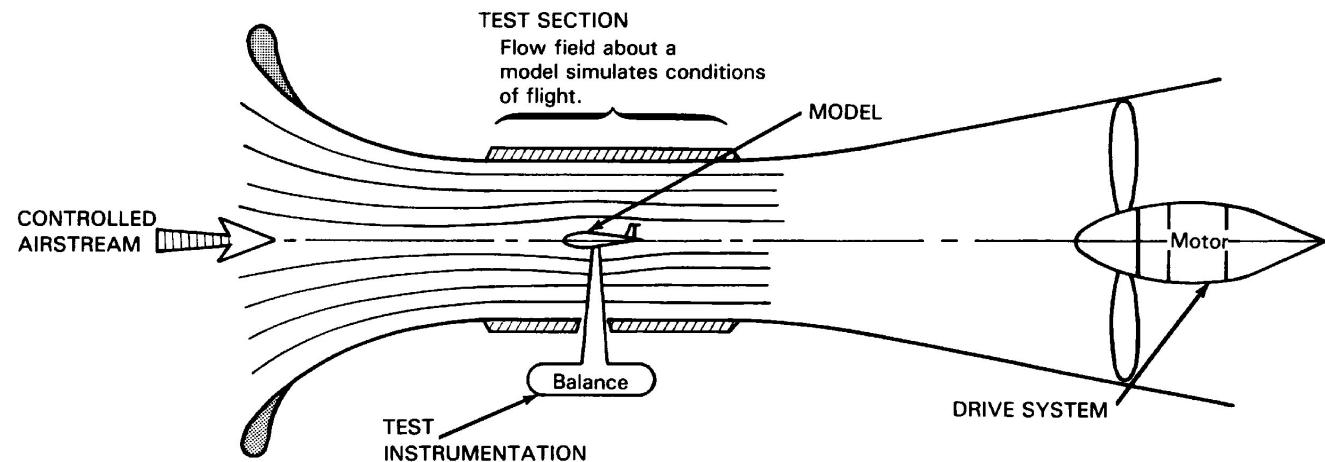


# Wind Tunnels

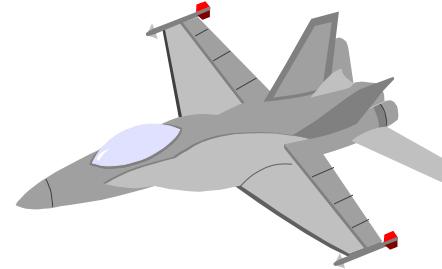
- Objective

- Accurately simulate the fluid flow about atmospheric vehicles 准确模拟飞行器周边流场
- Measure -Forces, moments, pressure, shear stress, heat transfer, flowfield (velocity, pressure, vorticity, temperature) 测量力、力矩、压强、热、流场等



Low Speed Vehicles - M<.3

$$U_{\infty}$$



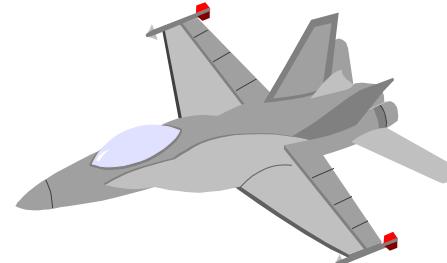
Gallilean Transformation

大气内飞行 Flight in atmosphere  
尺度 Scale = L

风洞 Wind Tunnel – 尺度 Model Scale =  $\ell$

Stationary Walls

$$U_{\infty}$$



### Issues 问题

Flow Quality - Uniformity and  
Turbulence Level  
Wind Tunnel Wall Interference  
Reynolds Number Simulation

$$Re = \frac{\rho U_{\infty} L}{\mu} \neq \frac{\rho U_{\infty} \ell}{\mu}$$

## Reynolds Number Scaling

- Most important on vehicles with partial laminar flow. The transition is very sensitive to Reynolds Number
- Use “trip strips” or roughness to cause boundary layer transition on the model at the same location as on the full scale vehicle

## Transonic Regime .7<M<1.2

- Must Match Reynolds Number and Mach Number

$$Re = \frac{\rho U_\infty L}{\mu}$$

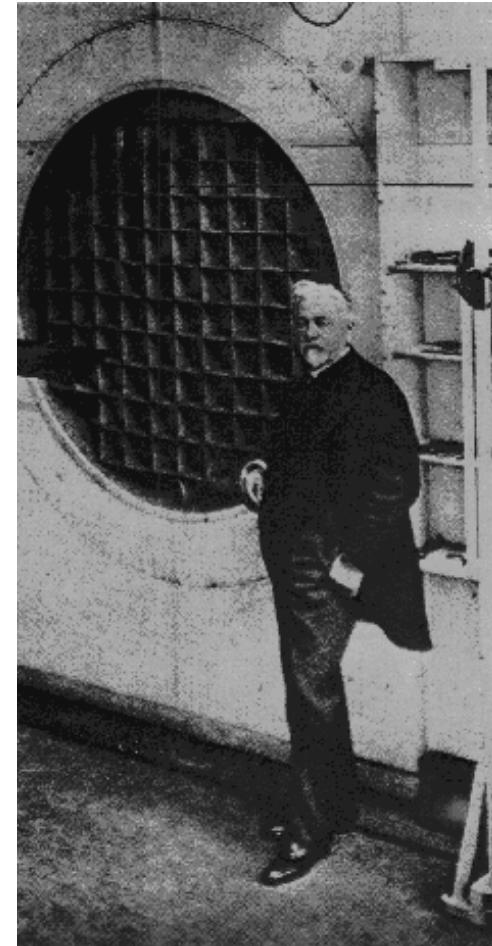
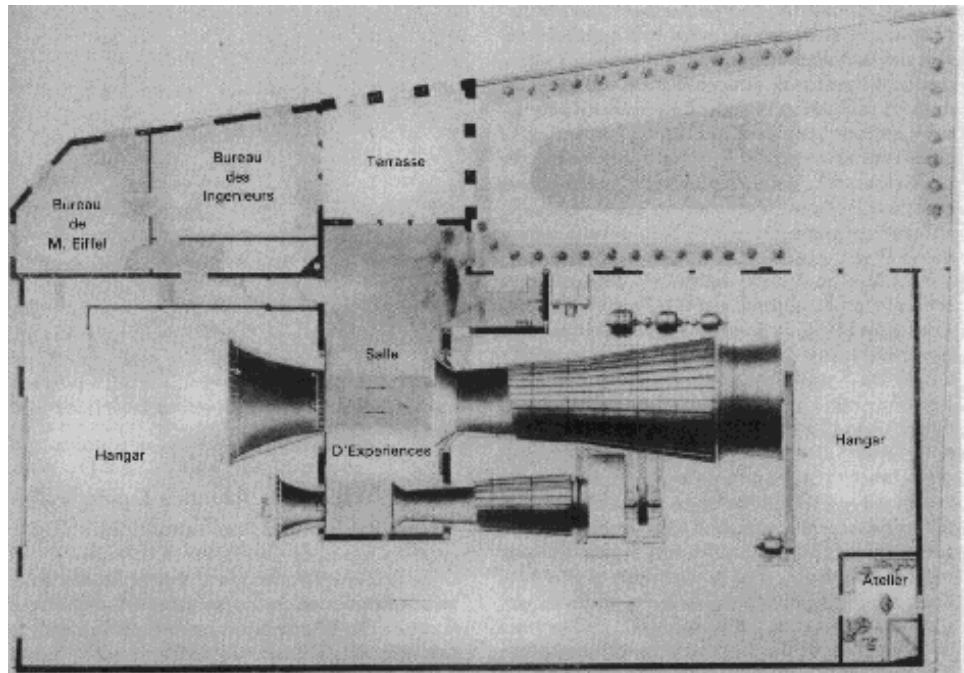
$$M = \frac{U_\infty}{c}$$

Must change fluid density and viscosity to match Re and M  
Cryogenic Wind Tunnels are designed for this reason

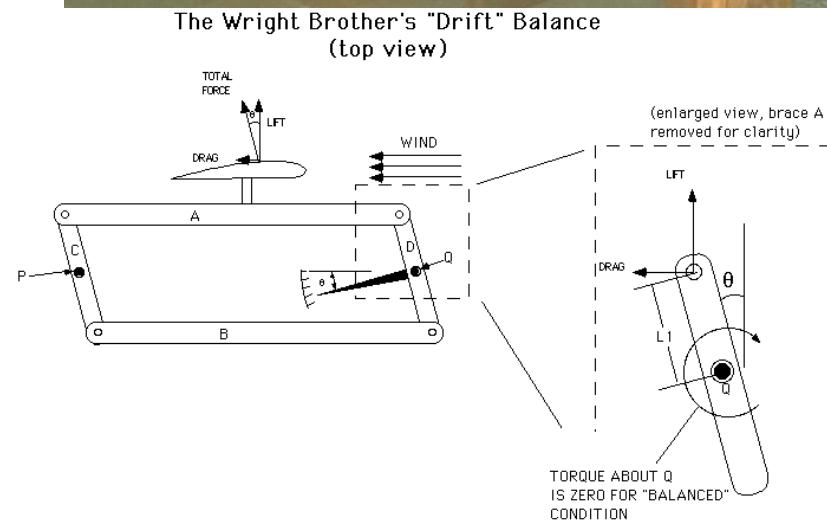
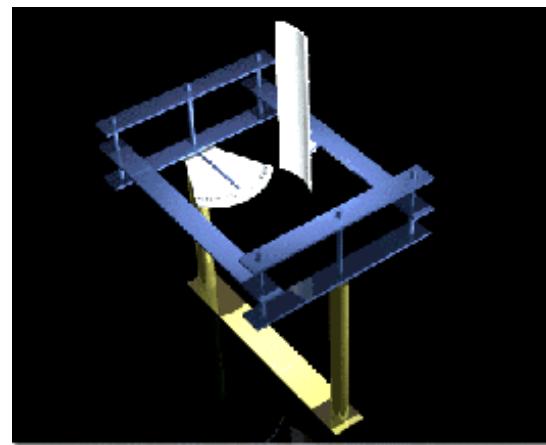
# History Whirling Arm



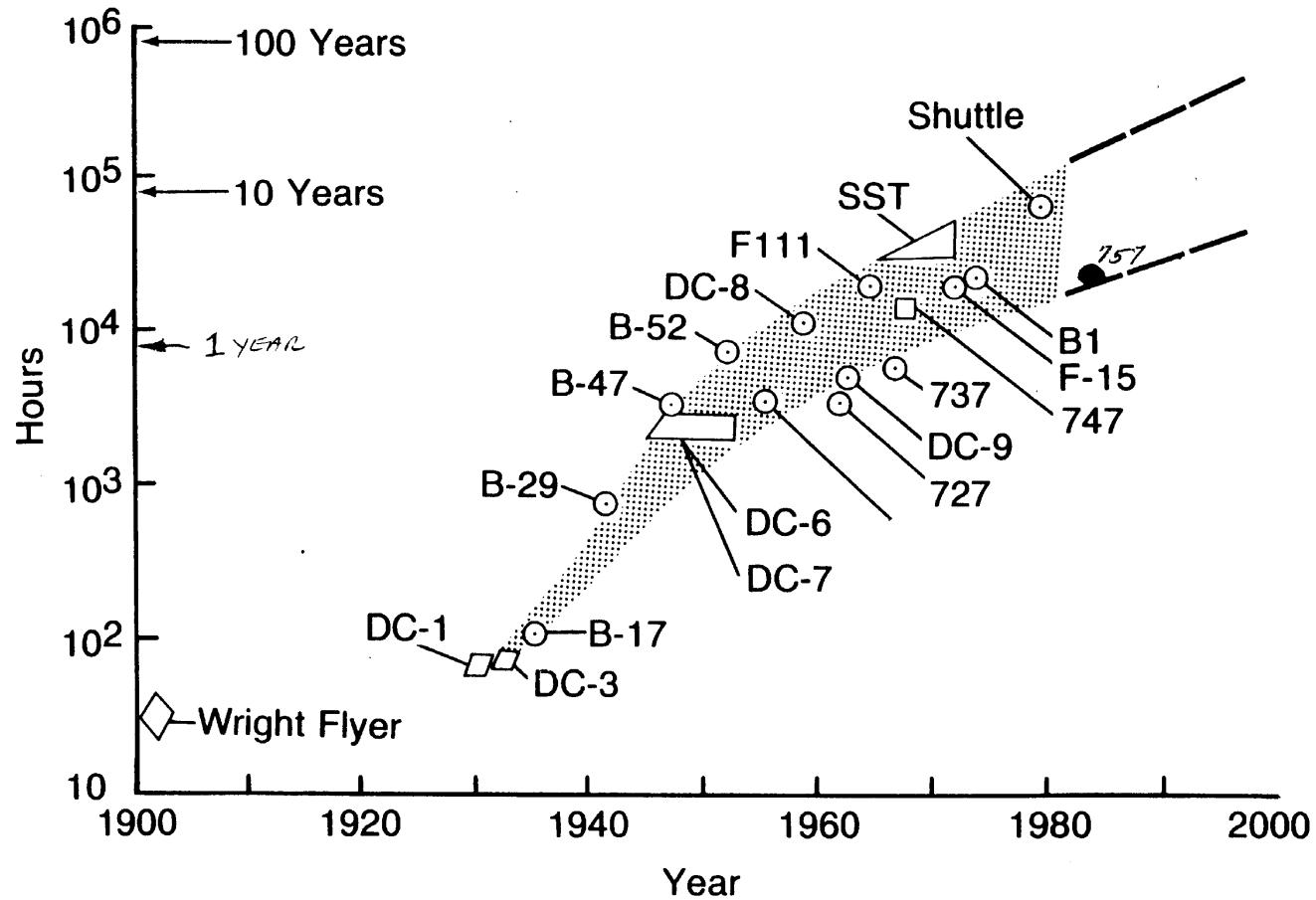
# Eiffel Tunnel



# Wright Brothers



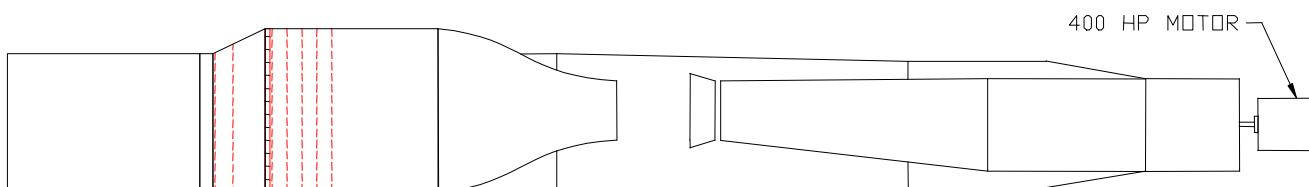
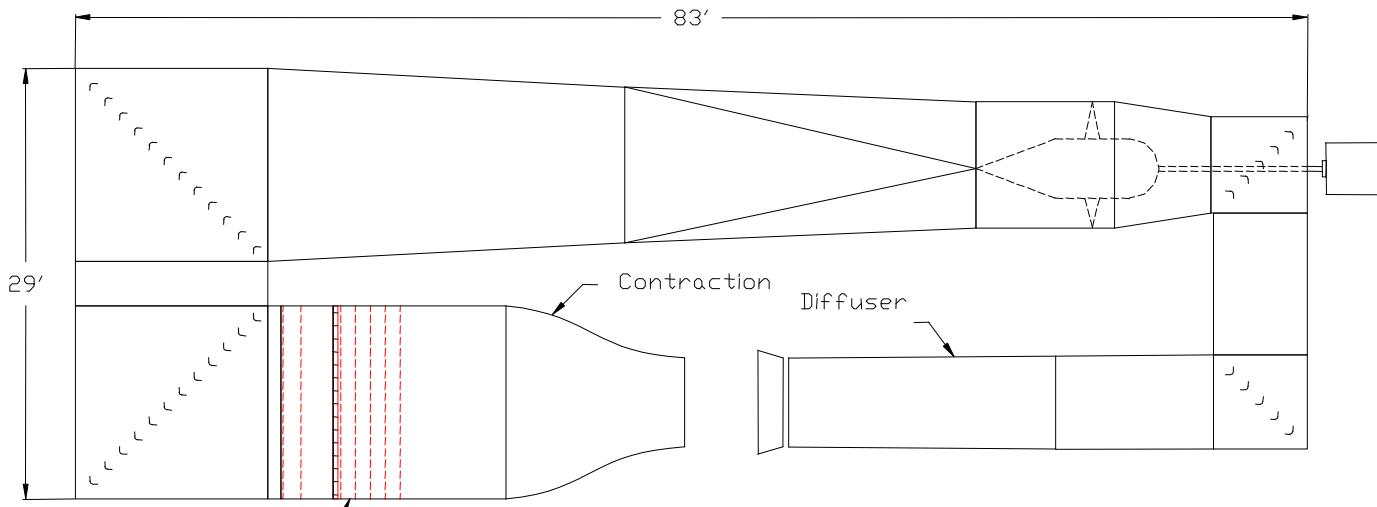
# Wind Tunnel Test Trend



# Wind Tunnel Layout

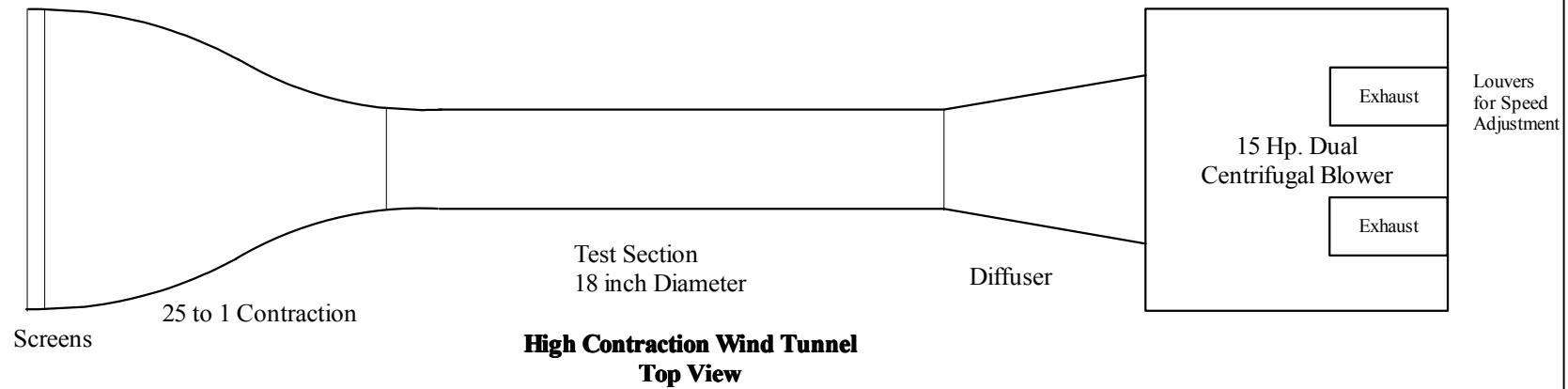
- Closed Return
- Open Return
- Double Return
- Annular Return

# Closed Return (open test section)

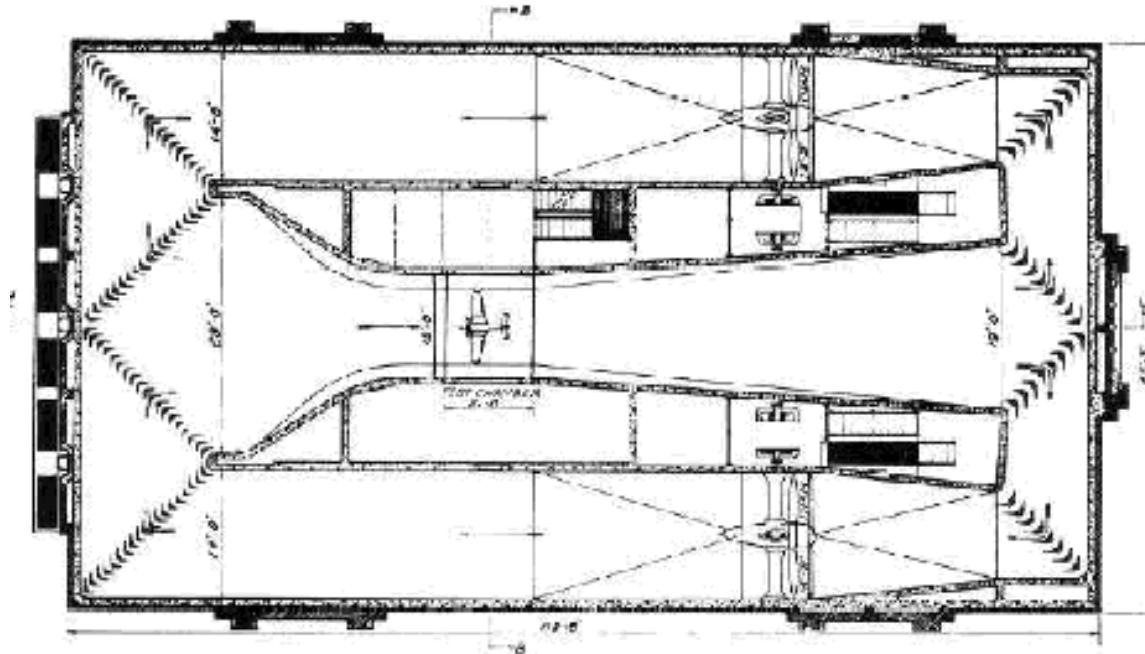


BOEING SUBSONIC WIND TUNNEL

# Open Return Closed Test Section

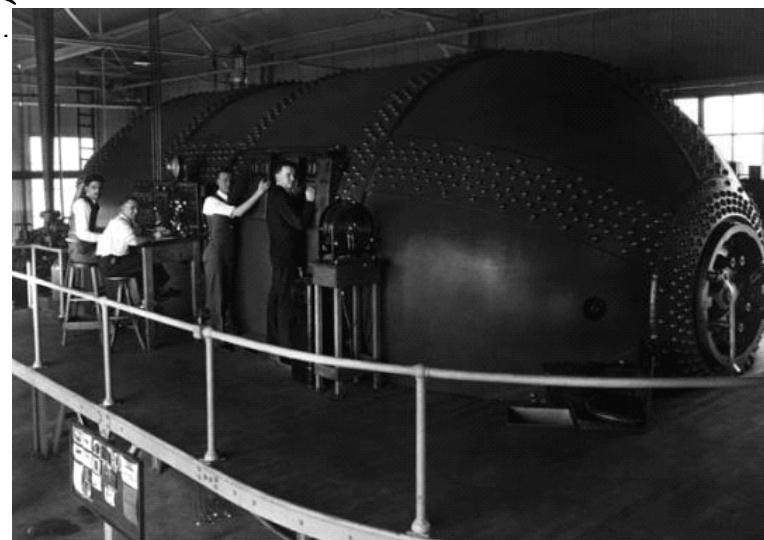
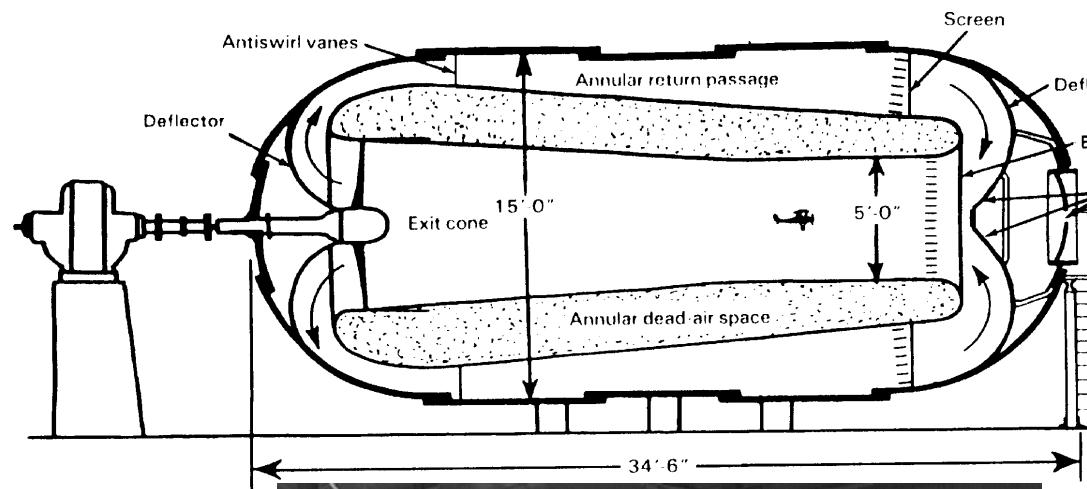


# Double Return



UNIVERSITY OF WASHINGTON  
AERONAUTICAL LABORATORY  
Kirsten Wind Tunnel

WIND TUNNELS OF NASA



Variable Density Tunnel, Being Used by NASA Staff  
NASA Langley Research Center

3/15/1929

Image # EL-1996-00143

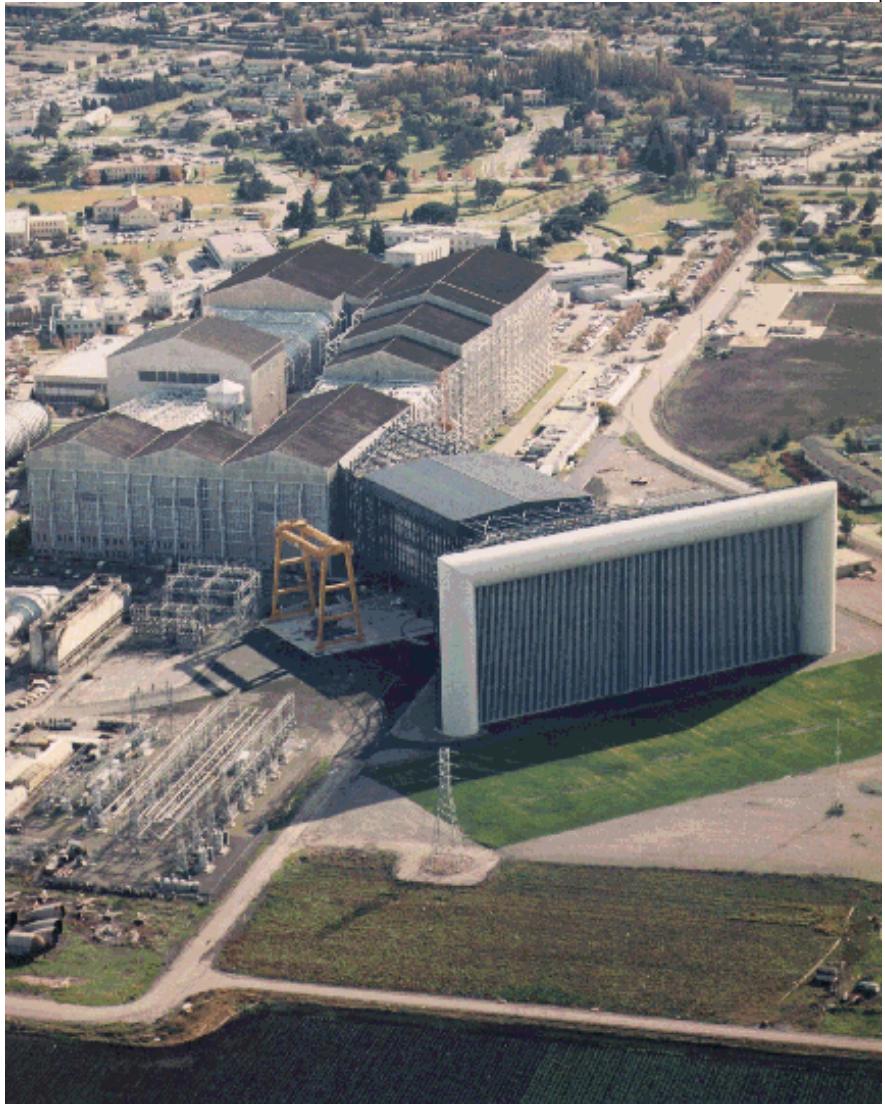
Annular Wind  
Tunnel

# Types of Wind Tunnels

- Subsonic
- Transonic
- Supersonic
- Hypersonic
- Cryogenic
- Specialty
  - Automobiles
  - Environmental- Icing, Buildings, etc.

# Subsonic Wind Tunnels

40' x 80' and 80' x 120'  
NASA Ames



## **40- by 80- Foot Wind Tunnel: Specifications**

### Primary Use:

The facility is used primarily for large-scale or full-scale testing of aircraft and rotorcraft, including high-lift and noise suppression development for subsonic and high speed transports, powered lift, high angle-of-attack for fighter aircraft and propulsion systems

### Capability:

Mach Number: 0-0.45

Reynolds Number per foot: 3 X 10<sup>6</sup>

Stagnation Pressure: Atmospheric

Temperature Range: 485 ° - 580 ° R

Closed circuit, single return, continuous flow, closed throat wind tunnel with low turbulence

Model-support systems available include a 3 strut arrangement with a nose or tail variable height strut, a semi-span mount and a sting

The entire model support can be yawed a total of 290 °

Six components of force and moment are measured by the mechanical, external balance under the test section, or by internal strain-gage balances in the sting or rotor testbeds

Test section walls are lined with a 10" acoustic lining, and the floor and ceiling have a 6" acoustic lining

## **80- by 120- Foot Wind Tunnel: Specifications**

### Primary Use:

The facility is used primarily for large-scale or full-scale testing of aircraft and rotorcraft, including high-lift development for subsonic transports, V/STOL powered lift, high angle-of-attack for fighter aircraft and propulsion systems

### Capability:

Mach Number: 0-0.15

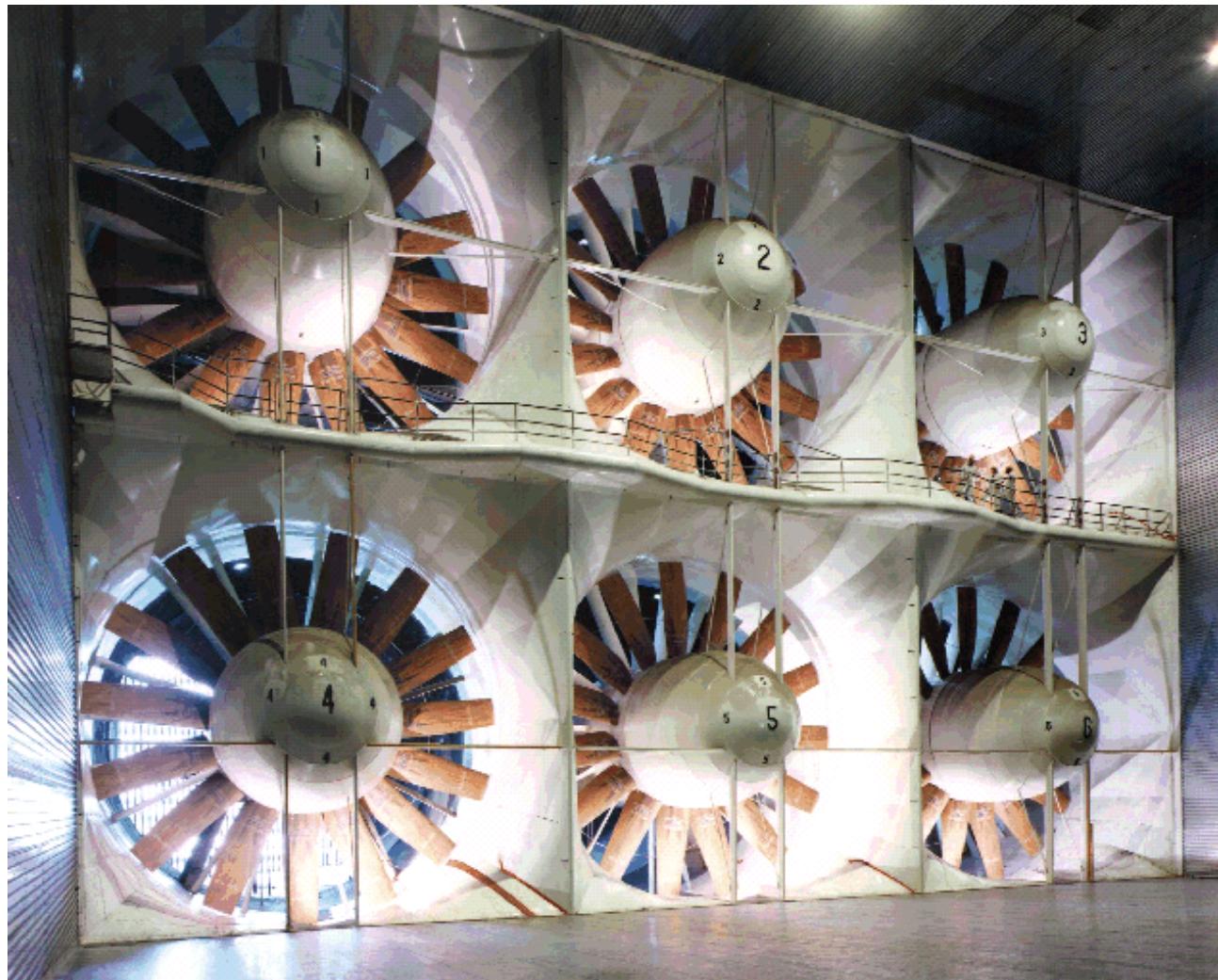
Reynolds Number per foot: 1.2 X 10<sup>6</sup>

Stagnation Pressure: Atmospheric

Temperature Range: 485 ° - 580 ° R

Indraft, continuous flow, closed throat wind tunnel

## Fans for 40x80 and 80x120



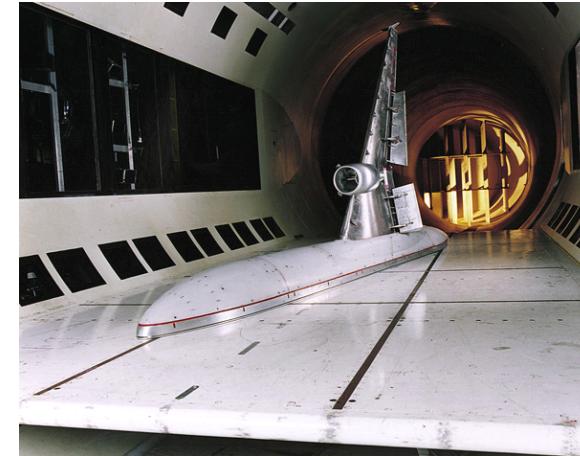
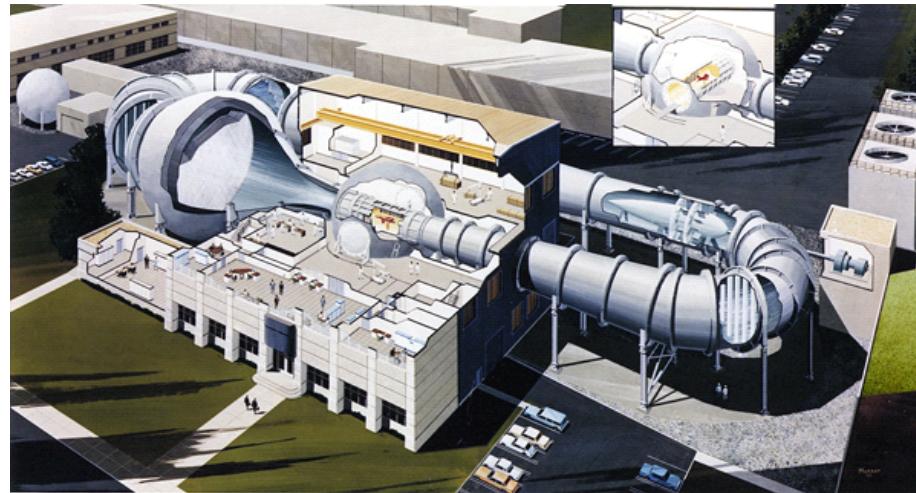
40'x80'

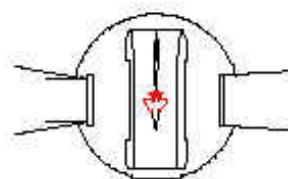
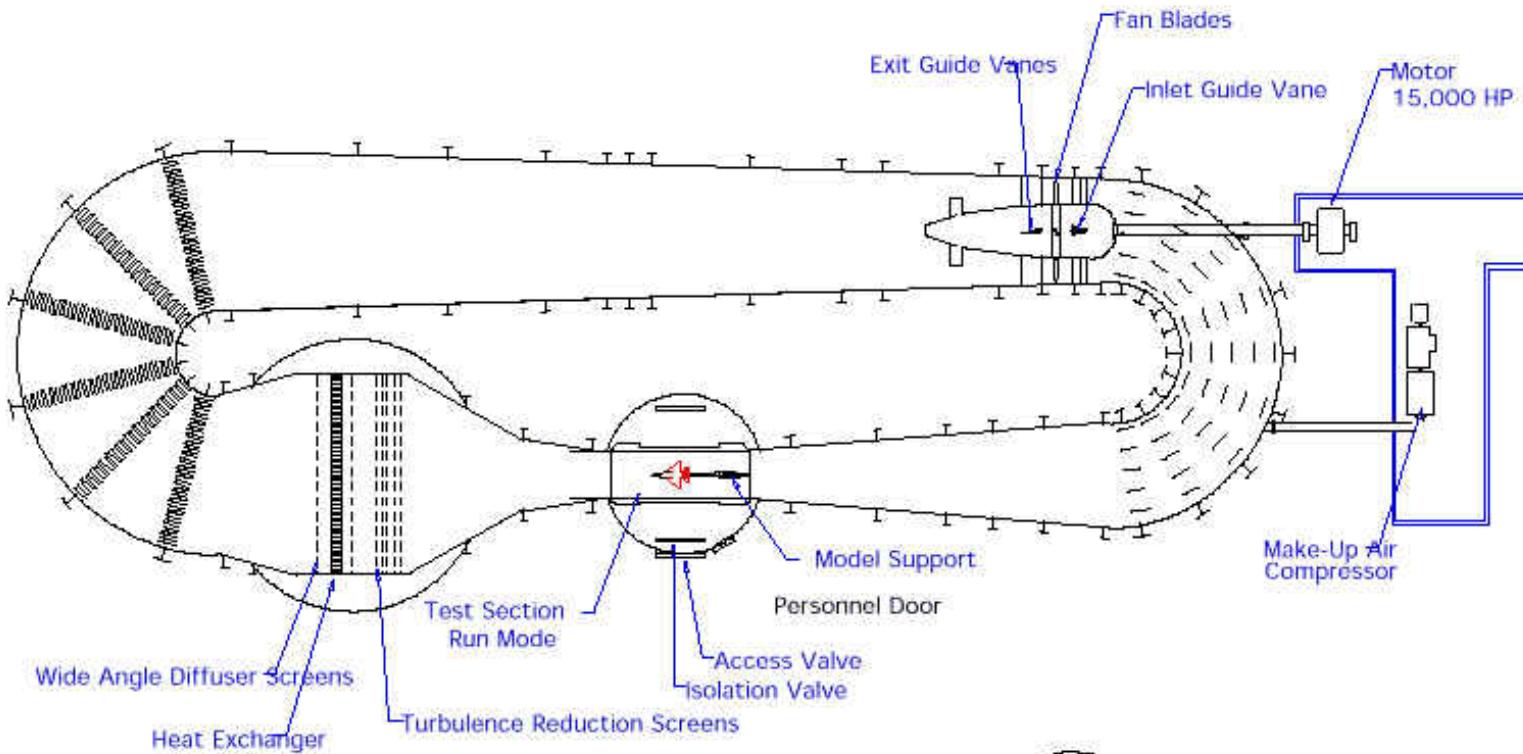


80'x120;



## 12 foot Pressure Tunnel





12ft Pressure Wind Tunnel  
NASA Ames Research Center

## **12-Foot Pressure Wind Tunnel: Specifications**

### **Primary Use:**

The facility is used primarily for high Reynolds number testing, including the development of high-lift systems for commercial transports and military aircraft, high angle-of-attack testing of maneuvering aircraft, and high Reynolds number research.

### **Capability:**

Mach Number: 0-0.52

Reynolds Number per foot: 0.1 - 12X10<sup>6</sup>

Stagnation Pressure, PSIA: 2.0 - 90

Temperature Range: 540 ° - 610 ° R

Closed circuit, single return, variable density, closed throat, wind tunnel with exceptionally low turbulence

### **Model-support systems available:**

Strut with variable pitch and roll capability

High angle-of-attack turntable system

Dual-strut turntable mechanism for high-lift testing

Semispan mounting system

Internal strain-gage balances used for force and moment testing

Capability for measuring multiple fluctuating pressures

Temperature-controlled auxiliary high-pressure (3000 psi)

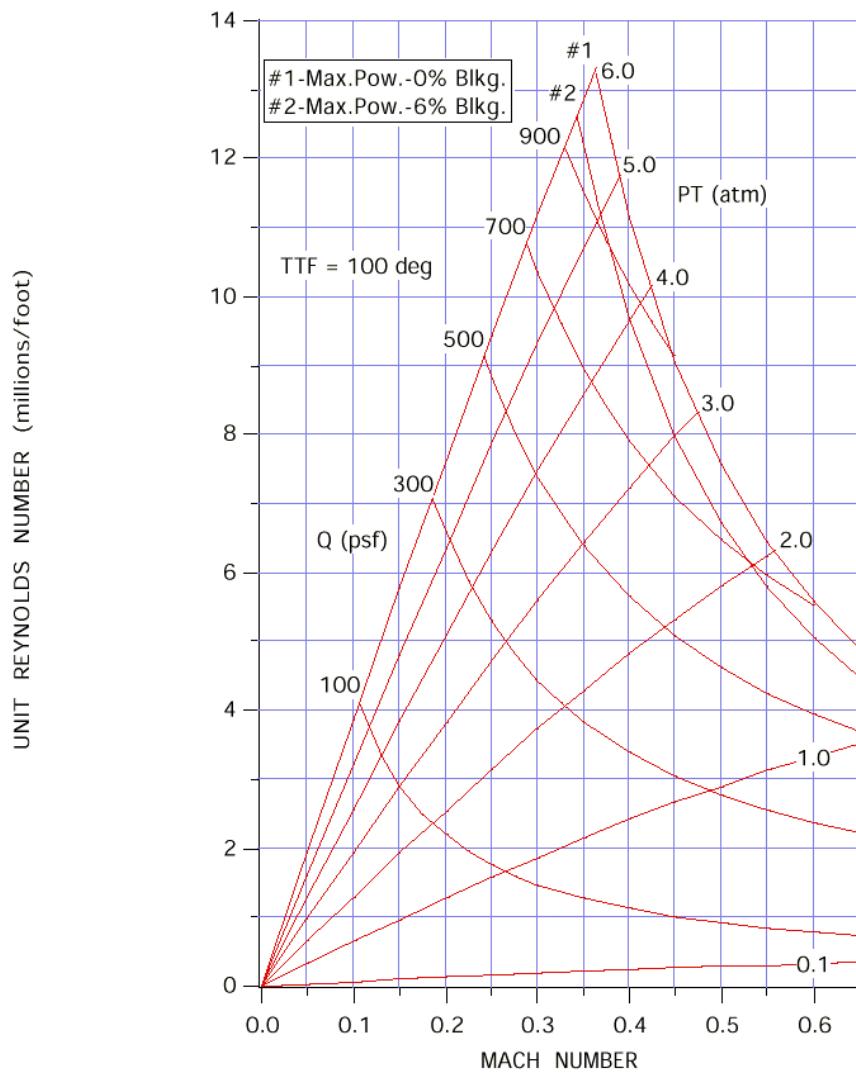


Figure 2-5. 12-Foot PWT Performance Chart

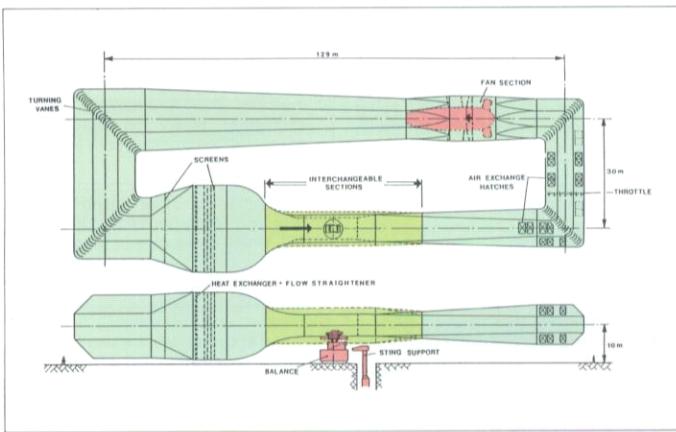


Fig. 3  
DNW's lay-out and  
main dimensions

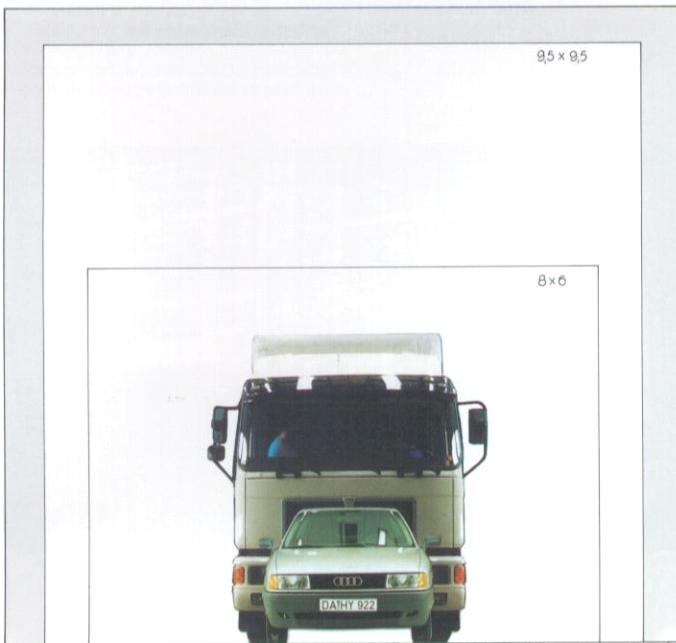


Fig. 4  
The two test sections  
used for road vehicle  
aerodynamics:  
8 m x 6 m for cars,  
9.5 m x 9.5 m for trucks.

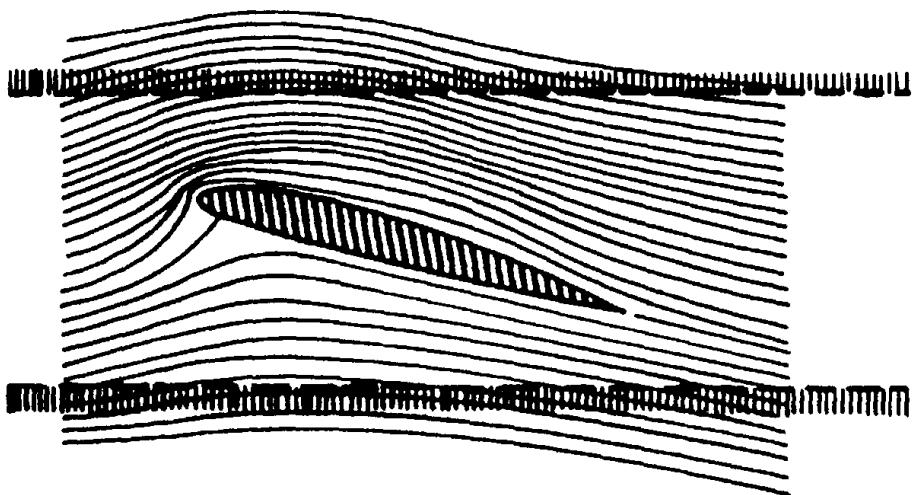
# Transonic Wind Tunnels

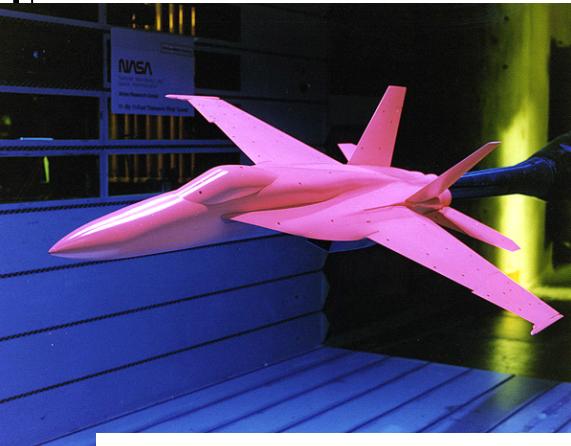
# Transonic Wind Tunnels

Wall interference is a severe problem for transonic wind tunnels.

Flow can “choke”  
Shock wave across the tunnel test section

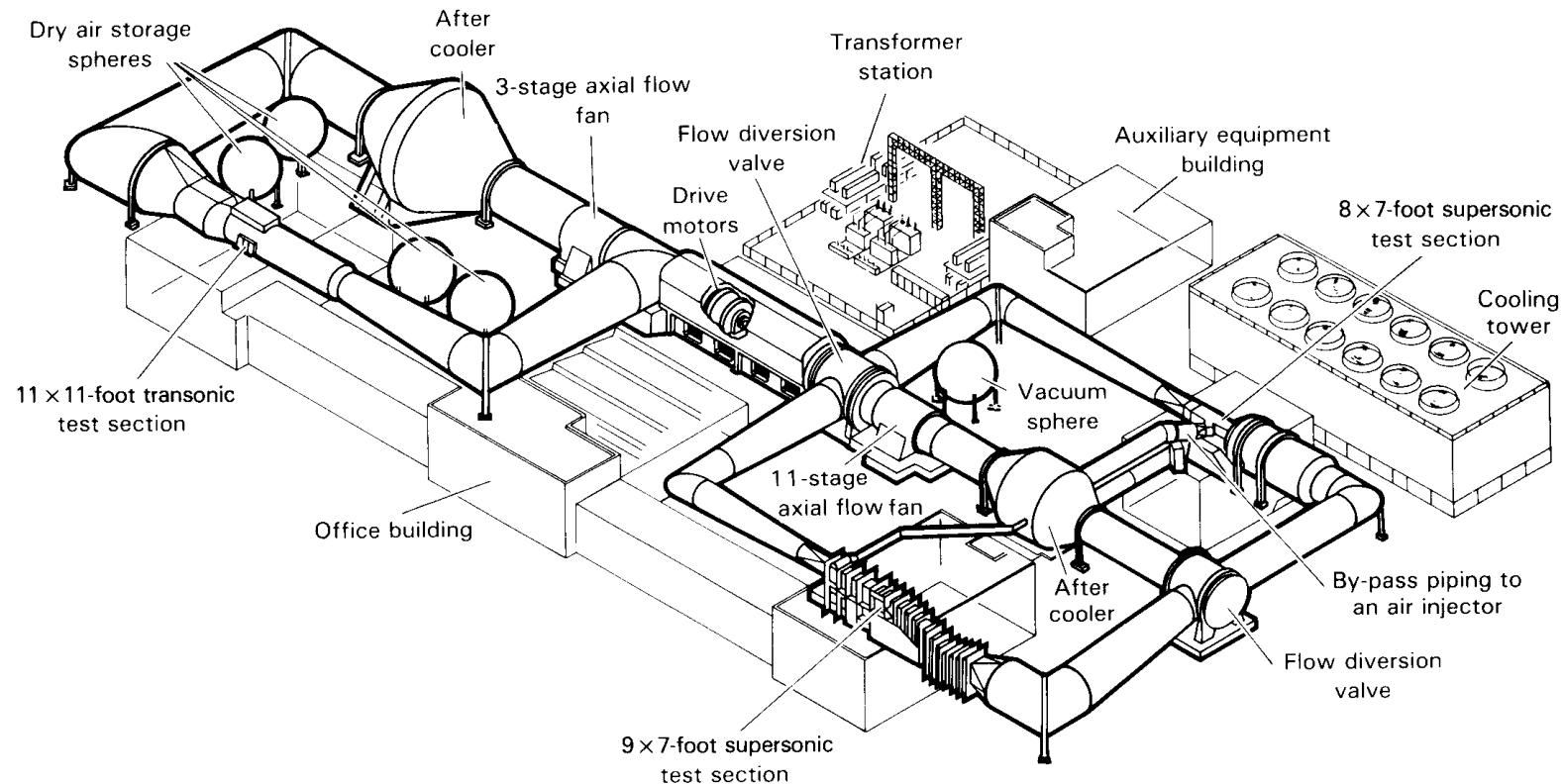
Two Solutions  
Porous Walls  
Movable Adaptive Walls





The Unitary Plan wind tunnels are a set of three interconnected tunnels that share a central main drive system that can be used to drive either a transonic leg or a supersonic leg. The Unitary Plan wind tunnels are as follows.

- 11ft Transonic Wind Tunnel
- 9x7ft Supersonic Wind Tunnel
- 8x7ft Supersonic Wind Tunnel



The 8x6/9x15 Complex at the NASA Lewis Research Center in Cleveland, Ohio is, is unique in its dual capacity role as both a high-speed and low speed test facility.

## 8x6 Functions & Capabilities

The 8x6 Foot Supersonic Wind Tunnel provides customers with a Facility capable of testing large scale aeropropulsion hardware:

In a continuous Mach 0-2.0 airstream

At varying Reynolds Numbers ( $3.6 - 4.8 \times 10^6/\text{ft}$ ) and altitude conditions (ambient to 38,000ft)

In either aerodynamic (closed) or Propulsion (open) cycle without exhaust scoops

Employing high data systems to support steady and transient data acquisition

Supported by a variety of systems including: Schlieren, infrared imaging, sheet lasers, LDV, GH2 fuel, high pressure air, and hydraulics.

### 8x6 Characteristics & Performance

Test section size      8ft H, 6ft W, 23.5ft L

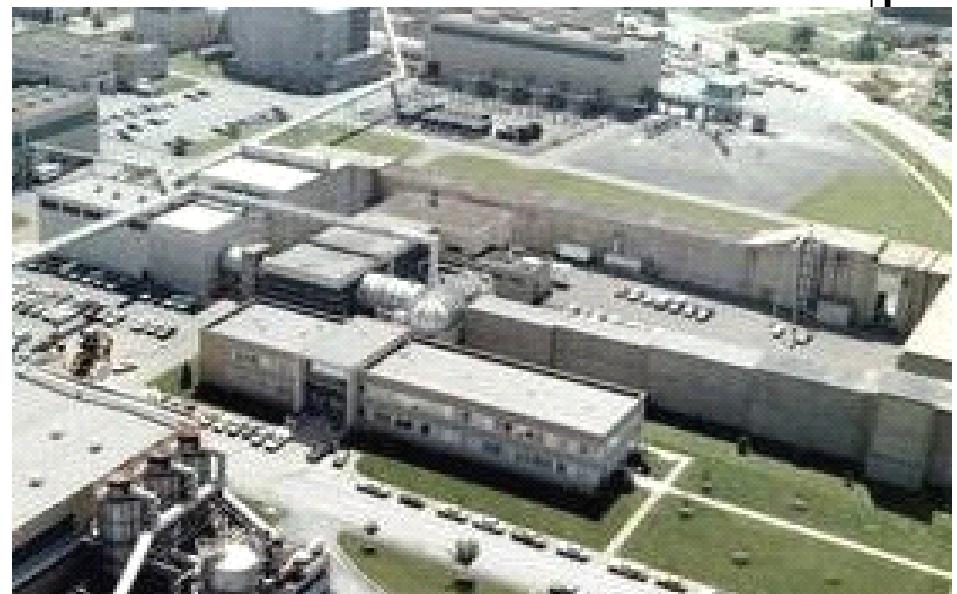
Mach number range    0 - 2.0

Relative altitude      1000 - 35000 ft

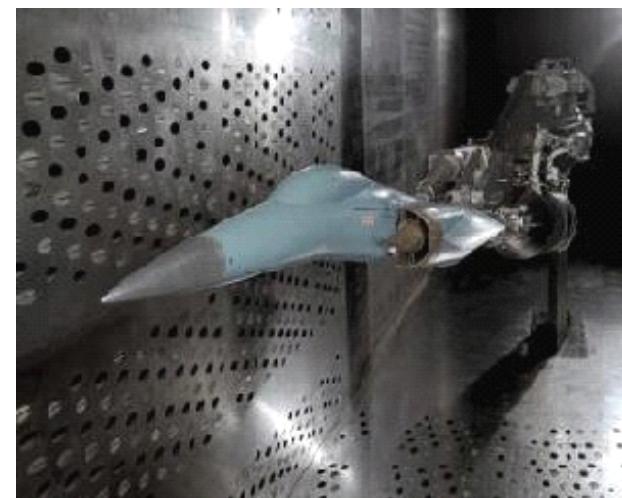
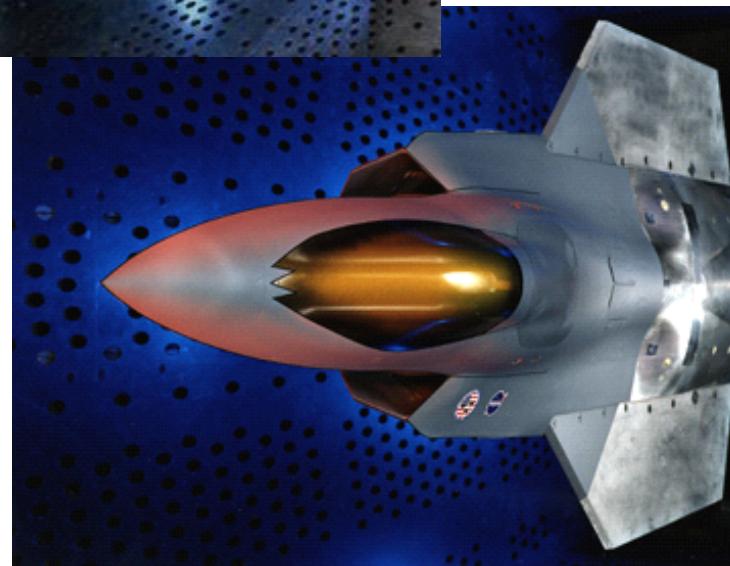
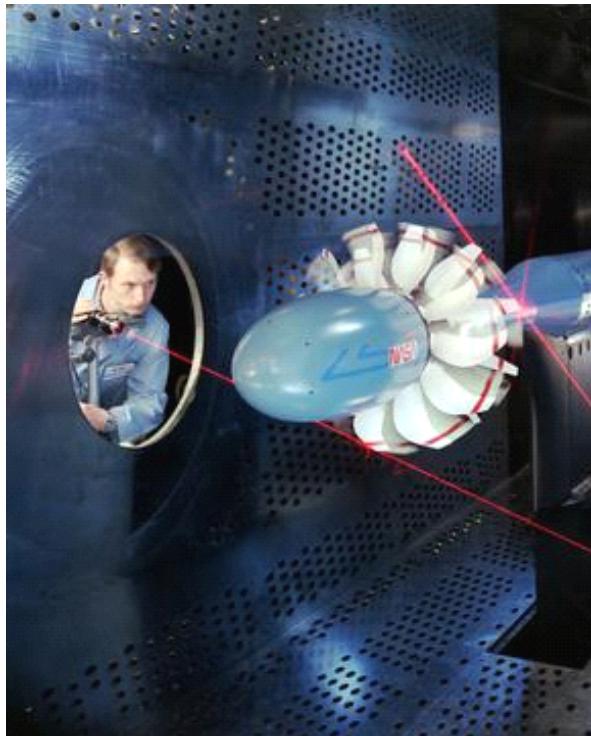
Dynamic Pressure       $3.6 - 4.8 \times 10^6/\text{ft}$

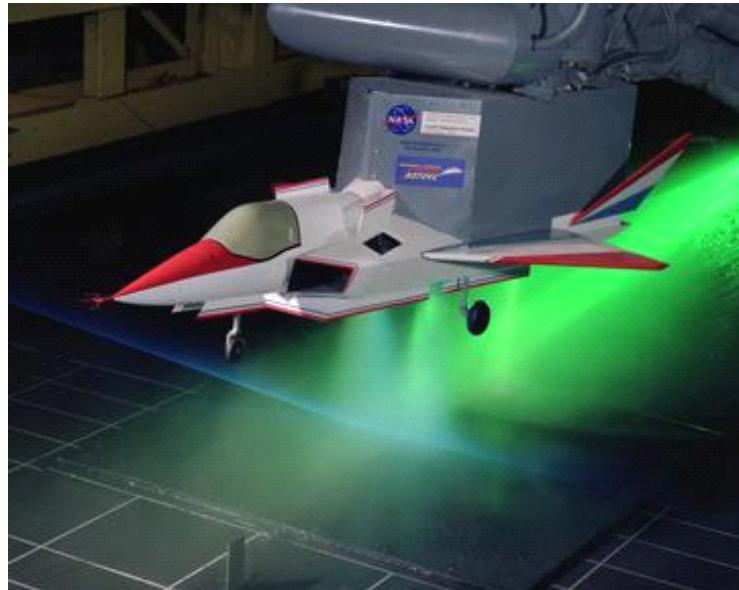
Stagnation Pressure    15.3 - 25 psia

Temperature            60 - 250oF

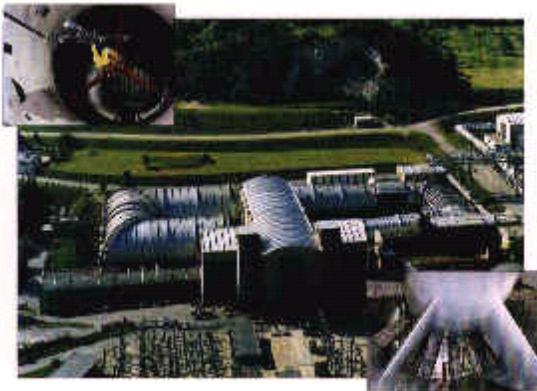


## 8x6 at NASA Lewis



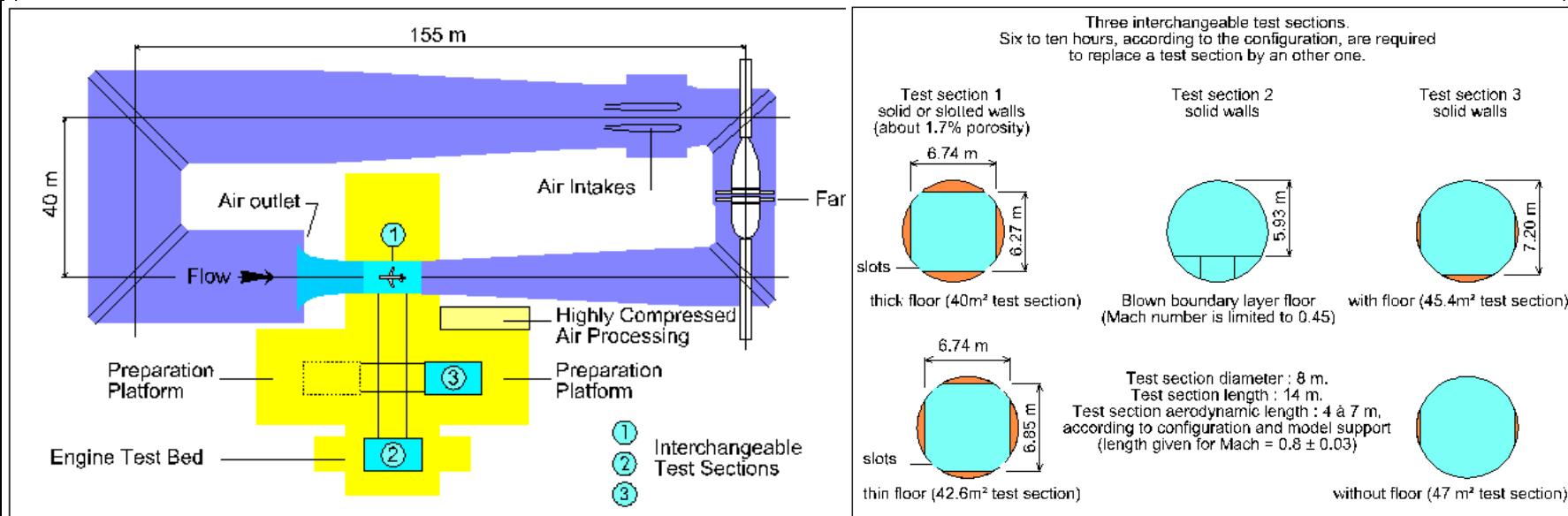


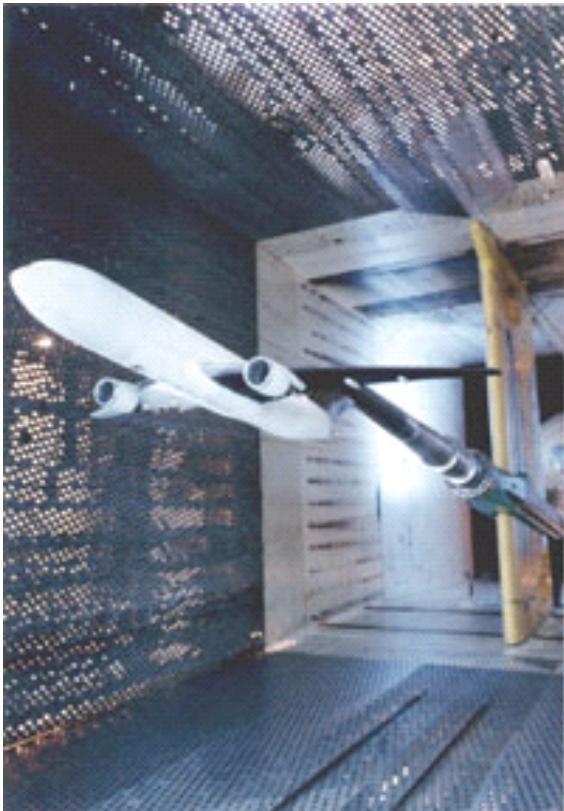
9x15 at NASA Lewis  
Back Leg of the 8x6



S1MA Wind Tunnel Atmospheric, closed-circuit, continuous flow wind tunnel, from Mach 0.05 to Mach 1

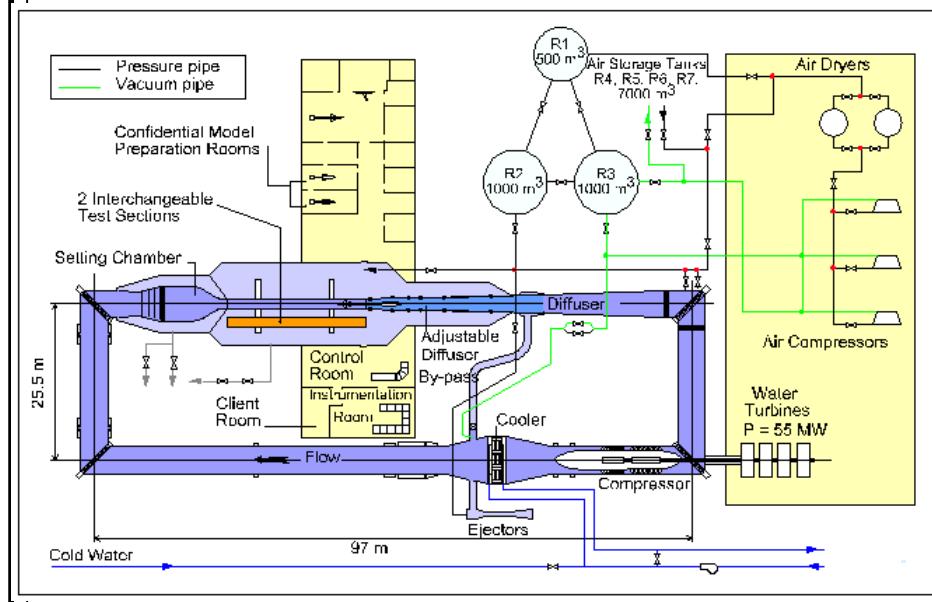
S1MA wind tunnel is equipped with two counterrotating fans, driven by Pelton turbines, the power of which is 88 MW;  
 Mach number is continuously adjustable from 0.05 to 1 by varying the fan speed from 25 to 212 rpm.





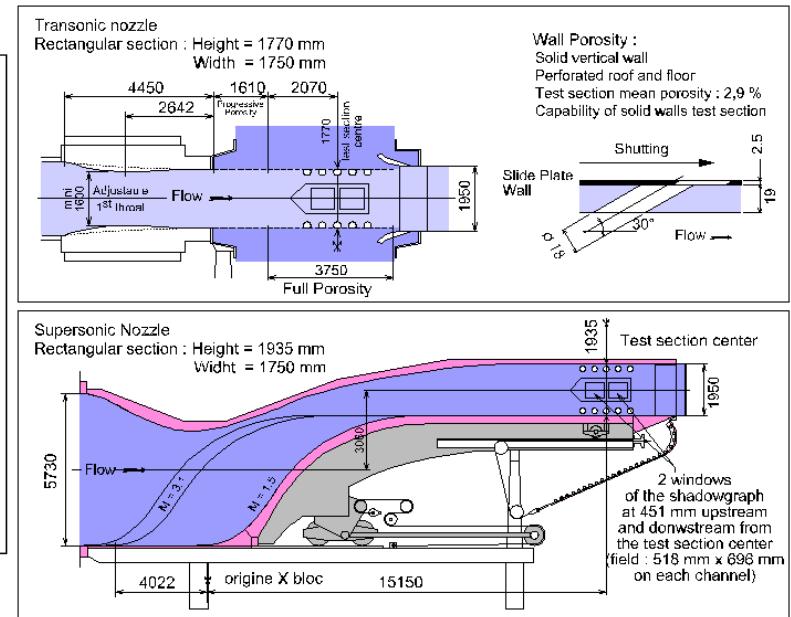
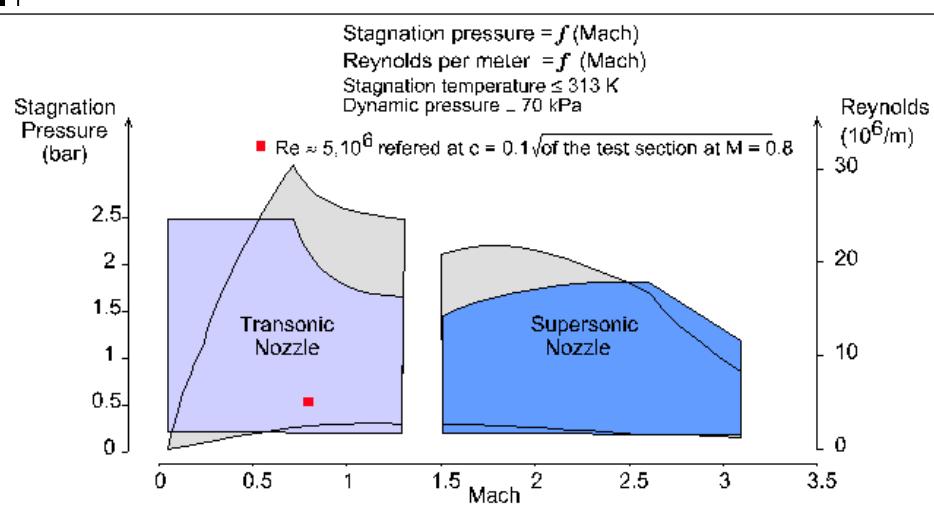
## 16T at AEDC

A model of Boeing's 767 commercial jet undergoes testing in one of AEDC's large wind tunnels. The 767 tests were the first in a series of tests of Boeing's large commercial jets at the center. AEDC signed a twenty year alliance with Boeing to test commercial aircraft.



DNERA

## S2Ma Wind Tunnel



# Supersonic Wind Tunnels

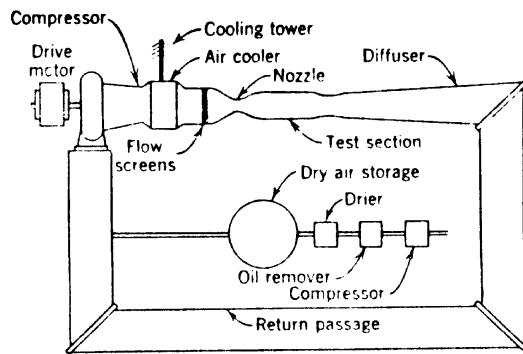


Fig. 1:1 Diagrammatic layout of closed-circuit, continuous flow, supersonic wind tunnel.

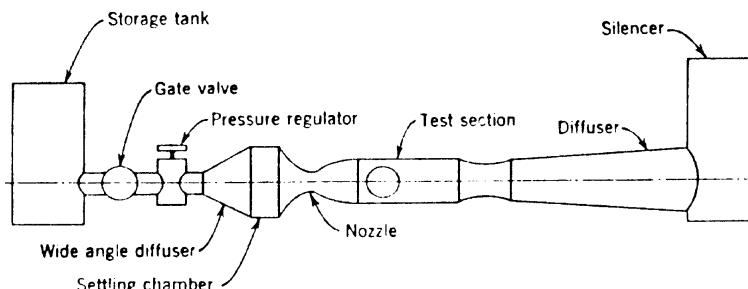


Fig. 1:2 Diagrammatic layout of intermittent blowdown tunnel.

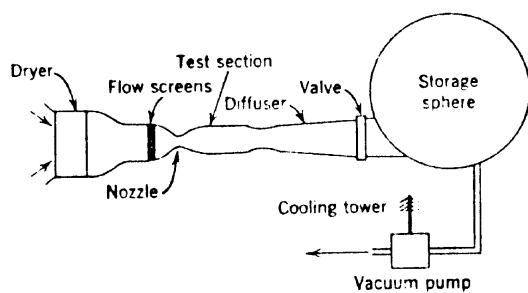
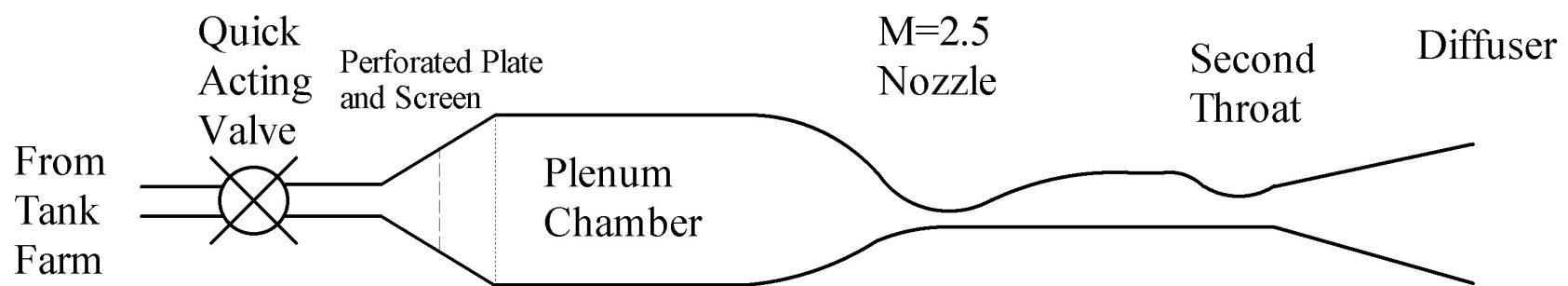
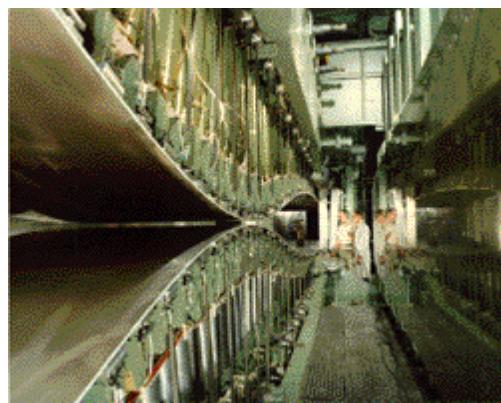


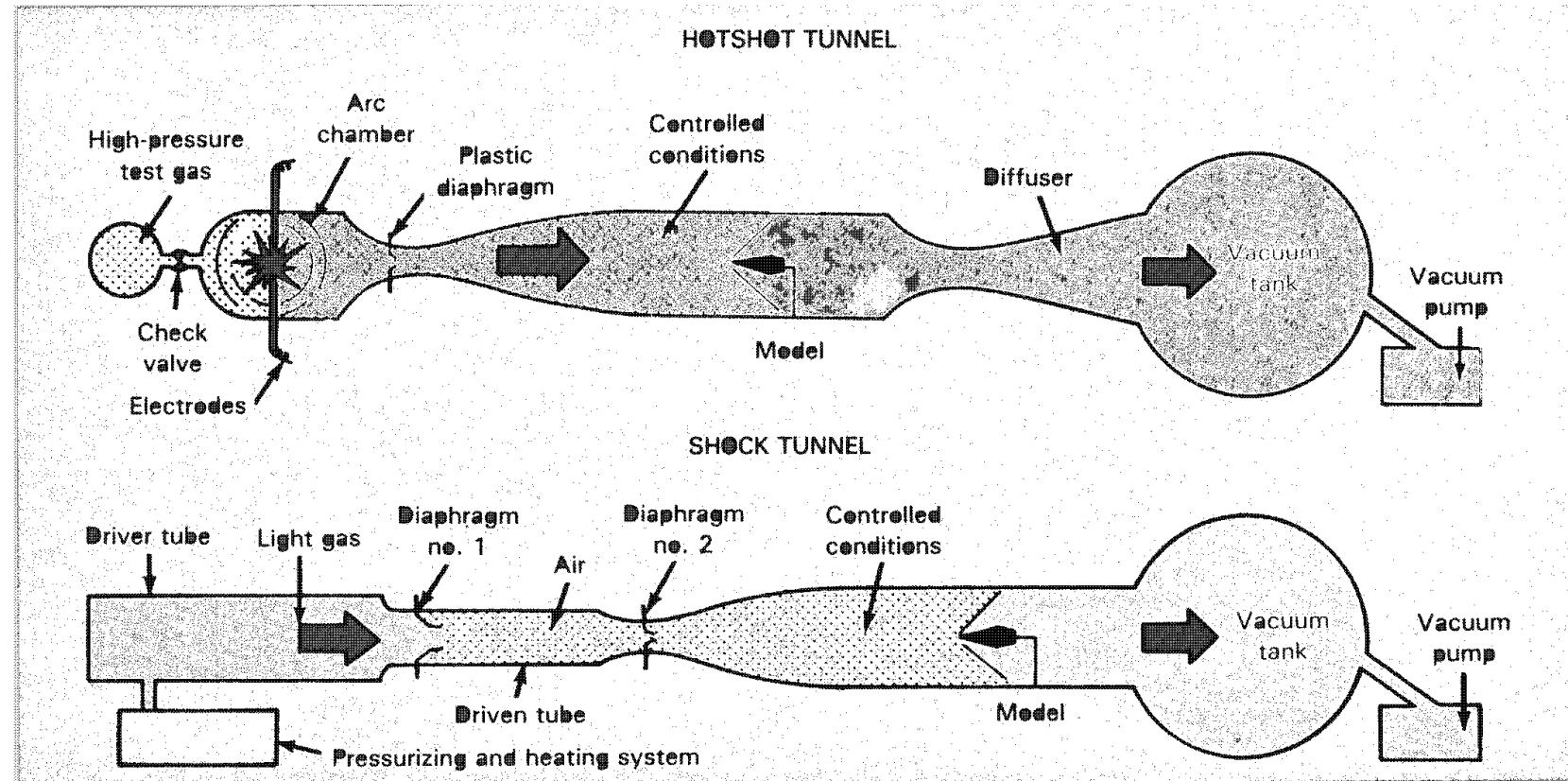
Fig. 1:3 Diagrammatic layout of intermittent in-draft wind tunnel.

Purdue University  
Aerospace Sciences Laboratory  
 $M=2.5$  Supersonic  
Blowdown Wind Tunnel

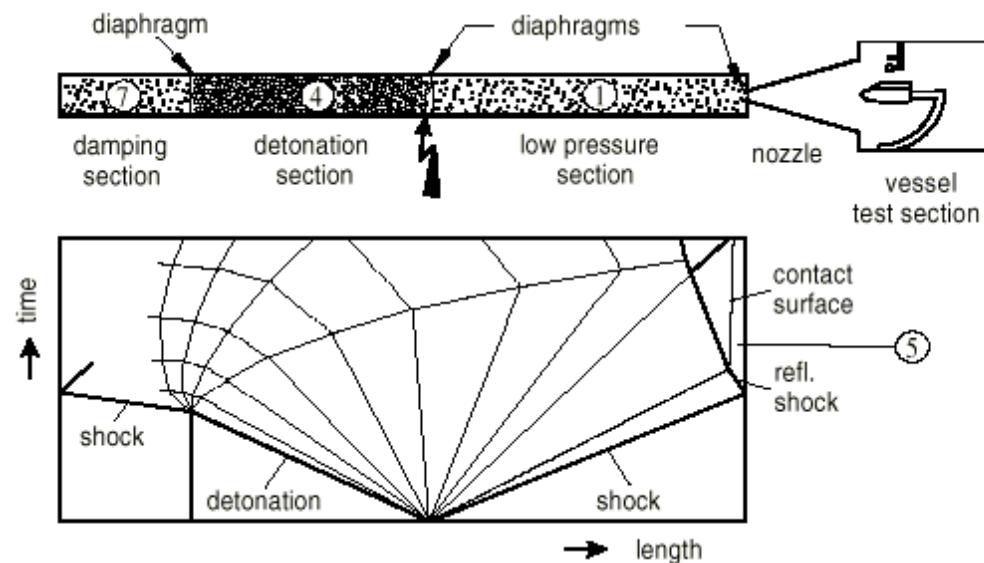




# Hypersonic Wind Tunnels



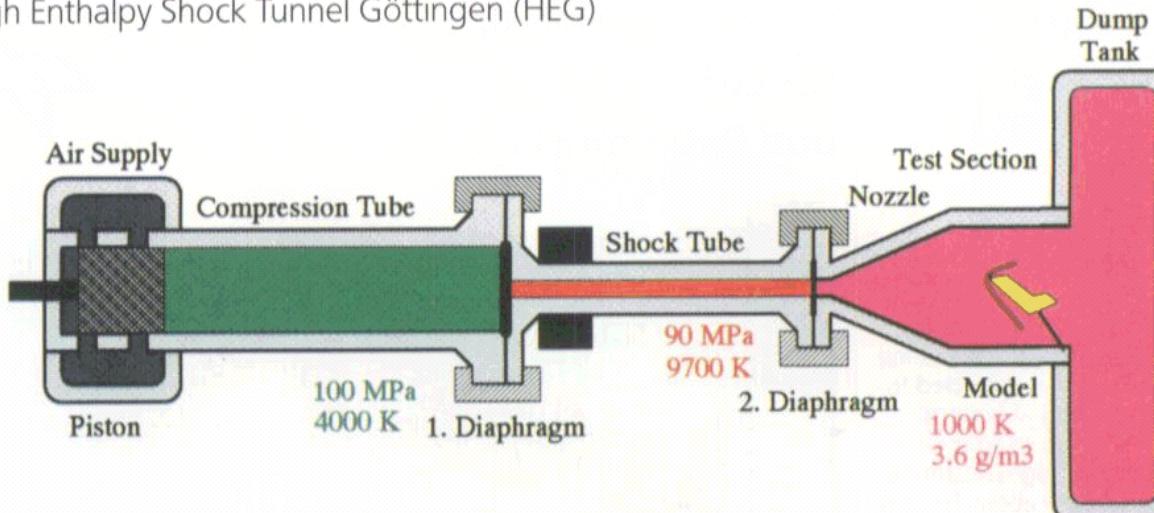
## **Principle Operation Detonation Driven Shock Tunnel SET- UP AND WAVE PLAN:**



Initial conditions:

- low pressure section: test gas air, about 25 kPa for tailored cond.
- deton. section: oxyhydrogen- helium/ argon mixtures, max. 7 MPa
- damping section: expansion volume; low initial pressures

## High Enthalpy Shock Tunnel Göttingen (HEG)



### The Facility

The free piston-driven shock tunnel HEG consists of an air buffer, a compression (driver) tube, separated from an adjoining shock tube via a metal diaphragm, and a subsequent nozzle and test section. A piston is accelerated through the compression tube by the air in the buffer, compressing the driver gas helium to high temperatures and pressures, whereby the diaphragm ruptures, leading to propagation of a strong shock through the shock tube. This shock reflects from the end wall, heating up the test gas (nitrogen, air,

carbon dioxide, etc.) to high pressures and temperatures – this gas reservoir expands through the nozzle and pro-

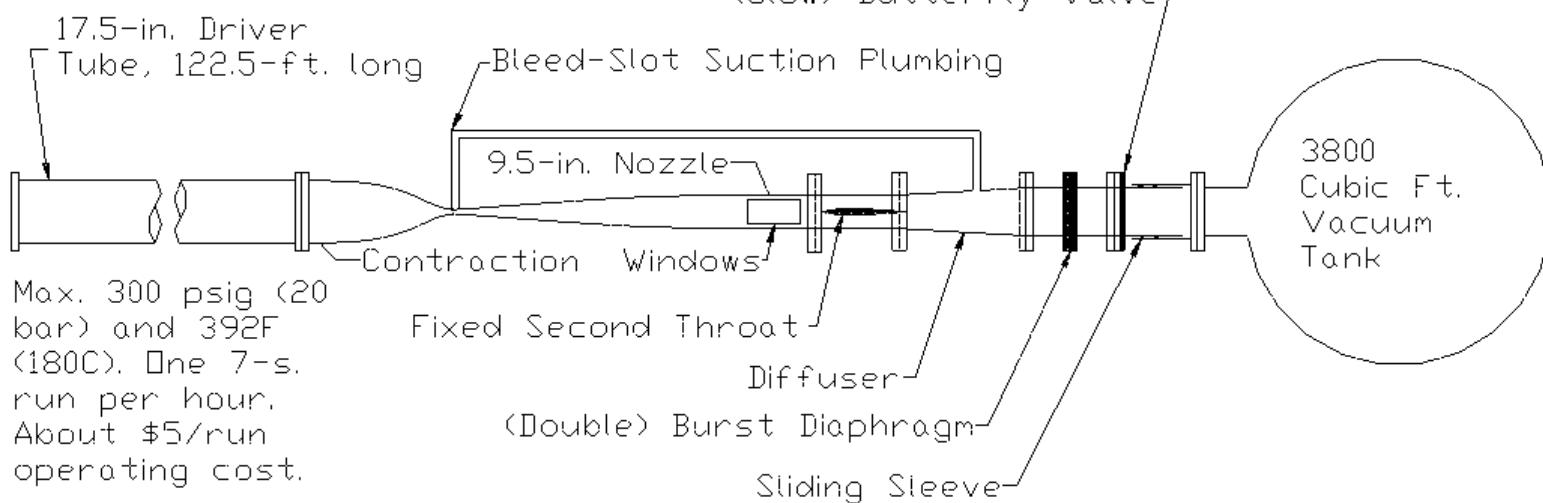
vides the free stream conditions in the test section. Total available test time is about 1 millisecond.

Condition	I	II	III	IV	V	VI
$P_0$ (MPa)	40	90	45	110	50	95
$T_0$ (K)	9100	9700	7300	8100	6400	6500
$h_0$ (MJ/kg)	21	22	13	15	11	11
$p_\infty$ (Pa)	430	1200	470	1300	520	980
$T_\infty$ (K)	790	1040	550	720	470	480
$\rho_\infty$ ( $\text{g}/\text{m}^3$ )	1.6	3.6	2.8	6.2	3.8	6.9
$M_\infty$	9.7	9.0	10.0	9.5	10.0	10.0
$u_\infty$ (m/s)	5900	6200	4800	5100	4400	4400

HEG standard operating conditions

sps 6-11-98

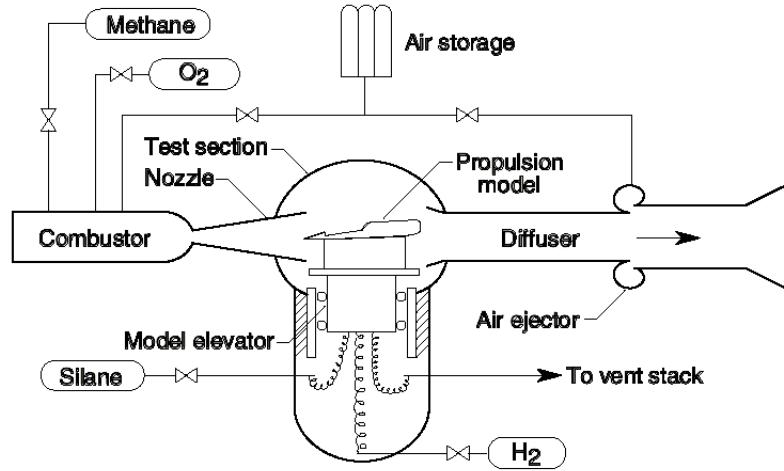
All Clean Stainless Steel from Second-Throat Section Upstream  
Unique Low-Noise Flow due to Laminar Nozzle-Wall Boundary Layer  
(Slow) Butterfly Valve



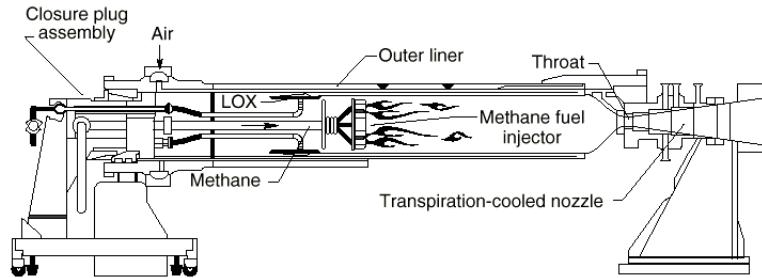
Schematic of Boeing Mach-6 Quiet-Flow Ludwieg Tube

# The NASA Langley 8-Foot High Temperature Tunnel (8' HTT)

enables the testing of large hypersonic airbreathing propulsion systems at flight enthalpies from Mach 4 to Mach 7.



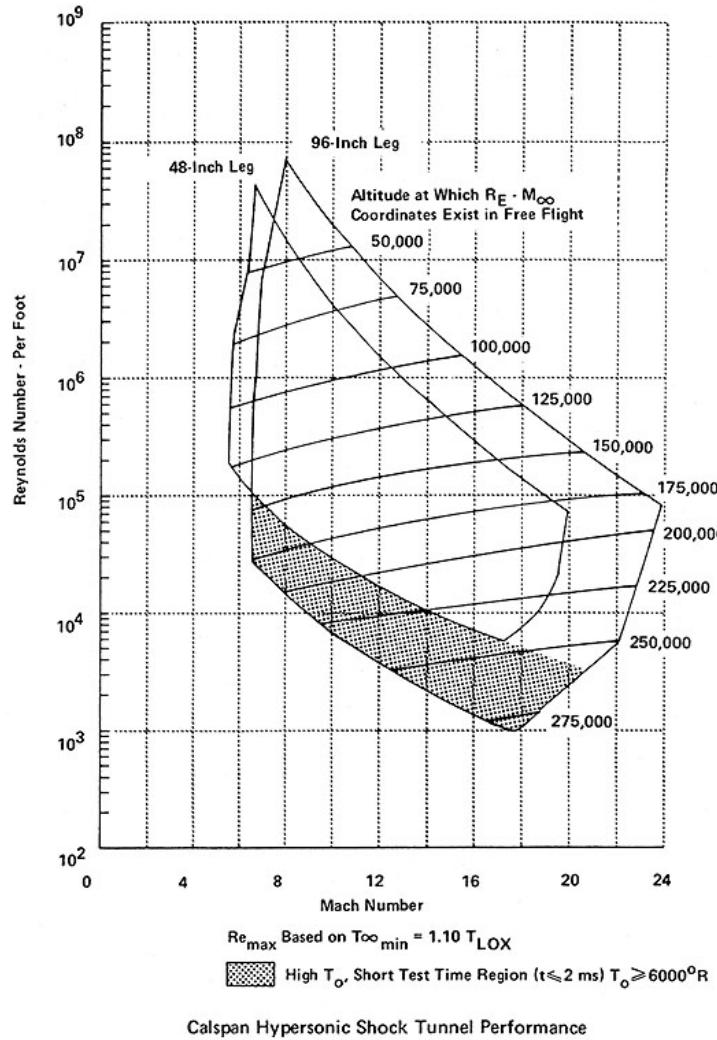
**Figure 2. Schematic drawing of the 8' HTT for airbreathing propulsion testing.**



**Figure 3. Schematic drawing of the 8' HTT combustor.**

# Hypersonic Shock Tunnels at Calspan

The performance chart shows that the high enthalpy 96-inch tunnel is capable of simultaneously duplicating velocity (total enthalpy) and density altitude over a wide range of hypersonic flight conditions. These test conditions cover the widest range of any in the country.





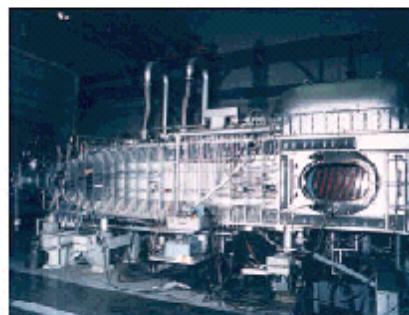
15-Inch Mach 6 Hi Temp. Air



20-Inch Mach 6 Air



20-Inch Mach 6  $CF_4$

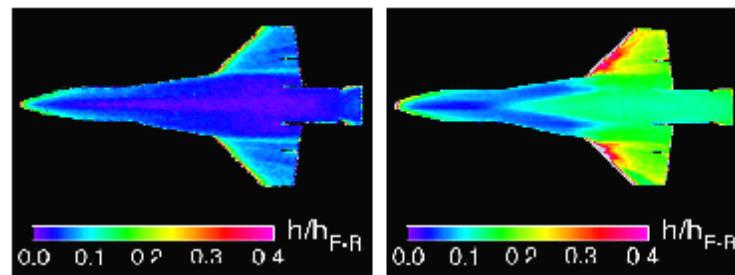


31-Inch Mach 10 Air



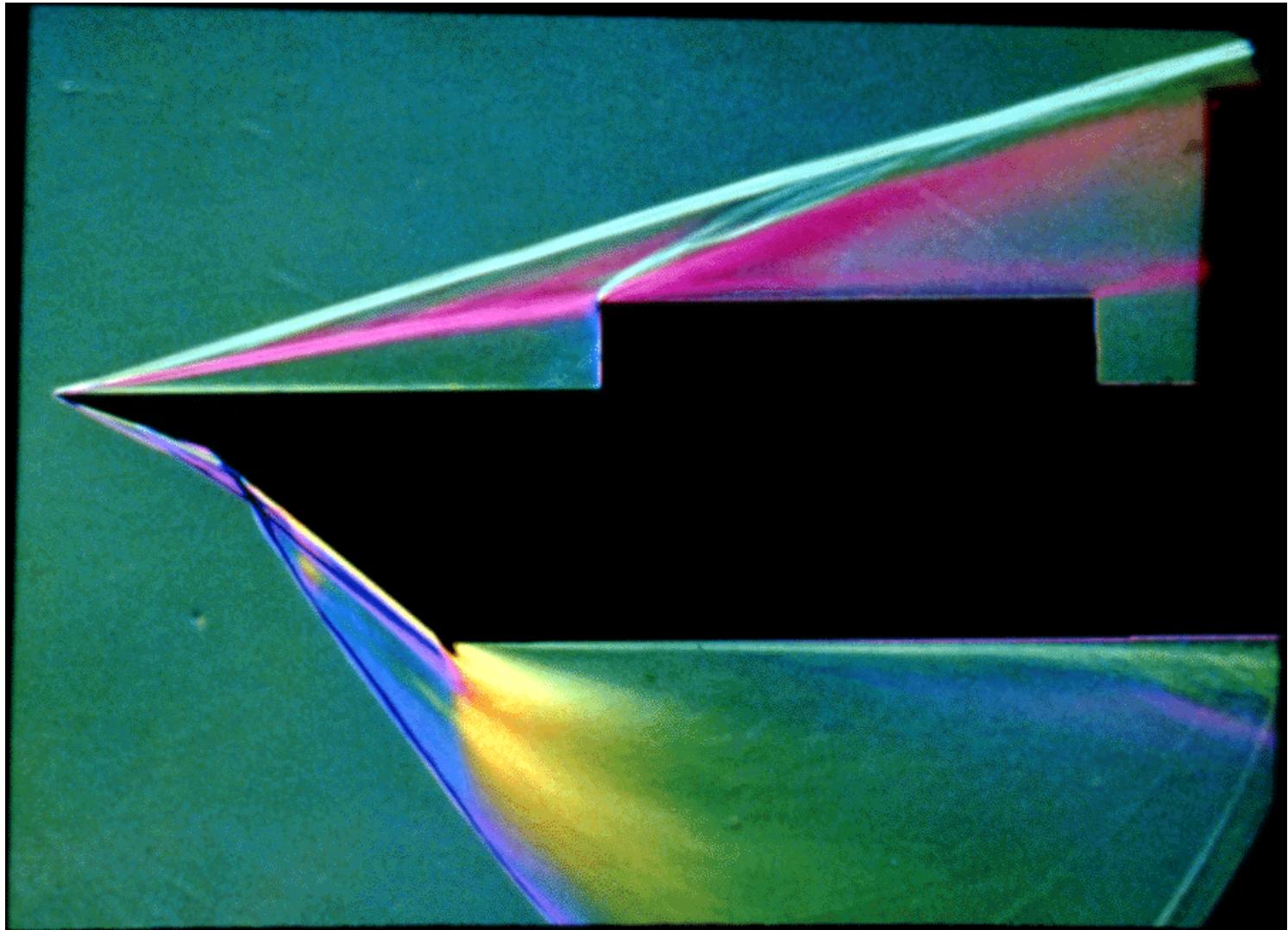
22-Inch Mach 15/20 He

Fig. 1 Facilities of the Aerothermodynamic Facilities Complex.

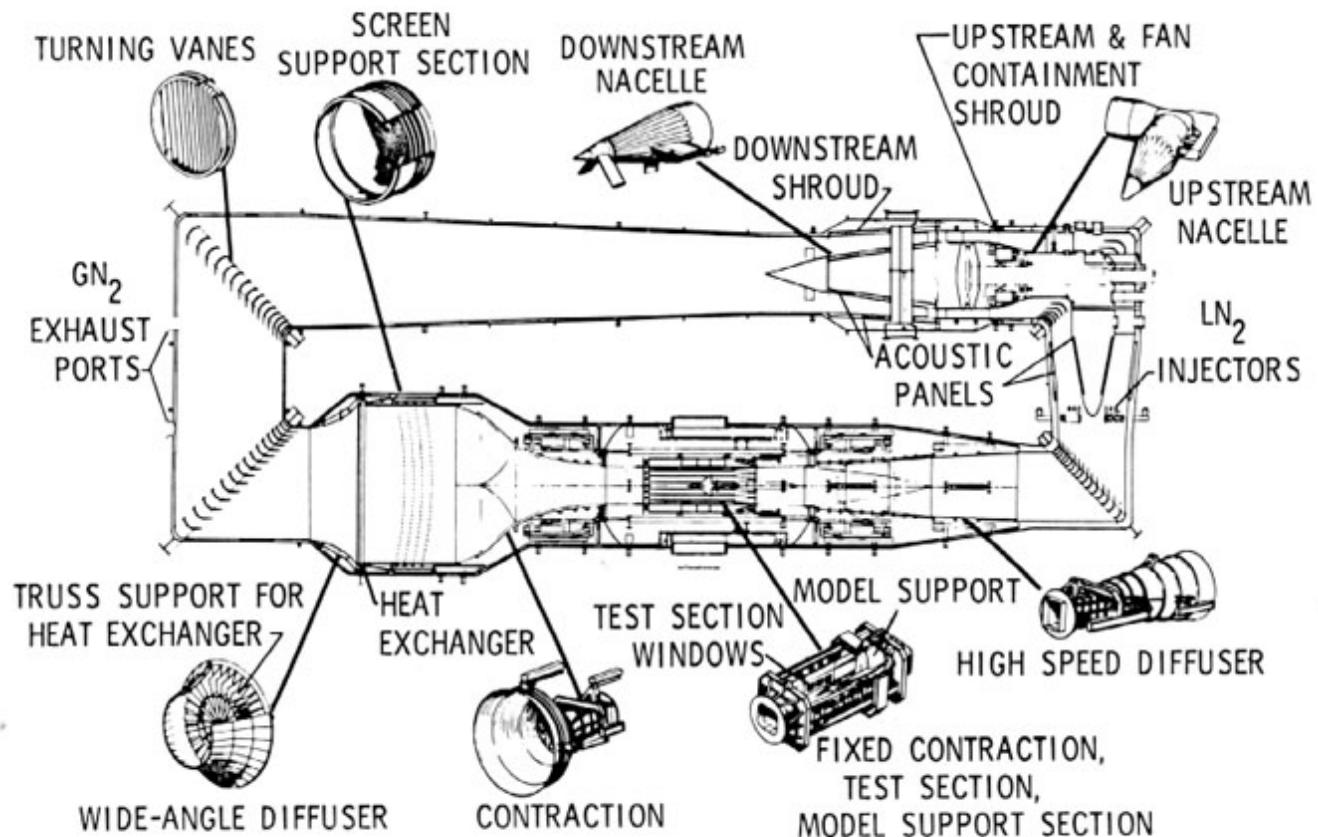


$Re_\bullet = 1.1 \times 10^6/\text{ft}$        $Re_\bullet = 7.9 \times 10^6/\text{ft}$

Fig. 6 Effect of Reynolds number on windward heating rates for X-34 at  $M_\bullet = 6$ ,  $\alpha = 0^\circ$ , and  $\delta_{CS} = 0^\circ$ .



## PRINCIPAL COMPONENTS OF THE NTF CIRCUIT



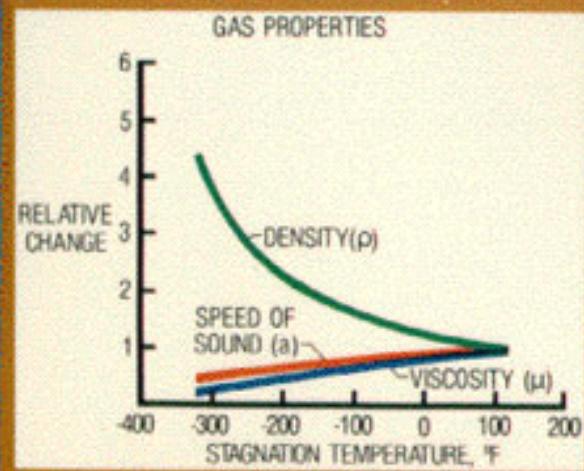
# Cryogenic Wind Tunnels

$$\text{REYNOLDS NO.} = \frac{\text{INERTIA FORCE}}{\text{VISCOSITY FORCE}} = \frac{\text{GAS DENSITY} \cdot \text{VELOCITY} \cdot \text{LENGTH}}{\text{GAS VISCOSITY}} = \frac{\rho VL}{\mu}$$

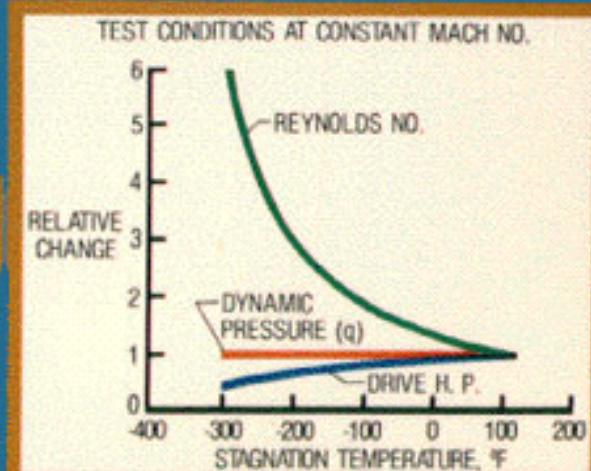
#### 4 WAYS TO INCREASE TEST REYNOLDS NUMBER

- INCREASE TEST MODEL SIZE
- INCREASE TEST PRESSURE OF GAS
- USE A HEAVY TEST GAS
- DECREASE TEST TEMPERATURE OF GAS

#### EFFECTS OF DECREASING TEMPERATURE



$$R = \frac{\rho \cdot V \cdot L}{\mu} = \frac{\rho \cdot a \cdot L}{\mu} \cdot \text{MACH NO.}$$



# NATIONAL TRANSONIC FACILITY

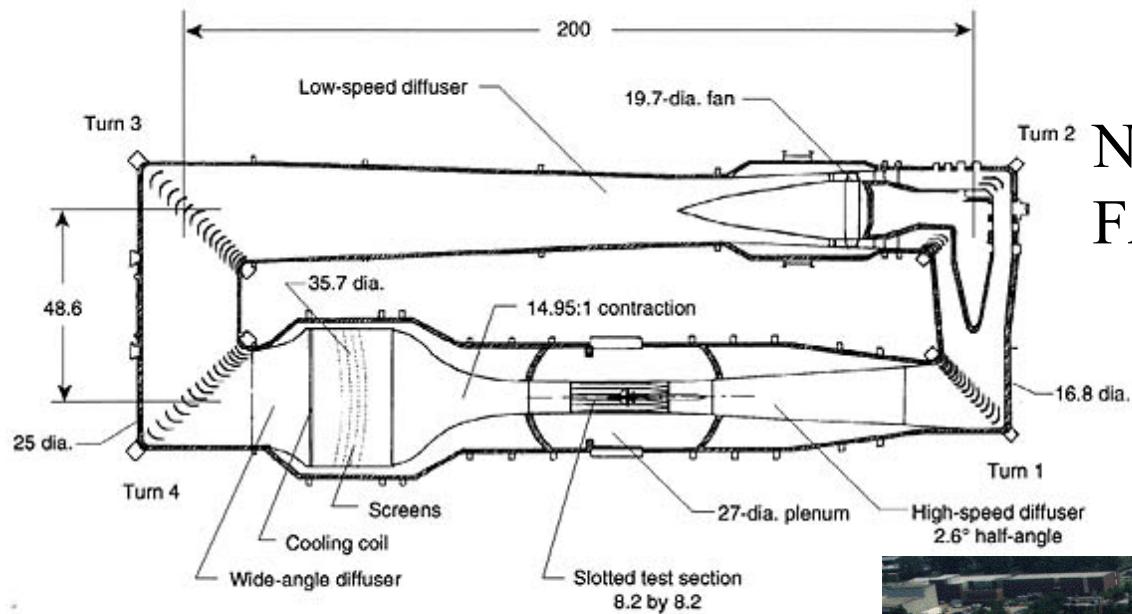
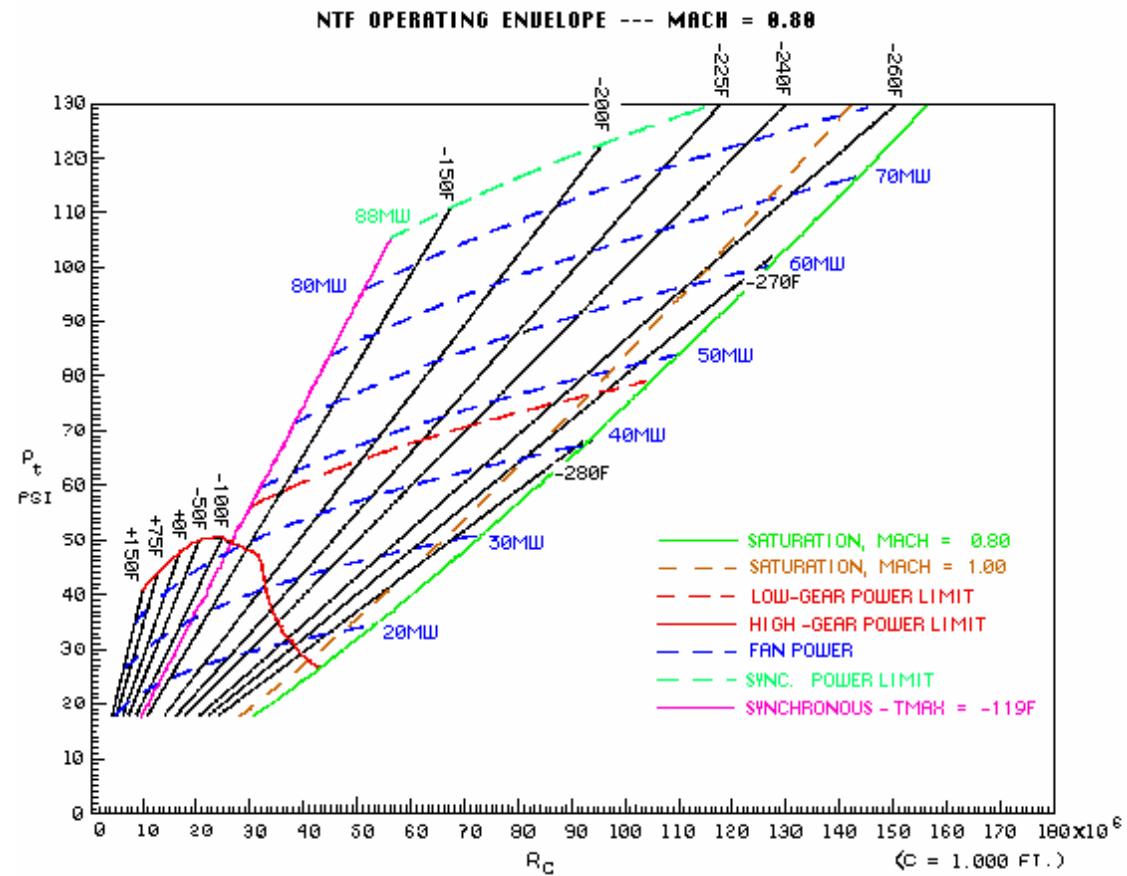
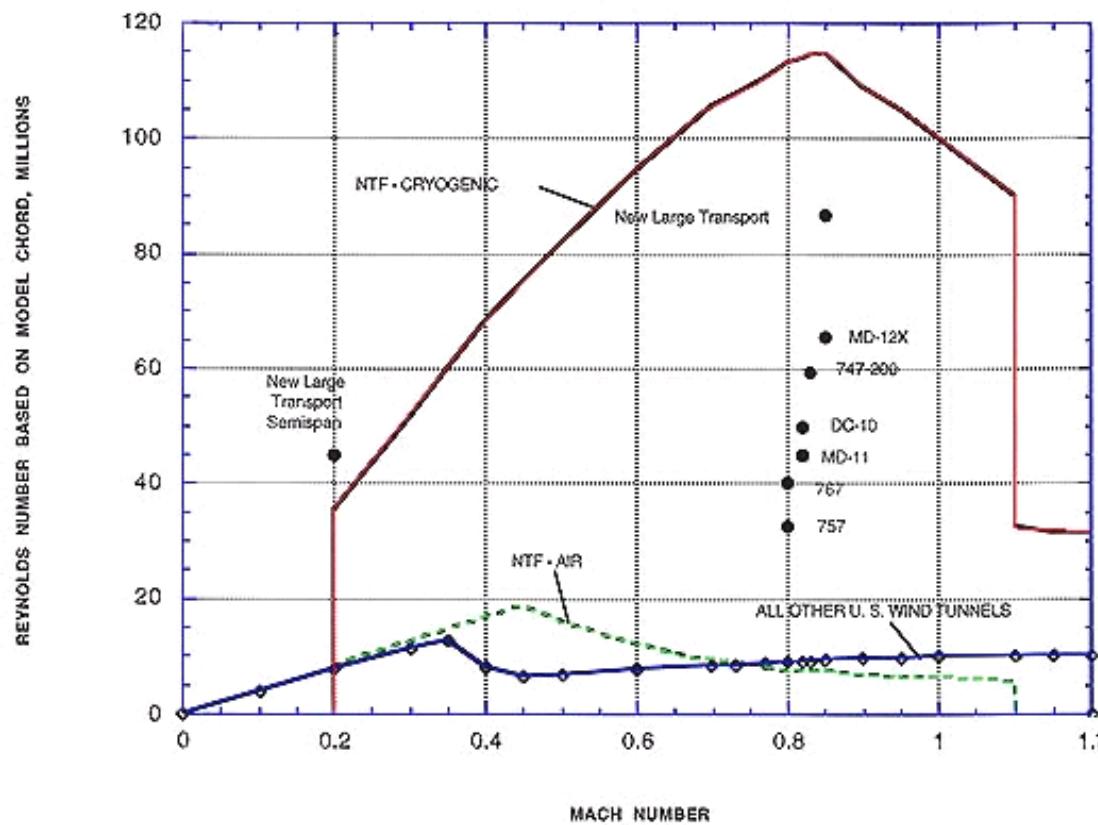


Figure 6. Plan view of NTTF tunnel circuit. All linear dimensions are in feet.

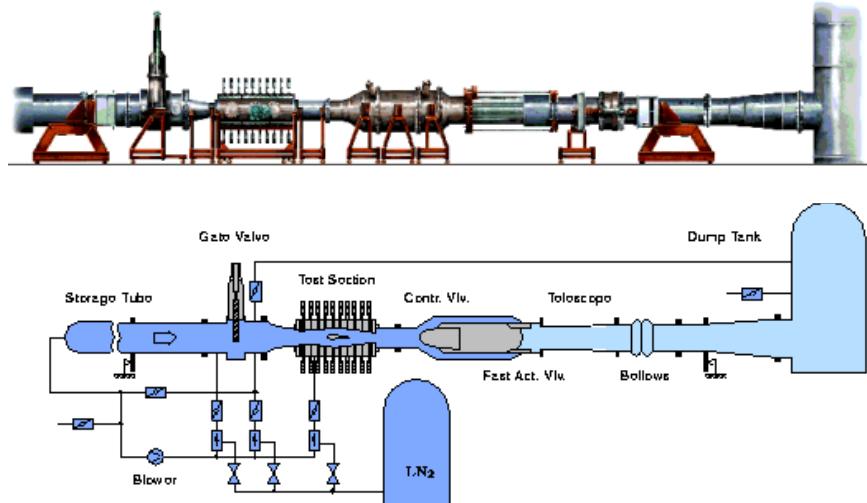




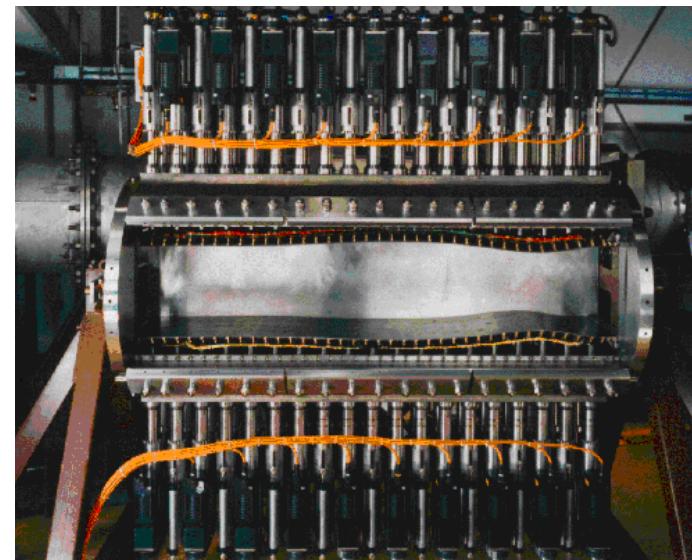
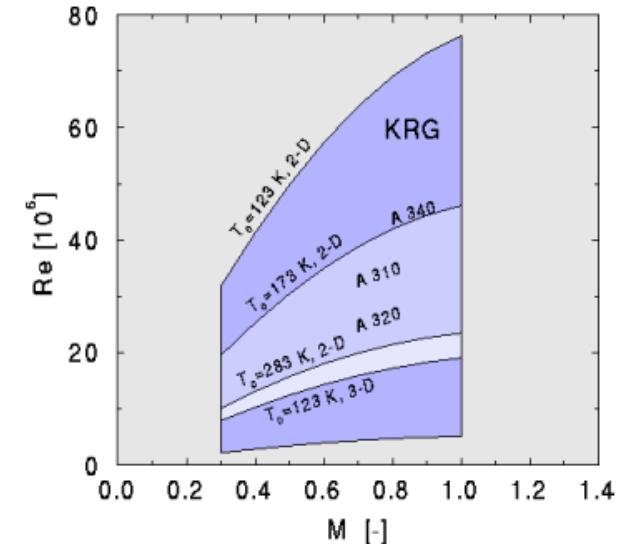
# NTF Capability



# The Cryogenic Ludwieg-Tube at Göttingen (KRG)

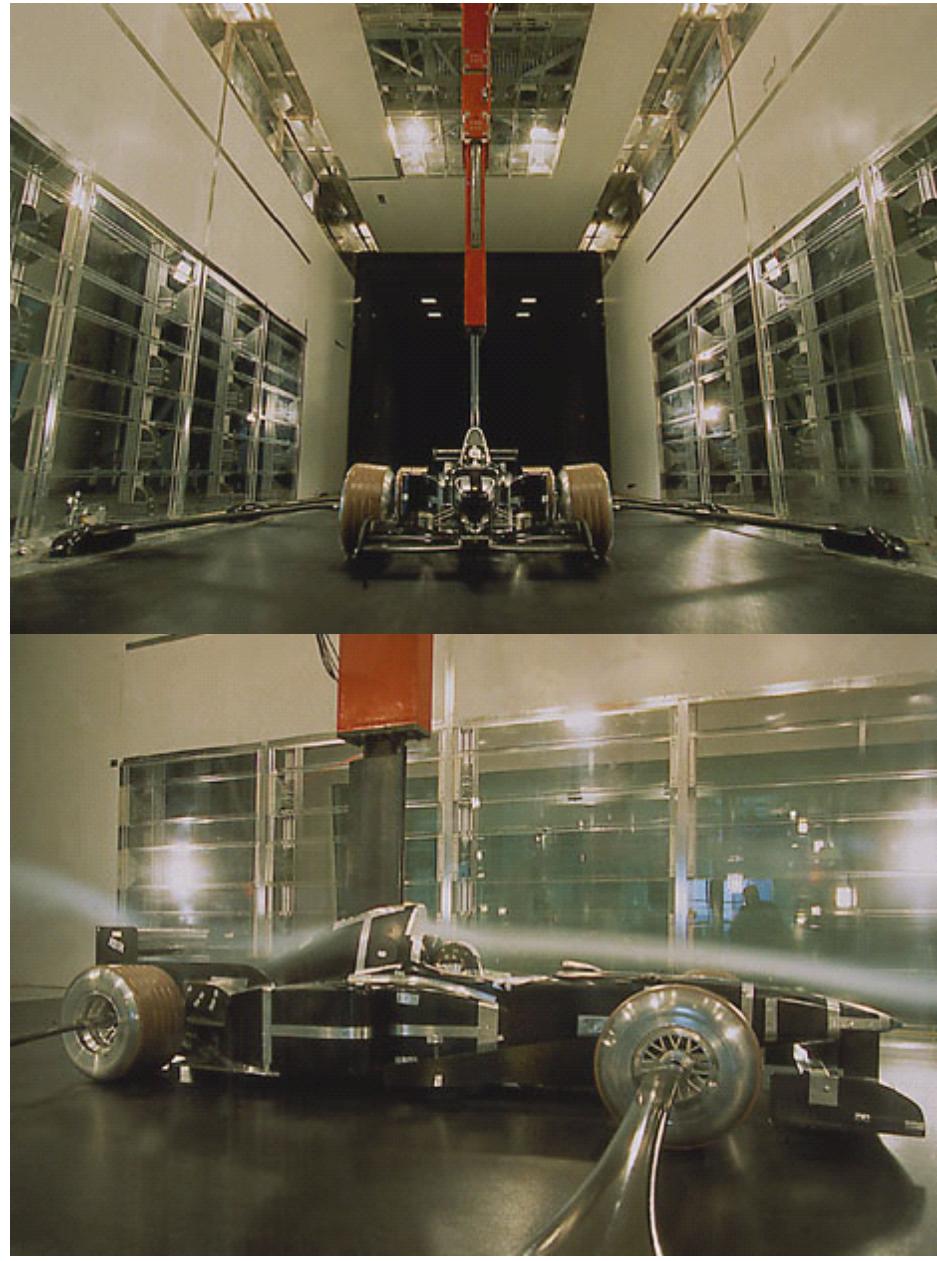


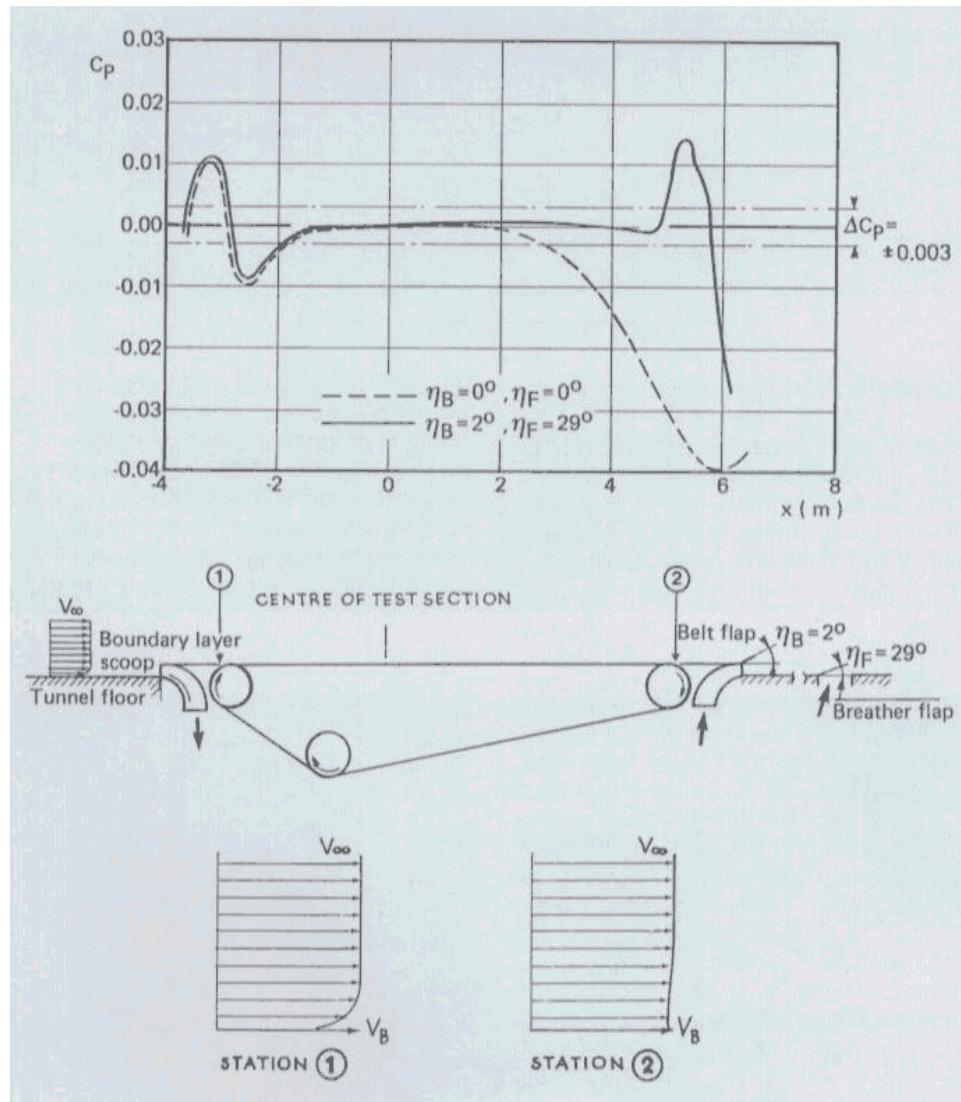
Tube	Diameter	0.8 m	Stagn. press. (max.)	10 bar
Test Section	Length	130 m	Temperature range	100 to 300 K
	Load. press. (max.)	12.5 bar	Mach number range	0.25 to 0.95
	Cross section	$0.4 \times 0.35 \text{ m}^2$	Reynolds no. (max.)	$60 \cdot 10^6$
	Length	2.0 m	Run time	0.6 to 1.0 s
	Model chord (typ.)	0.15 m		



Adaptive wall test section

# Automobile Wind Tunnels

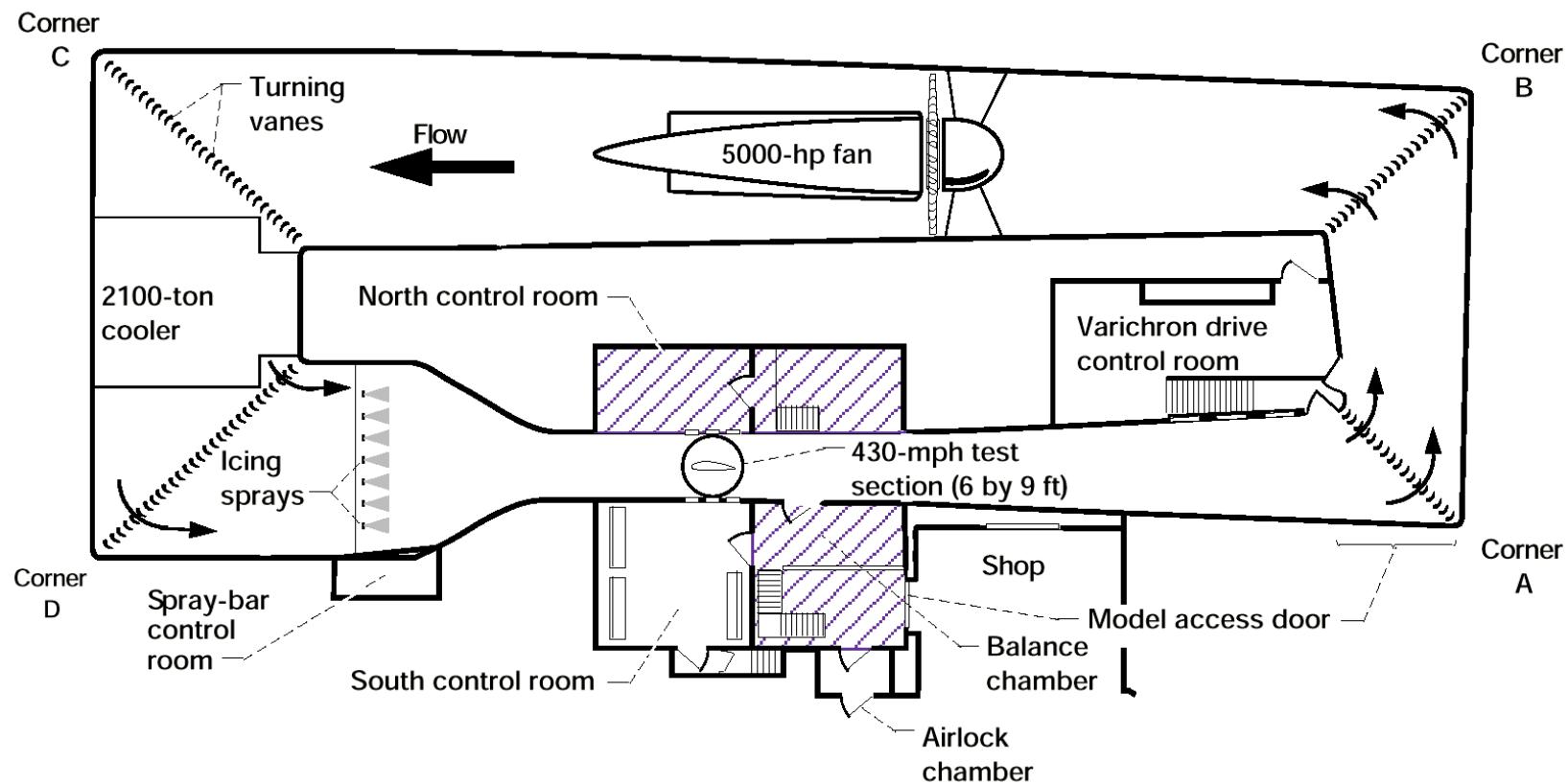


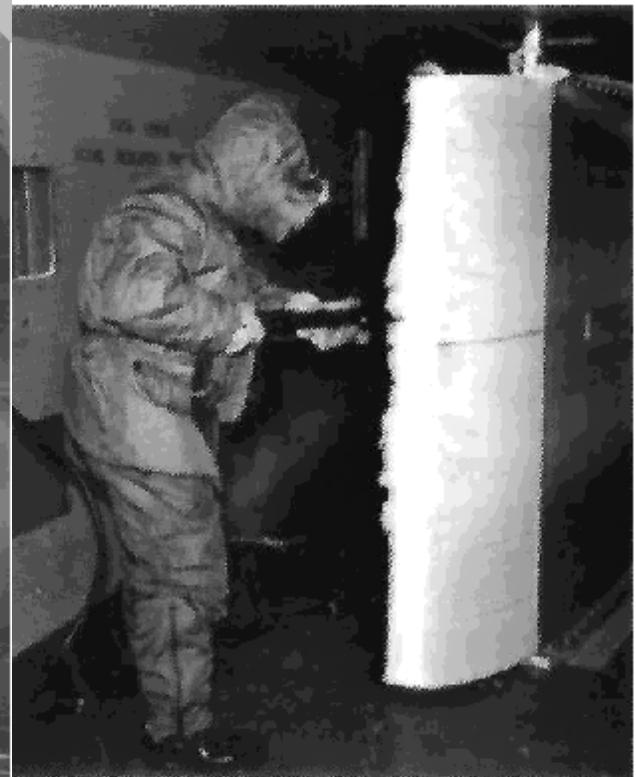
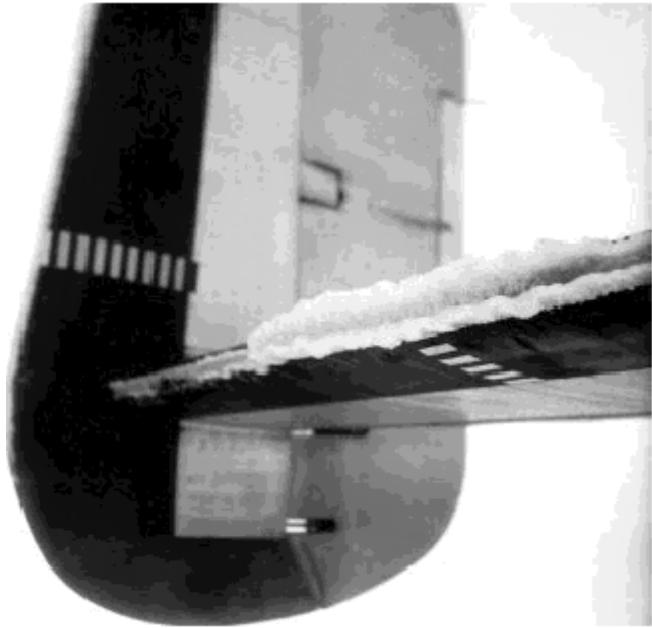


# Icing Wind Tunnels

# Icing Tunnel

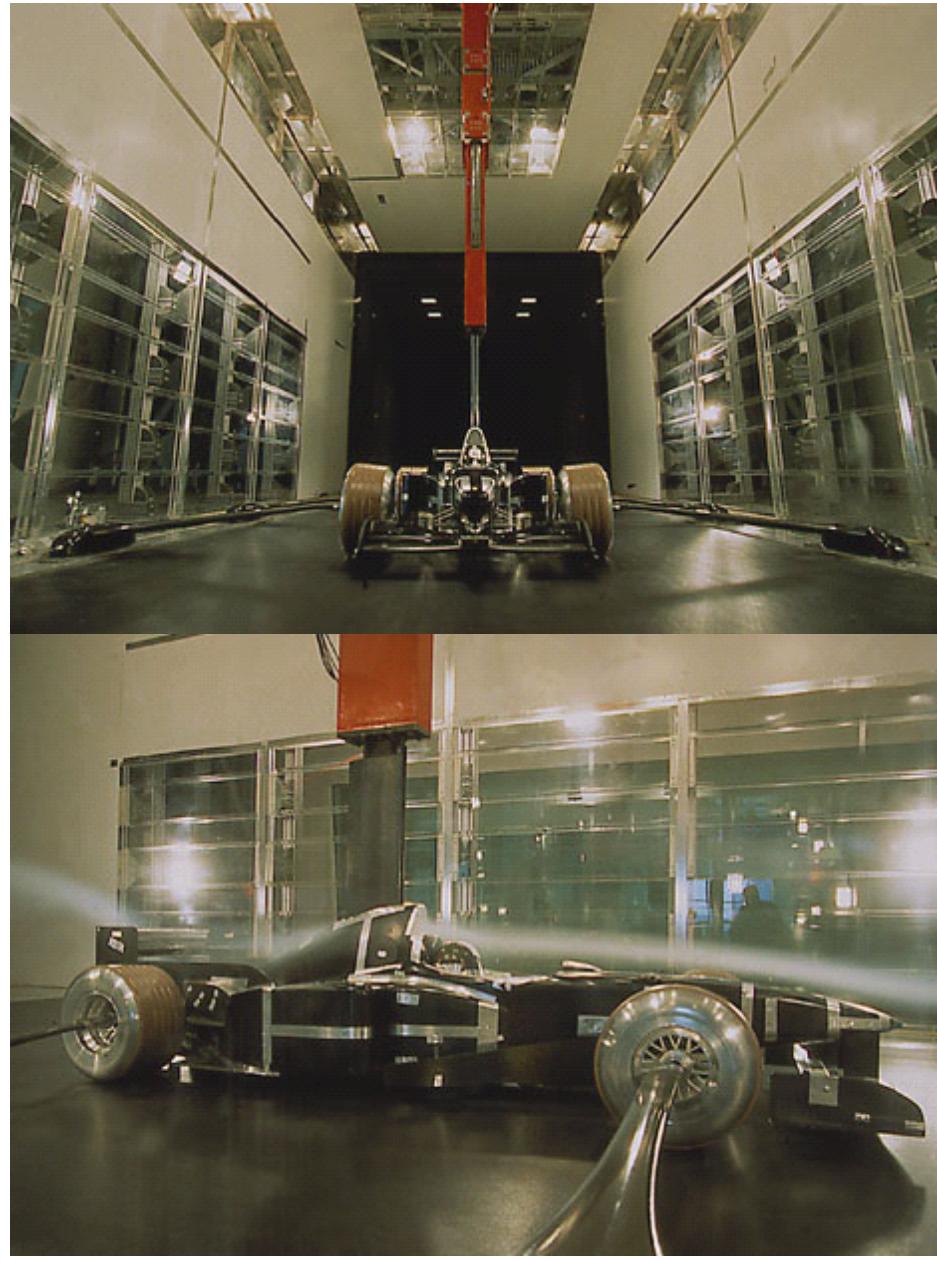
## NASA Lewis Research Center

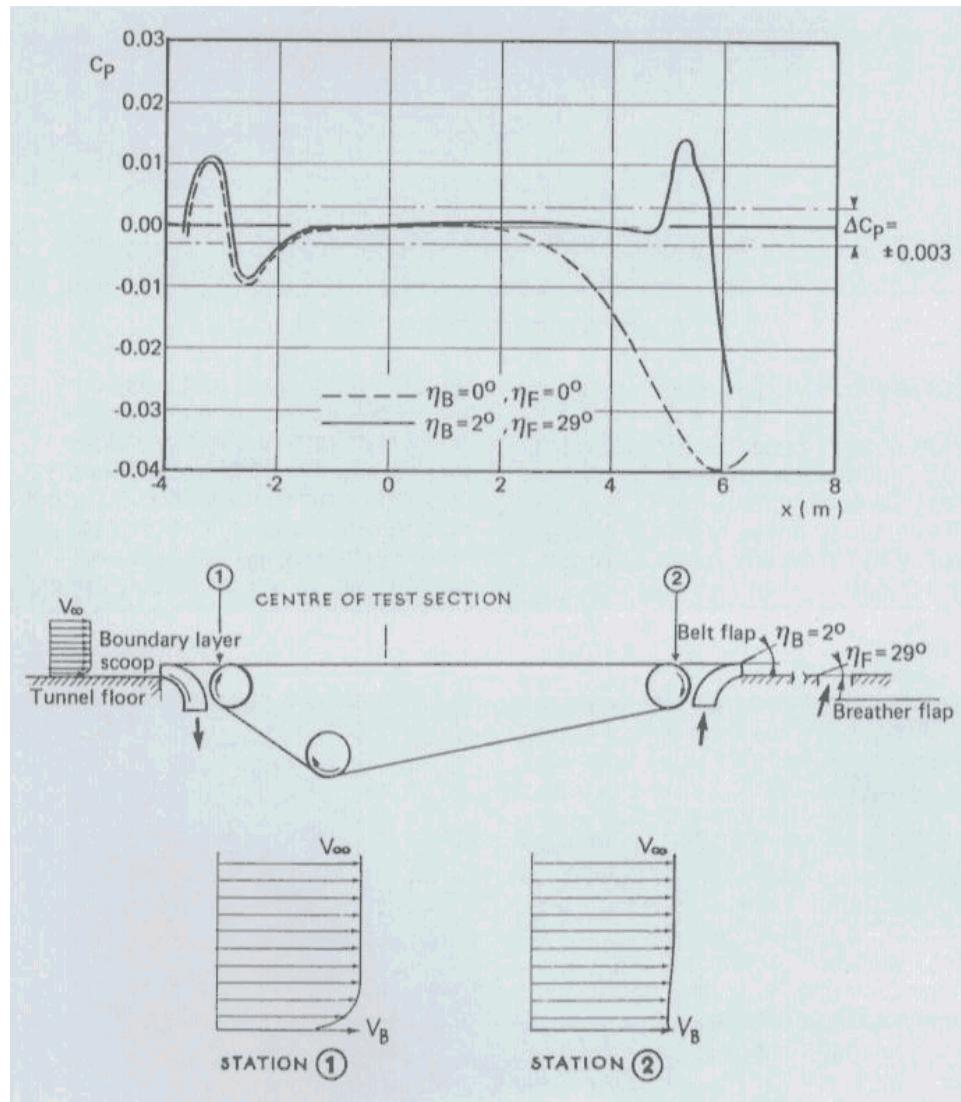




Wings

# Automobile Wind Tunnels





# Wind Tunnel Power Requirements

# Energy Ratio

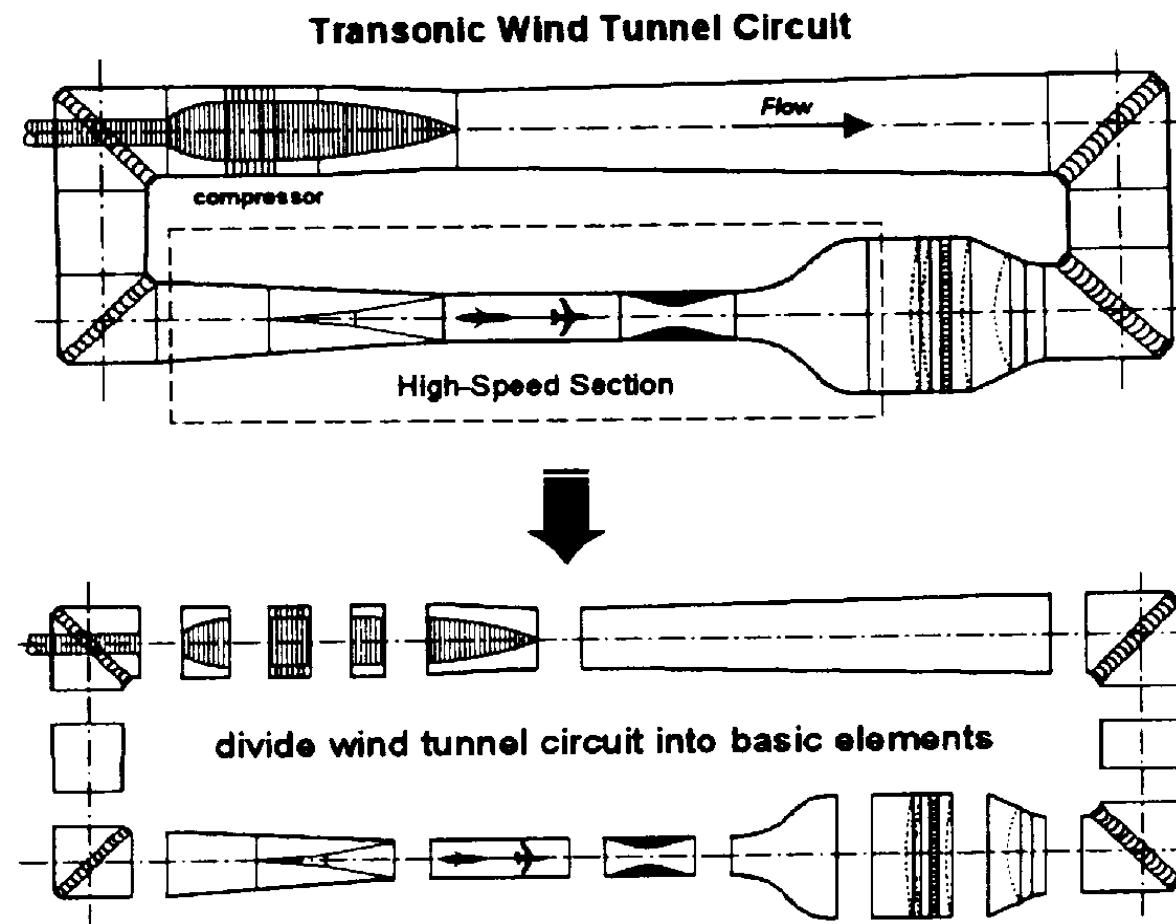
$$(E.R.)_t = \frac{\text{Jet Energy}}{\sum \text{Circuit Losses}} = \frac{1/2 \rho_0 U_0^3 A_0}{\sum \text{Losses}} = \frac{q_0 U_0 A_0}{\eta P}$$

Subscript 0 refers to the test section

P is the motor power

$\eta$  is the fan efficiency

# Wind Tunnel Circuit Elements



# Losses

$$K = \frac{p_{t1} - p_{t2}}{q}$$

Local Pressure Loss Coefficient

$$K_0 = \frac{p_{t1} - p_{t2}}{q_0} = K \frac{q}{q_0}$$

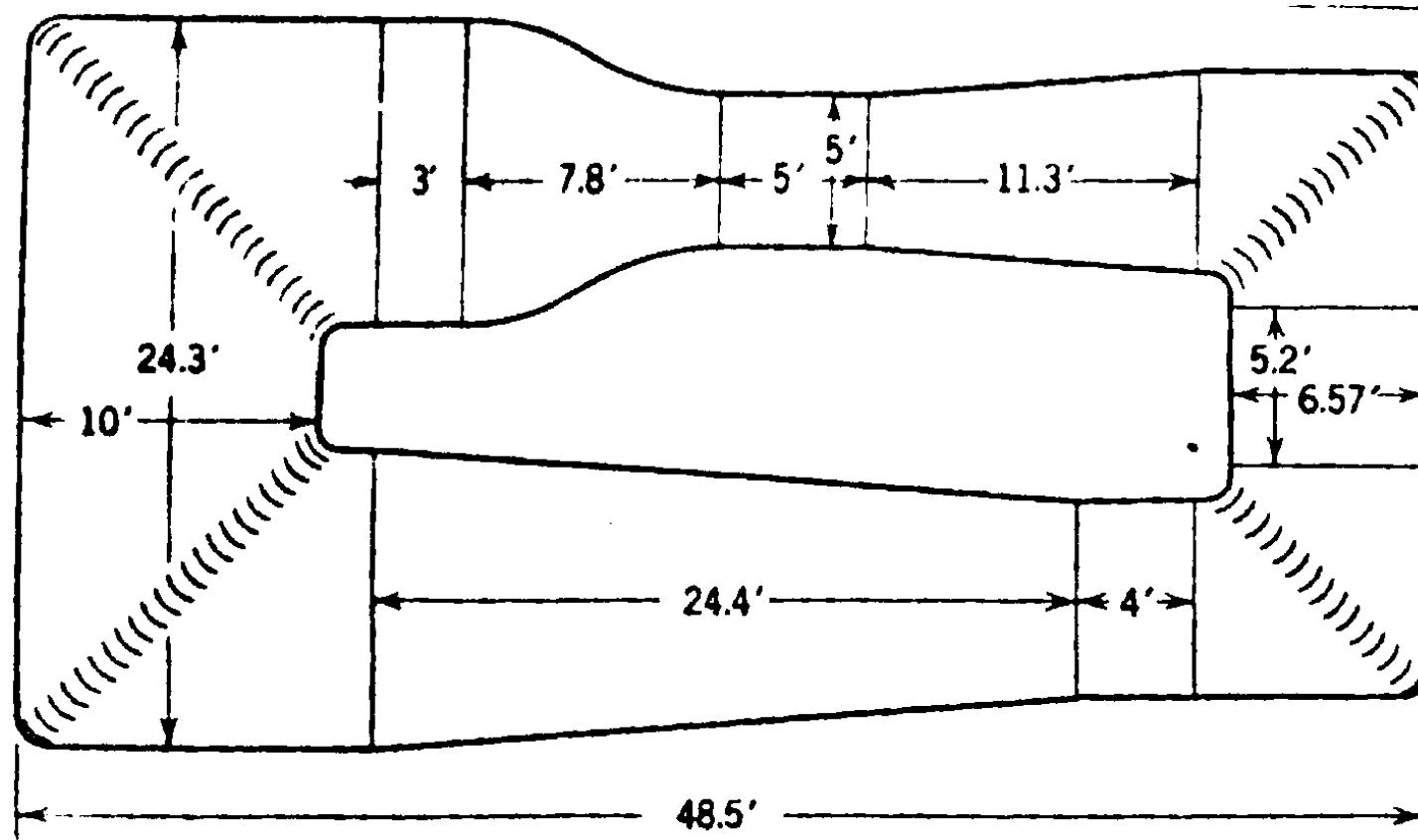
Pressure Loss Referred to Test Section

$$\Delta E = K_0 1/2 \rho_0 U_0^3 A_0$$

Section Energy Loss

$$(E.R.)_t = \frac{\text{Jet Energy}}{\sum \text{Circuit Losses}} = \frac{1/2 \rho_0 U_0^3 A_0}{\sum K_0 1/2 \rho_0 U_0^3 A_0} = \frac{1}{\sum K_0}$$

# Closed Return Tunnel



# Example - Closed Return Tunnel

	Section	Ko	% Total Loss
1	Test Section	.0093	5.1
2	Diffuser	.0391	21.3
3	Corner #1	.0460	25.0
4	Straight Section	.0026	1.4
5	Corner #2	.0460	25.0
6	Straight Section	.0020	1.1
7	Diffuser	.0160	8.9
8	Corner #3	.0087	4.7
9	Corner #4	.0087	4.7
10	Straight Section	.0002	.1
11	Contraction	.0048	2.7
	<b>Total</b>	<b>.1834</b>	<b>100.0</b>

$$(E.R.)_t = \frac{1}{\sum K_0} = \frac{1}{.1834} = 5.45$$

# Example - Open Return Tunnel

	<b>Section</b>	<b>K<sub>o</sub></b>	<b>% Total Loss</b>
1	Inlet Including Screens	.021	14.0
2	Contraction and Test Section	.013	8.6
3	Diffuser	.080	53.4
4	Discharge at Outlet	.036	24.0
	<b>Total</b>	<b>.150</b>	<b>100.0</b>

$$(E.R.)_t = \frac{1}{\sum K_0} = \frac{1}{.150} = 6.67$$

# Turbulence Management System

Stilling Section - Low speed and uniform flow

Honeycomb - Reduces Large Swirl Component of Incoming Flow

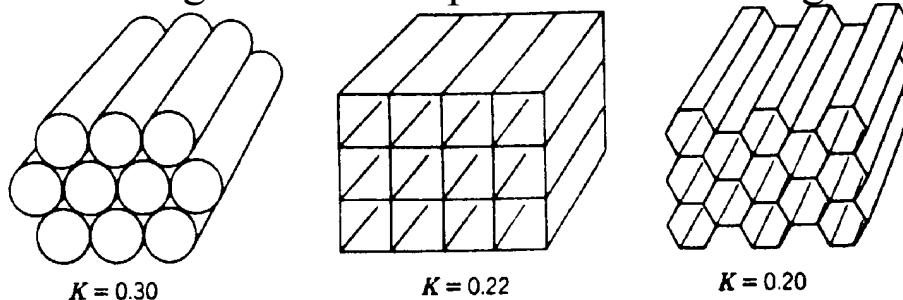
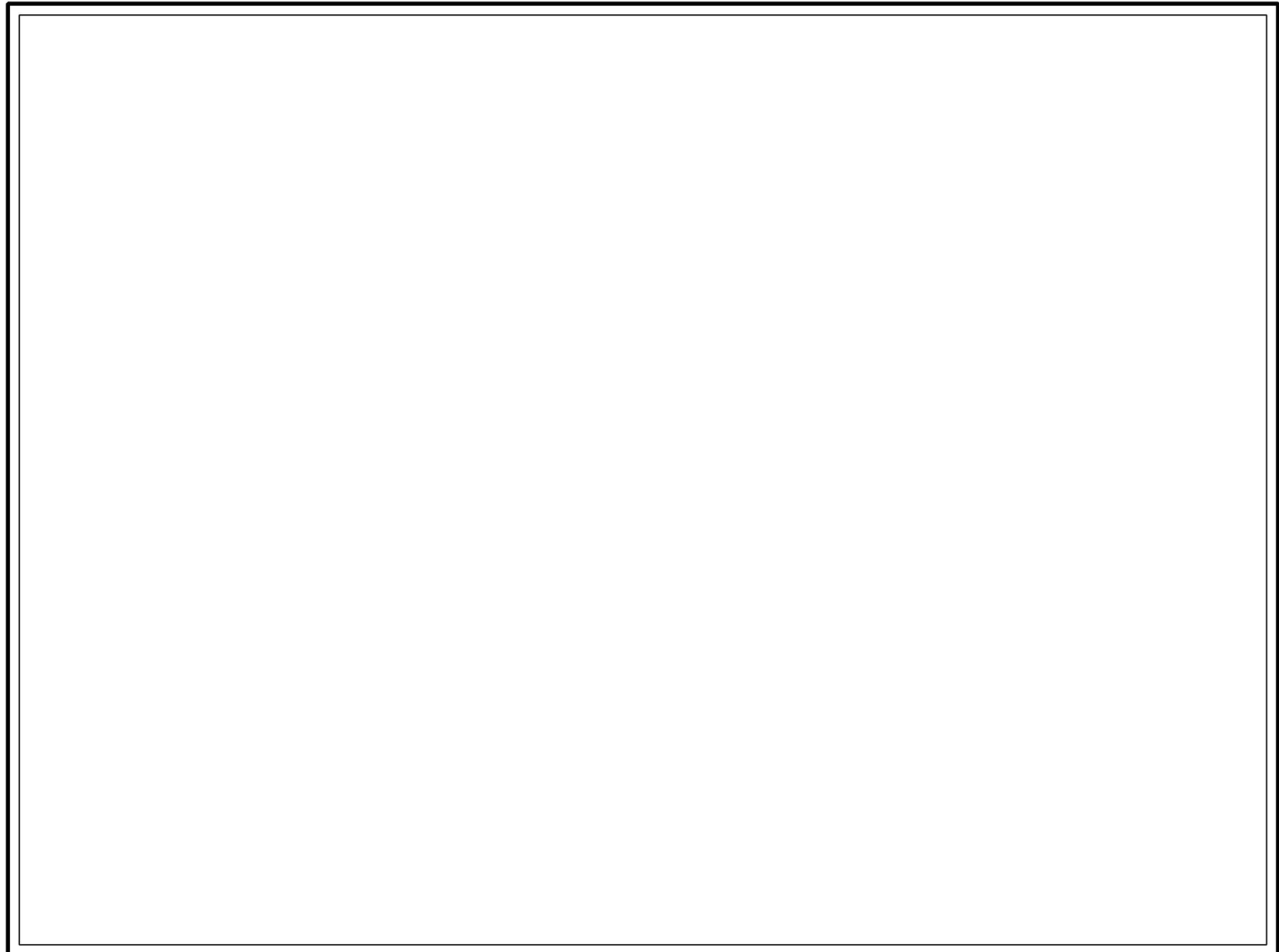


Fig. 2:16 Some honeycombs and their losses.

- Screens
- Reduce Turbulence [Reduces Eddy size for Faster Decay]
  - Used to obtain a uniform test section profile
  - Provide a flow resistance for more stable fan operation



# Contraction

Establish Uniform Profile at Test Section  
Reduce Turbulence

# Test Section

Test Section - Design criteria of Test Section Size and Speed Determine Rest of Tunnel Design

Test Section Reynolds Number

Larger JET - Lower Speed - Less Power - More Expensive

Section Shape - Round-Elliptical, Square, Rectangular-Octagonal with flats for windows-mounting platforms

Rectangular with filled corners

Not usable but requires power

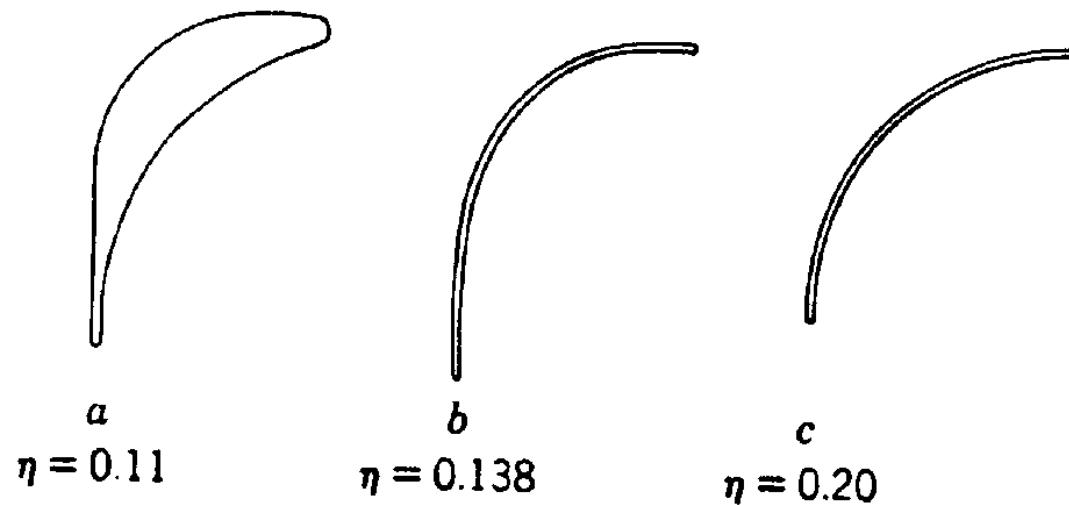
For Aerodynamics Testing 7x10 Height/Width Ratio

Test Section Length -  $L = (1 \text{ to } 2)w$

# Diffuser

# Corners

Abrupt Corner without Vanes  $\eta = 1.0$



# Speed Control

Fan