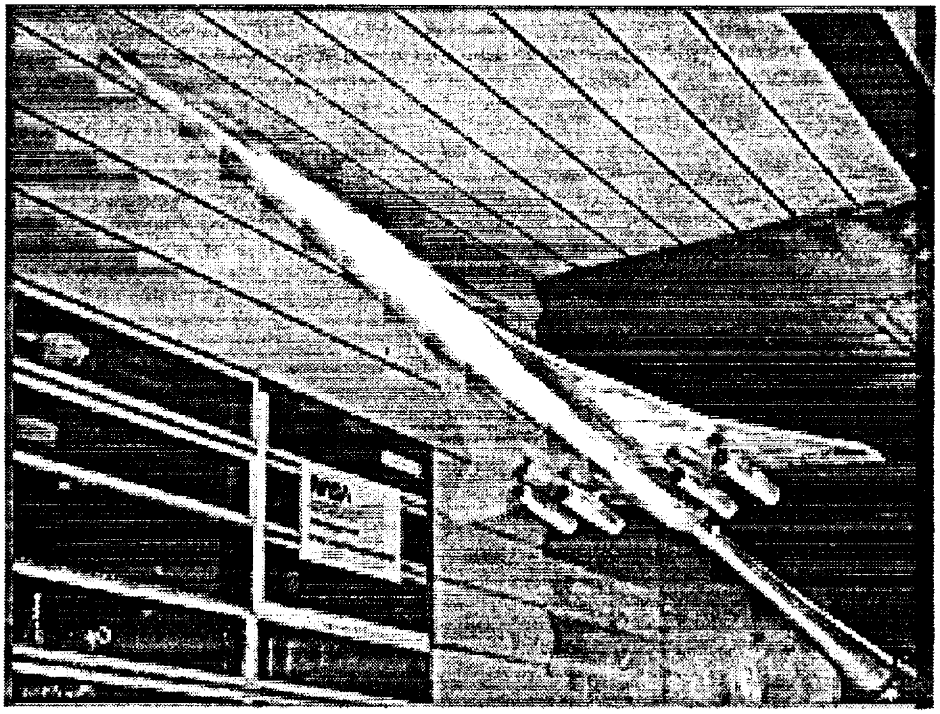

Figure 3. 2.7% Ref. H WB and MCTCB Captive Nacelles in 11x11

Figure 3 shows the axisymmetric nacelles installed on the WB and being tested in the 11x11.

- MODEL
  - Wing Body
    - Pressure Instrumentation
      - 280 on Upper and Lower Left Hand Wing Surfaces
      - 24 on Fuselage
      - Connections for 32 Pressures Taps on Right Hand Nacelles
    - 2.0 inch Diameter Task MK IA Force Balance
      - AX = ±160 lb., N1 = N2 = ±900 lb., S1 = S2 = ±450 lb., and RM = ±1000 in-lb.
      - Calibrated and Corrected for Temperature Effects on Zero Shift and Conversion Constant but not for Gradients Across Balance on AX, N1 and N2
    - 0.011 inch High Epoxy Boundary Layer Trip Discs Placed 0.64 inches Aft in Stream-wise Direction; Location Same as 1.7% Ref. H and Height based on Sizing Criteria in NASA TM 4363.

The wing is made out of 15-5 stainless steel heat treated to condition H1025. The forward and aft section of the fuselage are made out of 6061-T6 aluminum, while the mid section, that houses the balance, is made out of 17-4 stainless steel. The fuselage was cut off at station of 2904.6 inches for the model, and therefore does not include the empennage.

The upper and lower left hand wing surfaces are pressure instrumented, while the right hand wing accommodates pressure tubes from the nacelles that are mounted to the wing. Pressures were not measured on the aft fuselage base because the base collapsed to a knife edge. Tubing was installed on the sting to measure pressure just behind the balance for corrections to the data. There are 123 pressures on the upper wing surface shown in figure 4, 157 on the lower surface shown in figure 5, and 24 on the fuselage surface.

The WB forces were measured using a 2.0 inch diameter Task MK IA force balance that was housed in the balance block in the mid section of the fuselage. The capacity of the MK I balance is ±900 lb. for N1 and N2, ±450 lb. for S1 and S2, ±160 lb. for AX and ±1000 in-lb. for RM. The balance was calibrated at various temperatures so that temperature corrections could be made to get the best accuracy and repeatability out of the balance. It was very important to measure drag as accurately as possible. The balance repeated to within ±0.1% of full scale capacities on each gage when calibrated.

Epoxy trip discs were used to trip the boundary layer. The height chosen was 0.011 inches and they were placed 0.64 inches aft in the stream-wise direction on the upper and lower surface and 1 inch aft on the fuselage nose.

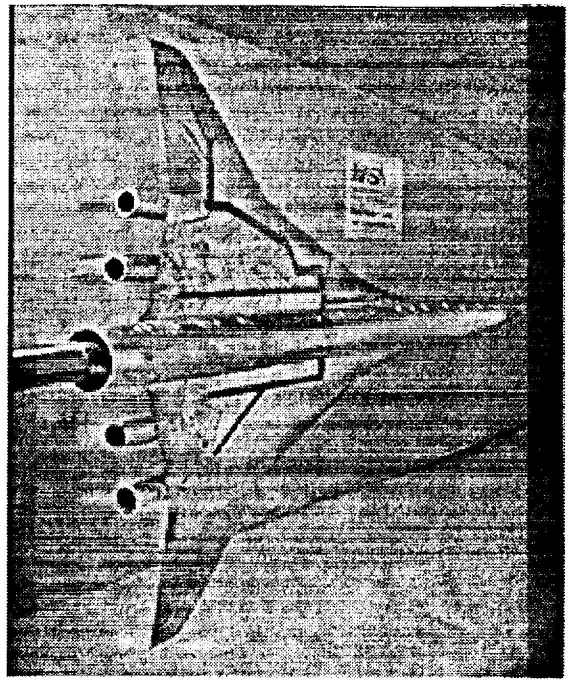

Figure 4. Upper Surface of 2.7% Ref. H WB and BTSSI Captive Nacelles in 9x7

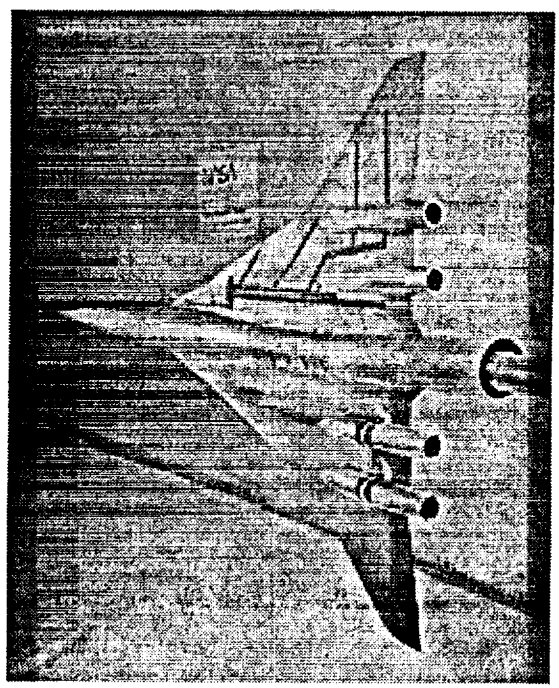

Figure 5. Lower Surface of 2.7% Ref. H WB and BTSSI Captive Nacelles in 9x7

- Captive Nacelles
    - Axisymmetric
        - Mixed Compression Translating Centerbody (MCTCB)
        - Inlet Designed for 509 lb./sec Turbine Bypass Engine (TBE)
        - Axisymmetric Nozzle
    - 2-D
        - Bifurcated Two Stage Supersonic Inlet (BTSSI)
        - Inlet Designed for 540 lb./sec TBE, but Scaled to Match MCTCB Inlet Area
        - Axisymmetric Nozzle
        - Tested with and without Ramp
    - 2 Base Pressures Measured to make Force Corrections
    - 3 Rows of 10 Pressure Taps: Inboard, Keel, and Outboard

The axisymmetric inlet nacelles are designated as the MCTCB, mixed compression translating centerbody, nacelles. The 2-D inlet nacelles are designated the BTSSI, bifurcated two stage supersonic inlet, nacelles.

The axisymmetric inlet nacelles represent the design for a Turbine Bypass Engine (TBE) with airflow of 509 lb./sec. The 2-D inlet nacelles represent the design for a TBE with airflow of 540 lb./sec. The 2-D inlet nacelle was scaled to match the inlet capture area of the axisymmetric inlet nacelle for this test so an evaluation of how the two types of inlets could be made.

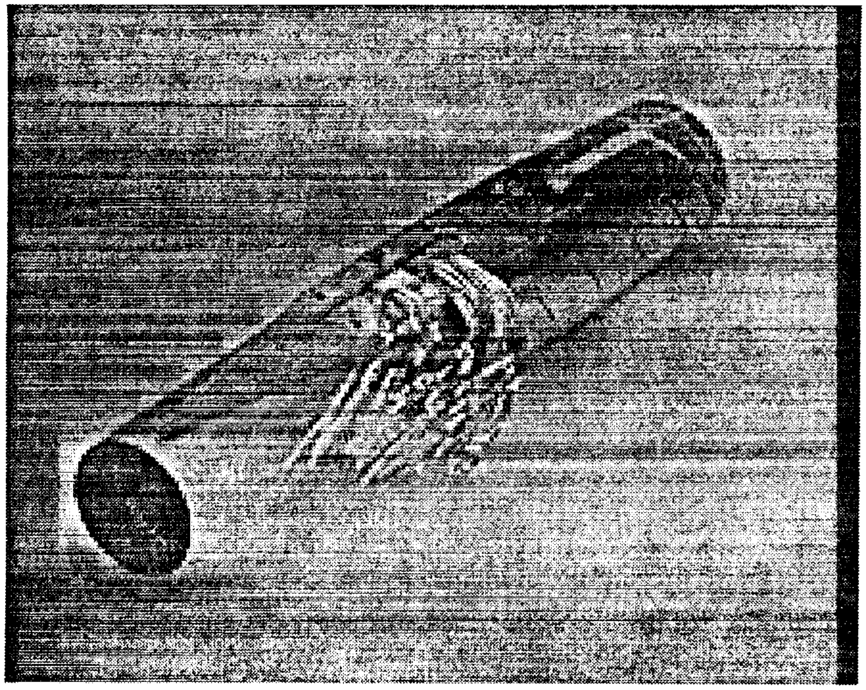

Figure 6. MCTCB Pressure Instrumented Captive Nacelle

The captive nacelles were all made out of 7075-T6 aluminum as well as the diverters. The right hand nacelles were pressure instrumented on the external and base surfaces. There are 30 external pressures on the MCTCB captive nacelles, figure 6.

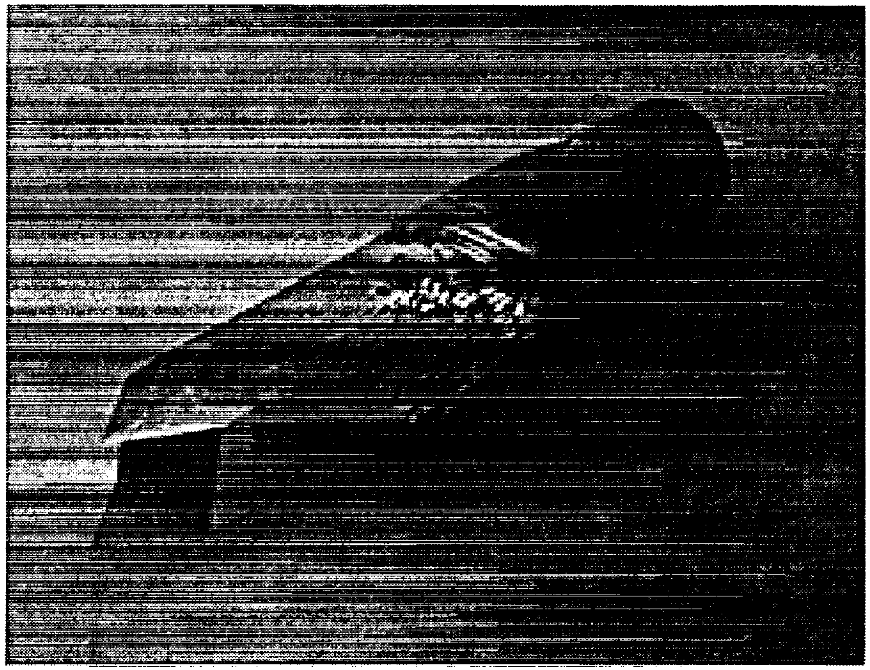

Figure 7. BTSSI Pressure Instrumented Captive Nacelle

There are 31 pressure taps on the BTSSI captive nacelles as well as one base pressure per right hand nacelle, figure 7.

- In-Proximity Nacelles
    - Nacelle Support System
        - Position in Axial, Spanwise, and Vertical
        - Mass Flow Ratio
            - Total Pressure Rakes in each Sting
            - Static Exit Pressure in each Sting
            - Based on 1972 Calibration
        - Video Camera Mounted on Sting to Monitor Nacelles
        - Remotely Controlled via Computer or Manual Drive Box
    - MCTCB Tested with and without Centerbody for Mach = <1.2, 1.65, 1.8, and 2.4
    - BTSSI Tested with and without Ramp: First Ramp Angle
    - Left Hand Nacelles
        - 4 External Rows of 10 Pressures: Crown, Inboard, Keel, Outboard
        - 4 Internal Rows of 2 Pressures: Used to Compute RN and Mach for Skin Friction Force Correction

The in-proximity nacelles were tested using a nacelle support system (NSS). The NSS is clamped to the main sting and can remotely position four nacelles under the wing in the axial, spanwise, and vertical directions. In addition to positioning the nacelles, the mass flow can be varied through the nacelles. The two left hand nacelles are pressure instrumented and the two right hand nacelles are force instrumented with custom built flow-through balances. The MCTCB and BTSSI nacelles were tested on the NSS. The 15 motors of the NSS are controlled by a computer control system via typed commands and hot keys or by a manual driver. The primary axial drive positions all four nacelles at one time, while each nacelle can be driven individually by its own axial drive motor. There is a drive motor for spanwise positioning of the inboard nacelles and another for the outboard nacelles. Each nacelle has a vertical drive motor and the remaining four motors drive mass flow plugs for each nacelle.

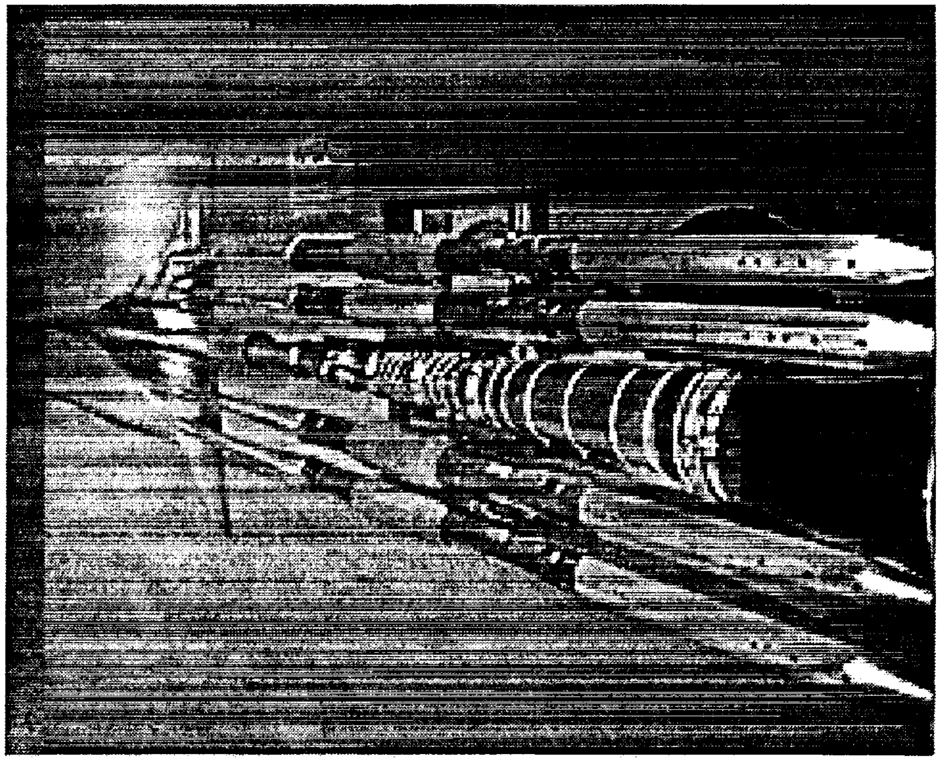

Figure 8. Lower Surface of NSS

Figure 8 shows the lower surface of the NSS. This figure illustrates the individual axial drive stings, mass flow exits, and the video camera attached to the main sting.

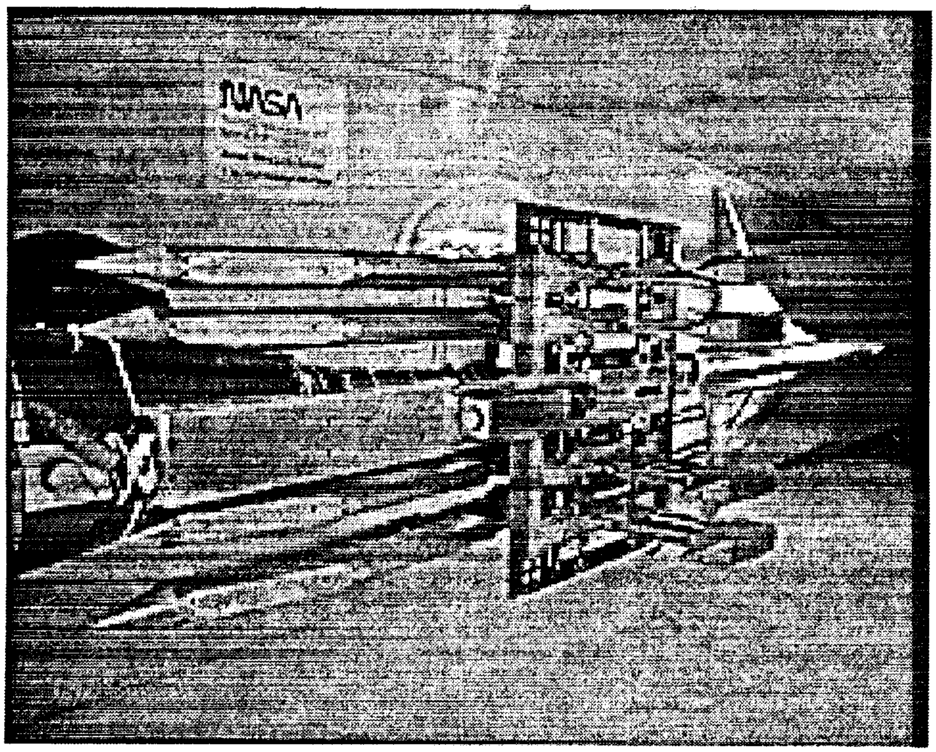

Figure 9. Upper Surface of NSS

Figure 9 shows the upper surface of the NSS. Observe the main axial drive system, spanwise, and individual vertical drives. The remotely driven vertical drive system was added to NSS for the SA1150 NAI test in 1992/93. The capability of the NSS to work more efficiently while the model is mounted in the vertical plane was also added to the NSS for this test.

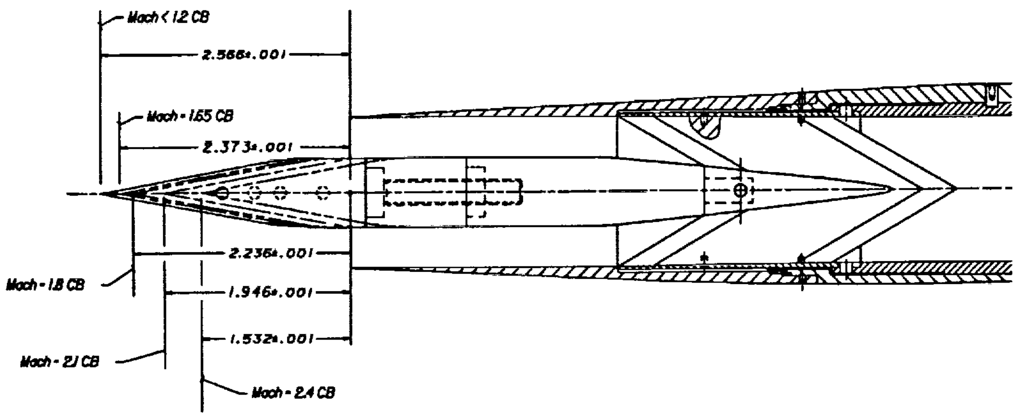

Figure 10. MCTCB Nacelle with Inlet Centerbody Assembly

During the NAI part of the test, the MCTCB nacelles were tested with and without inlet centerbodies for each of its designed Mach numbers. Supersonic spillage data was acquired at all Mach numbers for each of the inlet centerbodies installed. Figure 10 shows how the centerbody is assembled in the MCTCB nacelle. The inlet centerbody is attached to the non-metric part of the internal duct so that the nacelle balance did not measure its force. The only effects measured are how the forces of the WB and nacelles changed due to the inlet centerbody and test condition. The pressures of the WB and nacelles were also measured. The MCTCB captive nacelles were not tested with the inlet centerbody.

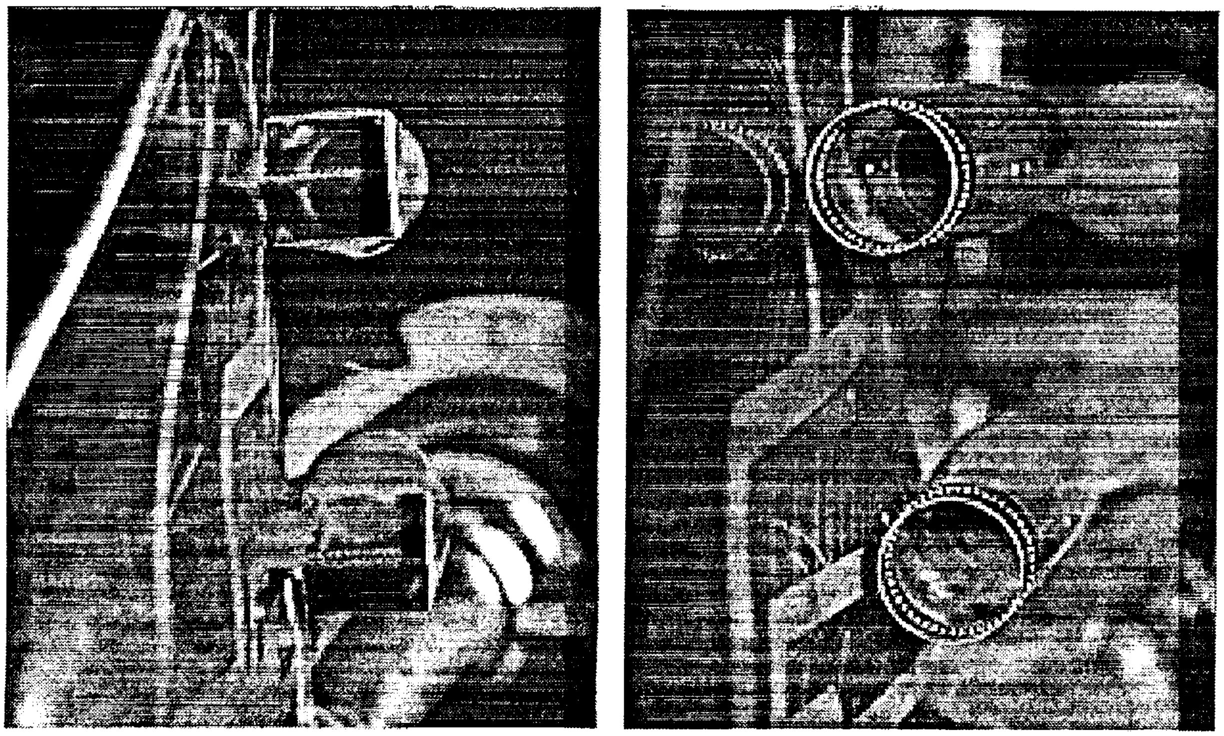

Figure 11. BTSSI and MCTCB Nacelles Installed

The BTSSI nacelles were tested with and without a ramp at all Mach numbers. Figure 11 shows the ramp installed in the BTSSI captive nacelles but was also installed in the in-proximity nacelles. The ramp only includes the first ramp angle that is part of the external flow field. The other ramp angles are internal and did not need to be modeled.

The nacelles were positioned in various locations and mass flow ratio was varied during the test. Angle of attack sweeps was the main variation in the run series, except when mass flow ratio was the varying parameter.

The left hand pressure instrumented nacelles were made out of 6061-T6 aluminum. A total of 188 pressures were measured during the test for the in-proximity nacelles. The left-hand nacelles had 40 external and 8 internal pressures for each inboard and outboard nacelle.

All of the nacelle stings had mass flow rakes. There were 16 total pressures and 4 static pressures measured per nacelle. Figure 11 illustrates the MCTCB pressure instrumented in-proximity nacelles.

- In-Proximity Nacelles (Continued)
    - Right Hand Nacelles Instrumented with a Force Flow Through Balance
        - Primary and Backup AX = ±10 lb., N1 = N2 = ±40 lb., and RM = ±10 in-lb.
        - Calibrated and Corrected for Temperature Effects on Zero Shift and Conversion Constant on AX, N1 and N2
        - Corrections to Axial Force
            - Pressure within the Fwd- and Aft- Balance Cavities
            - Pressure on the Fwd Lip Cavity
            - Across the Balance Seal
                - Calibration
                - f (Fwd Lip Cavity Pressure, Balance Force)
            - Skin Friction on the Nacelle Metric Internal Lip: Average Turbulent SF based on RN and Mach
            - BTSSI Metric Internal Duct Transition
            - BTSSI Ramp

The right hand force instrumented nacelles were made out of 17-4 stainless steel. The force instrumented nacelles housed flow through type balances that were designed and built by MicroCraft. The capacity of each balance is ±40 lb. for N1 and ±40 lb. for N2, ±10 lb. for AX1 and AX2, and ±10- in-lb. for RM. The nacelle balances repeated to within ±0.1 % full scale capacities of each gage when calibrated.

Corrections were made to the axial force measurements. Force corrections were made due to pressures measured within the forward and aft balance cavities. A force correction was made due to the pressures on the forward lip cavity. A force correction was made due to a force across the balance seal. A force correction was made due to the skin friction on the metric part of the internal duct ahead of the balance and past the inlet lip. A force correction was made due to the transition occurring in the BTSSI internal duct in the same region. Finally, a force correction was made due to the ramp installed in the BTSSI. Each of these forces was computed during the test except for the internal duct transition and ramp for the BTSSI. These two particular forces were estimated at all conditions subsequent to the test and then applied during the test. The other forces were computed based on the pressures and forces measured during the test. There were a total of 12 pressures, 6 for the inboard and 6 for the outboard, measured.

The MCTCB inlet centerbodies were attached to the non-metric portion of the internal duct and therefore no corrections were needed. The BTSSI ramp was attached to the metric portion of the internal duct. This in turn is measured by the nacelle balance. This force was estimated by Boeing at each condition subsequent to the test. The wind tunnel data was corrected for the force generated by the ramp during the test.

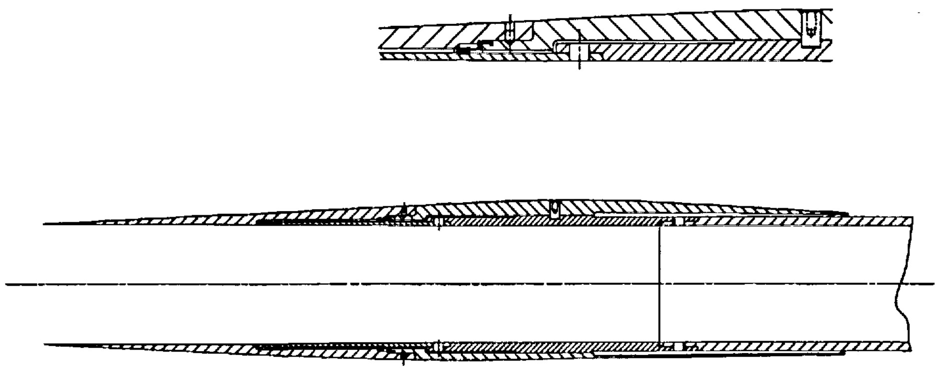

Figure 12. MCTCB Force Nacelle Assembly

Figure 12 shows the how the balance is installed in the MCTCB nacelle. Notice the location of the seal and the break between metric and non-metric parts of the internal duct. The balance measures the forces generated by the metric portion of the nacelle.. The metric portion includes the entire external nacelle surface and the forward 2.746 inches of the internal duct. Pressure taps were located on the front of the non-metric internal duct sleeve ahead of the balance. Pressure taps were also located on the forward part of the balance to measure a forward cavity pressure and on the aft part of the balance to measure aft cavity pressure. The same pressures were measured for the balance installed in the BTSSI nacelle. The installation of the balance in the BTSSI nacelle is exactly the same as for the MCTCB nacelle. The metric portion of the BTSSI internal duct is 4.628 inches. The BTSSI nacelle internal duct transitions from a 2-D cross-section to a circular one. The balance measures the force generated by this transition. The wind tunnel data is corrected for this force that were estimated by Boeing subsequent to the test at each condition.

- TEST PROGRAM

  - 9x7 from Dec. '93 to Feb. '94
    - Mach = 1.65, 1.8, 2.1, and 2.4
    - RN = 3 Million/Ft
    - Angle-of-Attack =-2° to 10°
    - Mass Flow Ratio = 1 to 0
    - Sublimation
    - UV Oil Flow Visualization
    - Schlieren
    - UV Crystal Flow Visualization

  - 11x11 from Mar. '94 to May '94
    - Mach = 0.8, 0.9,0.95,1.2, and 1.3
    - RN = 3 Million/Ft
    - Angle-of-Attack =-2° to 10°
    - Mass Flow Ratio = 1 to 0
    - Sublimation

Running was done at Mach numbers of 1.65, 1.8, 2.1, and 2.4 at a constant Reynolds number (RN) of 3x106/ft for the 9x7 test. Running was done at Mach numbers of 0.9, 0.95, 1.2 and 1.3 at a constant RN of 3x106/ft for the 11x11 test. The runs consisted of alpha and mass flow sweeps. The alpha sweeps were done from -2° to 5° by 0.25° and 5.5° to 10° by 0.5° increments. The mass flow sweeps were established by controlling the mass flow plugs from fully opened to closed. Seven plug positions between fully opened and closed were part of the mass flow sweep. The actual mass flow numbers depended on the configuration and the test conditions. Repeat runs were done throughout the test to establish drag data accuracy and repeatability.

When the nacelles were run isolated, the 9x7 test was run at Mach = 1.627, 1.771, 2.061, and 2.35 and the 11x11 test was run at Mach = 0.8, 0.9, 0.95, 1.193, and 1.29. These were the estimated local Mach numbers the inlet would see if the WB was present. The mass flow sweeps were done at 4°, 4.5°, and 5° to bracket the cruise point. When the nacelles were tested without the WB, the settings were 2.9°, 3.4°, and 3.9°. These numbers represent the same angle but without the incidence angle of the nacelles. Data was taken at 9 plug positions for each angle-of-attack to capture when the inlet would unstart. In addition to the runs described above, data was taken for the nacelles positioned differently from the location when the nacelles are mounted captively. Axial, span-wise, and vertical position studies were done. Effect of NSS on the WB forces was run also. On several occasions, data was taken for angle-of-attack sweeps at a constant mass flow ratio. The data taken at the constant mass flow ratio represents an engine throttle setting.

Wing Body	NSS	BTSSI	Ramp	MCTCB	Centerbody
x					
x		x			
x		x	x		
x				x	
x	x	x			
x	x	x	x		
x	x			x	
x	x			x	Mach 1.65
x	x			x	Mach 1.8
x	x			x	Mach 2.4
	x			x	Mach 2.4
	x			x	Mach 1.65
	x			x	Mach 1.8
	x			x	
	x	x	x		
	x	x			
x	x	x			

Table 1. Model Configurations Tested in 9x7

Table 1 lists the order of the model configurations tested in the 9x7. At the onset of the test, many studies were performed to optimize the data acquisition and tunnel condition settings. A sampling rate, humidity, balance temperature soak, cavity pressure settling time, and **bridge effect studies** were performed. During each configuration a number of repeat runs were done for the alpha sweeps to establish the repeatability and accuracy of the data. During the mass flow ratio sweeps, the mass flow was varied on one nacelle side at a time to get the effect of unstart on the wing body and nacelle forces. Pressures on both the wing and nacelles were also measured during the mass flow sweep runs. A mass flow sweep was done only on the right hand outboard (RO) nacelle at 3 constant angle-of-attacks to get the forces of the RO nacelle and WB. After these runs, mass flow sweep was done on the left hand outboard (LO) nacelle at the same 3 constant angle-of-attacks to get the nacelle and wing pressures. There were times when mass flow ratio was varied in both RO and RI nacelles to get mutual unstart effect on WB and nacelles.

Wing Body	NSS	BTSSI	Ramp	MCTCB	Centerbody
x					
x		x	x		
x		x			
x				x	
x					
x	x	x	x		
x	x	x			
x	x	x	x		
x	x			x	
x	x			x	Mach 1.2
	x			all	Mach 1.2
	x			all	
	x	outboard	x	inboard	
	x	outboard		inboard	
x	x			x	
x	x			x	Mach 1.2
x					
x				x	

Table 2. Model Configurations Tested in 11x11

Table 2 lists the order of the model configurations tested in the 11 x 11. This test was much shorter and more difficult to run because of inherent interference problems due to testing at transonic speeds. Similar studies up front were done in the 11x11 as the 9x7. The same type and quality of data were striven for here.

- DATA
  - Repeatability: $\Delta C_D < 0.5$ CTS
  - Accuracy: Data Compared with 1.7% Ref. H in BSWT $\Delta C_D < 2$ CTS
  - Nacelle Installation Drag Increments at Cruise
    - MCTCB: $\Delta C_D = 4.8$ CTS
    - BTSSI: $\Delta C_D = 9.3$ CTS
  - Flow Visualization

The data taken during these tests were extensive and this report does not give it justice. A lot of the data was and is still be analyzed by NASA, Boeing, McDonnell Douglas, and Lockheed. The emphasis of this report is on the data quality and overall difference between the MCTCB and BTSSI nacelles.

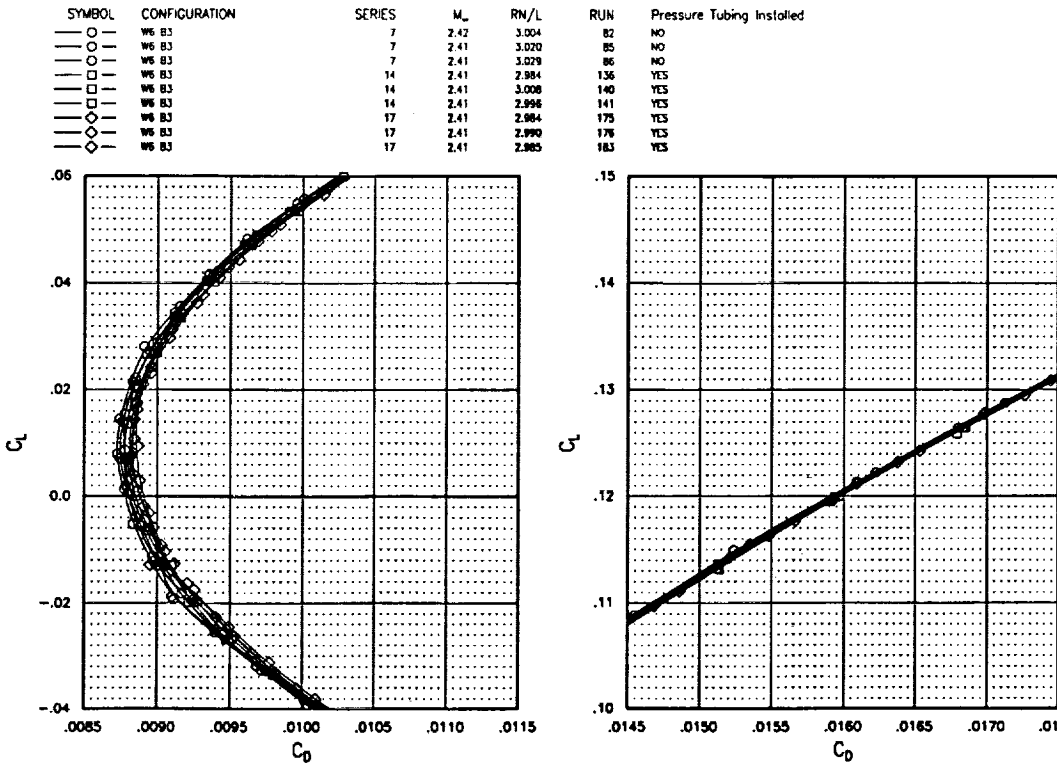

Figure 13. Drag Polar of WB Repeat Runs

It was very important to make sure the data quality was good to be able to distinguish differences between many configurations. Drag repeatability had to be less than 0.0001 or 1 drag count. The data generated during the test turned out to be better. It was less than a 0.5 drag count most of the times. Items that contributed to this result were detail procedures, calibrations, and measurements of the WB and nacelle balances, and angle-of-attack. Figure 13 shows a representative drag polar of repeat runs.

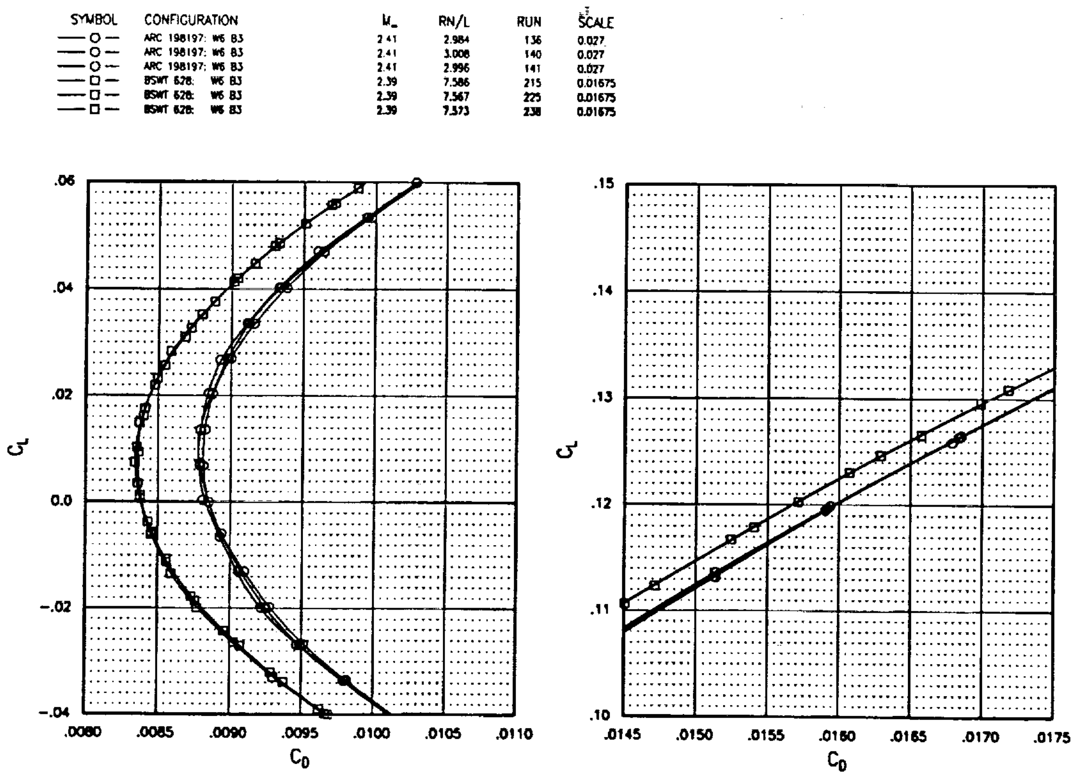

Figure 14. Drag Polar of 2.7% vs 1.7% Ref. H WB: Skin Friction $\Delta C_D = 0.0006$

The test began with many studies. There were sampling rate, humidity, balance temperature, and pressure bridging effect studies. Each of these studies established the best conditions for taking data. The first evaluation of the data came when comparisons were done with data collected on the 1.7% Ref. H model in the Boeing Supersonic Wind Tunnel (BSWT). This comparison established the magnitude level of the data. On average the data from the 2.7% Ref. H WB was 2 counts higher than the 1.7% Ref. H model over the angle-of-attack range. The 2 counts is attributable to trip drag. Figure 14 shows the drag polar for this comparison. The plot shows 6 counts more which is due to the skin friction of the model at different scales and RN.

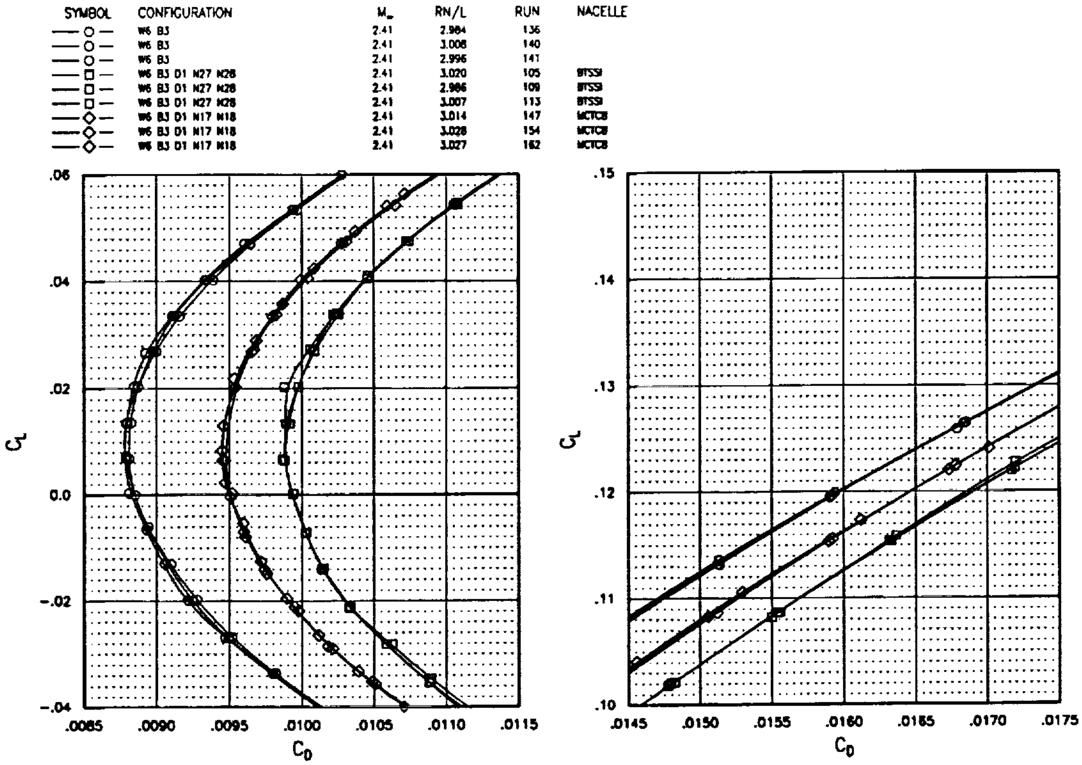

Figure 15. Drag Polar of MCTCB vs BTSSI Captive Nacelles Installed

The BTSSI nacelle measured 4.5 drag counts higher than the MCTCB. This increment was the same between the captive and the in-proximity testing. Figure 15 shows the drag polar of this comparison. The in-proximity testing measurements were 1.6 drag counts lower than in captive mode. This in turn says that the 1.6 counts are due to the diverter.

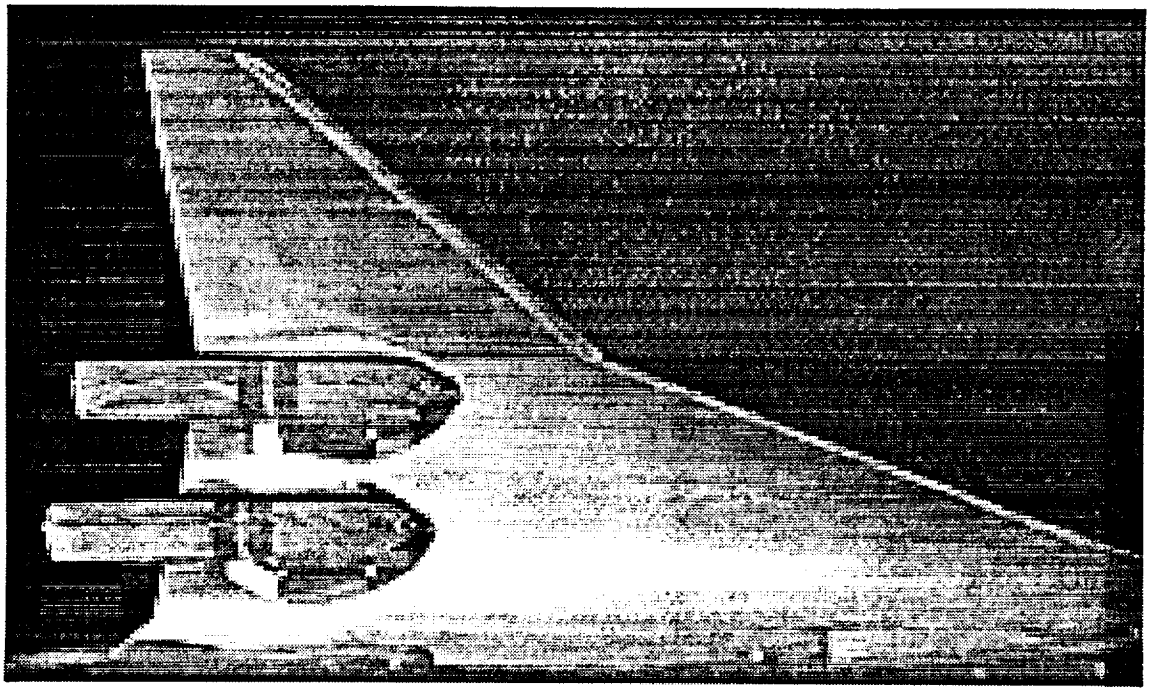

Figure 16. UV Oil Flow Visualization on WB and BTSSI In-Proximity Nacelles at Mach = 2.4

Data was also taken for supersonic spillage and steady-state inlet unstart effects. Flow visualization was performed to verify the boundary layer tripped using sublimation. Ultra-Violet (UV) Oil flow visualization was performed to evaluate the flow at all supersonic conditions with nacelles installed. Schlieren photos and video were taken when the nacelles were tested isolated to document the mass flow effect on the flow field around the nacelle and on inlet unstart. Figure 16 is a representative photo of flow visualization done in the 9x7.

- CONCLUSION
  - BTSSI
    - 4.5 Drag Counts Higher than MCTCB
    - 2 Drag Counts Attributable to the External Bevel Designed into the 2-D Inlet Contour
    - CFD Verified What Wind Tunnel Measured After the Test
  - Emphasis on Data Quality
    - Pre-Test Calibrations of Model Support System for Angle-of-Attack Measurements
    - Procedure for Measuring Reference Angle-of-Attack in Horizontal Plane
    - Balance Temperature Calibrations and Operating Procedures
    - Humidity and Data Sampling Studies
  - Drag Repeatability < 0.5 CTS in 9x7
  - Analysis and Reporting of Data will be in a NASA CTM
  - Data is Available from ARC or LaRC Data Base

Overall the test was a high quality data taking test. The test showed that the BTSSI nacelle has a drag penalty over the MCTCB. During the test a lot of the data was analyzed for its completeness. After the tests were over, Boeing and McDonnell Douglas had tasks to analyze the data and compare results to their CFD analysis. Data is still being analyzed by Boeing and Lockheed. NASA will report on the test in more detail. The NASA report will be a NASA CTM. The data is available through the author or through NASA Langley. Included with the data is the run schedule and descriptions of the forces and configurations.