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TECHNICAL REPORT AFATL-TR-74-145

WIND TUNNEL FACILITY EQUIPMENT AND TEST CAPABILITIES AT THE AIR FORCE ARMAMENT LABORATORY

BALLISTICS BRANCH
GUNS AND ROCKETS DIVISION

SEPTEMBER 1974

FINAL REPORT: December 1967 to June 1974

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AIR FORCE ARMAMENT LABORATORY
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The low speed wind tunnel testing facilities at the Air Force Armament Laboratory are described. The capabilities of the wind tunnel facility to aid in test design, model fabrication and instrumentation, and data collection and reduction are discussed. The physical characteristics of the wind tunnel are summarized, along with flow parameters such as turbulance and angularity. The hardware available to the test conductor for data collection and manipulation, including a digital data acquisition system and various support equipment and software, is described.

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PREFACE

This technical report describes the available equipment and capabilities for wind tunnel testing at the Air Force Armament Laboratory. The wind tunnel facility is a part of the Interior/Exterior Ballistics Branch (DLDL) of the Guns, Rockets, and Explosives Division. The report is oriented toward the Program Manager who wishes to evaluate the use of the facility for an aerodynamic testing program but who may not be familiar with all aspects of wind tunnel testing.

SSgt Samuel P. Williamson, Mr. Clarence E. Smith, and Mr. Goldman E. Parrish of the Ballistics Branch (DLDL) contributed significantly to the wind tunnel test section calibration, wind tunnel hardware development, and data acquisition system improvement, respectively.

This report has been reviewed and is approved.

ALFRED D. BROWN, JR., Colonel, USAF
Chief, Guns, Rockets, and Explosives Division

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TABLE OF CONTENTS (Concluded)

SECTION I

INTRODUCTION

The Air Force Armament Laboratory (AFATL) Wind Tunnel Facility has played an increasingly important role in the test and evaluation of non-nuclear munitions. The primary objective of the Wind Tunnel Facility is to provide subsonic aerodynamic in-house test support in the shortest amount of time, at minimum cost, and with the greatest amount of flexibility. The secondary purpose is to originate research and development projects that will contribute to the state of the art of conventional munitions technology.

The Wind Tunnel Facility (Figure 1) is housed in Building 419 located on Eglin AFB Test Area A-22 and consists primarily of a 28 by 40 inch subsonic wind tunnel and wind tunnel control console, a digital data acquisition system, and a vertical air jet. Support capabilities include a machine shop and electronics workshop.

The 28 by 40 inch subsonic wind tunnel was originally obtained under contract in December 1967 to complement existing and planned free flight aerodynamic test capabilities at AFATL. A digital data acquisition system, which was added to the facility in May 1972, increased the capabilities of the wind tunnel to cover a wide range of aerodynamic investigations.

An example of one type of munition tested in the facility is shown in Figure 2. This is the BLU-26/B fragmentation bomblet that was modified to include a tuft for improving the dispersion pattern. The test program for this bomblet included the use of the vertical air jet at the Wind Tunnel Facility.

The following equipment operating instructions and manuals are available for reference at the AFATL Wind Tunnel Facility:

Operation and Maintenance Manual for Eglin AFB Spin and Oscillation System, Aerolab Support Company, December 1967.

Operating and Service Manual for Astrosystems Digital Angle Indicator, Manual A610, Astrosystems, Inc., September 1971.

Operating and Service Manual For Systron-Donner Model 1037 50MC Counter, Systron-Donner Corporation, 1967.

Data Acquisition System Manual, Volumes I through II. Manual No. 62348, Hewlett-Packard Company, June 1972.

Honeywell 1508A Light Beam Oscillographic Recorder Manual, Honeywell Corporation, July 1969.

Ampex TR-1300A Recorder/Reproducer Manual, Ampex Corporation, September 1970.

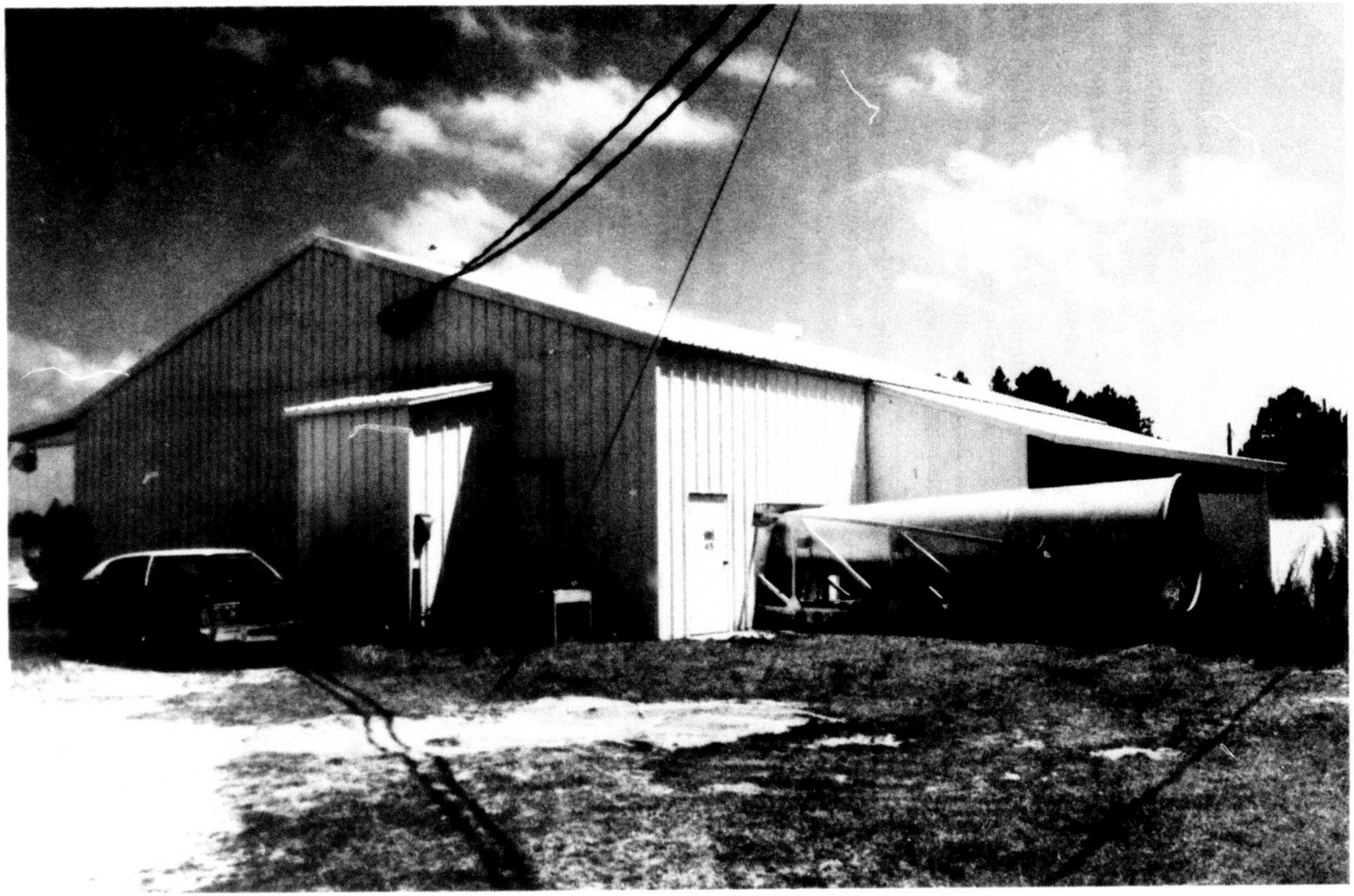

Figure 1. AFATL Wind Tunnel Facility

Figure 2. BLU-26/B Bomblet with Tuft Modification

Operating Instruction for Aerolab Pyramidal Balance, Aerolab Supply Company, December 1967.

Roy, J. F.: Calibration Report for VHB-13 Balance. Vought Aeronautics Division, LTV Aerospace Corporation, August 1971.

Calibration Report for EAF-1 Balance. NASA Langley Research Center, January 1974.

Instruction Manual for Transducer Indicator Model CD-25. Dynascience Corporation, July 1969.

SECTION II

WIND TUNNEL

The wind tunnel (Figure 3) is the continuous flow, open-circuit, subsonic type and was manufactured by the Aerolab Supply Company, Hyattsville, Maryland. The principal components are the electric motor, centrifugal fan, settling chamber, contraction cone, test section, and diffuser. The wind tunnel is constructed such that air is drawn into the centrifugal compressor and ducted to the settling chamber. The contraction cone, decreasing in cross sectional area, increases the flow velocity and also connects the settling chamber to the test section. The test section has a constant cross sectional area and is followed by the diffuser which increases in cross sectional area and exhausts the wind tunnel flow to the atmosphere.

1. ELECTRIC MOTOR

A Westinghouse Life-Line T Model TBDP AC Electric Motor (Figure 4) drives the centrifugal fan. The motor is a 3-phase induction (delta connected) type having a constant speed of 1780 revolutions per minute at a line frequency of 60 hertz. The motor is rated at 150 horsepower at 480 volts and 166 amperes per phase. Starting the wind tunnel requires more than 500 amperes per phase, while normal operation requires approximately 150 amperes per phase.

2. CENTRIFUGAL FAN

The Westinghouse Size 3054, Class II, Centrifugal Fan (Figure 4) has an inlet vane control. The inlet area of the fan is approximately 20.8 square feet, and the exit area is approximately 30.8 square feet. This fan rotates at 835 revolutions per minute and has a maximum mass flow rate of approximately 4.75 slugs per second under standard sea level conditions.

The velocity of the wind tunnel is controlled by changing the angle of the fan inlet vanes. This varies both the volume of air entering the fan cage and the angle at which the flow strikes the fan blades. Flow velocity is continuously variable up to a maximum of 200 feet per second (Mach 0.18) at standard sea level conditions. The velocity of the wind tunnel can be controlled and monitored from the wind tunnel control console discussed in Section III.

3. SETTLING CHAMBER

The settling chamber (Figure 5) is 6 feet high by 8 feet wide and is the section where the flow velocity is minimum. Installed in the settling chamber are a honeycomb and five damping screens (Figure 6). The honeycomb, which is 8 inches thick with hexagonal cells approximately 3/16 inch across, is used to straighten the flow before it reaches the wind tunnel test section. The damping screens are used for the reduction of turbulence in the wind tunnel flow. Two 14-mesh damping screens (0.012 inch diameter wire) follow the honeycomb in the direction of the flow. The final three screens are 20 mesh with 0.009 inch diameter wire.

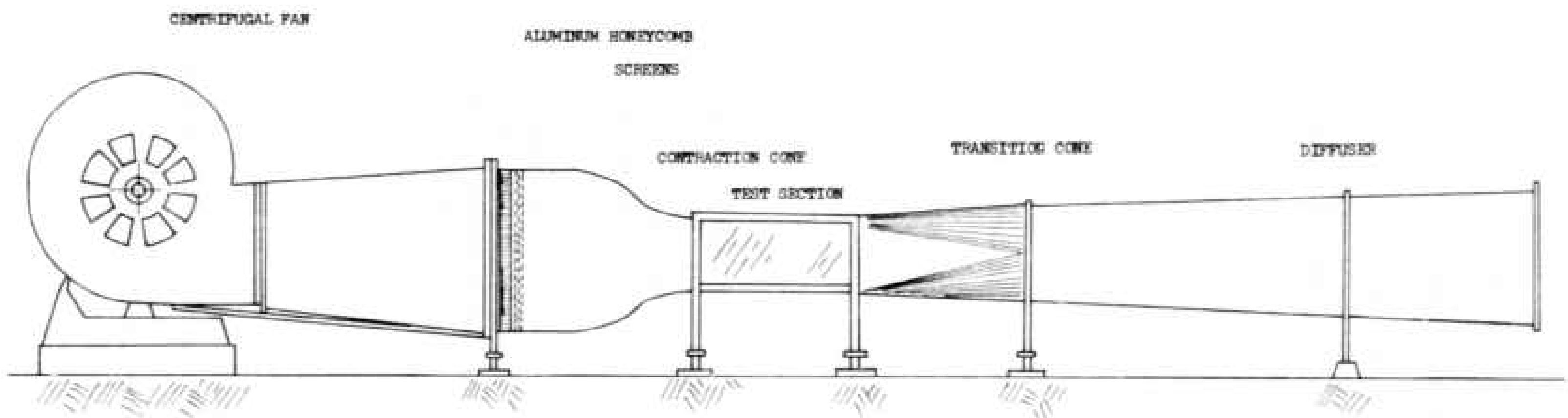

Figure 3. Wind Tunnel Schematic

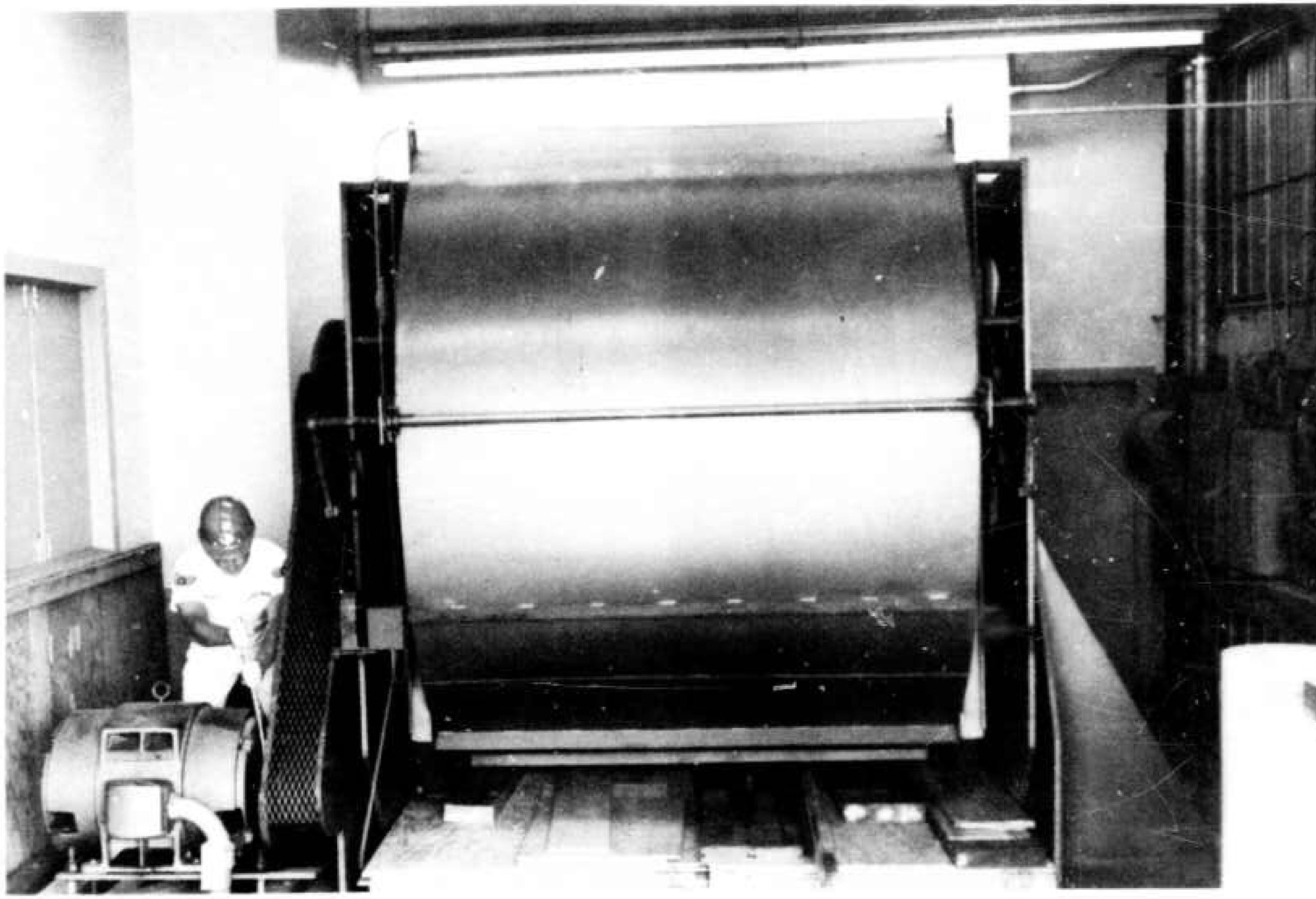

Figure 4. Wind Tunnel Electric Motor and Centrifugal Fan

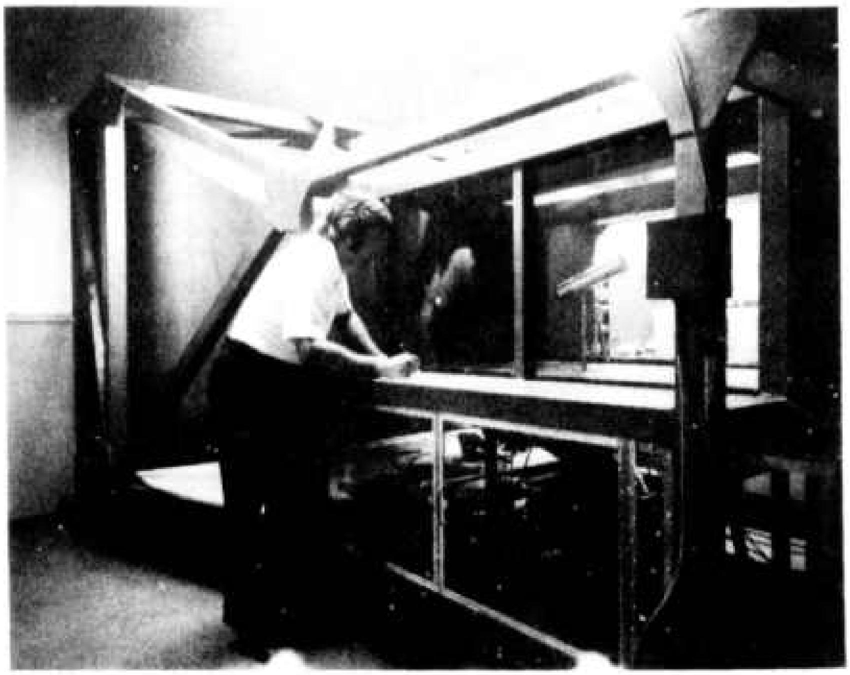

Figure 5. Wind Tunnel Settling Chamber, Contraction Cone, and Test Section

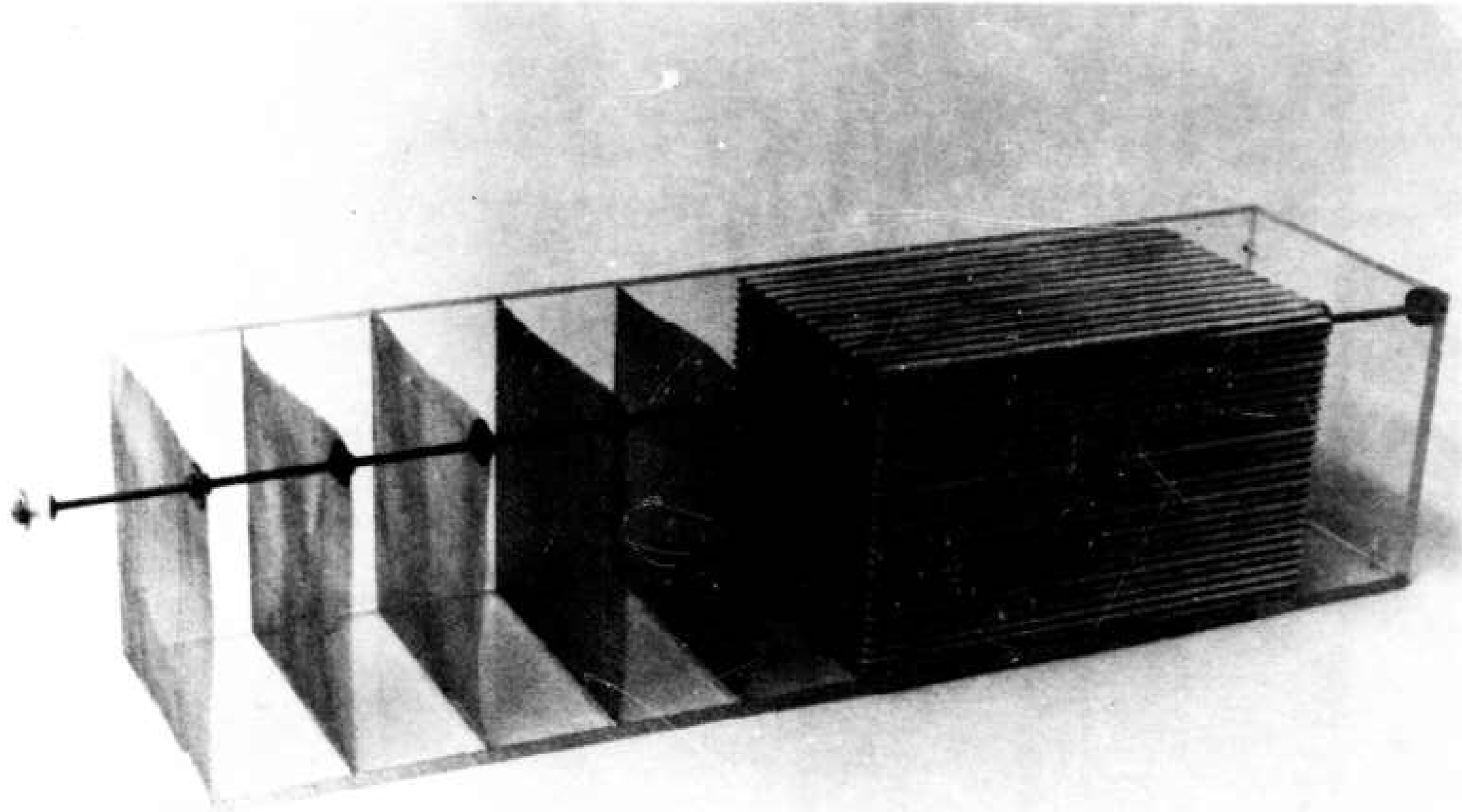

Figure 6. Honeycomb and Damping Screen Installation Model

4. CONTRACTION CONE

The contraction cone (Figure 5) is rectangular in cross section and has an area contraction ratio of approximately 6.17.

5. TEST SECTION

The test section (Figure 5) is 28 inches high by 40 inches wide by 66 inches long and has transparent plastic side walls for viewing. Two basic types of test model support can be used: a variable pitch sector support and an external balance, rotating table support. The model supports will be discussed in detail in Section V. The test section, together with the wind tunnel control console and data acquisition system, is completely housed in an environmentally controlled room.

6. DIFFUSER

The diffuser (Figure 7) transistions from a rectangular cross section at the test section to a circular cone having an exit diameter of 70 inches. The divergence angle of the diffuser is approximately 3.7 degrees. The diffuser extends outside the building and is screened to keep foreign matter out of the tunnel.

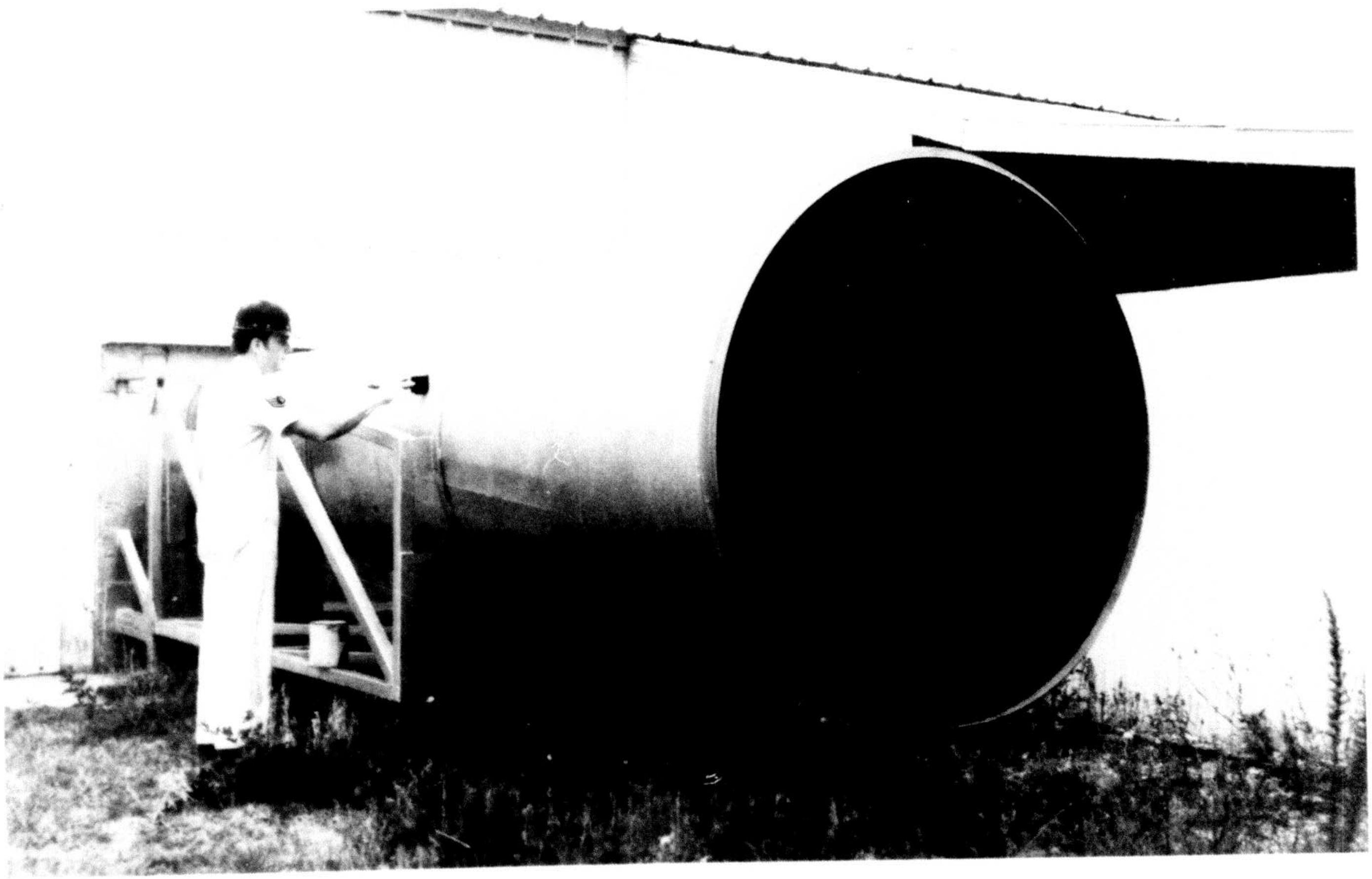

Figure 7. Wind Tunnel Diffuser

SECTION III

WIND TUNNEL CONTROL CONSOLE

The wind tunnel control console (Figures 8 and 9) consists of the following four panels equipped to control and monitor all wind tunnel functions: Pressure control panel, wind tunnel main control panel, sting sector or external balance table angle indicator panel, and communications panel.

1. PRESSURE CONTROL PANEL

The pressure control panel monitors, regulates, and controls compressed air and bottled nitrogen gas to the wind tunnel test section. Compressed air is used for dynamic models driven by an air motor. The nitrogen supply is filtered and is used with gas bearing model mounts. Air pressure is adjustable from 0 to 80 pounds per square inch and nitrogen pressure from 0 to 2,000 pounds per square inch. Adjustable pressure regulators are provided for both gas systems.

2. MAIN CONTROL PANEL

The main wind tunnel control panel (Figure 8) monitors and controls the following functions from left to right and top to bottom:

(a) An electric hour meter records the wind tunnel operating time to the nearest 0.1 hour.

(b) Three ammeters monitor the current drawn by each phase of the electric motor.

(c) Wind tunnel power key switch prevents inadvertent wind tunnel operation.

(d) Start/stop switches are used to actuate power relays to start and stop the wind tunnel motor. (An emergency stop switch is located adjacent to the test section door.) The start switch is protected by a hinged safety cover to prevent unintentional operation of the wind tunnel.

(e) A row of indicator lights displays the wind tunnel operational status. The following wind tunnel functions are monitored: fan room inlet doors (open/closed), key switch (unlock,lock), test section door (open/closed), and main power switch (on/off). These wind tunnel functions are also connected with interlock switches to prevent wind tunnel operation if a nonoperational or unsafe condition exists.

(f) The model angle of attack on the pitch sector or the model yaw angle on the external balance table is controlled by increase and decrease switches that are selectable for operation with either the external balance table or the pitch sector support. The angle display for both mounting systems is located in the sting angle indicator panel (Figure 9).

(g) The velocity pressure transducer amplifier has calibration and balance controls mounted on the main control panel and operates in conjunction with the velocity indicator.

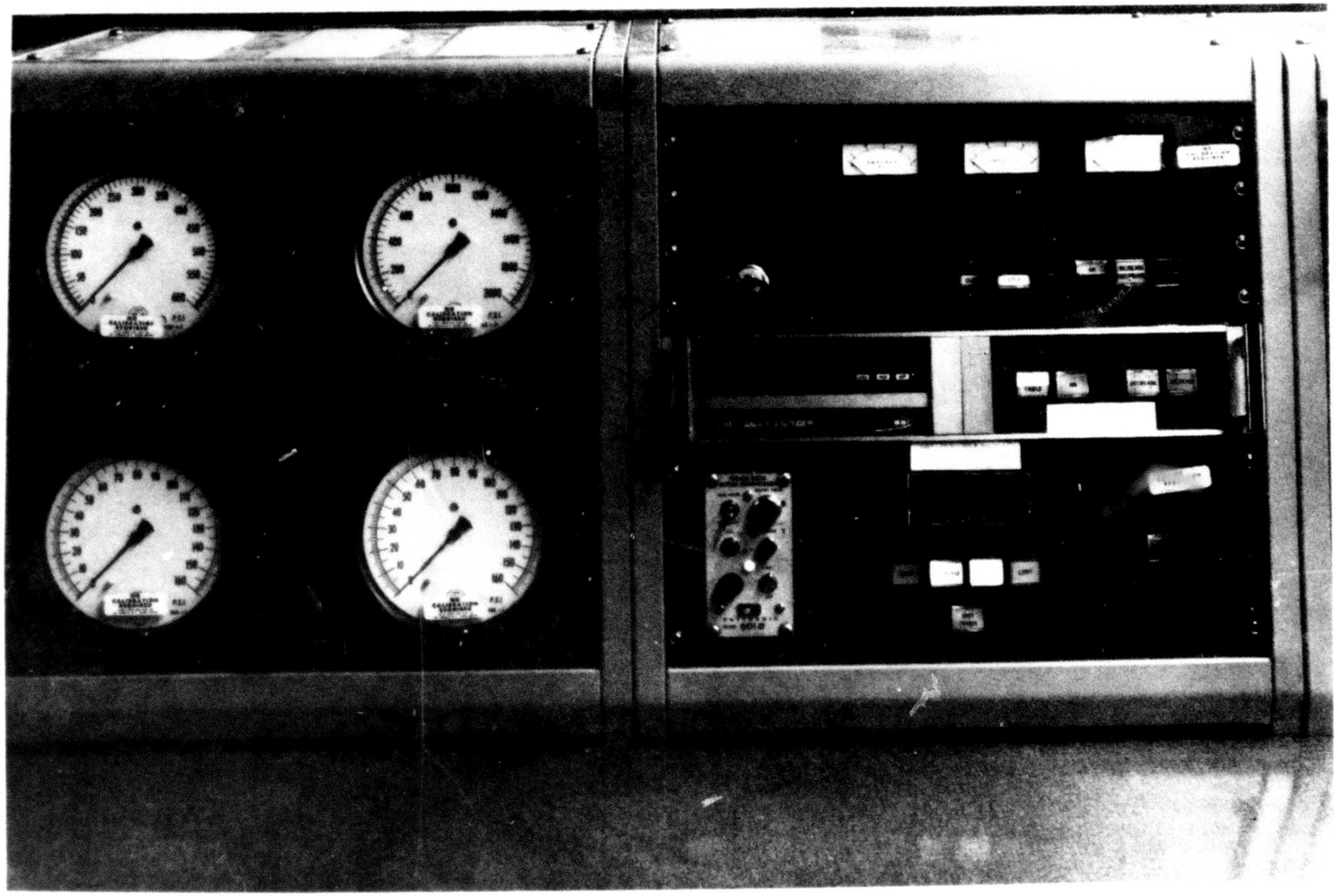

Figure 8. Pressure and Main Control Panels

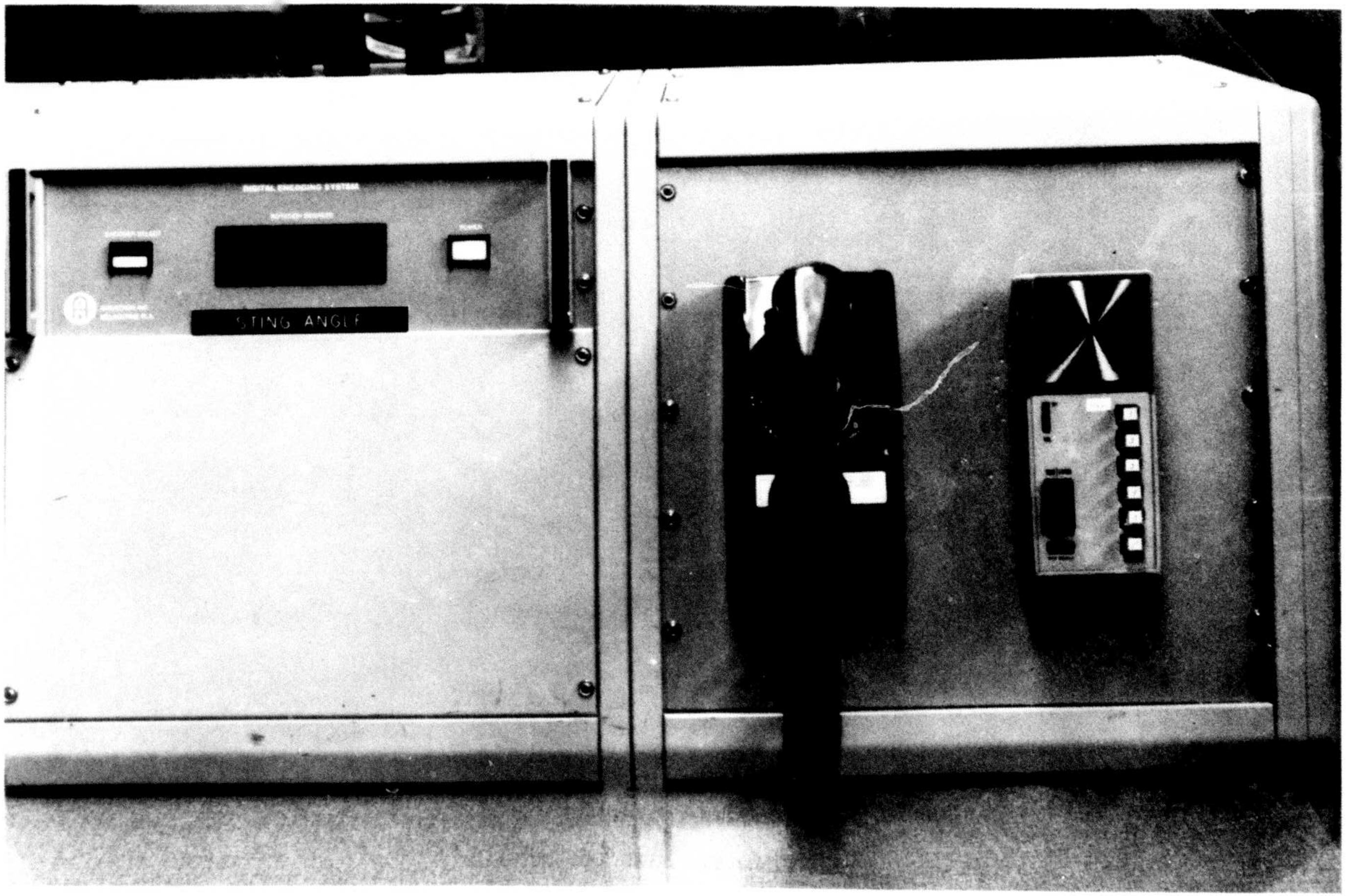

Figure 9. Sting Angle Indicator and Communication Panel

(h) The velocity indicator displays the test section velocity to 0.1 foot per second. The velocity is determined by using the incompressible Bernoulli equation (Reference 1) in the form

$$V = \sqrt{\frac{2\Delta P}{\rho\left(\frac{C^2 - 1}{C^2}\right)}}$$

Where:

ΔP represents the pressure difference across static pressure plates located in the settling chamber and test section

V is the test section velocity

ρ is standard sea level density

C is the contraction ratio

The pressure difference is measured by a strain gage pressure transducer. The transducer output is converted by electronic multiplication and square root circuits to provide a direct velocity indication in feet per second referenced to standard atmospheric conditions. The velocity indicator also furnishes binary coded decimal (BCD) velocity data to the data acquisition system.

(i) The velocity increase/decrease switches initiate servo positioning of the inlet guide vanes on the centrifugal fan. Limit light indicators display maximum and minimum inlet guide vane position.

3. ANGLE INDICATOR PANEL

The sting angle indicator panel (Figure 9) contains the digital encoding system for display and data transmission of the external balance table position or the pitch sector support angle. The angle is measured by alsolute angle encoders on both the sector and table and is displayed by an electronic digital display to $\pm$ 0.1 degree accuracy. The angle encoder output is switch selected to the digital encoding system. The digital encoding system also transmits BCD angle data to the data acquisitic system.

4. COMMUNICATIONS PANEL

The communications panel (Figure 9) has an intercom station and a Class A telephone tied in to the Eglin AFB switchboard.

Reference:
1. Domasch, D. O.: Airp... dynamics. Pitman Publishing Company, 1967.

SECTION IV

DATA ACQUISITION

Acquisition of wind tunnel data is performed primarily by an analog signal conditioning rack and a digital data acquisition system. In addition, portable support instrumentation is available. The data acquisition system (Figures 10 and 11) is housed in the wind tunnel control room.

1. ANALOG SIGNAL CONDITIONING

Most of the analog signal conditioning equipment is installed in an instrumentation rack adjacent to the data acquisition system and behind the wind tunnel control console. Data lines are hard wired from the wind tunnel test section to the rack in radio frequency interference (RFI) shielded cable troughs. The data lines are terminated at patch panels to increase the instrumentation configuration flexibility when taking data. This flexibility also enables the wind tunnel instrumentation to be compatible with other data systems.

The analog signal conditioning equipment consists of the following:

(a) Fourteen Honeywell Accudata 105 Gage Control Units that provide excitation, balancing, and electronic calibration of strain gage bridges. The excitation is continuously variable from 3.5 to 11.5 volts for 350-ohm strain gages and from 1.5 to 5 volts for 120-ohm strain gages for four-arm bridge circuits. Balancing and calibration of the bridge circuit and gage control units are provided by controls on the gage control unit face. A maximum of 16 input channels can be accomodated.

(b) Four Hewlett-Packard 2471A System Data Amplifiers provide signal amplification. Each amplifier is a single plug-in circuit board, consisting of two identical and independent amplifier channels. Each channel provides up to ± 10 volts and 50 milliamperes full scale output. Gains for each channel are switch-selectable and have four calibrated positions from 1 to 1,000 in decade multiple steps. Bandwidths are also selectable for each channel by plug-in jumpers, with a choice of 10, 100, 1,000, and 10,000 hertz. Up to 10 amplifier boards (20 channels) may be installed in the amplifier combining case.

(c) Six Fairchild Model 7050 Multimeters (3 1/2 digit and sign) measure DC voltages and resistances. Full scale range may be selected from 1.5 to 1,000 volts DC or 1.5 kilohms to 15 megohms. Meter accuracy is ± 1 millivolt and ± 1 ohm (Reference 2).

(d) A Systron-Donner 1037 Counter measures pulse frequencies, pulses per given time period, time between pulses, and pulse time average. A prescaler may be used for any desired number of pulses or to scale the frequency measurement to engineering units. The counter can measure frequencies up to 50 megahertz and periods with 100 nanosecond resolution.

Reference:
2. Parrish, G. E.: USAF Armament Laboratory Wind Tunnel Test Facility Instrumentation Modernization. AFATL-TR-73-51, Air Force Armament Laboratory, March 1973.

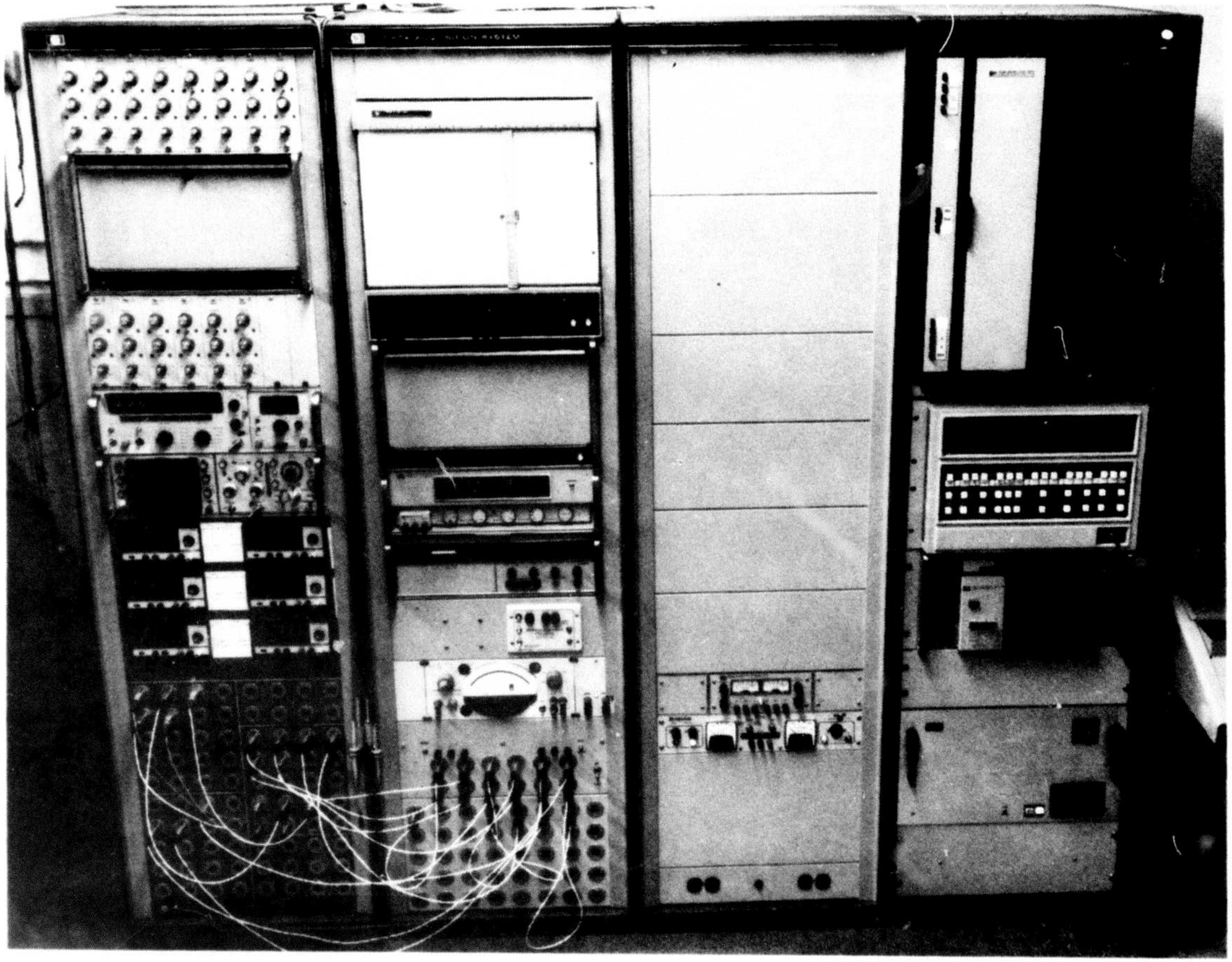

Figure 10. Analog Signal Conditioning Rack and Digital Data Acquisition System

Figure 11. Data Acquisition System Teleprinter

(e) A Hewlett-Packard 180AR Oscilloscope monitors signal waveforms. The oscilloscope has a 50 megahertz dual channel vertical amplifier and a time base, time delay generator. The oscilloscope screen is 8 by 10 centimeters and mounts a Polaroid camera pack and adapter.

(f) A Hewlett-Packard 7004B X-Y Recorder records analog signals on a paper sheet up to 11 inches by 17 inches. A DC preamplifier plug-in has 14 calibrated input ranges from 0.5 millivolt per inch and an input impedence of 1 megohm. A DC attenuator plug-in has eight ranges from 0.1 volt per inch to 20 volts per inch. A time base plug-in utilizes a ramp generator and has eight calibrated sweep speeds from 0.5 to 100 seconds per inch. A filter plug-in provides 55 or 70 dB of noise rejection of AC signals of 50 hertz, or greater.

(g) The patch panel has 20 data channels and contains additional 0.1 hertz cutoff signal filters. The patch panel output can be routed to the data acquisition system for further data reduction.

(h) Other support equipment located in the data acquisition system racks includes a General Radio Frequency Meter and Descriminator and two independent voltage and current supplies.

2. DIGITAL DATA ACQUISITION SYSTEM

The data acquisition system collects digital or analog data from multiple sources, manipulates the data, and records the results. The acquisition of data can be manually controlled step by step or programmed under the control of a digital computer. The data acquisition system provides maximum flexibility in equipment utilization and organization for the collection of wind tunnel data (Reference 2). The components of the data acquisition system are as follows:

(a) A Hewlett-Packard 2019A Reed Scanner, which has 20 data channels, can scan at a maximum rate of 40 channels per second. The reed scanner can accept analog voltages that are $\pm$ 10 volts DC peak. The reed scanner can operate manually or under programmable control of a digital computer.

(b) A Hewlett-Packard 2402A Integrating Digital Voltmeter (IDVM) performs analog to digital conversion. The IDVM provides five digit resolution over a range of 0.1 to 1,000 volts full scale. The IDVM is capable of making a maximum of 40 five-digit measurements per second using signal integration over 1/60 second to reject super-imposed noise. The instrument also provides both a visual readout to the operator and a BCD output to the data acquisition system.

(c) A Hewlett-Packard 2570A Coupler/Controller is the system interface between the data equipment and a digital computer. The coupler/controller is capable of linking up to eight BCD or American Standard Code for Information Interchange (ASCII) digital devices. Interface cards included in the coupler/controller are for the teleprinter, digital controller/processor, six BCD input channels, time of day, interval pacing, and diagnostic control.

(d) A Hewlett-Packard 2100A Computer can control all instrument measurement functions, provide temporary data storage, perform numerical calculations, and coordinate recording and display devices. The computer is characterized by a 16-bit word length and a memory size of 16,3B4 words main-frame expandable to 32,768 words. The computer has a memory cycle time of 9B0 nanoseconds and has 14 input/output channels for external devices. The computer is presently interfaced with a time base generator, seven-channel digital magnetic tape transport, digital voltmeter, paper-tape reader, serial interface, paper-tape punch, teletype, cathod ray tube (CRT) terminal, digital-to-analog converter, and 16-bit relay register.

(e) A Hewlett-Packard 2600A CRT Terminal is the standard communication device for the system. This device has a standard teletype keyboard, as well as an 11-key calculator-type number pad and complete cursor motion controls. The electronic display accomodates 25 lines, each of 72 characters, at a time.

(f) A Hewlett-Packard 7210A Digital Plotter may be used to plot raw data points as they are collected, calculated data points, and to plot fitted curves, all under control of the 2100A Computer. The plotter can use either plain or pre-lined paper up to 11 by 15 inches in size.

(g) A Hewlett-Packard 2754B Teleprinter is the basic output listing device for the system. This machine can produce a typewritten page as well as punched paper tape. Information can also be input via the teleprinter by paper tape or keyboard. The paper tape punching and reading rate is a maximum of 10 characters per second, using an eight-bit ASCII code on 1-inch paper. The teleprinter will accept a maximum of 100 words per minute typing speed.

(h) A Hewlett-Packard 2758A Tape Reader/Reroller can accurately read punched paper tape to 500 characters per second and can eliminate tape rewinding by automatically rerolling the tape as it is read. The tape reader reads eight-bit characters on 1-inch tape using a photoelectric pick-up.

(i) The Hewlett-Packard 7970B seven-Track Digital Magnetic Tape Unit has three selectable read/write densities of 200, 556, and 800 bytes per inch (bpi). This magnetic tape unit used 1/2-inch magnetic tape on 10 1/2-inch reels with IBM-compatible non-return-to-zero IBM (NRZI) recording mode. The end-of-tape and beginning-of-tape reflective strip detector is also IBM compatible. The magnetic tape unit is interfaced with a digital computer and can be used as a mass data storage device, program library, or a temporary information storage file.

(j) A Remex RPR1075 BCX Paper Tape Punch punches an 8-bit character on 1 inch paper tape at the rate of 75 characters per second.

(k) The software library includes a calculator program, a BASIC interpreter, and FORTRAN and ALGOL compilers. The library also includes numerous programs designed for data acquisition using the wind tunnel instrumentation. These programs are capable of utilizing instrumentation under complete control of the digital computer.

Software routines are provided to implement the fixed and floating point operations of addition, subtraction, multiplication, and division. Other floating point operations include sine, cosine, tangent, square root, arctangent, hyperbolic tangent, natural logarithm, and natural exponent. The range of fixed point numbers is -32,768 to +32,767, and the range of floating point numbers is 10^{-38} to 10^{+38}.

3. PORTABLE INSTRUMENTATION

A Honeywell 1508A Light Beam Oscillographic Recorder (Figure 12), installed in a portable instrumentation rack, records frequencies of 0 to 13 kilohertz by the use of light beam galvanometers on photo-sensitive paper. Twelve channels of data may be recorded with two additional channels for event markers. The maximum writing speed is greater than 50,000 inches per second. The recorder drive has 12 speeds that vary, in factors of 2, from 0.15 to 120 inches per second in steps by a factor of 2. Time lines may be printed at 10, 1, 0.1, or 0.01 second intervals. Externally generated time lines may be printed at up to 100 lines per second. Ten Honeywell Accudata 104 and two Accudata 120 DC differential amplifiers are included in the oscillograph. The former has gain steps of 10, 20, 30, 50, 100, 150, and 250, plus a vernier for continuous control between steps, while the latter has gain steps of 10, 20, 50, 100, 200, 500, and 1,000, plus a vernier.

Six of the Accudata 105 Gage Controls may be installed in a rack adapter for use with strain gage inputs to the amplifiers and oscillograph. The input/outputs of the gage controls and amplifiers are controlled through a patch panel on the rear of the rack.

A portable Ampex TR-1300A Seven-Track 1/2-Inch Magnetic Tape, Recorder/Reproducer (Figure 13) is used for recording and reproduction of analog signals. The available tape speeds are 1 7/8 to 60 inches per second in 6 steps . Four channels each of direct record/reproduce and FM record/reproduce electronics may be used in any combination totaling seven channels. The direct channels have a frequency response from 50 to 300 kilohertz and the FM channels have a response from 0 to 40 kilohertz. A voice log channel may be used for narrative on an edge track. A remote control unit may be used to control the recorder if safety conditions imposed by the test prevent the presence of an operator for manual operation.

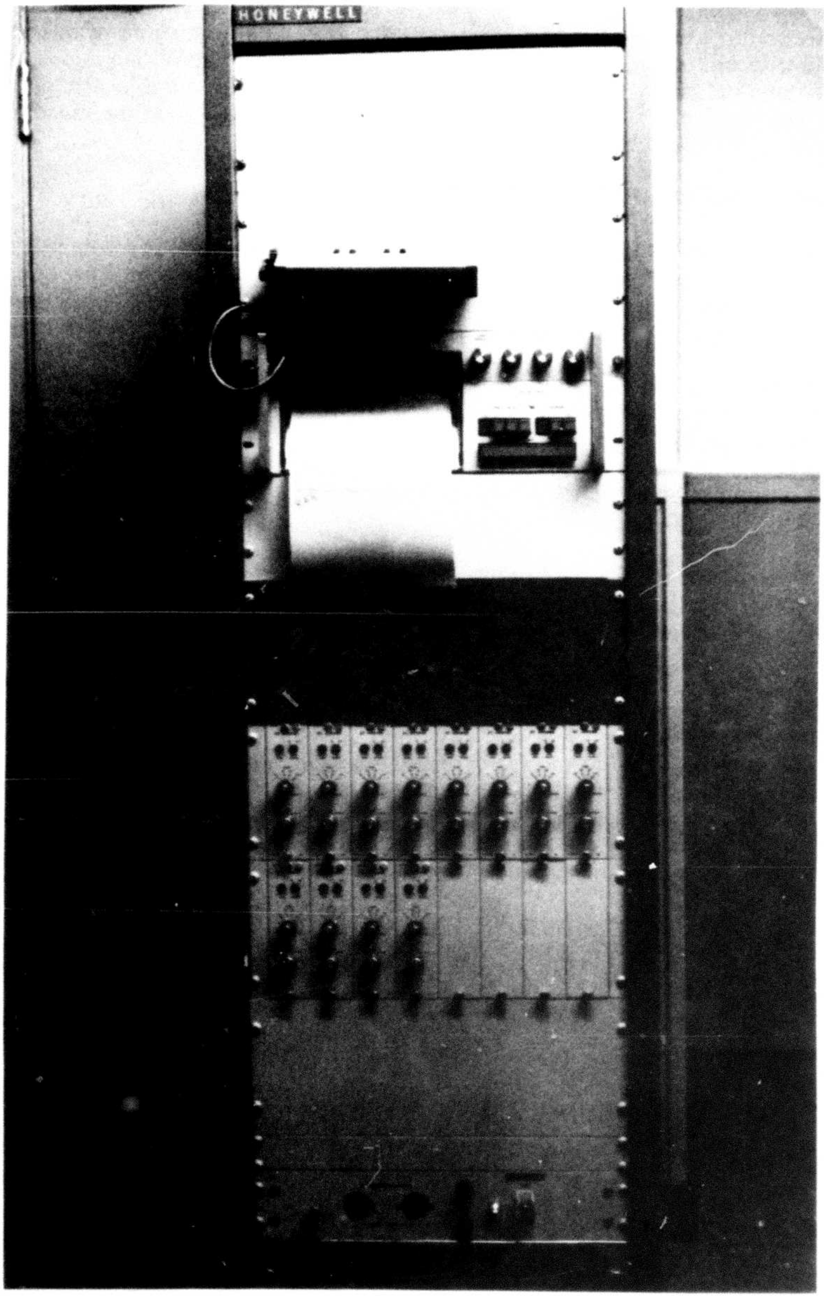

Figure 12. Light Beam Oscillographic Recorder

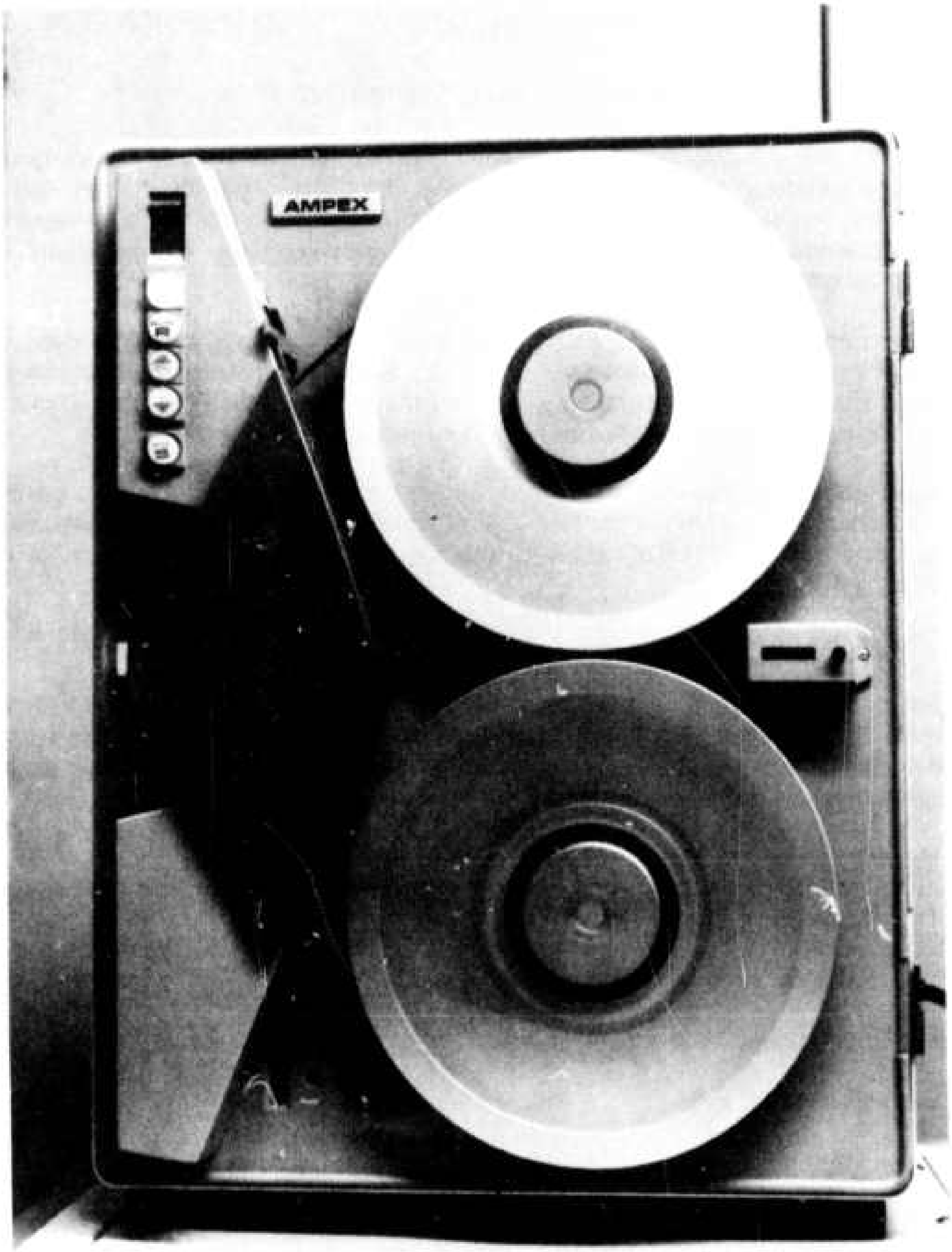

Figure 13. Magnetic Tape Recorder/Reproducer

SECTION V

WIND TUNNEL EQUIPMENT

The AFATL Wind Tunnel provides a reliable, inexpensive, and flexible aerodynamic test capability for a variety of munitions, such as bombs, bomblets, dispensers, mines, fuzes, rockets, missiles, and targets. The wind tunnel also provides a tool for in-house research involving aerodynamics, flight dynamics, aerodynamic dispersal concepts for munitions, and munitions stabilization techniques.

The wind tunnel can be used to determine subsonic aerodynamic static and dynamic coefficients of munitions at various angles of attack. Static aerodynamic coefficients include lift, drag, and side forces; also, pitch, yaw, and roll moments may be obtained. Dynamic coefficients include Magnus force and moment, and pitch and roll damping.

The wind tunnel is suitable for free-flight testing. A munition or test model can be released or launched in the wind tunnel test section and photographed to determine position and velocity as a function of time. The position and orientation data can be used to determine aerodynamic coefficients.

1. EXTERNAL BALANCE

An external force and moment balance (manufactured by Aerolab Supply Company) is located under the wind tunnel test section (Figure 14). The external balance is a six-component, pyramidal (or virtual center) strain gage balance and is enclosed with clear plastic for moisture and dust protection. Load capacities are as follows:

(a) Normal force, lb	$\pm$ 100
(b) Drag force, lb	$\pm$ 100
(c) Side force, lb	$\pm$ 100
(d) Pitching moment, in-lb	$\pm$ 250
(e) Yawing moment, in-lb	$\pm$ 250
(f) Rolling moment, in-lb	$\pm$ 250

The external balance can be calibrated to an accuracy within 0.5% of full scale, over limited load ranges.

The analog output of the external balance strain gages is produced by Honeywell Accudata 105 Gage Control Units described in Section IV. The strain gage output is relayed to Hewlett-Packard 2471A System Data Amplifiers, which are set for a gain of 1000. The signal is then relayed through a patch board to the data acquisition system for recording and reduction. Data from any or all of the external balance components can be obtained by a computer program.

Figure 14. External Balance, Rotating Table Support

The external balance table and model support can rotate ±180 degrees in yaw and can be remotely controlled from the main control console. The position of the table is also indicated remotely on the main control console. The external balance table also has ±30 degree pitch capability.

2. PITCH SECTOR SUPPORT

The pitch sector support system (manufactured by Aerolab Supply Company) consists of a servo controlled sector with sting attachment socket and is mounted on top of the test section (Figure 15). The sector moves up and down about a pitch center located 29.0 inches downstream from the beginning of the test section. The pitch range of the sector is continuously variable to ±20 degrees. The sting attachment socket secures model stings to the sector. Stings are typically made so the model pitch center coincides with the sector pitch center. Yaw angle capability does not exist on the pitch sector, but the roll position can be changed by rotating the model sting in the sting attachment socket. The pitch sector can be completely removed from the test section to facilitate model testing not requiring this system. Also, stings can be fabricated for testing of special models.

3. SUPPORTS AND STINGS

The three basic model mounting systems for the wing tunnel are the external balance table, the pitch sector support, and the dynamic wind tunnel support system.

a. External Balance Table Stings

The external balance table uses transverse, horizontal, and vertical stings for supporting wind tunnel models as follows:

(1) The transverse sting can be used for static and dynamic model testing (Figures 16 and 17). The static transverse sting is simply mounted through the side of a test model. The model is fixed to the sting by a set screw against a flat bearing on the sting. The ends of the sting are supported by struts to the external balance table. The struts have clear plastic covers to reduce strut tare effects.

The dynamic transverse sting support is the same as the static sting support with one exception. The set screw is replaced by a bearing mount in the model such that the model is free to pitch. The dynamic transverse sting can be used for pitch damping tests.

(2) The external balance table also has a horizontal sting and sting support (Figures 18 and 19). The sting support base mounts directly to the external balance table. A sting mounts in the sting support socket and is adapted for use with the VHB-13 internal strain gage balance. Since the support and sting are mounted to the external balance table, a model can be yawed ± 180 degrees.

(3) The vertical static sting mounts perpendicular to the external balance table (Figures 20 and 21). The vertical static sting is used for static model tests and usually mounts through the bottom or top of a model with a set screw. An image fairing for the vertical static sting mounts to the test section ceiling and a tare fairing mounts to the wind tunnel floor.

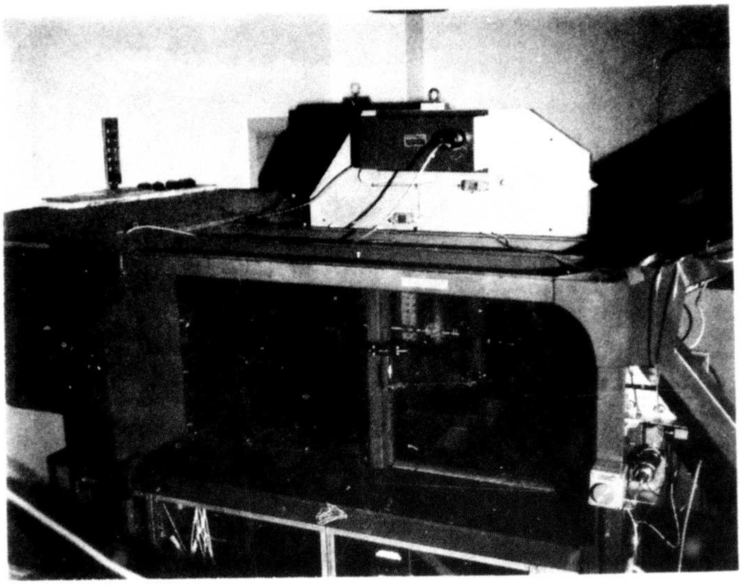

Figure 15. Pitch Sector Support

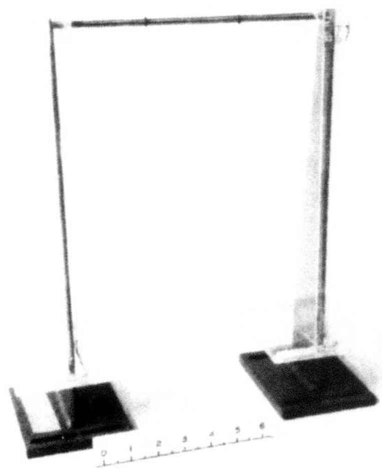

Figure 16. Transverse Static and Dynamic Sting

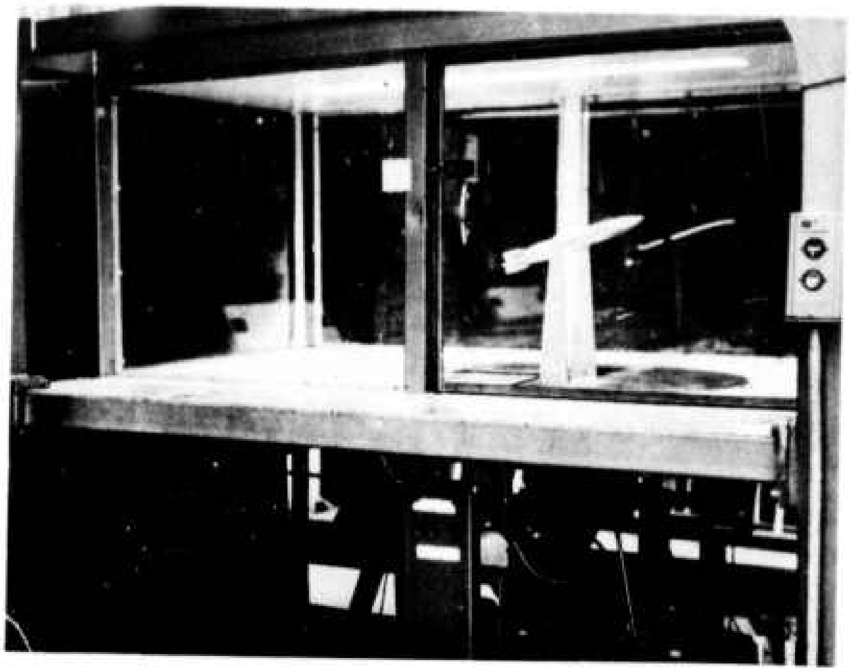

Figure 17. Transverse Sting and Model Installation

Figure 18. Horizontal Sting and Sting Support

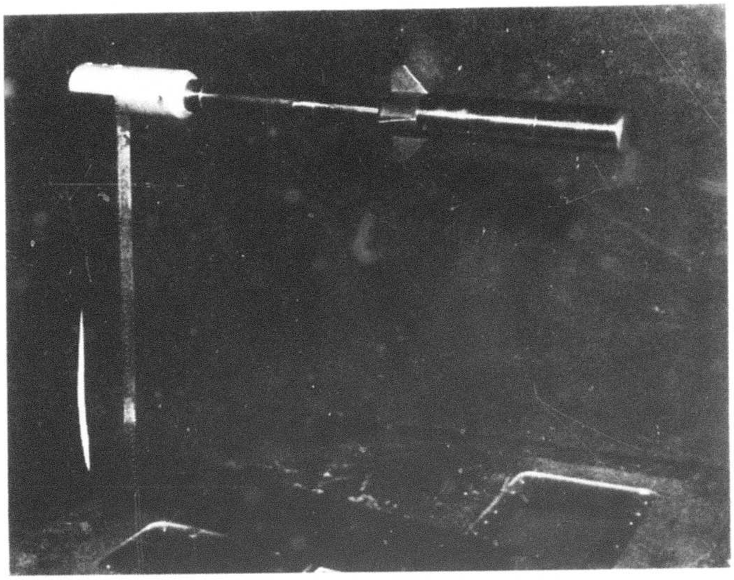

Figure 19. Horizontal Sting Support and Model Installation

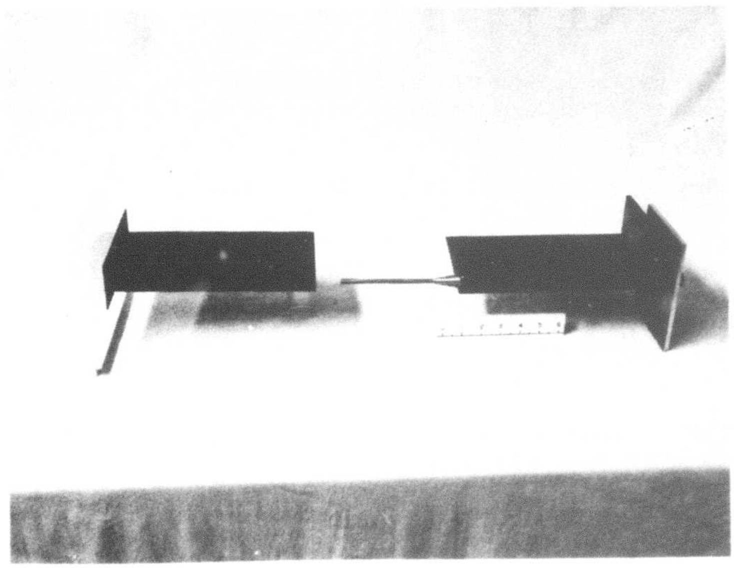

Figure 20. Vertical Static Sting

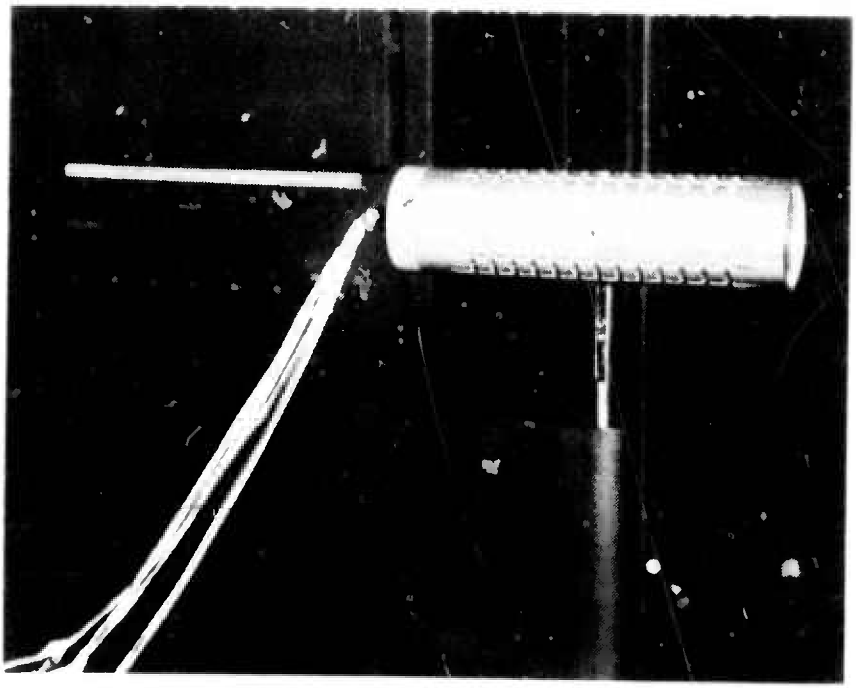

Figure 21. Vertical Static Sting and Model Installation

(4) The vertical dynamic sting uses a perpendicular sting and mounts to the wind tunnel ceiling (Figures 22 and 23). The top of the vertical sting has bearing supports that allow the model to yaw.

(5) The remote controlled vertical sting has a vertical support that can be geared to an electric motor (Figure 24). With this equipment, the yaw angle of a model can be changed remotely. The remote controlled vertical sting is mounted to the test section ceiling and uses a potentiometer to indicate model yaw angle remotely. Image fairing for the remote controlled vertical sting mount on the test section floor, and a tare fairing is mounted to the wind tunnel ceiling.

b. Pitch Section Support Stings

Various pitch sector support stings (Figure 25) are available. All sector stings are designed to lock in the sector support socket and most are designed for use with an internal strain gage balance. Test models are mounted on the sector sting so that the model center of rotation coincides with the pitch sector rotation center.

c. Dynamic Wind Tunnel Support System Stings

A dynamic wind tunnel model system (Figure 26) is available for testing axisymmetric model configurations under simulated coning motions. The simulated coning motion is at a constant angle of attack and at either steady or variable coning rates. The test model can

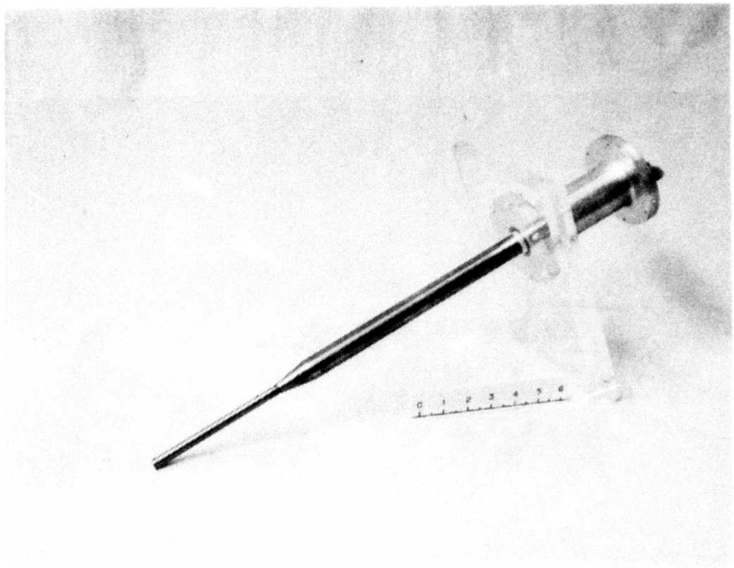

Figure 22. Vertical Dynamic Sting

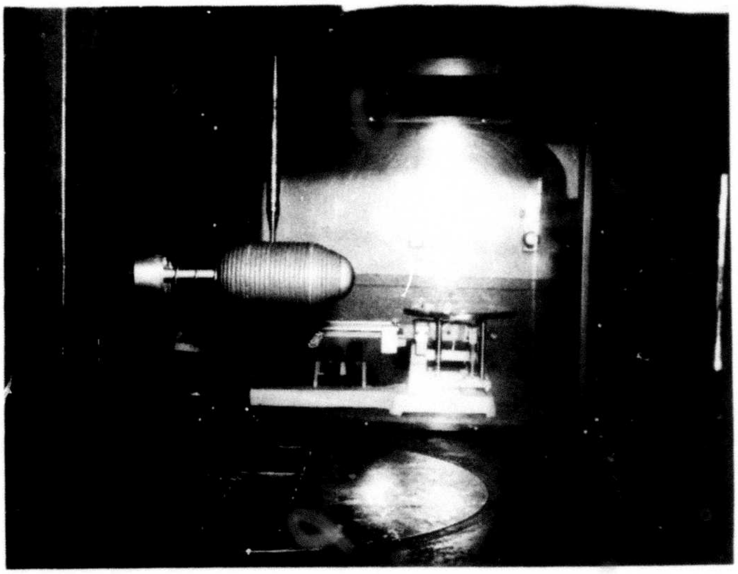

Figure 23. Vertical Dynamic Sting and Model Installation

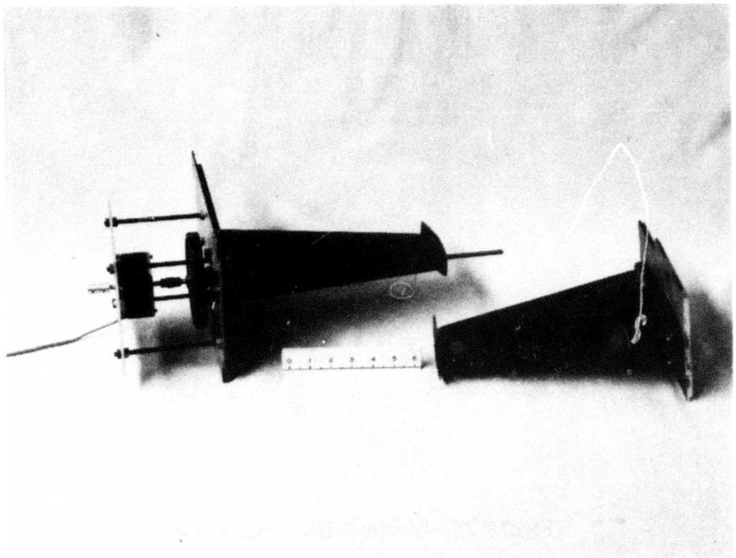

Figure 24. Remote Controlled Vertical Sting

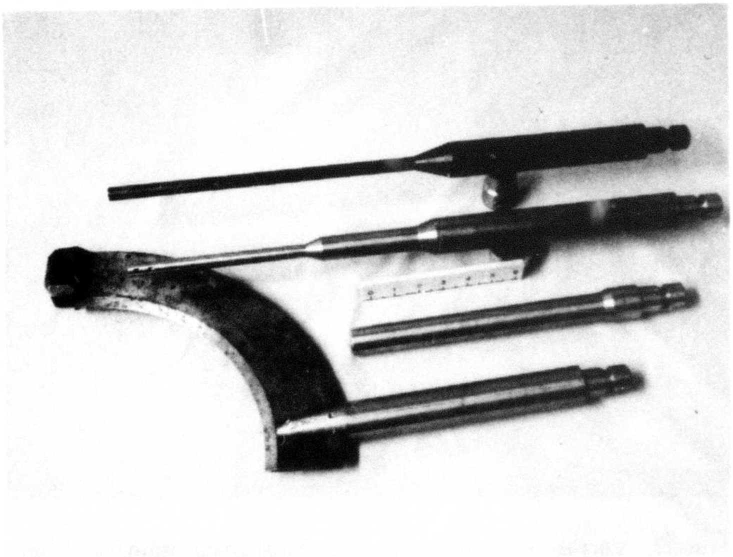

Figure 25. Pitch Section Stings

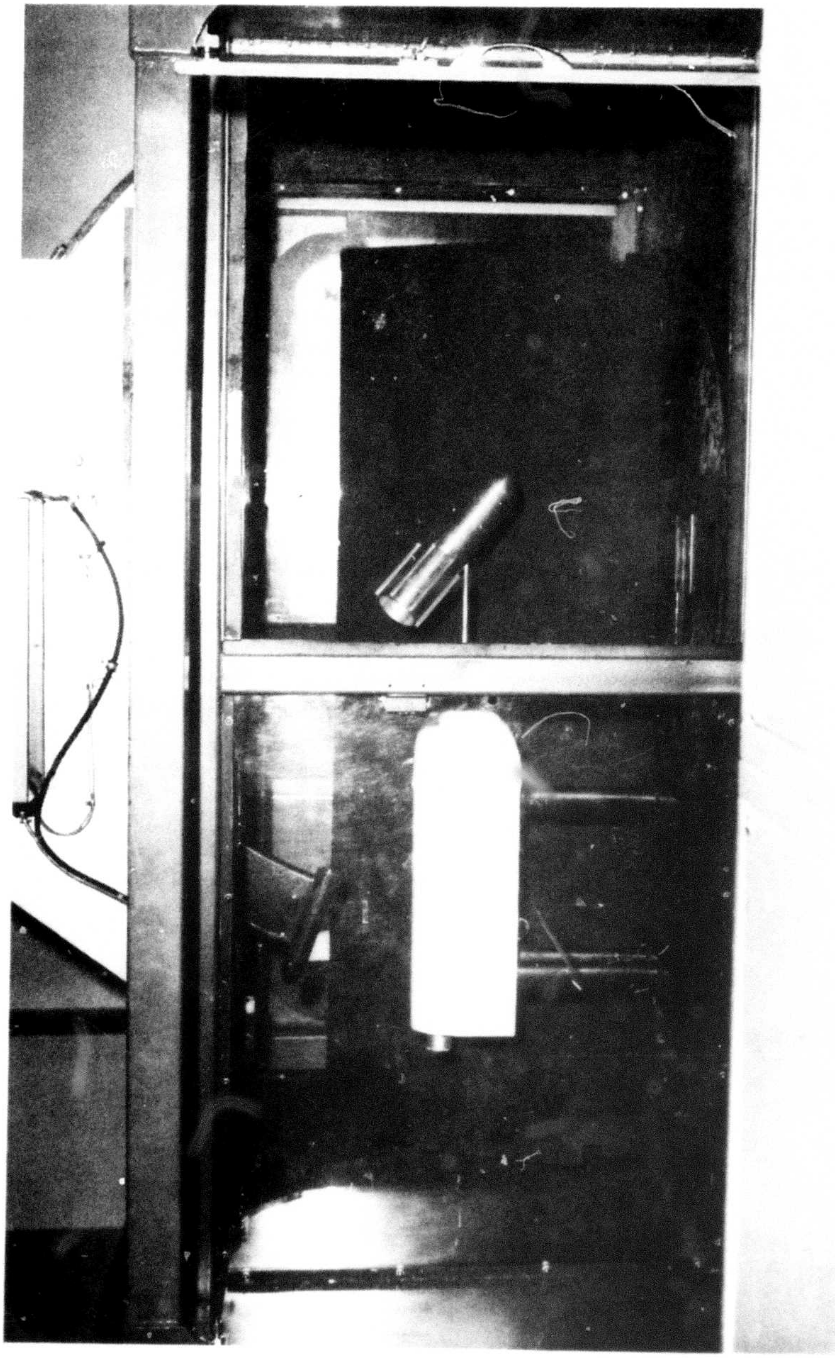

Figure 26. Dynamic Wind Tunnel Support System Installation

also be free to roll about its longitudinal axis or locked at a specific roll orientation. The system employs measured model coning and rolling angular rate data to derive aerodynamic moments. The coning rate can be determined by a precision sting angle recording device. The model roll rates must be recorded optically. Detailed information can be found in Reference 3.

4. INTERNAL BALANCES

Three internal strain gage balances are available for tunnel model testing; one has five components and two have six components.

a. The five-component strain gage balance (manufactured by the Arnold Engineering and Development Center) is identified as 400-Y-35-054 (Figure 27). A sting support for the internal balance is shown in Figure 28. The load capacities are as follows:

Normal Force , lb	±5
Axial Force, lb	±5
Side Force, lb	±1.5
Pitching Moment, in-lb	±5
Yawing Moment, in-lb	±1.5

The accuracy of the 400-Y-35-054 balance is within 0.25% of full scale.

b. One of the six component internal strain gage balance (manufactured by LTV Corporation) is identified as VHB-13 (Figure 29). The sting supports for the internal balance are shown in Figure 30. The load capacities are as follows:

Normal Force, lb	±20
Axial Force, lb	±5
Side Force, lb	±10
Pitching Moment, in-lb	±20
Yawing Moment, in-lb	±10
Rolling Moment, in-lb	±8

The accuracy of the VHB-13 balance is within 0.6% of full scale.

Reference:
3. Brunk, J. E.: Monte Carlo Analysis of S-Curve and Roll-Through-Zero Bomblet Dispersion Characteristics. AFATL-TR-73-15, Air Force Armament Laboratory, January 1973.

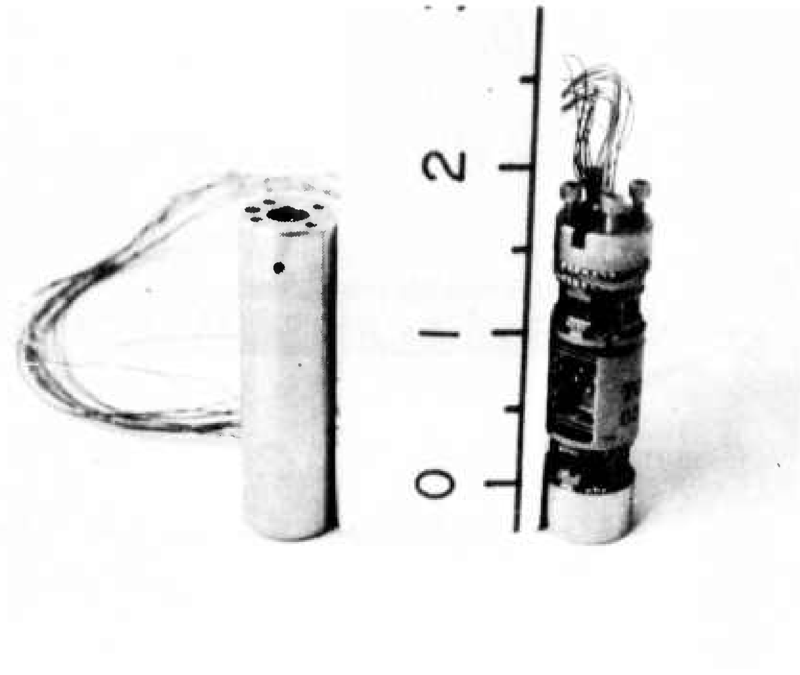

Figure 27. 400-Y-35-054 Internal Balance

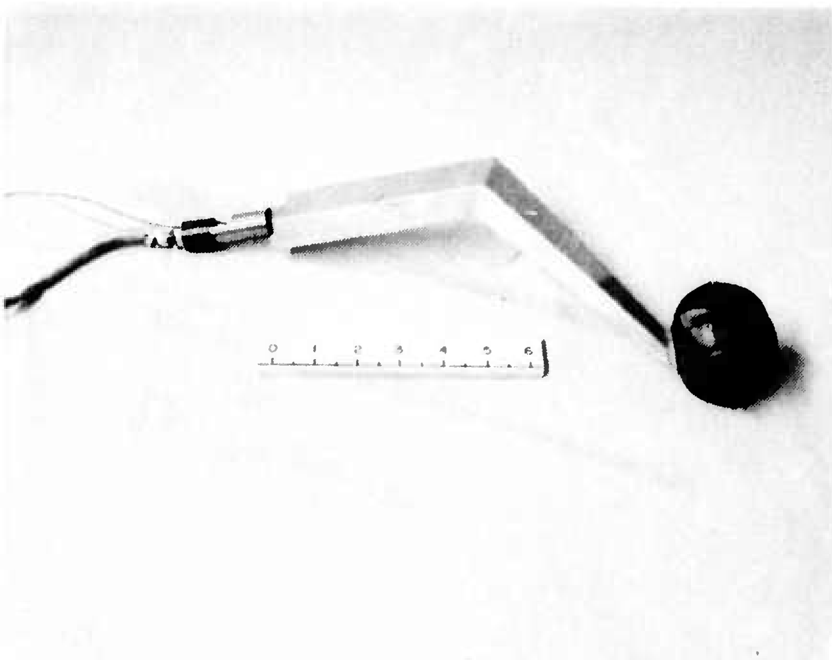

Figure 28. 400-Y-35-054 Internal Balance Sting

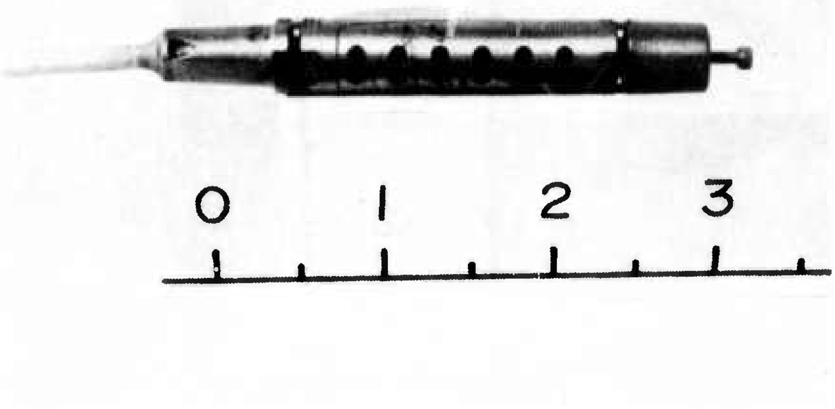

Figure 29. VHB-13 Internal Balance

Figure 30. VHB-13 Internal Balance Stings

c. The other six-component internal strain gage balance (Figure 31) (manufactured by NASA/Langley Research Center is identified as EAF-1. The load capacities are as follows:

Normal Force, lb	± 12
Axial Force, lb	± 4
Side Force, lb	± 4
Pitching Moment, in-lb	± 16
Yawing Moment, in-lb	± 4
Rolling Moment, in-lb	± 4

The accuracy of the EAF-1 balance is within 0.5% of full scale.

5. PRESSURE MEASUREMENTS

The wind tunnel instrumentation is also capable of making pressure distribution measurements. The wind tunnel is equipped with a scanning valve that has 50 remotely selectable ports, a Dynasciences Model CD-25 Pressure Indicator, and a Model P7D-1.0 PSID Pressure Transducer (Figure 32), and can be controlled under a data acquisition program. The pressure transducer is a variable reluctance type and has a pressure range from 0 to 1 pound per square inch differential (PSID). A Setra Model 237 Pressure Transducer having a range of ± 0.25 PSI can be used with the scanning valve.

Three manometers (Figures 33 and 34) are also available for pressure measurements. An alcohol manometer is used as a backup wind tunnel velocity indicator. This manometer is calibrated in miles per hour and inches of alcohol. A water manometer is used for low pressure systems. A mercury manometer is used for measuring relatively high pressures.

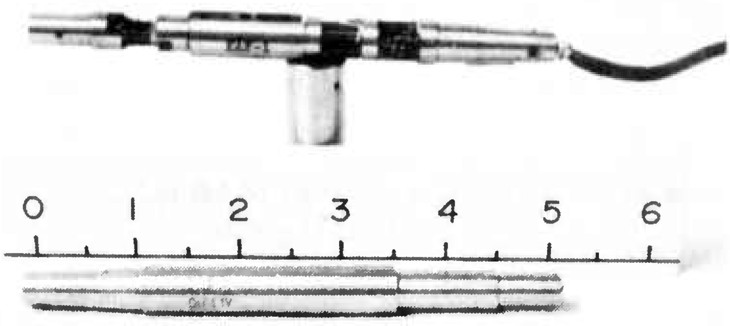

Figure 31. EAF-1 Internal Balance

Figure 32. Pressure Transducer and Scanning Valve

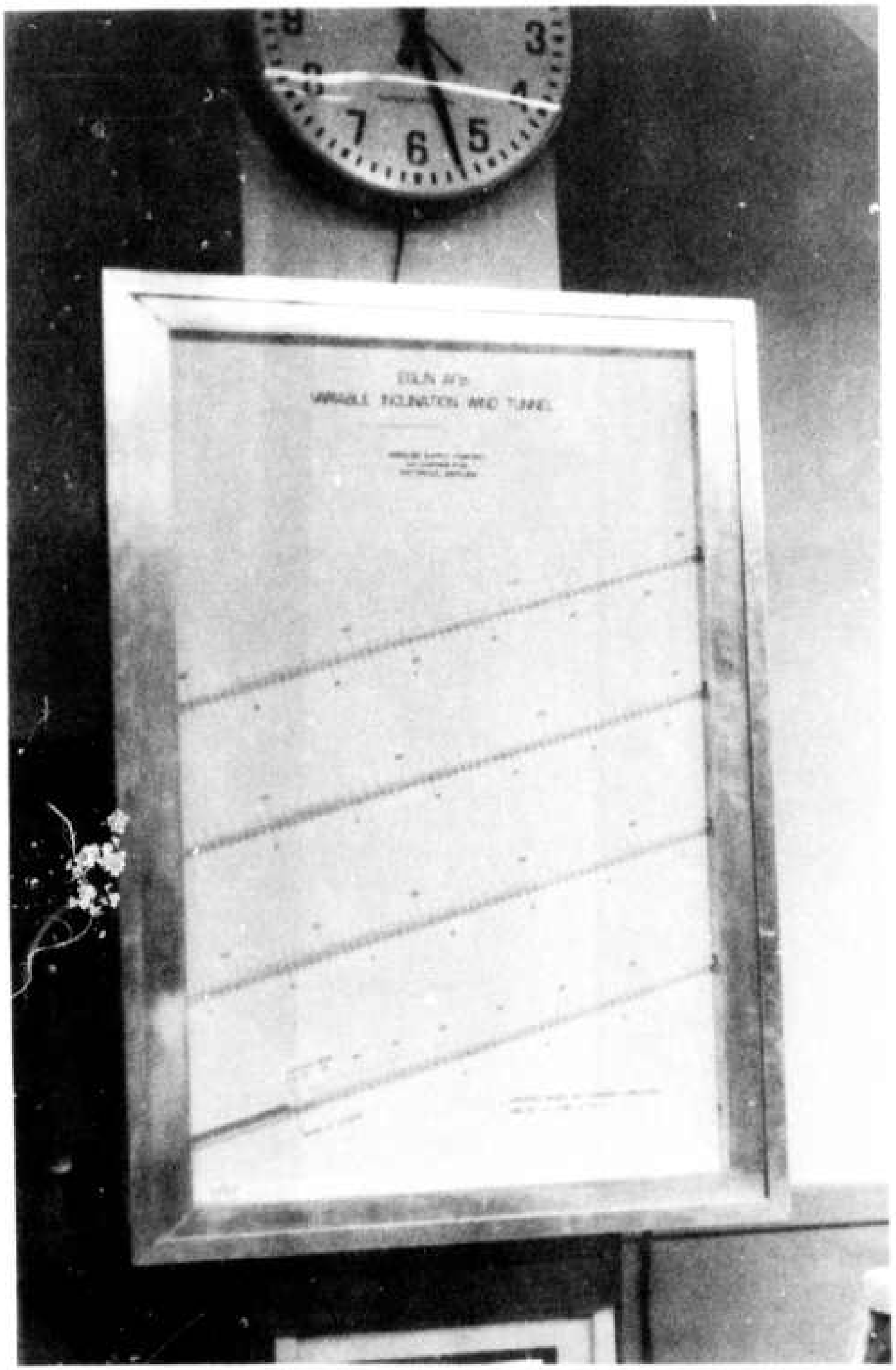

Figure 33. Alcohol Manometer

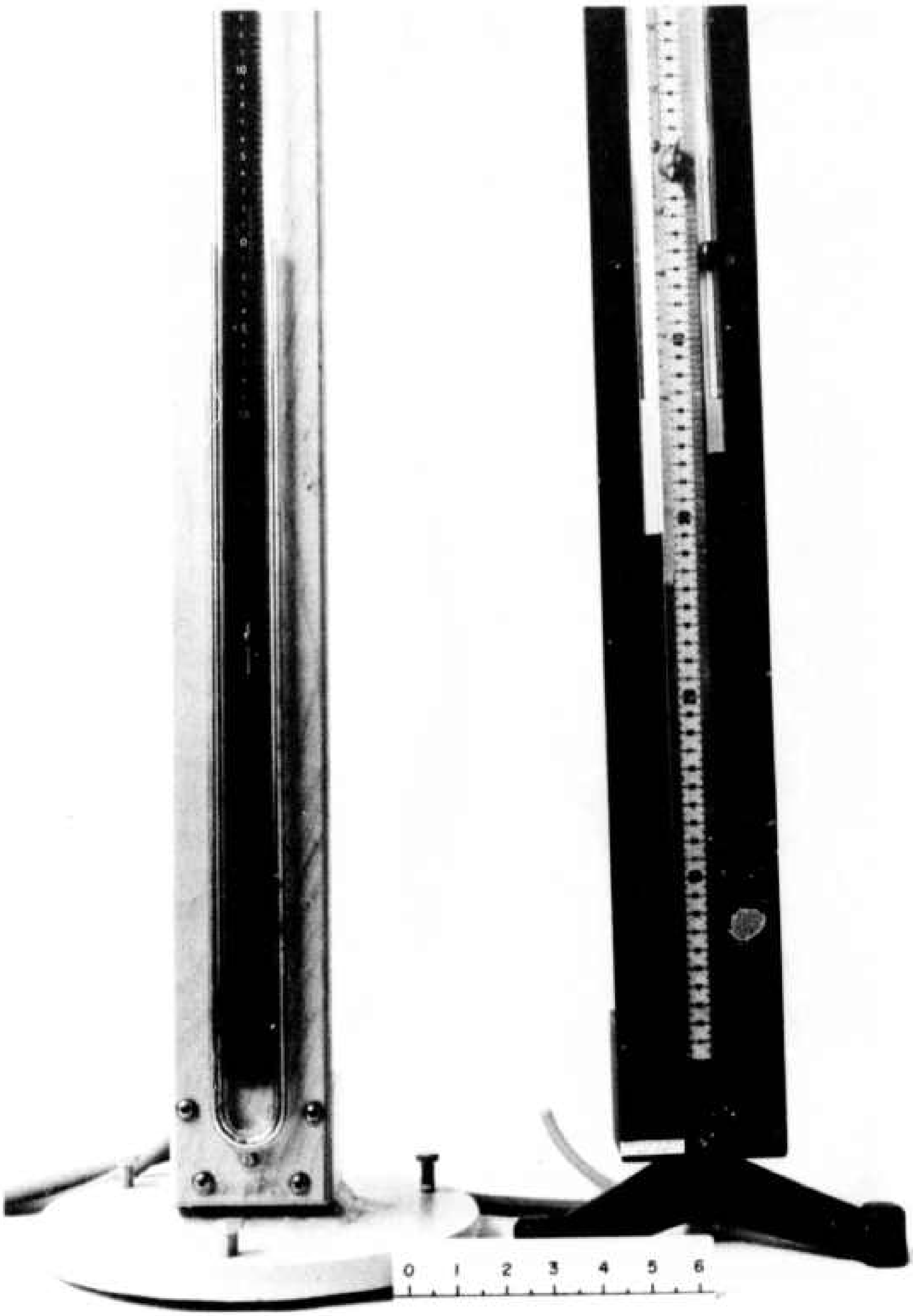

Figure 34. Mercury and Water Manometers

SECTION VI

WIND TUNNEL TESTING

1. MODEL SIZE

The maximum size of wind tunnel models for force and moment measurements is dependent on the balance load capacities. Model weight and vibration should also be considered when determining the anticipated load range. Models as small as 1.2 inches in diameter and using an internal balance can still be mounted to a sting support.

2. TEST PROGRAMS

The following are some of the typical projects that have been investigated in the AFATL Wind Tunnel:

a. Wind tunnel test of modified BLU-87/B Fragmentation Bombs (Figure 35) obtained static and free oscillation aerodynamics data for a standard and 11 modified configurations. The objective of the test was to provide data which could be used to increase the dispersion of the BLU-87/B bomb (Reference 4).

b. The Monte Carlo analysis of S-curve and roll-through-zero bomblet (Figure 36) dispersion characteristics test involved designing a dynamic wind tunnel model support system for testing S-curve bomblets (Reference 3).

c. A dispersion technique for the MK82 bomb (Figure 37) involved wind tunnel testing of drag base plates for use in dispersing MK82 bomb clusters (Reference 5).

Reference:
4. Schlegal, M. O.: Wind Tunnel Tests of Modified BLU-87/B Fragmentation Bombs. AFATL-TR-72-132, Air Force Armament Laboratory, July 1972.
5. McGirr, P. G.; Schlegal, M. O.: A Dispersion Technique for the MK82 Bomb, AFATL-TR-73-146, Air Force Armament Laboratory, July 1973.

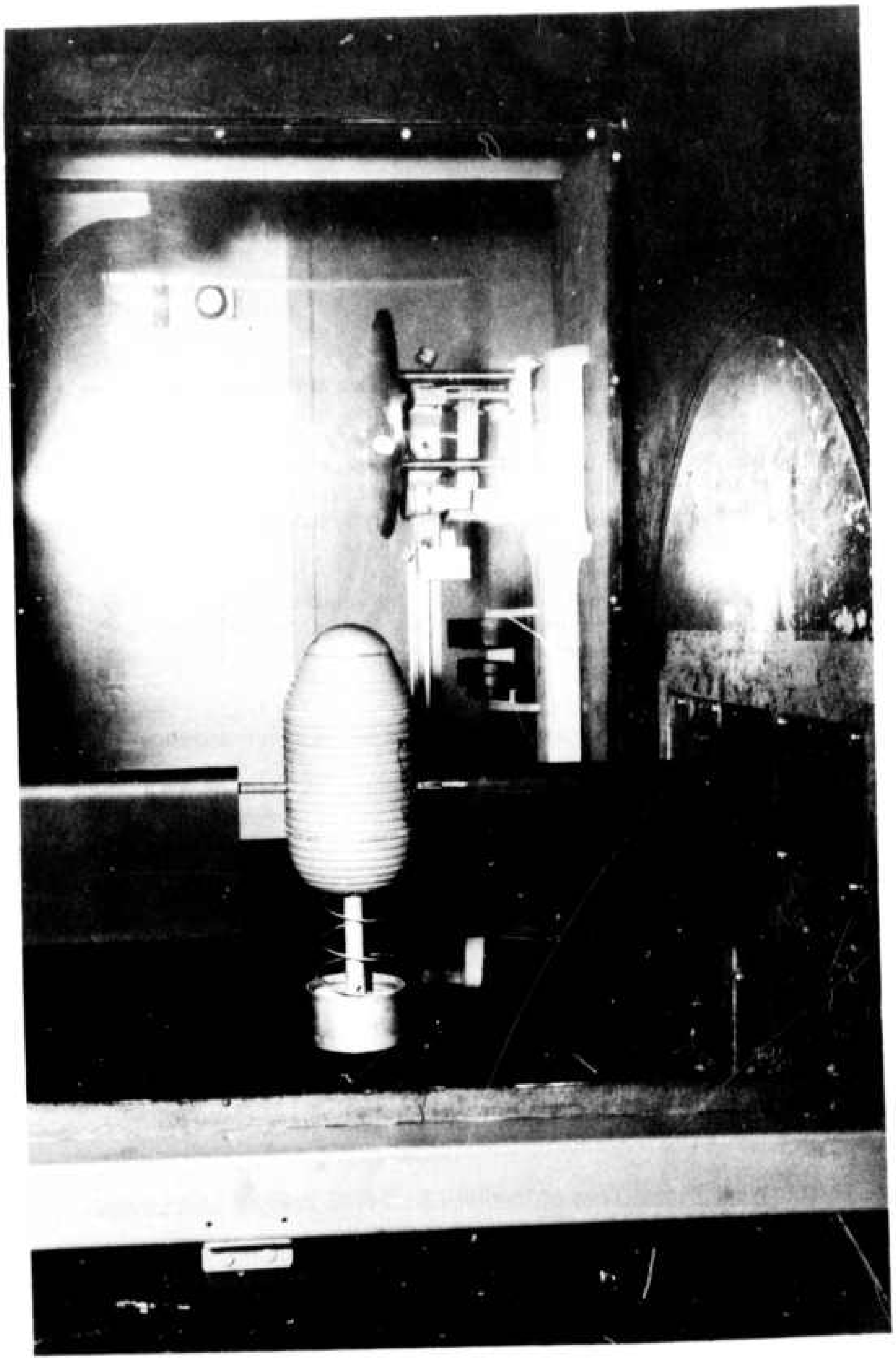

Figure 35. Wind Tunnel Test of the Modified BLU-87/B

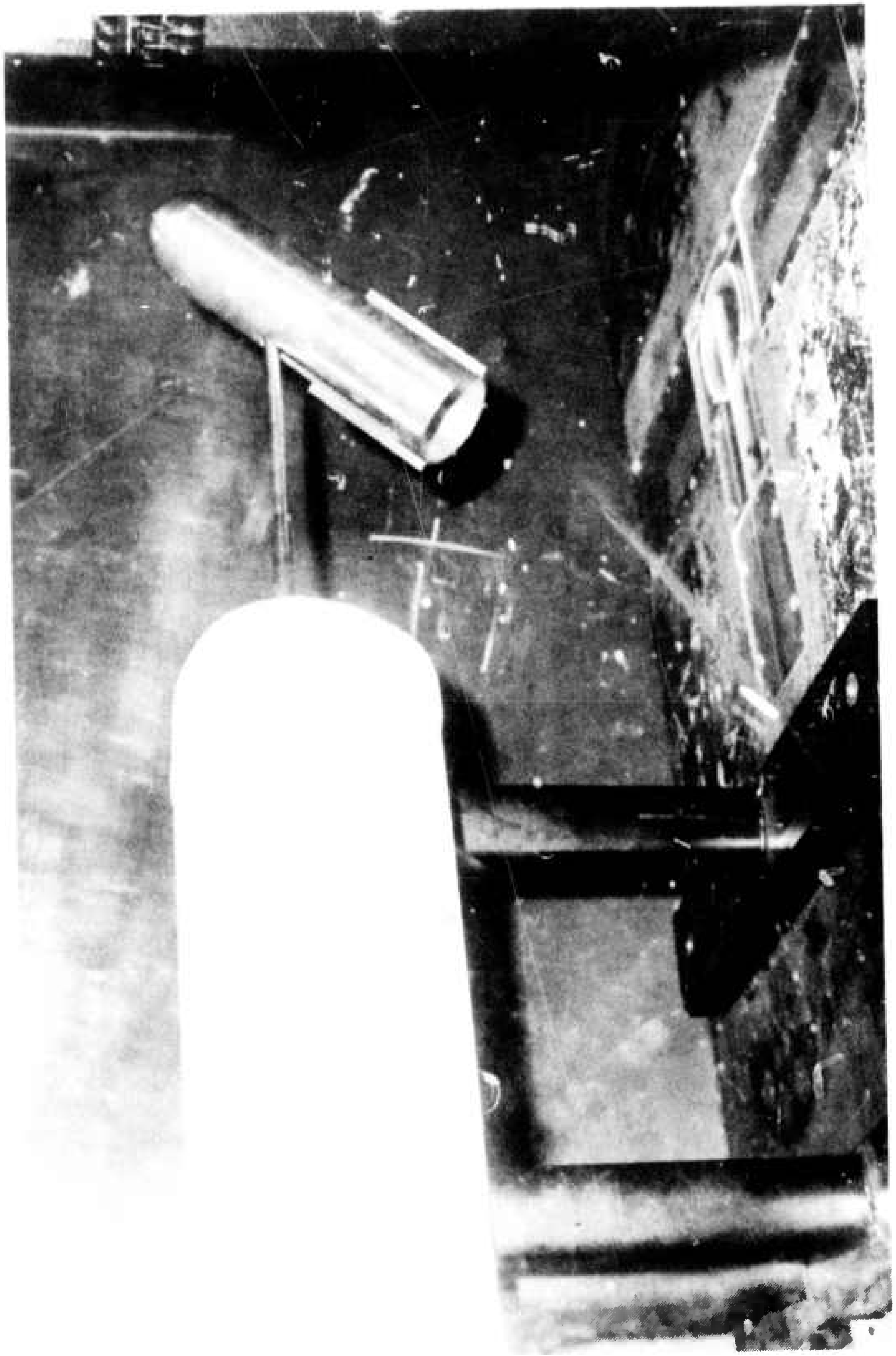

Figure 36. Wind Tunnel Tests of the S-Curve Bomblet

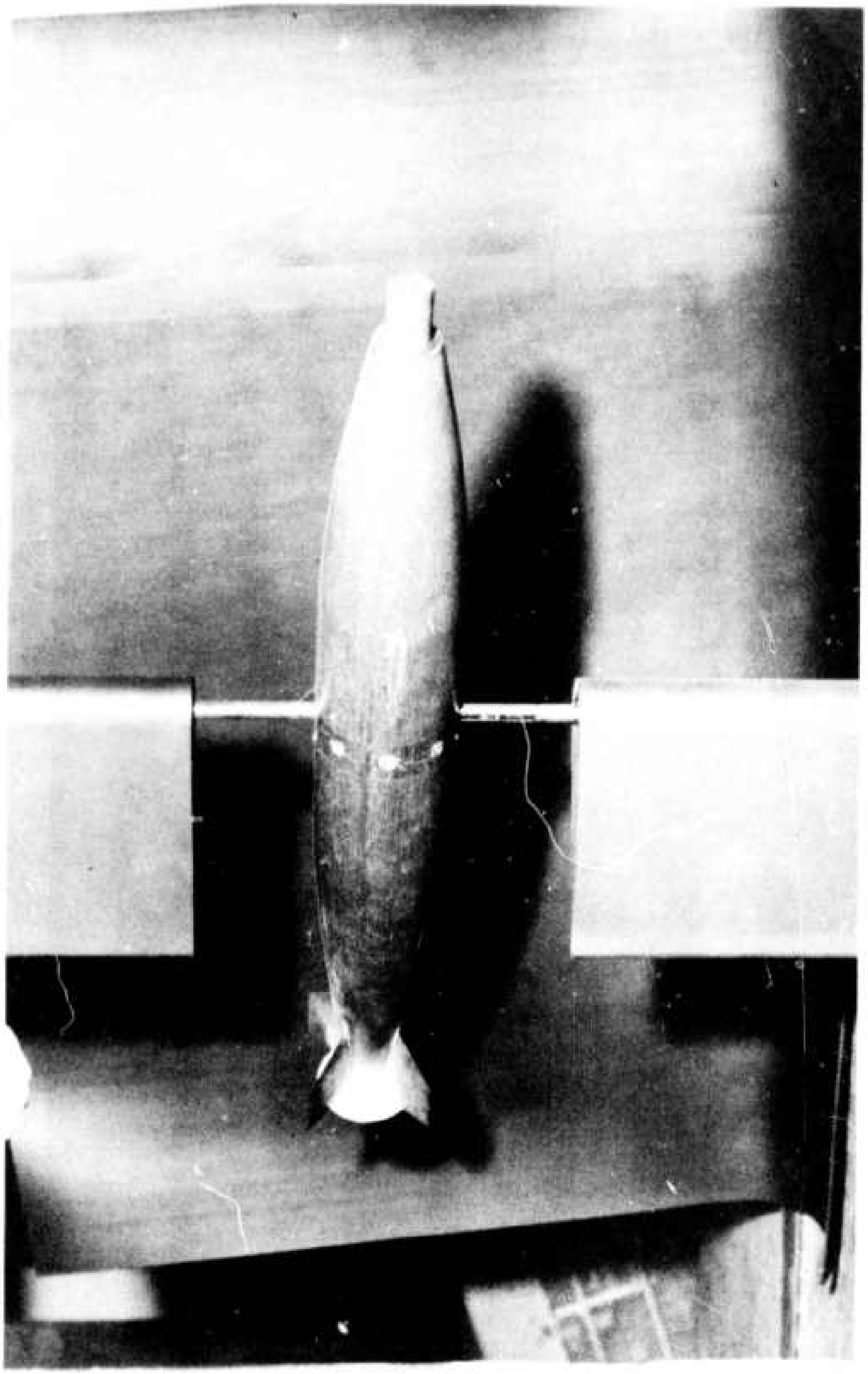

Figure 37. Wind Tunnel Tests of the MK82 Bomb

SECTION VII

WIND TUNNEL CALIBRATION

In an effort to achieve high quality wind flow through the test section, a flow straightening honeycomb and five damping screens (described in Section II) were installed in the settling chamber. A test section flow calibration was made to determine the final flow parameters for design and evaluation inputs of wind tunnel tests. Three calibration tests were made, including velocity indicator calibration, turbulence factor determination, and flow angle calibration.

1. VELOCITY INDICATOR CALIBRATION

Because the velocity indicator on the control panel (described in Section III) is used in recording velocity data during a test, a calibration test compared the velocity indicator display to the test section centerline velocity. The test section centerline velocity was measured using a pitot-static tube (manufactured by Aerolab Supply Company) mounted on the sting sector support (Figures 38 and 39). The centerline velocity was determined using the following equation:

$$V = \sqrt{\frac{2q}{\rho}}$$

Where

V is the velocity

q is the dynamics pressure

ρ is the standard air density

The dynamic pressure was measured using the scanning value and pressure transducer. A data acquisition program was used to record the velocity indicator display and to calculate the test section centerline velocity. The velocities, as well as the calculated difference and the percent difference, were tabulated.

The calibration resulted in adjusting the velocity indicator so that the display velocity, compared to the centerline velocity, was within 1 percent from 100 to 200 feet per second and within 2 percent from 50 to 100 feet per second. For specific tests, the velocity indicator can be adjusted to within 0.5 percent of the centerline for small velocity intervals. Also, it was noted that the wind tunnel maximum velocity was decreased by approximately 20 feet per second due to the addition of the honeycomb and damping screens.

2. TURBULENCE FACTOR DETERMINATION

Due to turbulence, wind tunnels characteristically have higher Reynolds numbers than does free air. The turbulence factor (TF) of a wind tunnel must be determined in order to compare the data from the tunnel to free-flight test data and to test data from other wind tunnels. The turbulence factor can be expressed as the ratio of the critical Reynolds numbers of a sphere in a wind tunnel to free air. A detailed presentation of turbulence factor principles is included in Appendix A. For wind tunnels, turbulence factors are greater than 1 and should be less than 1.4 to be considered adequate for testing (Reference 6).

Pressure spheres were used to determine the turbulence factor of the AFATL Wind Tunnel. A pressure sphere has an orifice at the front stagnation point and four interconnected and equally spaced orifices at the rear. The pressure difference, ΔP, between the front and rear orifices was measured using a scanning valve and pressure transducer. The pressure difference is non-dimensionalized by dividing by the dynamic pressure, q, to form a pressure coefficient, $\Delta P/q$. A pressure coefficient of 1.22 corresponds to the critical Reynolds number of a sphere.

The two pressure spheres were 5.0 inches and 8.58 inches in diameter (Figures 40 to 43). The pressure sphere diameter determined the velocity at which the critical Reynolds number will occur; therefore, the turbulence factor can be determined at different wind tunnel testing velocities. The spheres were mounted on the sting sector support.

A data acquisition program recorded pressure differences and velocity, calculated $\Delta P/q$ and Reynolds number, and tabulated the results. The data are presented in Figures 44 and 45. The test data indicated a turbulence factor of approximately 1.03 at 150 feet per second and 1.06 at 85 feet per second.

3. FLOW ANGLE CALIBRATION

The flow angle calibration was made using a yaw head that was 2.25 inches in diameter (Figure 46). The yaw head has four forward orifices which are positioned in pairs in perpendicular horizontal and vertical planes. A pressure difference between the horizontal orifices determines the flow yaw angle, and the pressure difference between the vertical orificies determines the flow pitch angle. The pressures were measured with the scanning valve and pressure transducer. A data acquisition program recorded the pressure differences, calculated the flow angle using potential flow principles (Appendix B), and tabulated the results. The yaw head was mounted on the pitch sector support.

The data given in Figures 47 and 48 were taken with several angle determinations at the same velocity. The sign convention used to describe the pitch and yaw flow angles is the same for a positive angle of attack and positive sideslip angle. The pitch flow angle data depicts the pitch flow angle to have a consistent spread and a mean that decreases as velocity increases. The yaw flow angle data indicate that the yaw angle spread decreases with the mean tending toward zero as the velocity increases.

Reference:

6. Pope, Alan; Harper, John J.: Low Speed Wind Tunnel Testing. J. Wiley & Sons, Inc., New York., 1966.

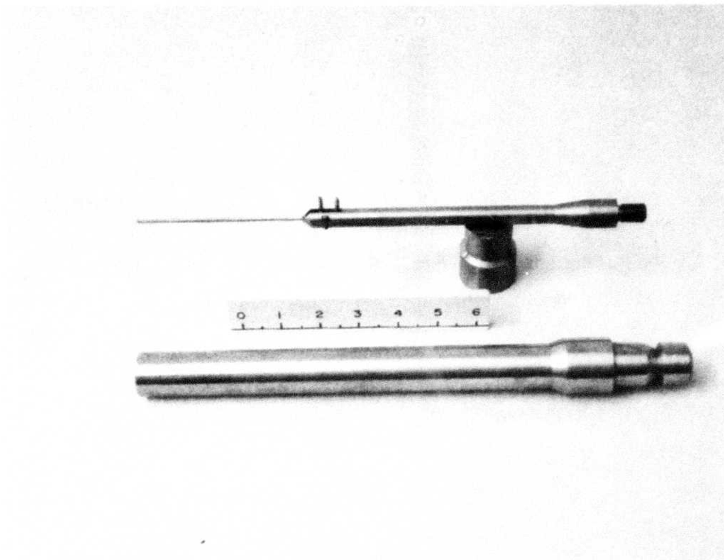

Figure 38. Pitot Static Tube

Figure 39. Pitot Static Tube Installation

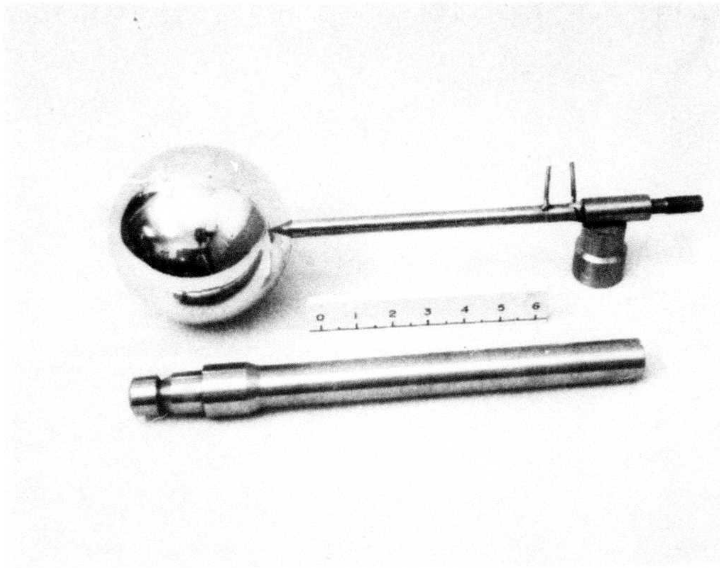

Figure 40. 5-Inch Pressure Sphere

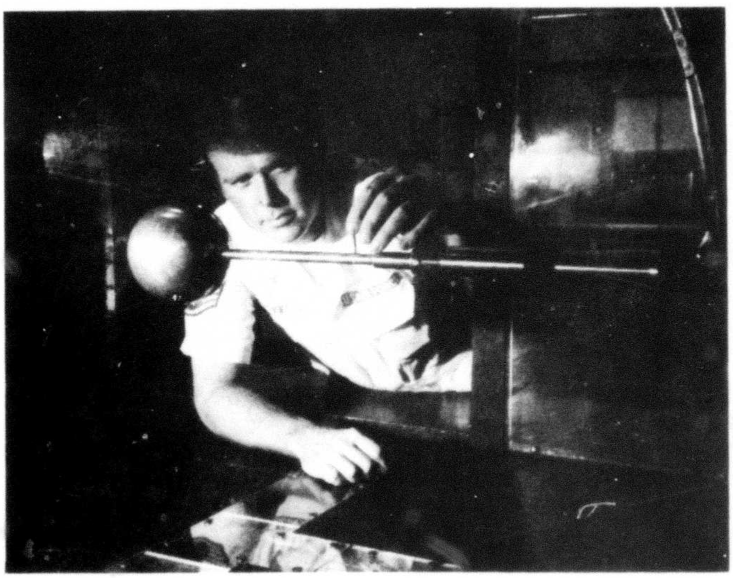

Figure 41. 5-Inch Pressure Sphere Installation

Figure 42. 8.58-Inch Pressure Sphere

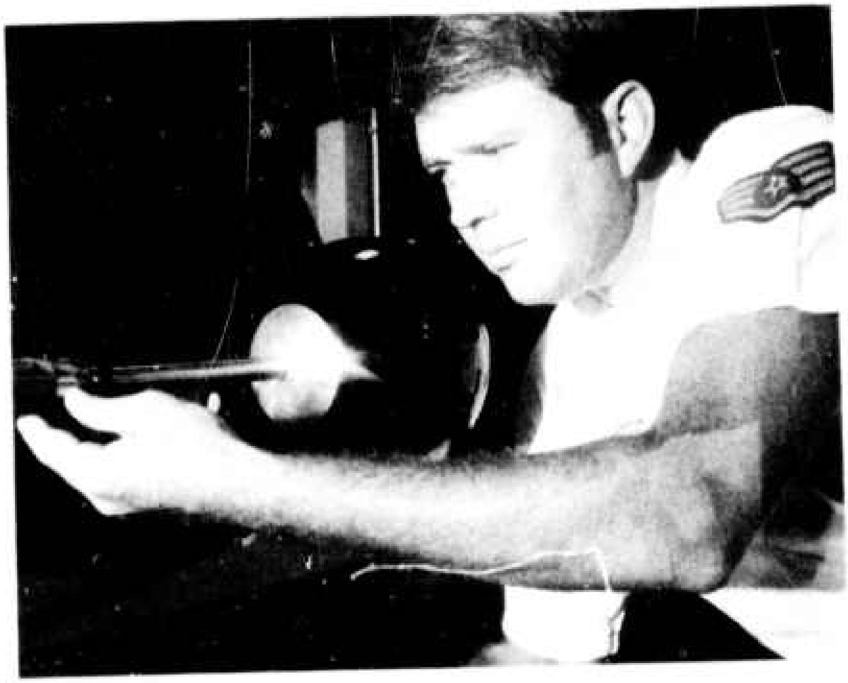

Figure 43. 8.58-Inch Pressure Sphere Installation

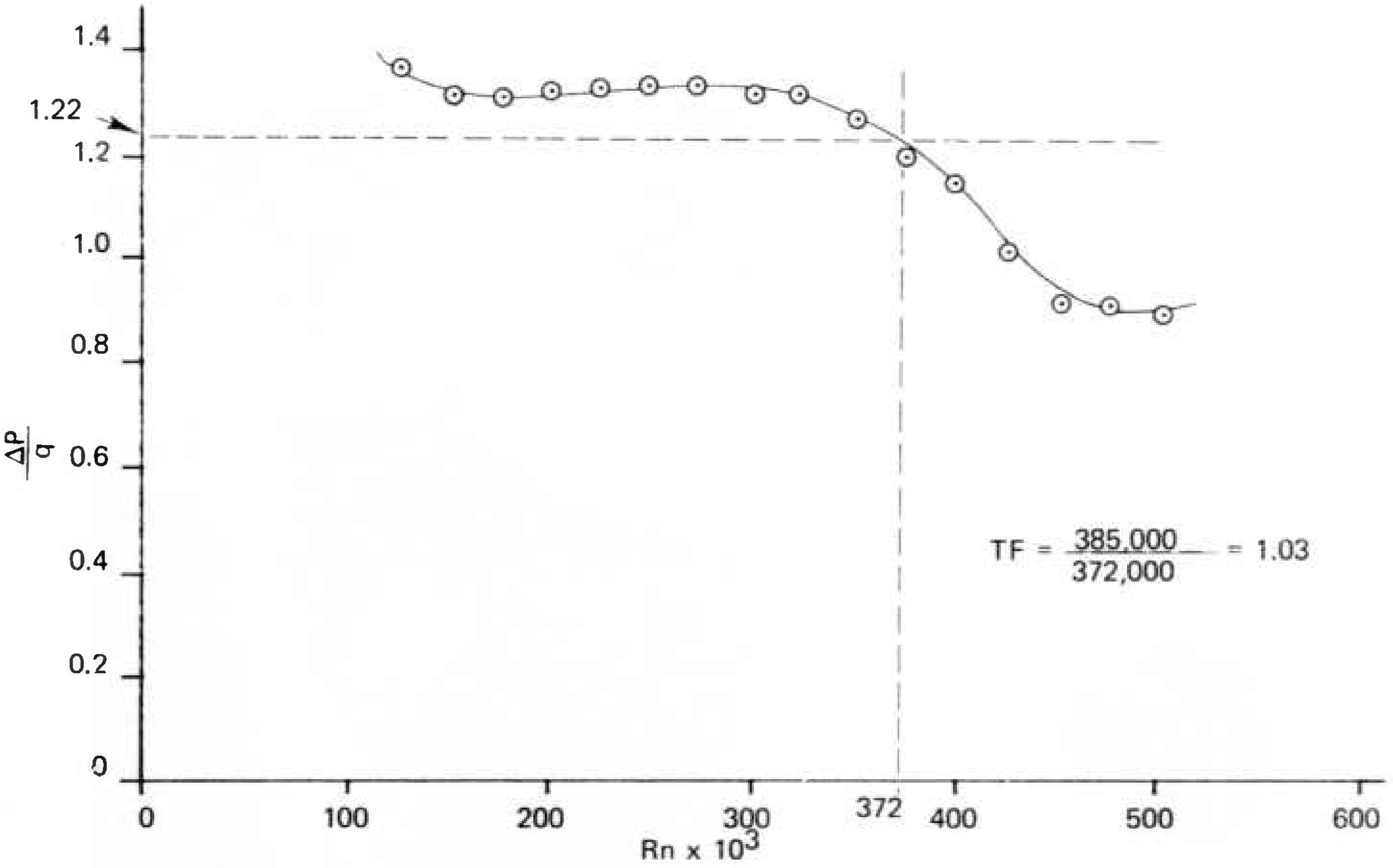

Figure 44. Variation of Pressure Coefficient with Reynolds Number (5.0 Inch Pressure Sphere)

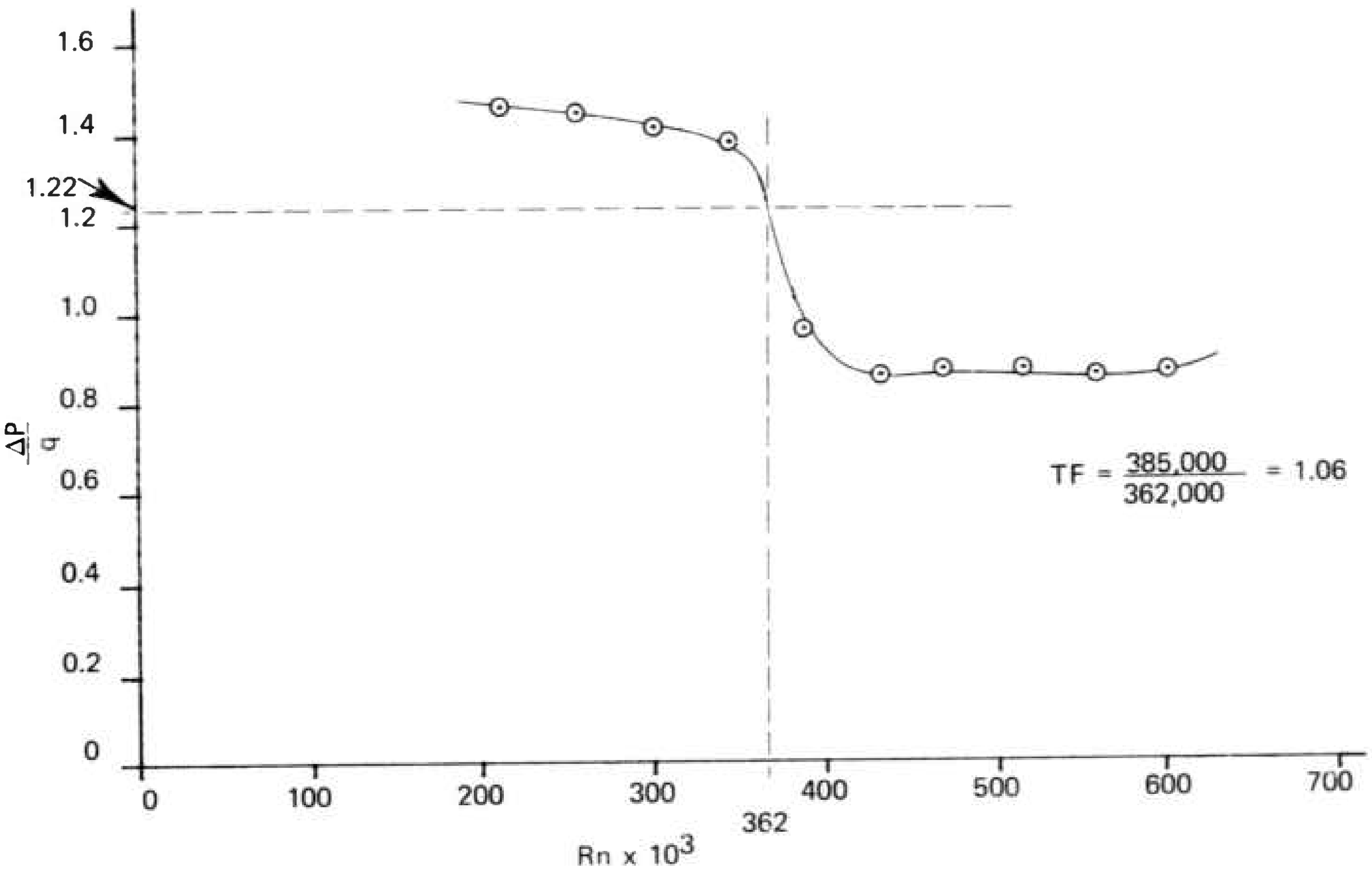

Figure 45. Variation of Pressure Coefficient with Reynolds Number (8.58 Inch Pressure Sphere)

Figure 46. Yaw Head

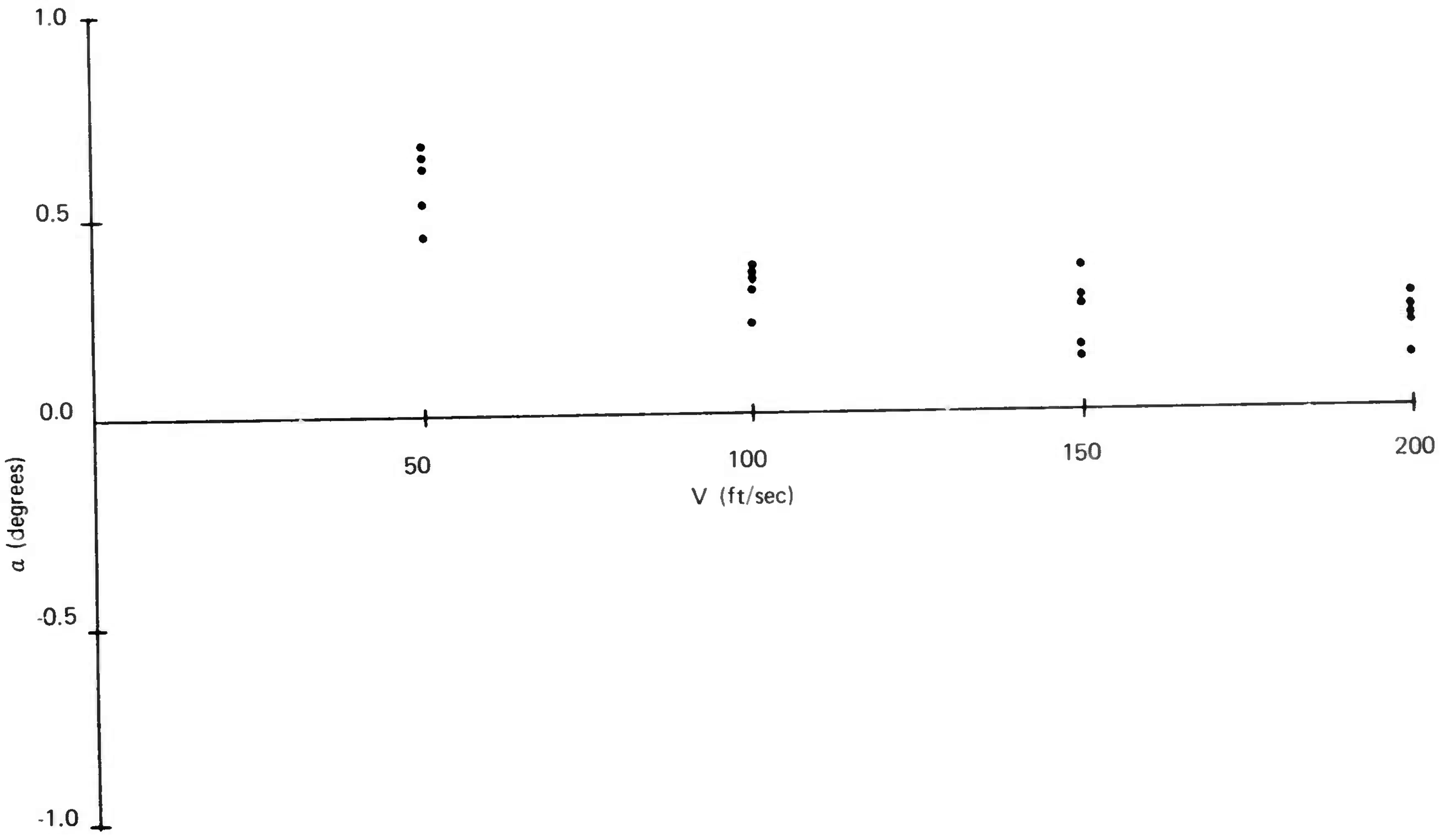

Figure 47. Variation of Test Section Flow Pitch Angle with Test Section Velocity

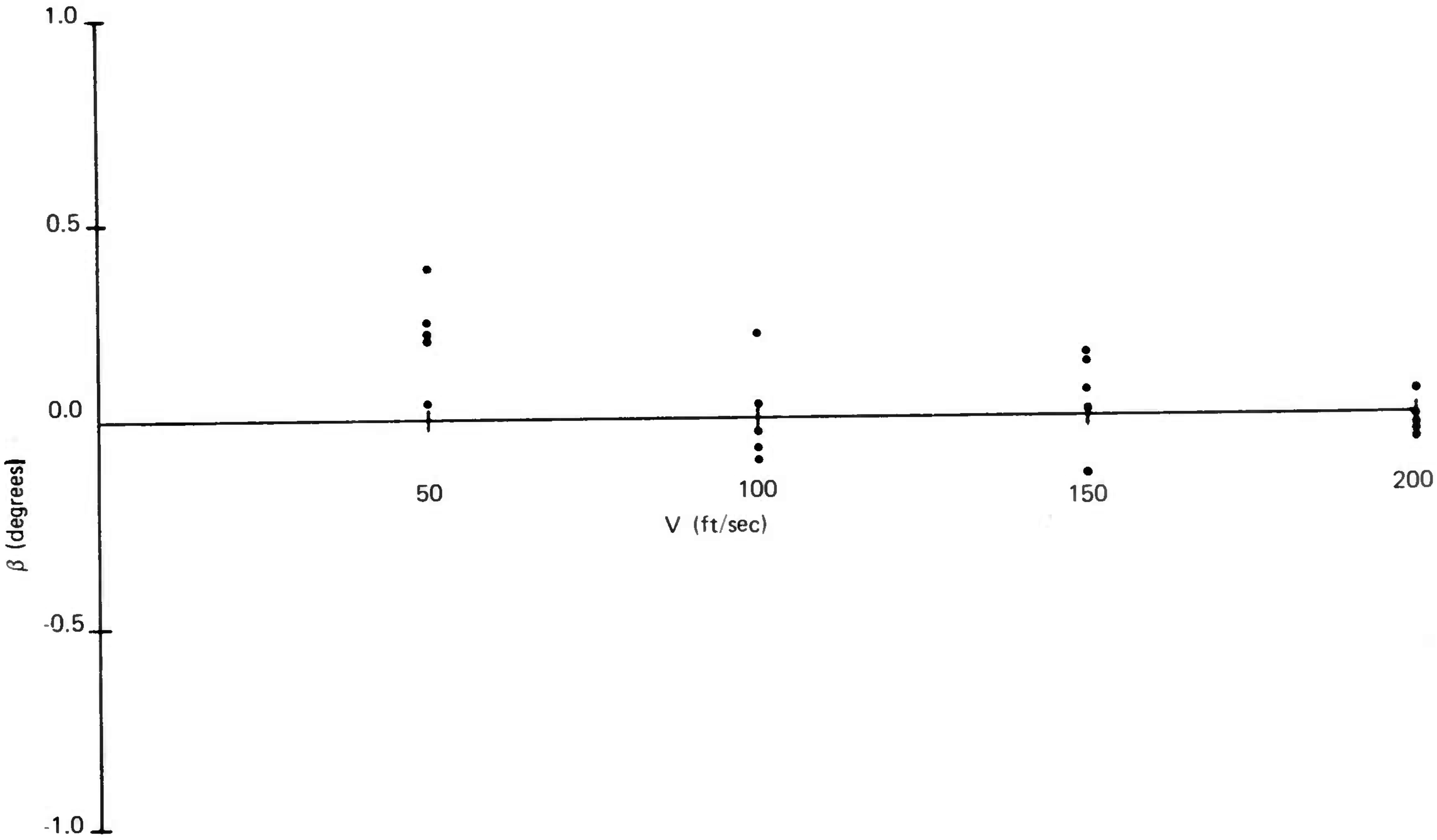

Figure 48. Variation of Test Section Flow Yaw Angle with Test Section Velocity

SECTION VIII

VERTICAL AIRJET

The AFATL Wind Tunnel Facility has a vertical air jet test system that was designed and fabricated at the AFATL BARS Facility (Reference 7) to test spherical bomblet performance. The air jet (Figure 49) is used to suspend test munitions in a jet of air such that gravity forces are balanced by aerodynamic forces. When so suspended, the characteristics of test munitions can be examined under free flight conditions.

The vertical airjet system consists of an air compressor and storage tank, a regulator, valve system, a three-port discharge nozzle, and a transparent plastic cylindrical test section. The system air compressor and storage tank (Figure 50) has a 150-pound per square inch capacity. The vertical air jet is capable of continuous operation at a velocity range of 200 to 400 feet per second. The system regulator, valve system, discharge nozzle, and transparent plastic cylindrical test section are contained in the air jet console (Figure 49). The air jet console is supplied with air from the compressor and storage tank through a flexible rubber hose.

Reference:
7. Mayer, P. C.: Ballistic/Aerodynamics Research System (BARS) Facility. AFATL-TR-74-26, Air Force Armament Laboratory, January 1974.

Figure 49. Vertical Air Jet

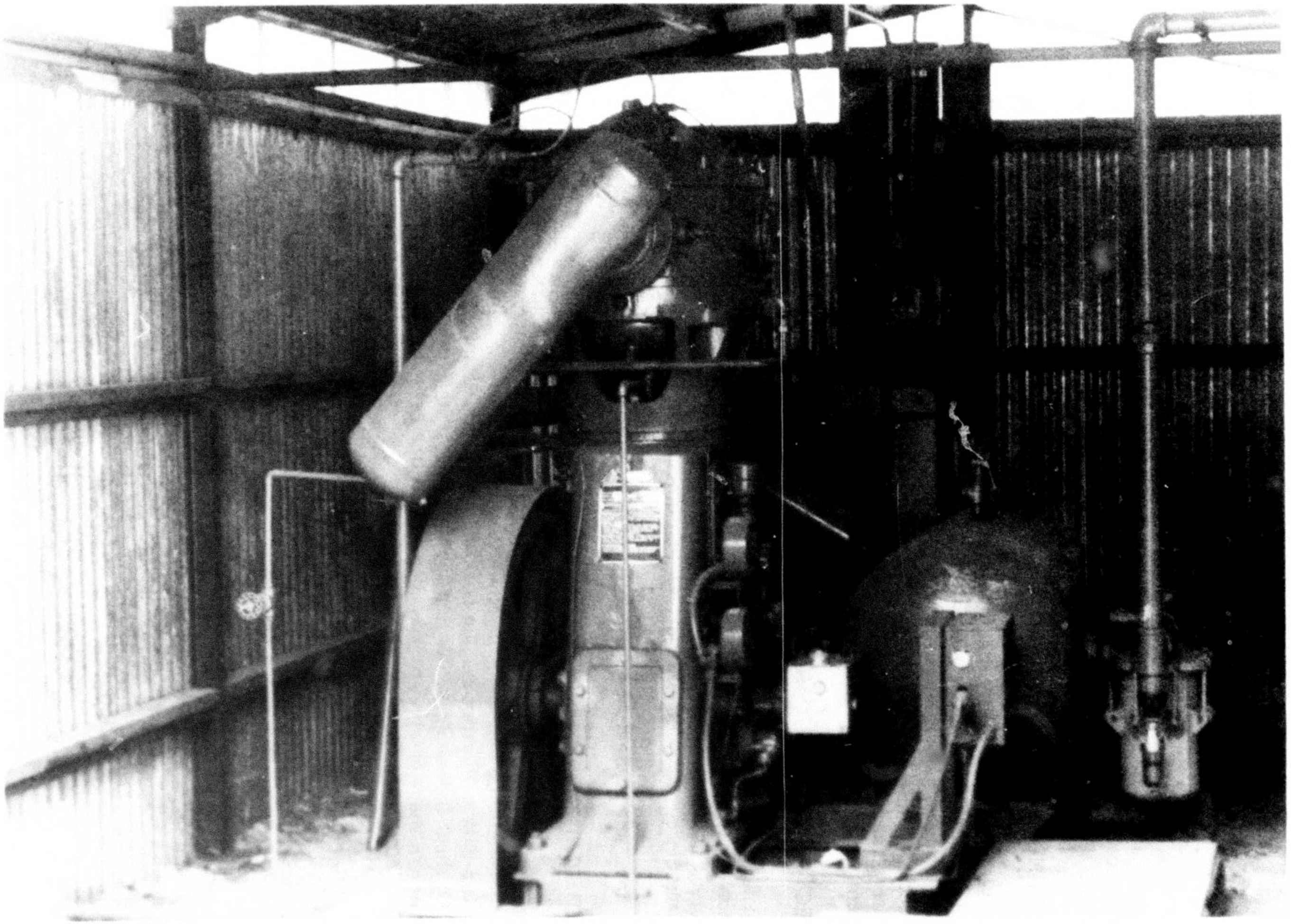

Figure 50. Vertical Air Jet System Air Compressor and Storage Tank

SECTION IX

PROJECT SUPPORT

The AFATL Wind Tunnel Facility has several project support capabilities other than the wind tunnel and the associated data acquisition system. These capabilities fall under the heading of preparation of articles for testing and creation of specialized equipment and instrumentation to facilitate data generation and collection.

1. MACHINE SHOP

The Wind Tunnel Facility maintains a machine shop equipped to provide model fabrication on a quick-reaction time basis. The stock of materials kept on hand, includes aluminum, brass, and stainless steel in sizes necessary for adequate flexibility. In addition, the shop has specialized hardware and equipment unique to wind tunnel model fabrication. A full time machinist is assigned to the facility to handle fabrication and modification of test articles, equipment, and fixtures (Figure 51).

2. ELECTRONICS WORKSHOP

The facility maintains a small electronics repair and fabrication workshop to provide maximum flexibility in test monitoring equipment and model instrumentation. An extensive bench stock of electronic parts and a complete array of test equipment allow the creation of specialized devices without long delays. Instrumentation technicians are assigned to the Wind Tunnel Facility, and electronics engineers are available for coordination, design, construction, and repair of any equipment required to conduct a successful test program.

3. PHOTOGRAPHY

The facility maintains a limited capability for in-house photographic data collection and test documentation. The available equipment includes a 4 by 5 inch Speed Graphic (C-3) still camera with a 16-exposure film pack adapter, a 4 by 5 inch Polaroid back, and a six-shot automatic sheet film changer. Motion picture equipment consists of a Millican DB-5M high speed camera that operates at either 128 or 400 frames per second. The cameras are shown in Figure 52.

The motion picture camera can be equipped with either a 20 to 60mm zoom lens or a fixed focal length 25mm lens, both of which are on hand. Also available is a Polaroid oscilloscope camera, with adapters so it can be used on the Data Acquisition dual-channel monitoring oscilloscope.

The wind tunnel test section has transparent plastic sides and an 8-inch wide transparent window along the top centerline. Photo equipment may be mounted on both sides of the tunnel and on top to provide orthagonal coverage of models mounted in the test section.

All film processing support is provided by the Eglin AFB Photographic Laboratory. Additional photographic support can be scheduled through the Photographic Laboratory or Photo-Physics Laboratory.

Figure 51. Typical Machine Shop Work

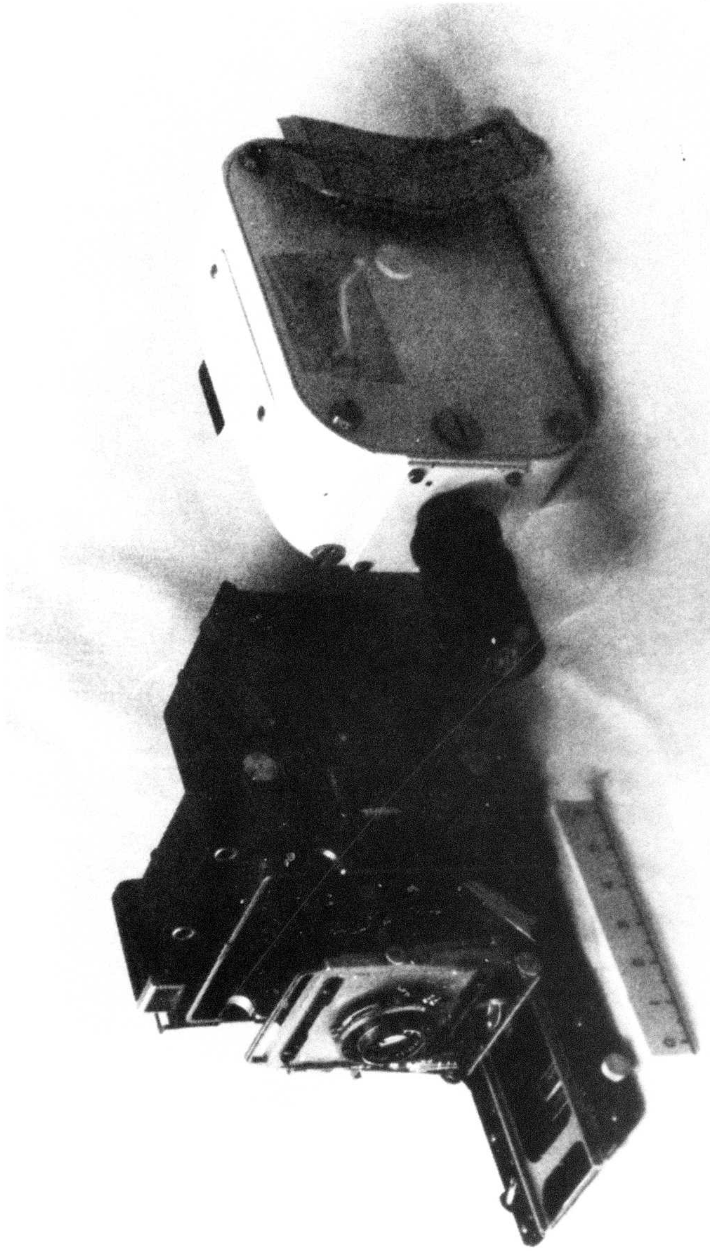

Figure 52. Speed Graphic (C-3) and Milican DB-5M Cameras

4. PROJECT COORDINATION

It is essential that the project engineer maintain a close liaison with wind tunnel facility personnel from the inception of each program. Program scheduling should be carefully coordinated by users in order to take full advantage of the facility capabilities. In many cases, a properly designed and scheduled test can significantly reduce the time spent changing model configurations and equipment arrangement and thereby increase the amount of useful data collected during the alloted time.

While engineering drawings of required models and fixtures are always desirable, facility personnel can work from less formal plans if necessary, but only if there is close coordination with the program originators. A failure to consider materials, special tooling, unique fabrication procedures, and hardware requirements during model and test design will introduce program delays.

SECTION X

FUTURE IMPROVEMENTS

Although the AFATL Wind Tunnel Facility is presently versatile enough to handle many testing requirements, the capabilities are somewhat limited in two areas: maximum operating speed and data output formats available. Corrections for these limitations are under development.

The maximum operating speed in the wind tunnel is approximately 200 feet per second. Removable test section inserts of reduced area, now being designed, will increase the wind tunnel velocity to approximately 500 feet per second. The smaller cross-sectional area will reduce maximum model size, but the trade-off will prove favorable in many cases.

Planned additions to the data acquisition system include expanded computer core memory, a magnetic disc unit for operating system program storage, and remote sensors for barometric pressure and ambient temperature.

APPENDIX A

TURBULENCE FACTOR

Turbulence produced by the wind tunnel fan, guide vanes, and vibration of the walls causes the wind tunnel flow to behave similar to free air but at a higher Reynolds number. A turbulence factor, TF, can be defined as the factor by which the true Reynolds number, Rn_t, is increased to an effective Reynolds number, Rn_e, and it can be written as

$$Rn_e = TF \times Rn_t \tag{A-1}$$

The turbulence factor can be determined by a turbulence (drag) sphere. The drag coefficient of a sphere is a function of velocity and decreases abruptly when the flow over the sphere transitions from laminar to turbulent. The Reynolds number at which the transition takes place is related to the turbulence already present in the flow; therefore, the drag coefficient of a sphere can be used to measure turbulence. The drag, D, of a sphere is measured at various wind tunnel speeds and a drag coefficient can be written as

$$C_D = \frac{D}{(\rho/2)\,\pi\,(d^2/4)\,V^2} \tag{A-2}$$

Where:

d is the sphere diameter

V is the velocity

ρ is the air density

The sphere drag coefficient is plotted against the true Reynolds number. The Reynolds number at which the drag coefficient is equal to 0.3 is referenced as the critical Reynolds number, Rn_c. The critical Reynolds number that occurs in free air for a sphere is 385,000, and the turbulence factor can be written as

$$TF = 385{,}000/Rn_c \tag{A-3}$$

An alternate method of determining the turbulence factor in a wind tunnel uses a pressure sphere. The pressure sphere has an orifice at the front stagnation point and four interconnected and equally spaced orifices at the rear. The rear orifices are located 22.5 degrees from the theoretical rear stagnation point. The pressure difference, ΔP, is measured and divided by the dynamic pressure, q, to form a non-dimensional pressure coefficient, $\Delta P/q$. A pressure coefficient of 1.22 has been directly related to a sphere drag coefficient of 0.3. As a result, the Reynolds number at which the pressure coefficient is equal to 1.22 is referenced as the critical Reynolds number. The turbulence factor can now be determined as in the case of the turbulence sphere.

APPENDIX B

TEST SECTION FLOW ANGULARITY

Flow direction in a wind tunnel test section can be determined by using a yaw head, which is a sphere having two pairs of orifices in perpendicular planes. The orifices in the same plane are 90^o apart. When the orifices are aligned in the wind tunnel horizontal and vertical planes, the flow, yaw angle, β, and pitch angle, α, can be determined.

The principles of the yaw head are based on potential flow theory and can be developed with four basic flow assumptions. The flow is assumed to be (1) three dimensional, (2) steady, (3) irrotational, and (4) incompressible. A sphere can be modeled as a doublet with the potential function

$$\Phi_d = \frac{-u \cos \theta}{4\pi r^2} \qquad \text{(B-1)}$$

Where:

r and θ are polar coordinates of a point from the origin, and u is a constant to be determined (Figure B-1).

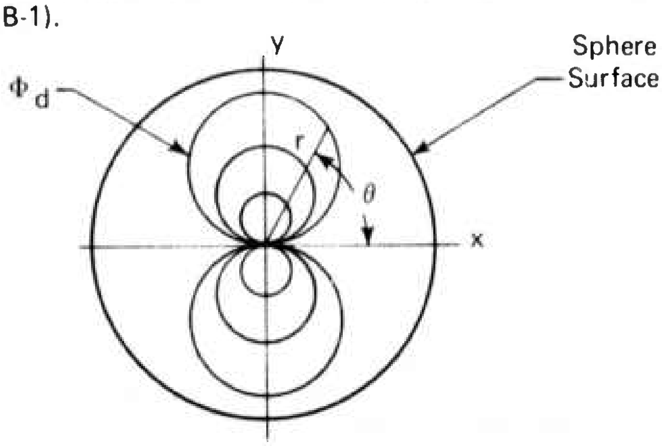

Figure B-1. Doublet Representation

Uniform flow can be represented with velocity potential

$$\Phi_u = V_\infty x \qquad \text{(B-2)}$$

Where :

V_∞ is the free stream velocity

x is the displacement in the positive x direction.

Uniform flow can be depicted as shown in Figure B-2.

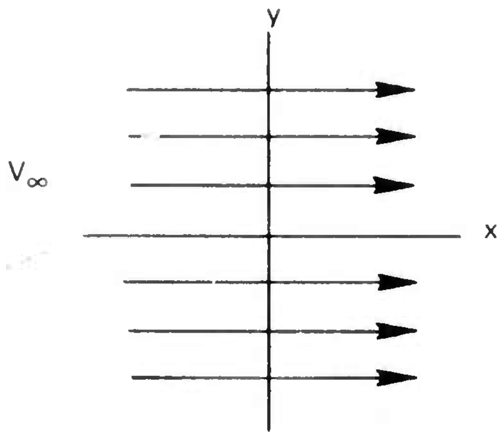

Figure B-2. Uniform Flow

Therefore, a sphere in a uniform flow can be modeled as the superposition of a doublet and uniform flow and can be represented with the potential function

$$\Phi = V_\infty x - \frac{u \cos \theta}{4\pi r^2} \tag{B-3}$$

After substituting $x = r \cos \theta$, the potential function becomes

$$\Phi = (V_\infty r - \frac{u}{4\pi r^2}) \cos \theta \tag{B-4}$$

The boundary conditions for a sphere of radius a are

$$V_r (a, \theta) = 0 \tag{B-5}$$

$$\lim_{r \to \infty} \vec{V} = V_\infty \tag{B-6}$$

Taking the partial derivative of Equation (B-4) with respect to r and applying the first boundary condition

$$V_r = \frac{\partial \Phi}{\partial r} = \left(V_\infty + \frac{u}{2\pi r^3}\right) \cos \theta \tag{B-7}$$

which for r = a

$$V_r(a,\theta) = \left(V_\infty + \frac{u}{2\pi a^3} \right) \cos\theta = 0. \tag{B-8}$$

Solving for u gives

$$u = -2\pi a^3 V_\infty \tag{B-9}$$

Substituting u into Equation (B-4) results in

$$\Phi = V_\infty \left(r + \frac{a^3}{2r^2} \right) \cos\theta \tag{B-10}$$

The velocity field for flow over a sphere can thus be written

$$V_r = \frac{\partial \Phi}{\partial r} = V_\infty \left(1 - \frac{a^3}{r^3} \right) \cos\theta \tag{B-11}$$

$$V_\theta = \frac{1}{r} \frac{\partial \Phi}{\partial \theta} = -V_\infty \left(1 + \frac{a^3}{2r^3} \right) \sin\theta \tag{B-12}$$

At the surface of a sphere of radius a, the velocity components from Equations (B-11) and (B-12) become

$$V_r\,(a,\theta) = 0 \tag{B-13}$$

$$V_\theta\,(a,\theta) = -\frac{3}{2} V_\infty \sin\theta \tag{B-14}$$

Now, for a yaw head oriented with points P_1 and P_2 in a vertical plane and 90^o apart (Figure B-3), the Bernoulli Equation may be written as

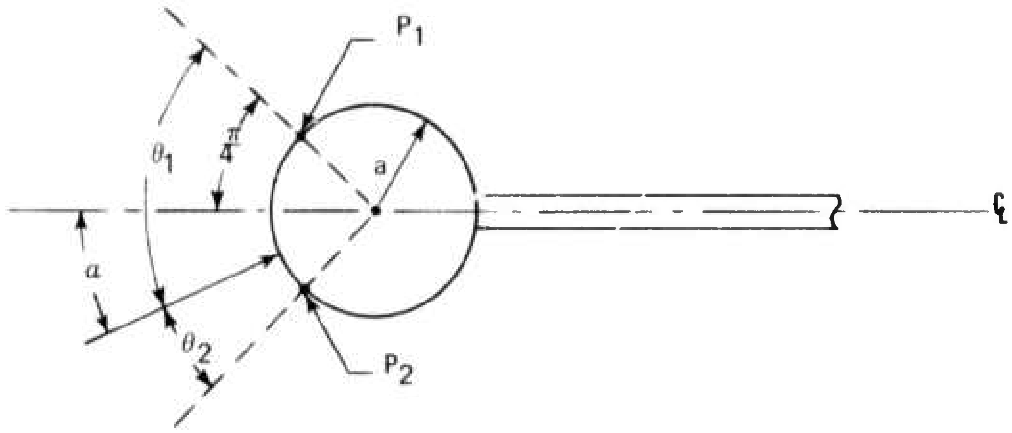

Figure B-3. Yaw Head Geometry

$$\frac{1}{2} \rho V_1^2 + P_1 = \frac{1}{2} \rho V_2^2 + P_2 \tag{B-15}$$

Making use of Equation (B-14) gives

$$\frac{9}{8} \rho V_\infty^2 \sin^2 \theta_1 + P_1 = \frac{9}{8} \rho V_\infty^2 \sin^2 \theta_2 + P_2 \tag{B-16}$$

After rearranging, Equation (B-16) becomes

$$\Delta P = P_2 - P_1 = \frac{9}{8} \rho V_\infty^2 (\sin^2 \theta_1 - \sin^2 \theta_2) \tag{B-17}$$

The pressure coefficient becomes

$$\frac{\Delta P}{q_\infty} = \frac{9}{4} (\sin^2 \theta_1 - \sin^2 \theta_2) \tag{B-18}$$

Substituting $\theta_1 = \frac{\pi}{4} + \alpha$

$$\theta_2 = \frac{\pi}{4} - \alpha$$

the pressure coefficient becomes

$$\frac{\Delta P}{q_\infty} = \frac{9}{4}\ [\sin^2 (\frac{\pi}{4} + \alpha) - \sin^2 (\frac{\pi}{4} - \alpha)] \tag{B-19}$$

Using standard trigonometric identities results in

$$\frac{\Delta P}{q_\infty} = \frac{9}{4}\ (2 \cos \alpha \sin \alpha) \tag{B-20}$$

or,

$$\frac{\Delta P}{q_\infty} = \frac{9}{4} \sin 2\alpha \tag{B-21}$$

Solving for α gives

$$\alpha = \frac{1}{2} \sin^{-1} (\frac{4}{9}\ \frac{\Delta P}{q_\infty}) \tag{B-22}$$

Using the small angle approximation results in

$$\alpha = \frac{2}{9}\ \frac{\Delta P}{q_\infty} \tag{B-23}$$

A similar development can be used to show

$$\beta = \frac{2}{9}\ \frac{\Delta P}{q_\infty} \tag{B-24}$$

Where

ΔP is the pressure difference in the yaw plane.

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