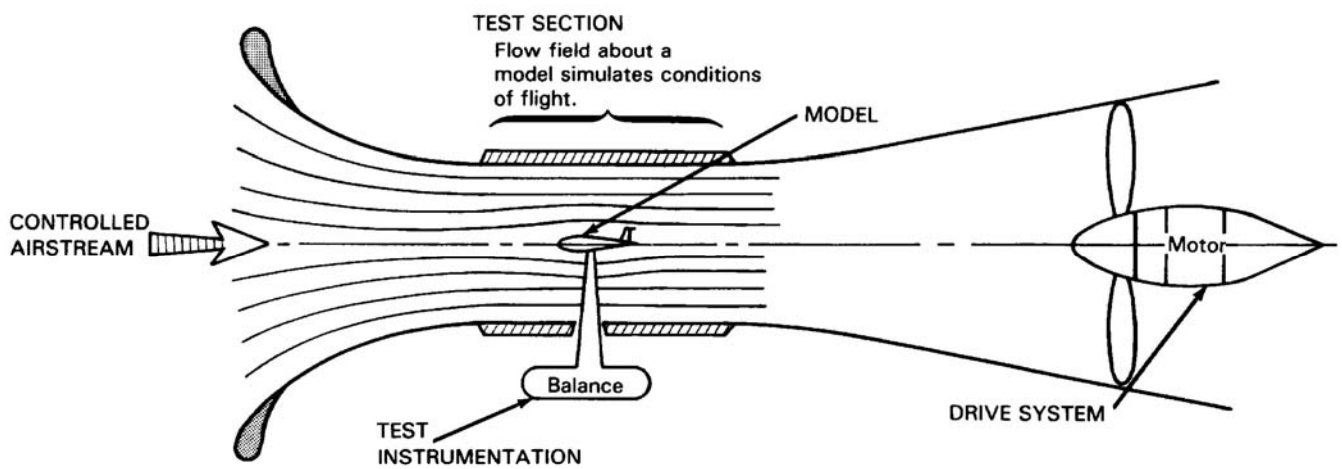
Wind Tunnels

Ashish J. Modi

Wind Tunnels

- Objective
  - Accurately simulate the fluid flow about atmospheric vehicles
  - Measure -Forces, moments, pressure, shear stress, heat transfer, flowfield (velocity, pressure, vorticity, temperature)

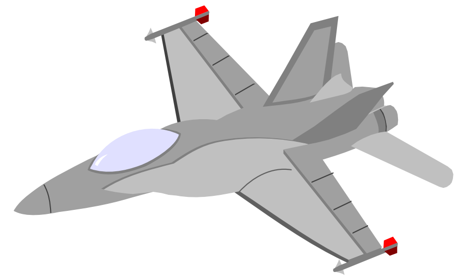


Compressible vs. Incompressible Flow

- A flow is classified as incompressible if the density remains nearly constant.
- Liquid flows are typically incompressible.
- Gas flows are often compressible, especially for high speeds.
- Mach number, Ma = V/c is a good indicator of whether or not compressibility effects are important.
  - Ma < 0.3 : Incompressible
  - Ma < 1 : Subsonic
  - Ma = 1 : Sonic
  - Ma > 1 : Supersonic
  - Ma >> 1 : Hypersonic

Low Speed Vehicles - M<.3

U_∞ ←



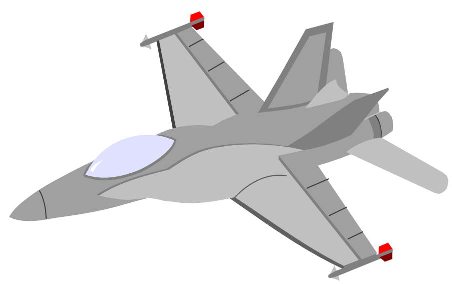
Gallilean Transformation

Flight in atmosphere
Scale =L

Wind Tunnel - Model Scale = ℓ

Stationary Walls

U_∞ →



Issues

Flow Quality - Uniformity and Turbulence Level

Wind Tunnel Wall Interference

Reynolds Number Simulation

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

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 0.7<M<1.2

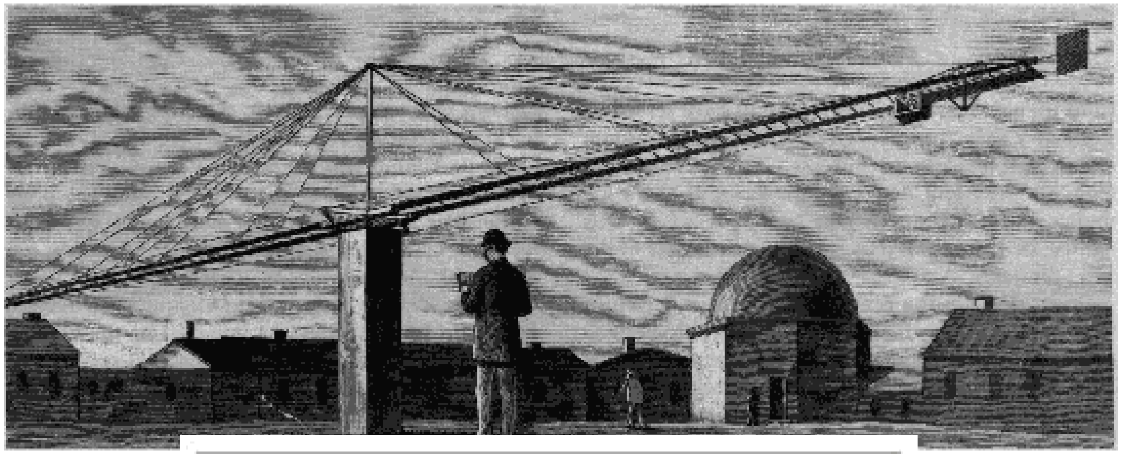
- Must Match Reynolds Number and Mach Number

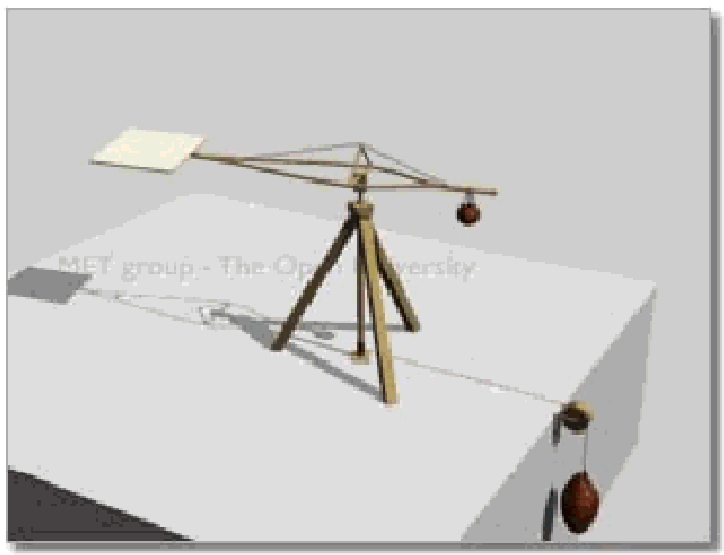
$$\mathrm{Re} = \frac{\rho U_{\infty} L}{\mu}$$

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

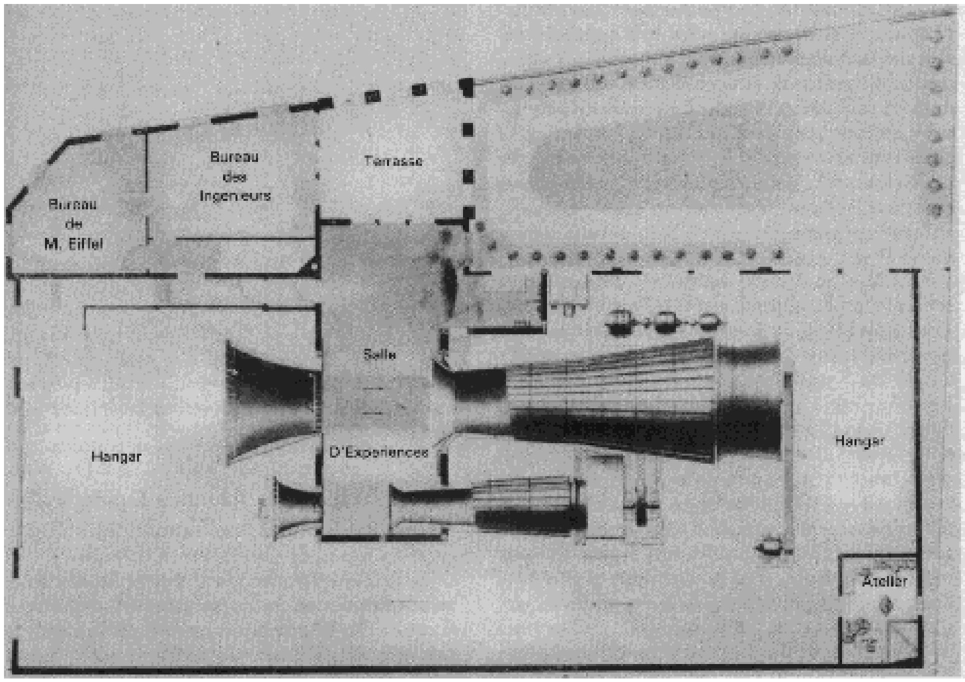
Must change fluid density and viscosity to match Re and M
Cryogenic Wind Tunnels are designed for this reason

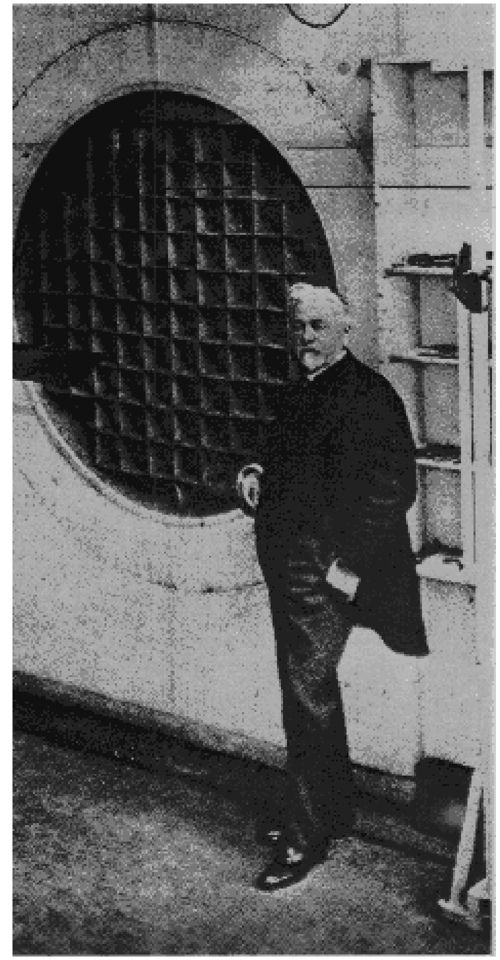
History Whirling Arm



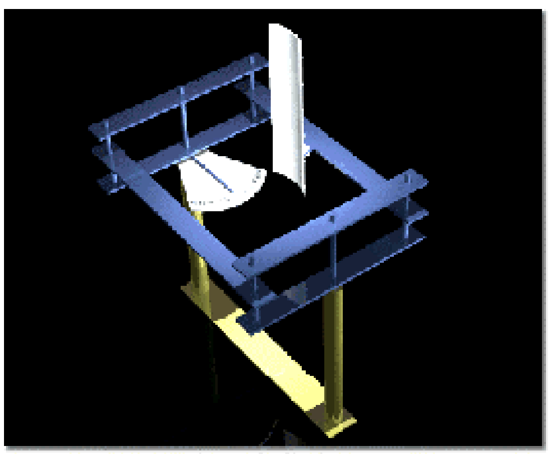


Eiffel Tunnel

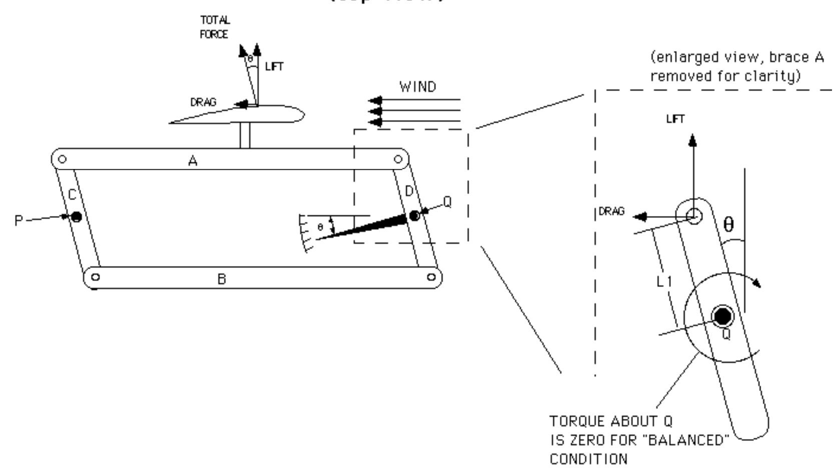




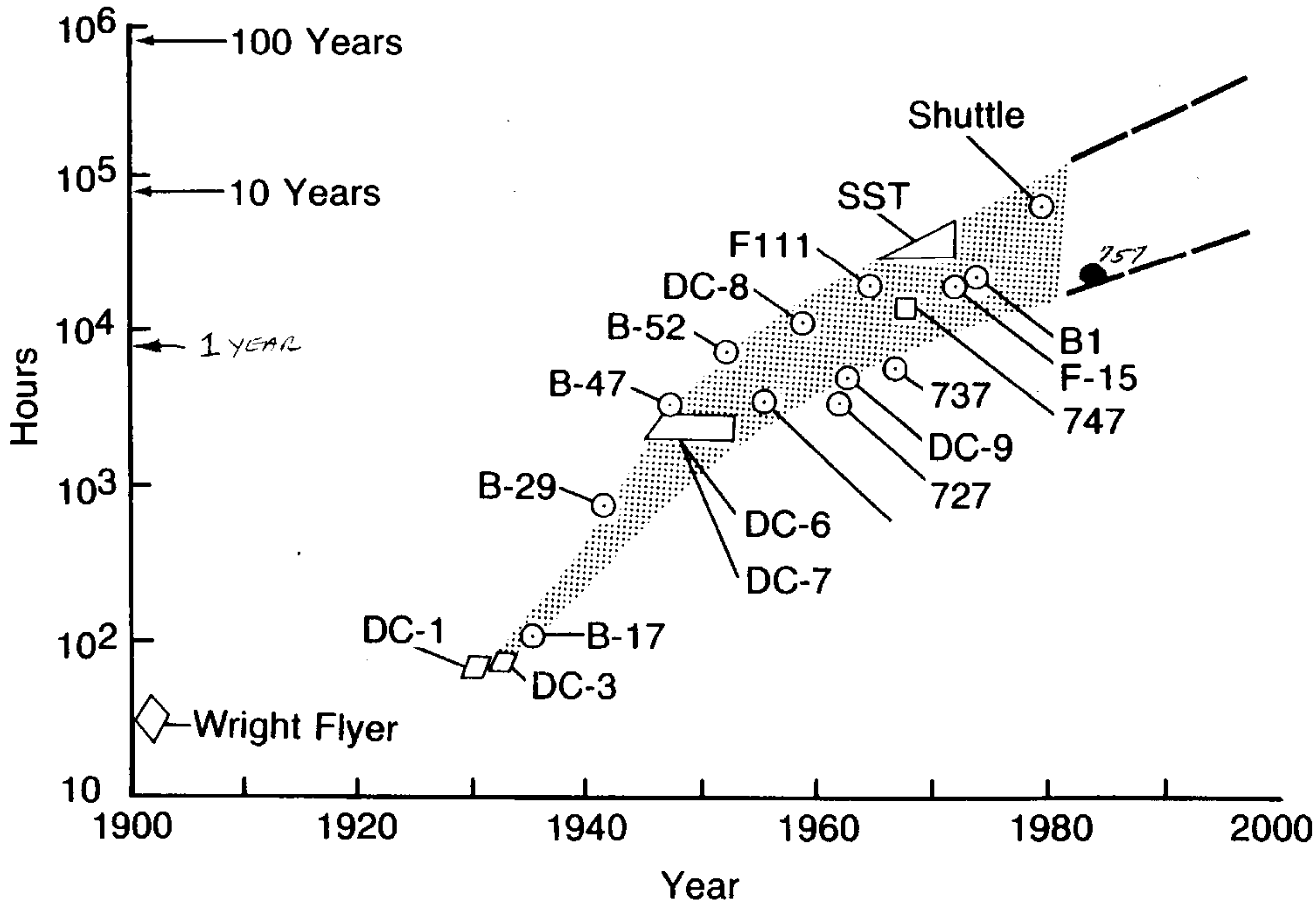
Wright Brothers



The Wright Brother's "Drift" Balance
(top view)



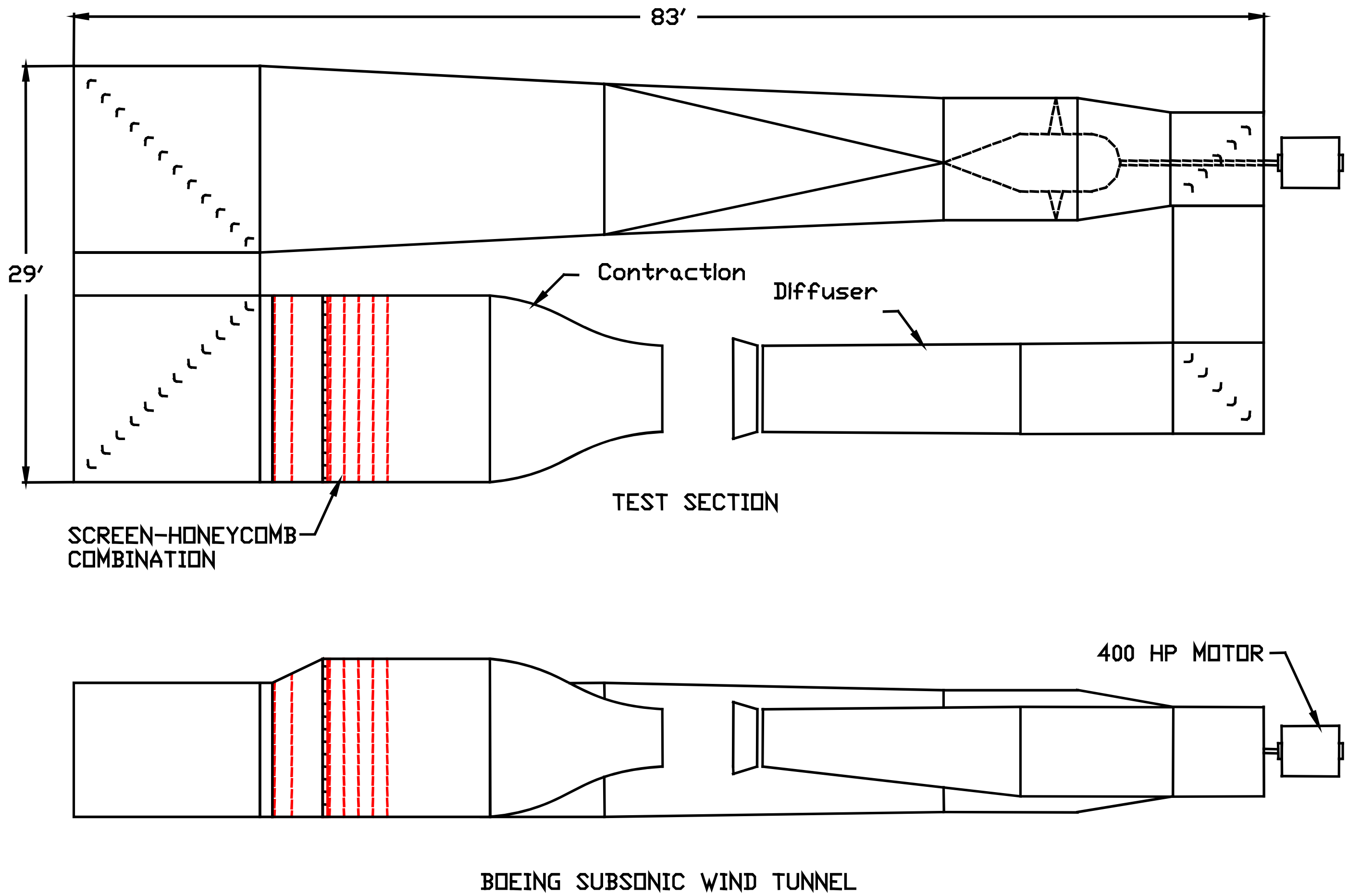
Wind Tunnel Test Trend



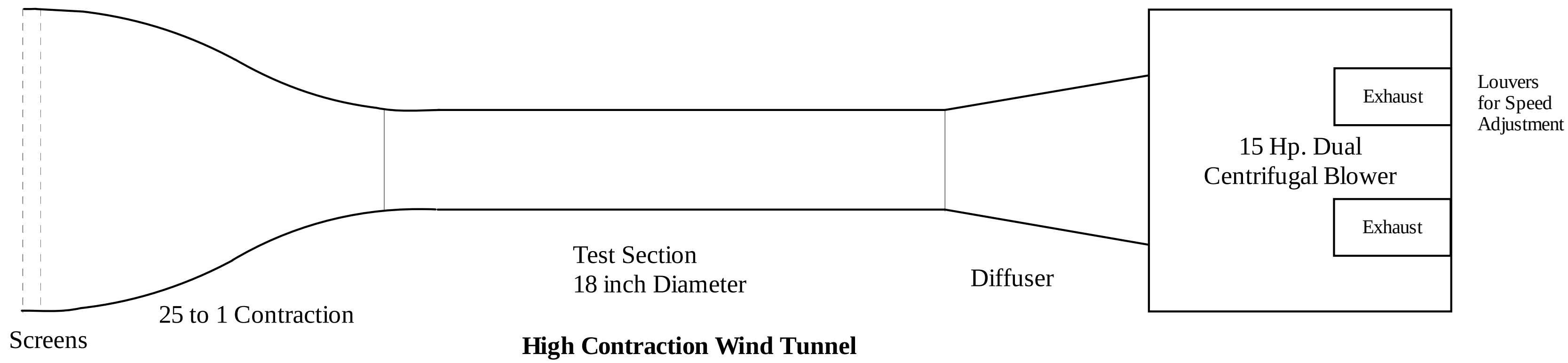
Wind Tunnel Layout

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

Closed Return
(open test section)

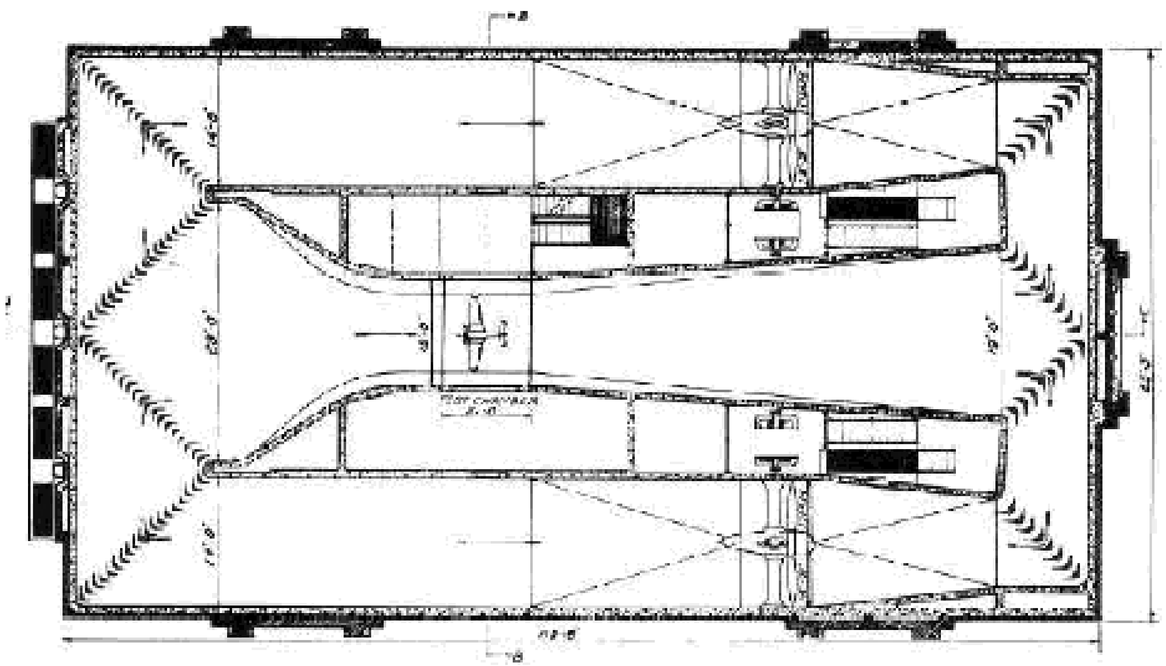


Open Return
Closed Test Section



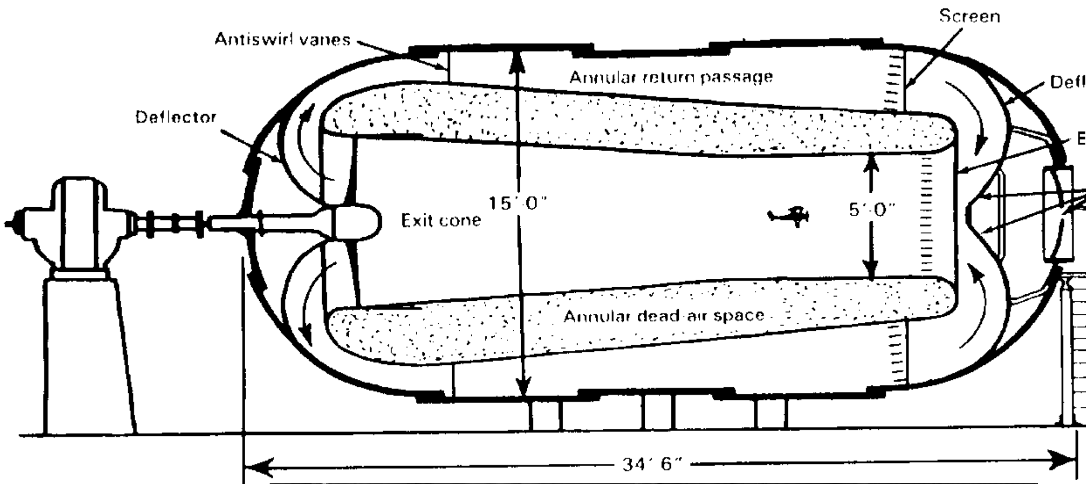
High Contraction Wind Tunnel
Top View

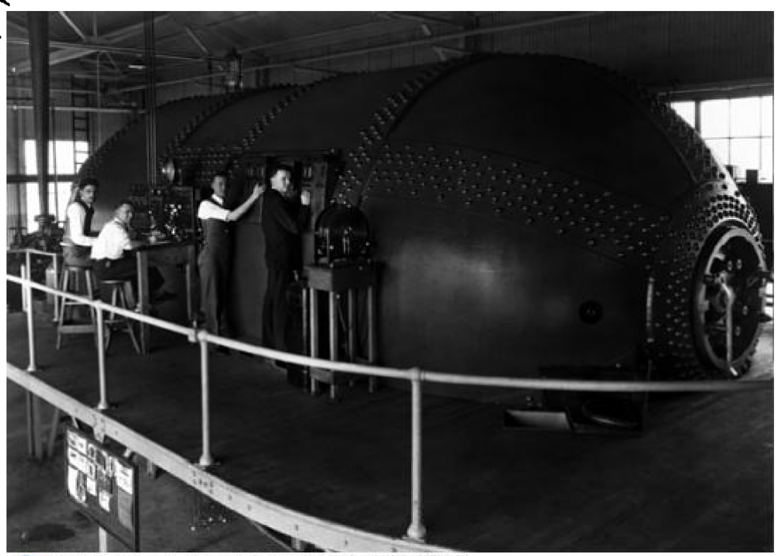
Double Return



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: 3×10^6

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

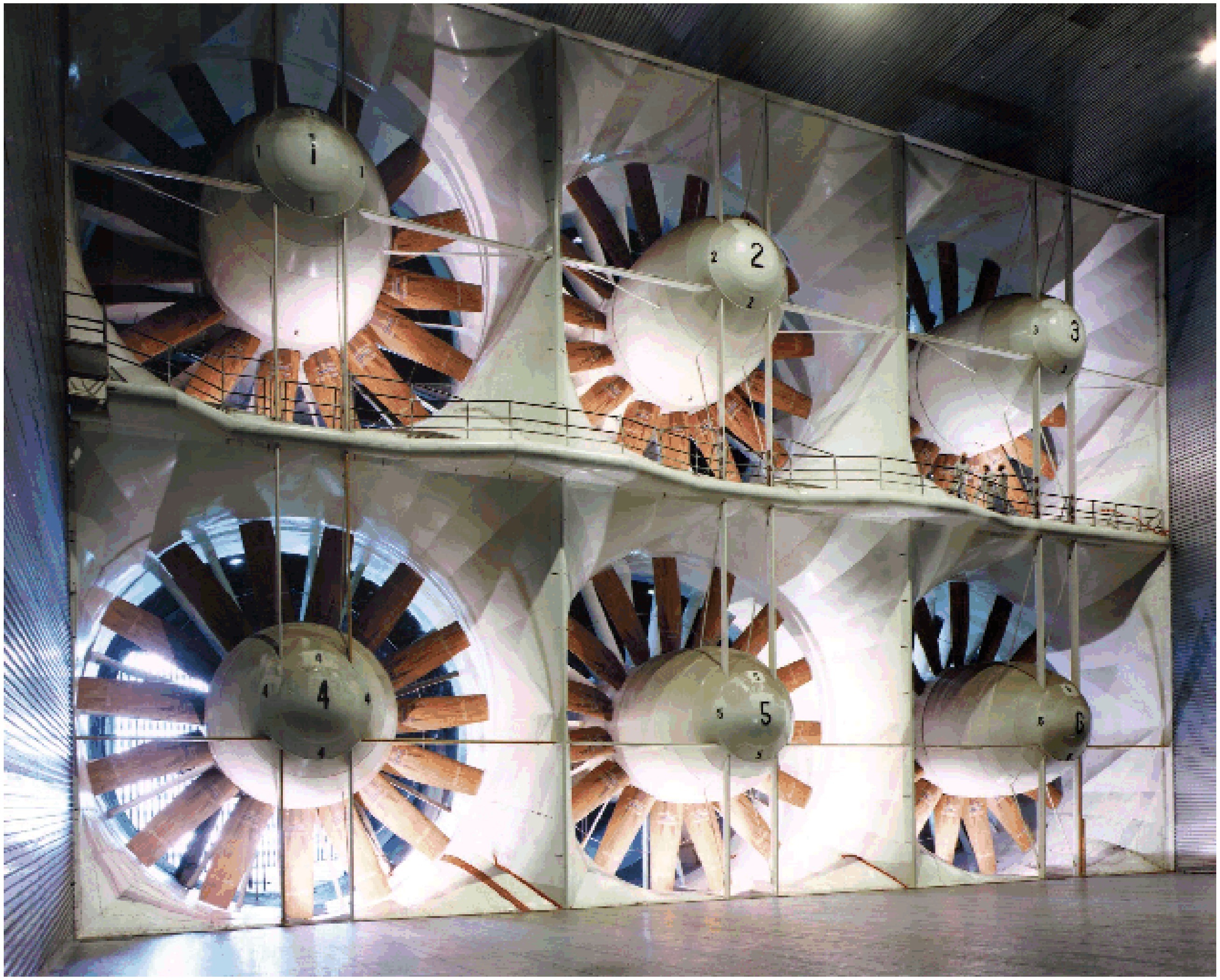
Reynolds Number per foot: 1.2×10^6

Stagnation Pressure: Atmospheric

Temperature Range: 485 ° - 580 ° R

Indraft, continuous flow, closed throat wind tunnel

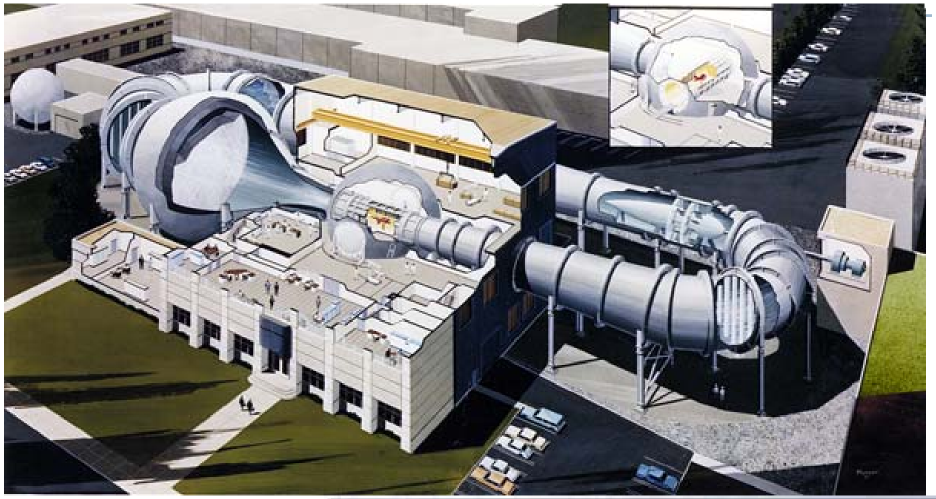
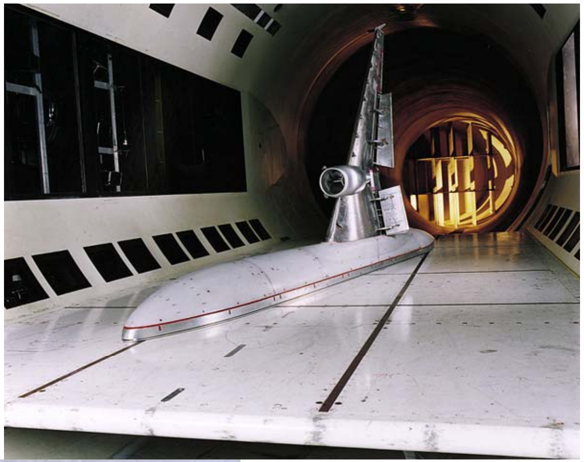
Fans for 40x80 and 80x120

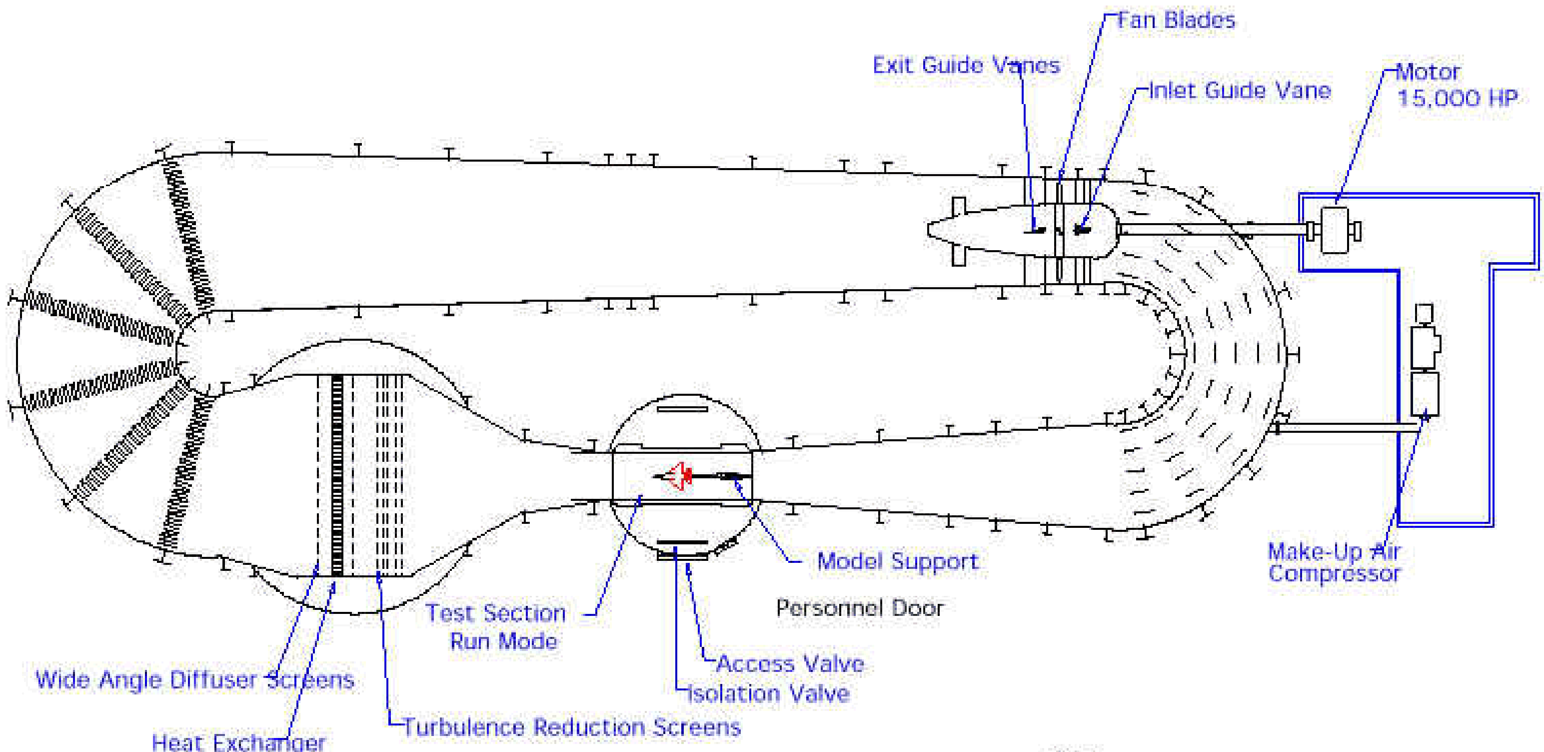


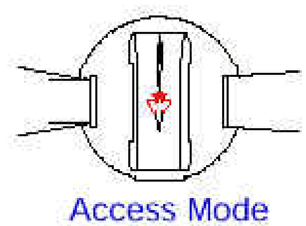
40’x80’

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: $0.1 - 12X10^6$
- 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)

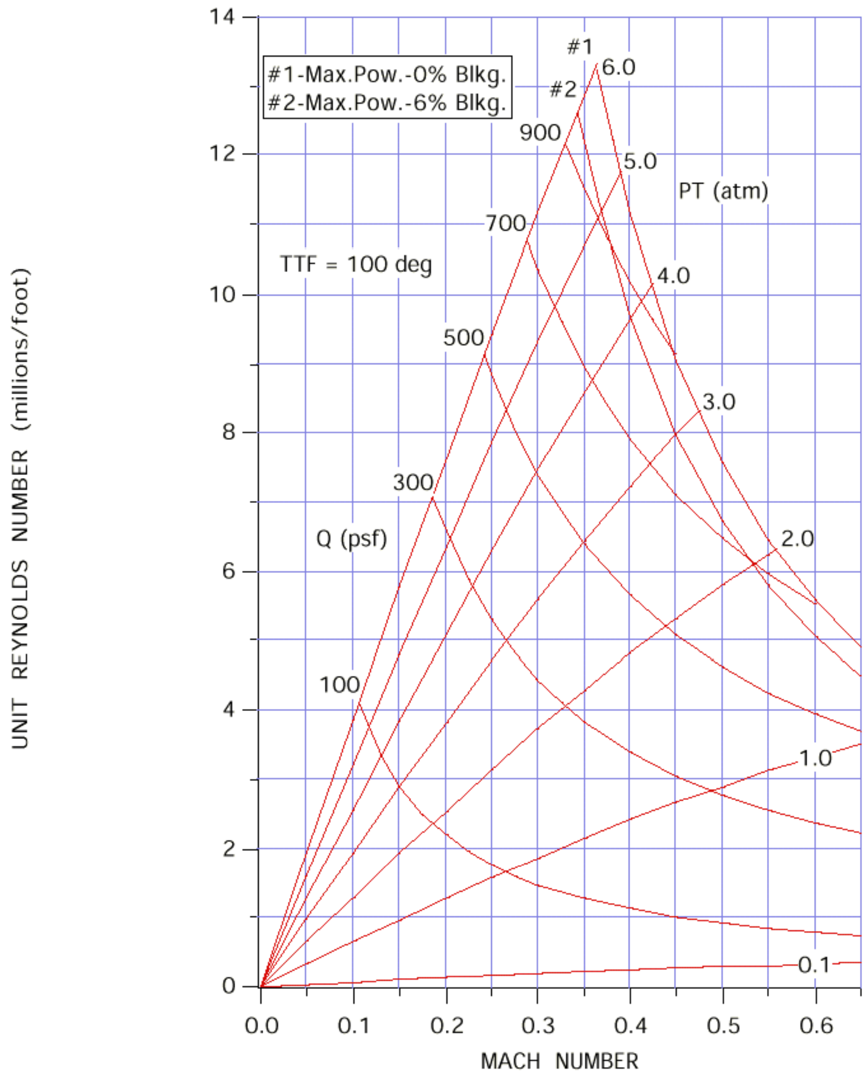


Figure 2-5. 12-Foot PWT Performance Chart

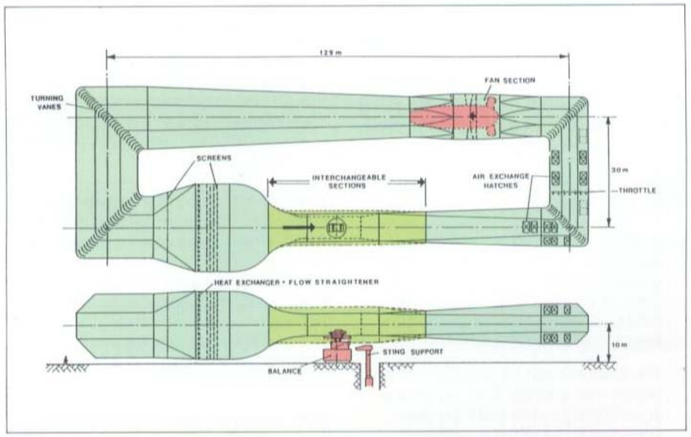


Fig. 3

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

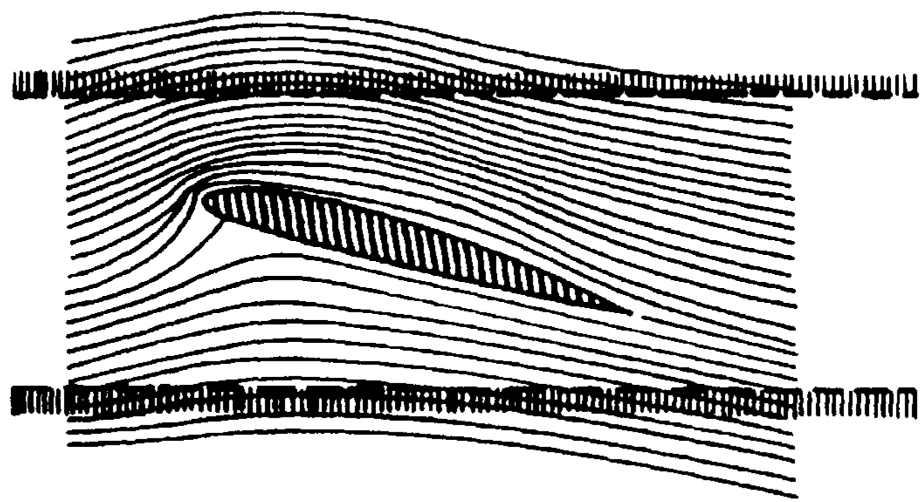
Wall interference is a severe problem for transonic wind tunnels.

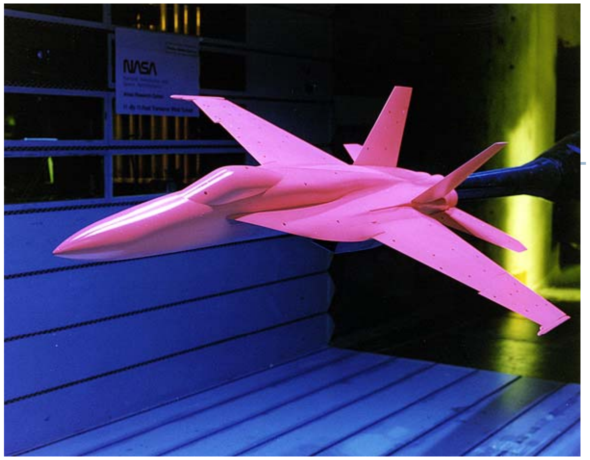
Flow can “choke”

- Shock wave across the tunnel test section

Two Solutions

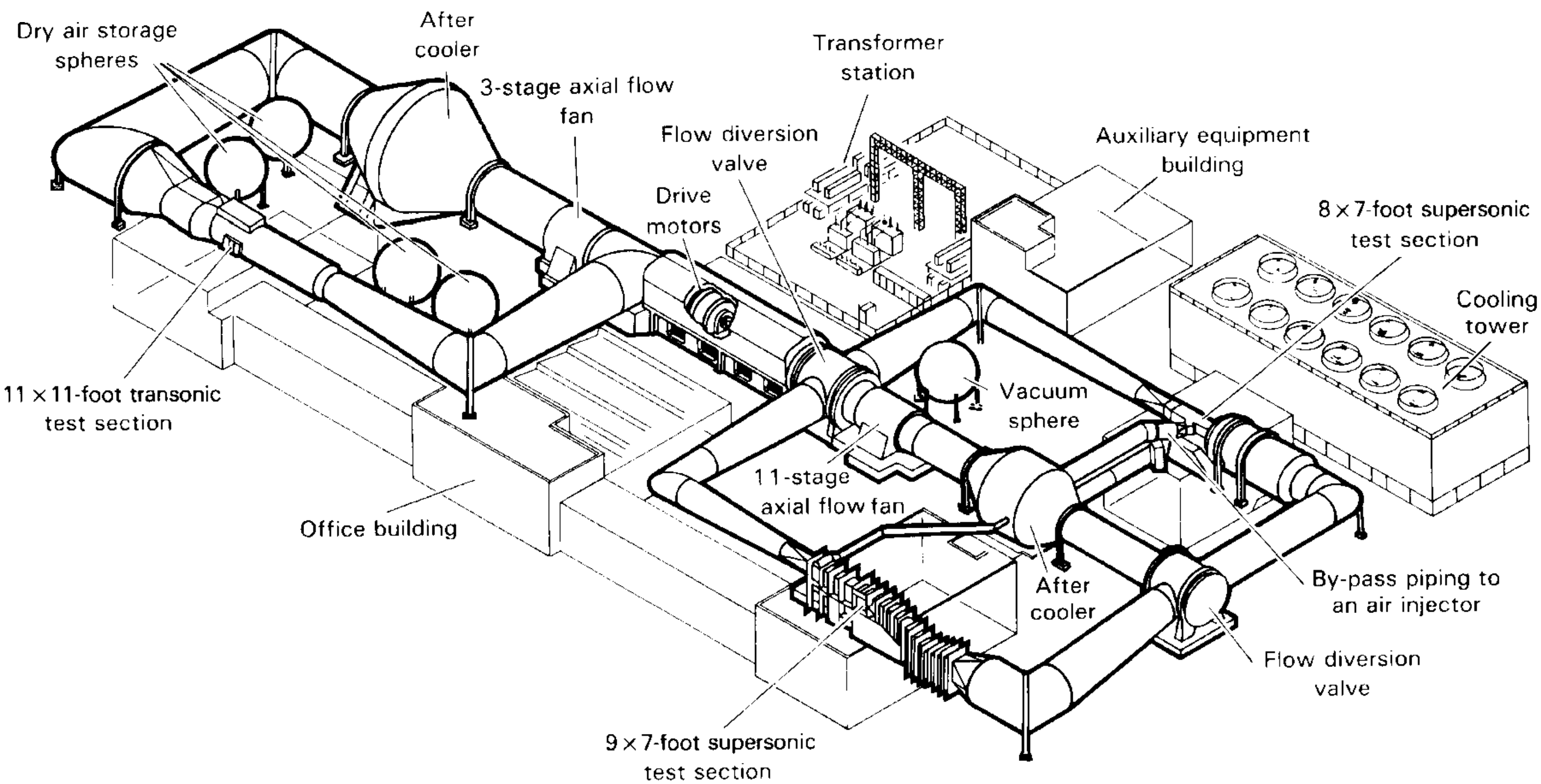
- Porous Walls
- Movable Adaptive Walls





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.

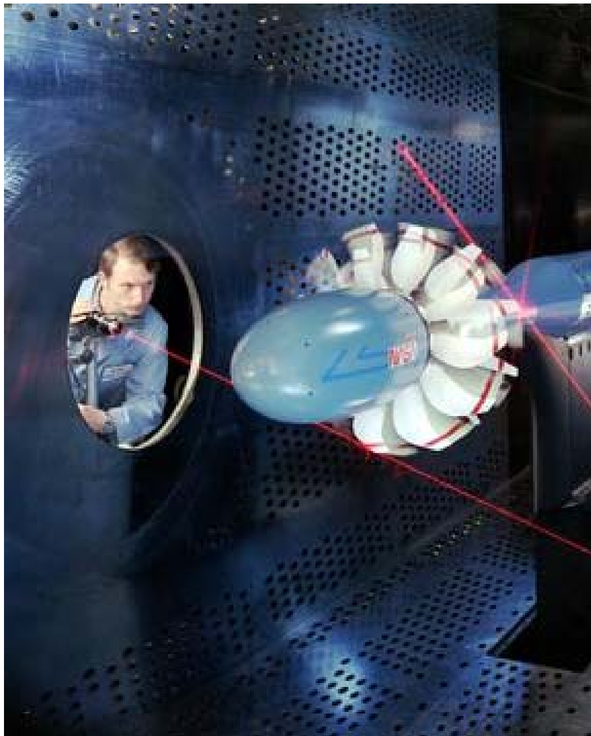
8x6 Functions & Capabilities

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

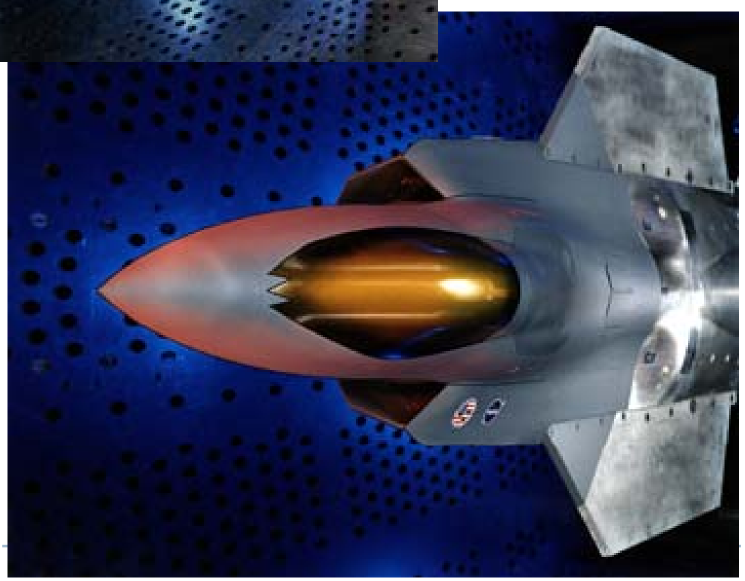
- In a continuous Mach 0-2.0 airstream
- At varying Reynolds Numbers (3.6 - 4.8 x 106/ft) and altitude conditions (ambient to 38,000ft)
- In either aerodynamic (closed) or Propulsion (open) cycle without exhaust scoops
- Employing high data systems to support steady and transient data acquisition
- Supported 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 x 106/ft
Stagnation Pressure	15.3 - 25 psia
Temperature	60 - 250^{o}F



8x6 at
NASA Lewis

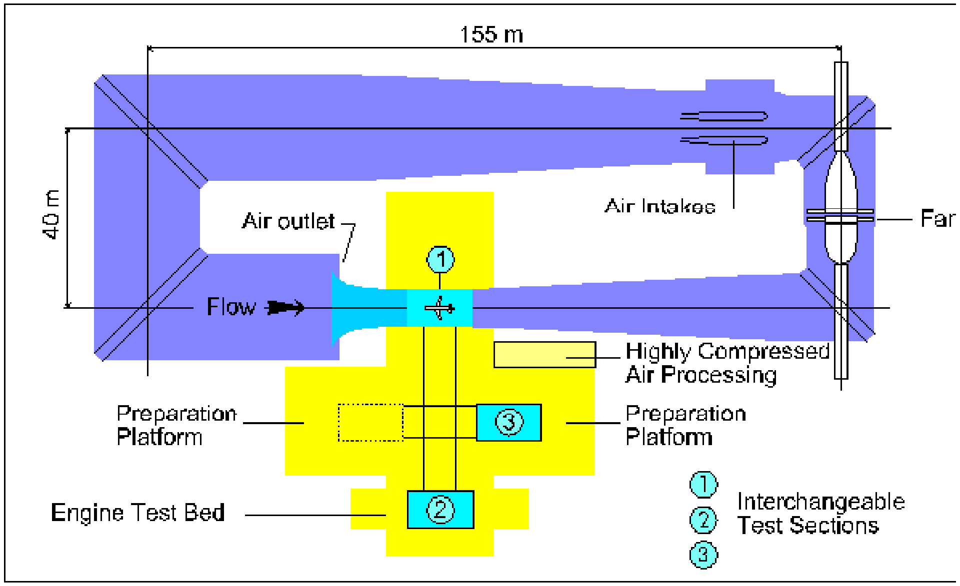


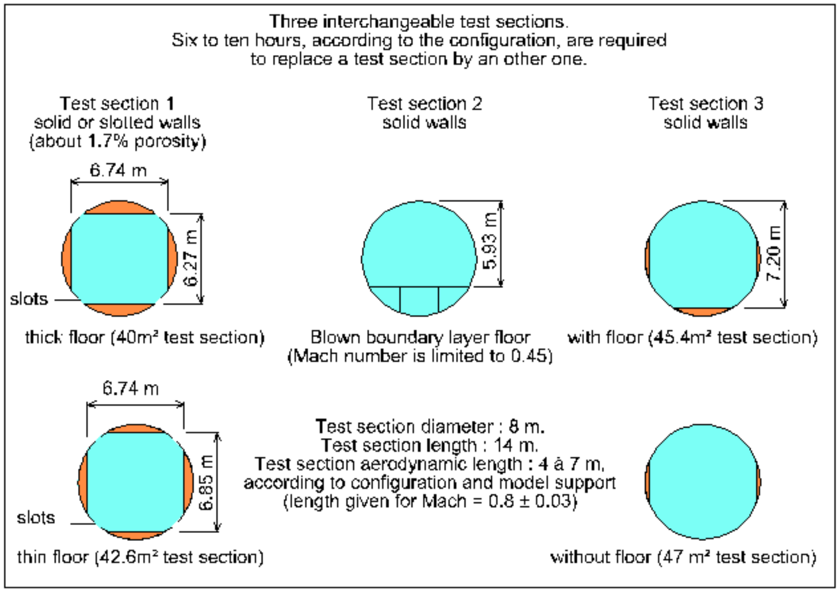
9x15 at NASA Lewis
Back Leg of the 8x6

Modane-Avrieux

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.

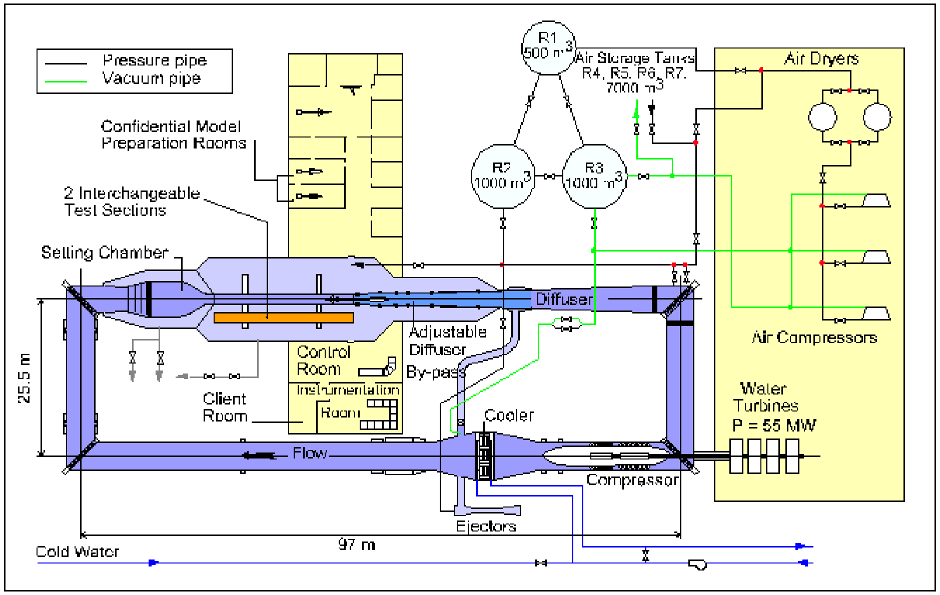


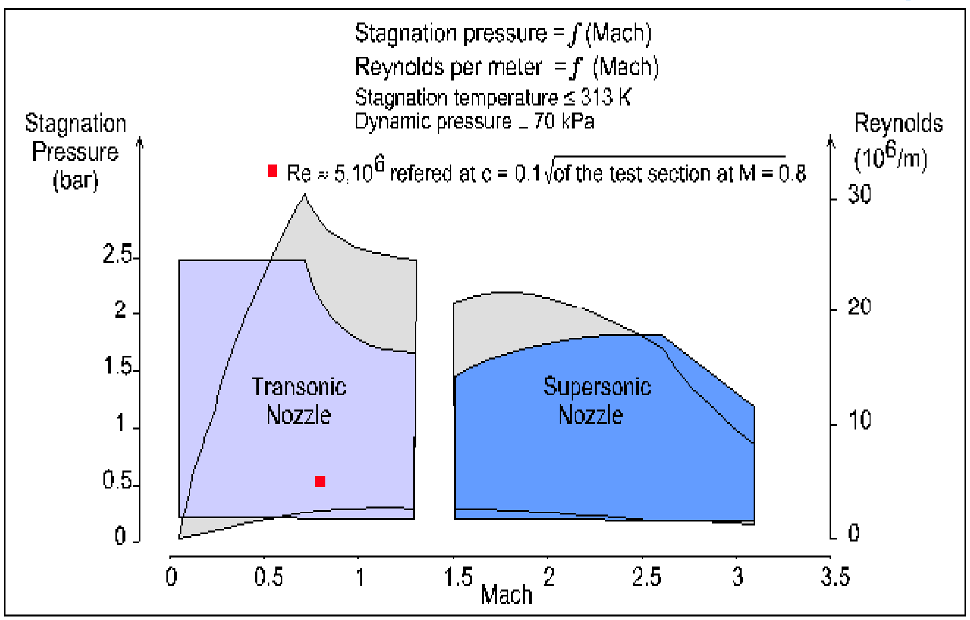


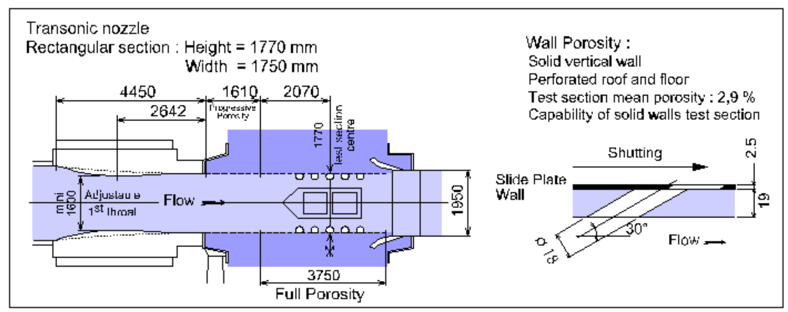
A model of Boeing's 767 commercial jet undergoes testing in one of AEDC's large wind tunnels. The 767 tests were the first in a series of tests of Boeing's large commercial jets at the center. AEDC signed a twenty year alliance with Boeing to test commercial aircraft.

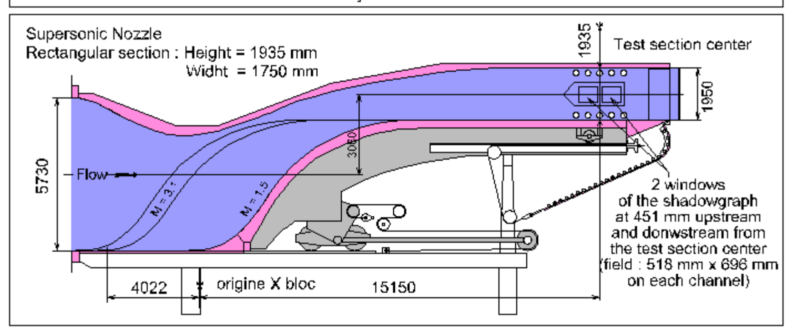
16T at AEDC

S2Ma Wind Tunnel









Supersonic Wind Tunnels

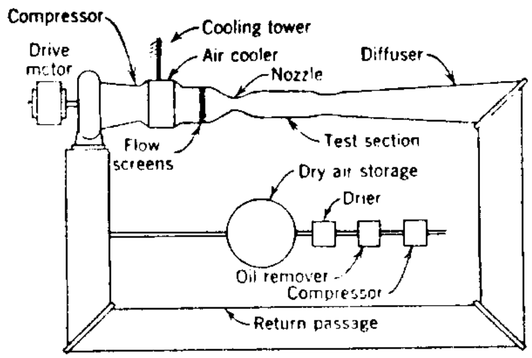


Fig. 1:1 Diagrammatic layout of closed-circuit, continuous flow, supersonic wind tunnel.

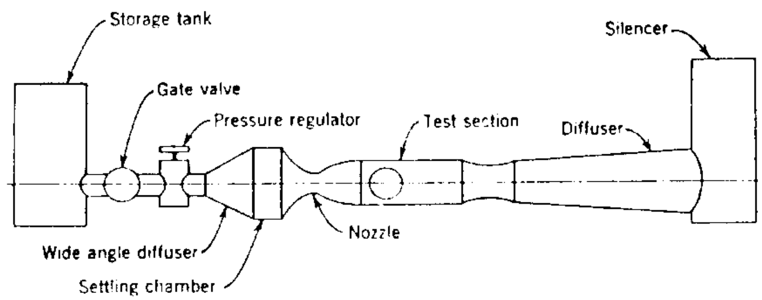


Fig. 1:2 Diagrammatic layout of intermittent blowdown tunnel.

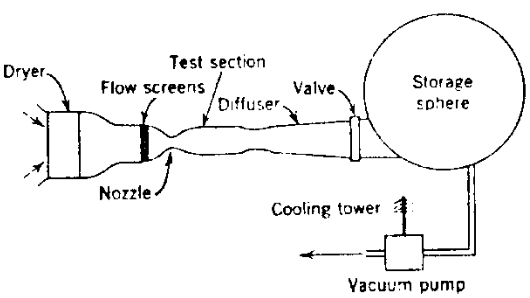
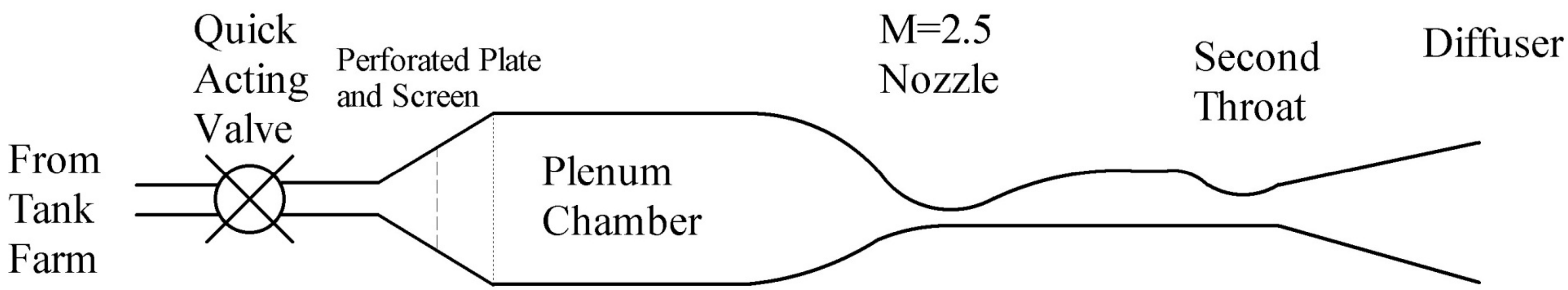
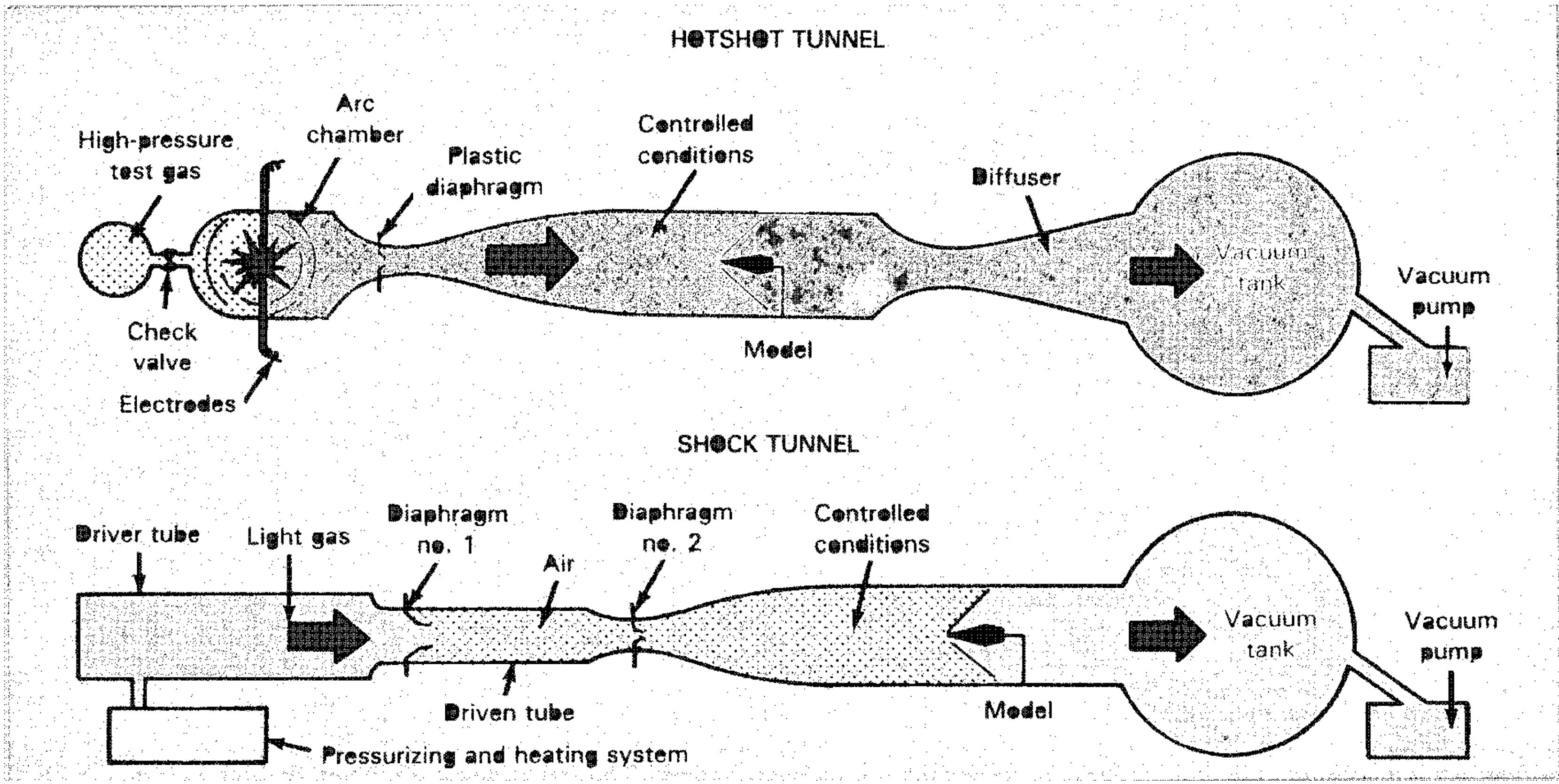


Fig. 1:3 Diagrammatic layout of intermittent indraft wind tunnel.

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

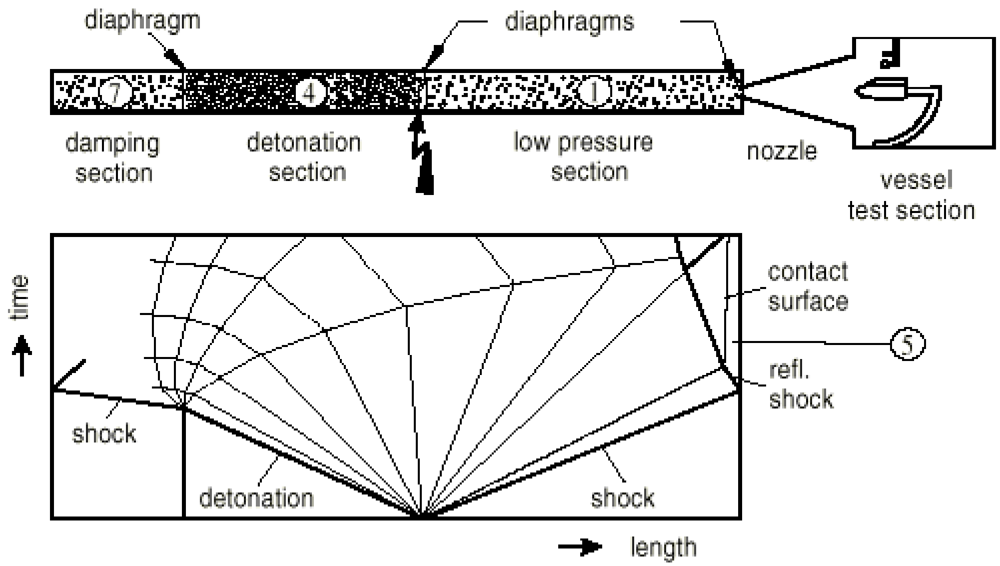


Hypersonic Wind Tunnels


HOTSHOT TUNNEL
High-pressure test gas
Arc chamber
Plastic diaphragm
Controlled conditions
Diffuser
Vacuum tank
Vacuum pump
Check valve
Electrodes
Model
SHOCK TUNNEL
Driver tube
Light gas
Diaphragm no. 1
Air
Diaphragm no. 2
Controlled conditions
Vacuum tank
Vacuum pump
Driven tube
Model
Pressurizing and heating system

Principle Operation Detonation Driven Shock Tunnel

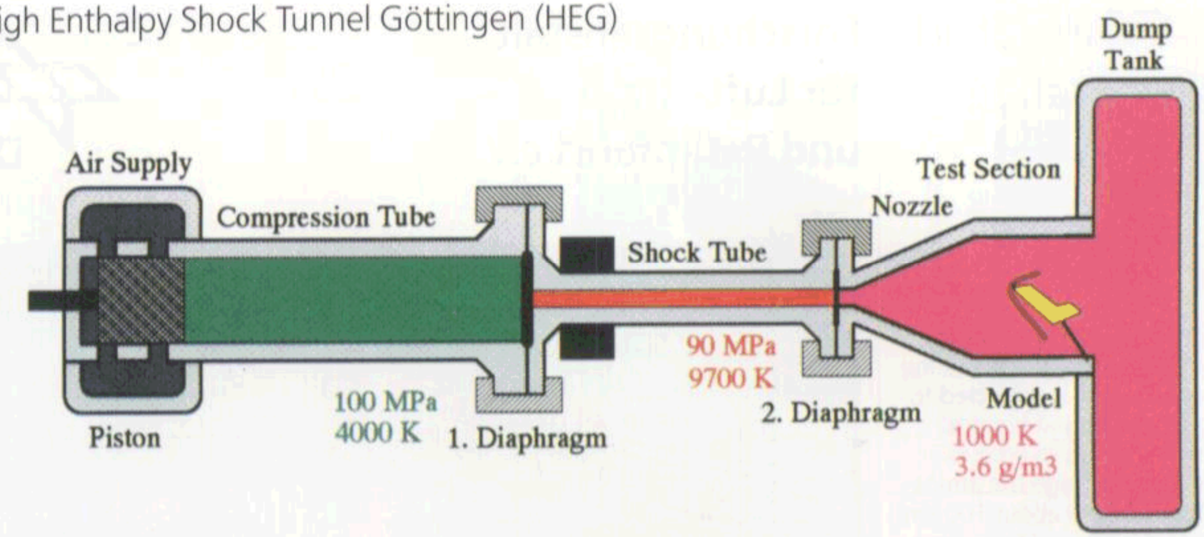
Set- up and wave plan:



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)

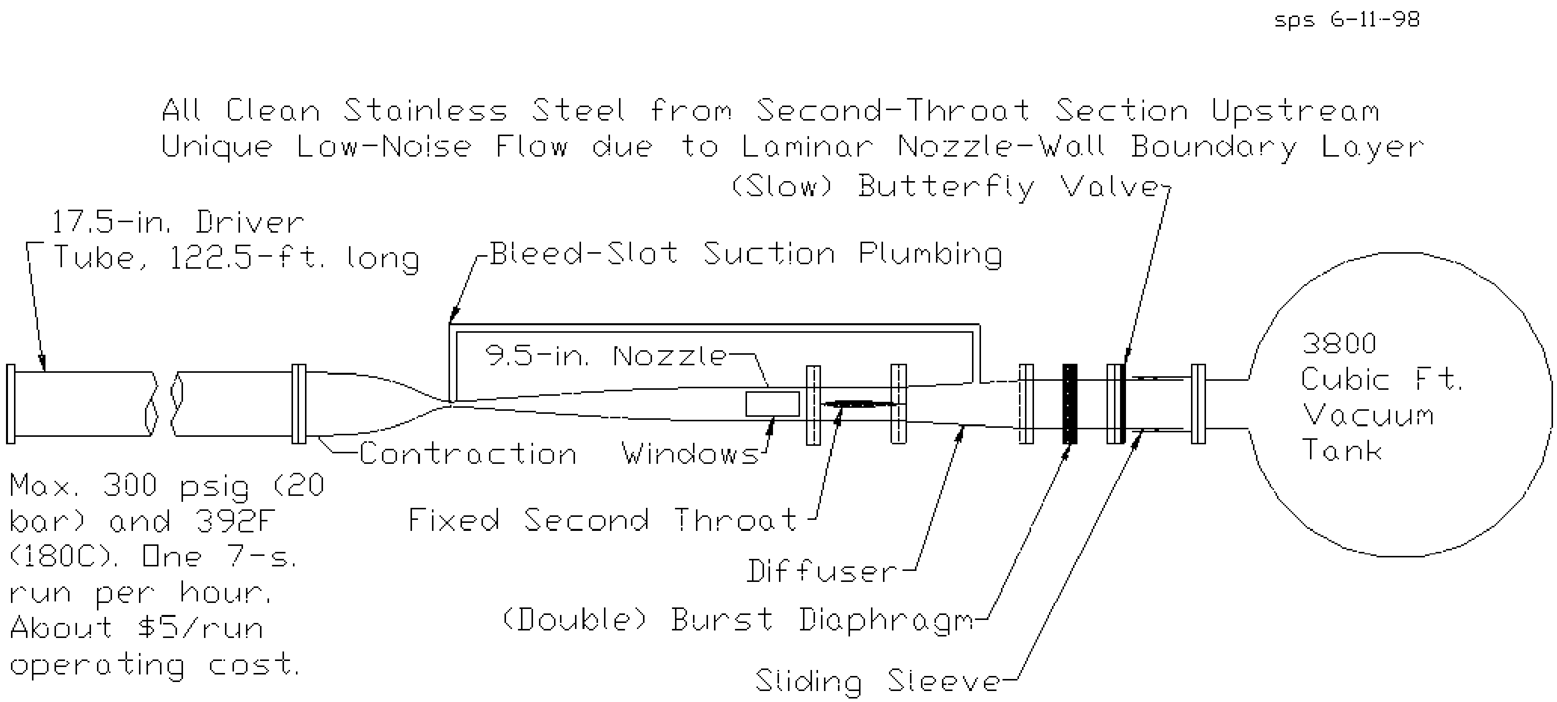


The Facility

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 provides 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_∞ (Pa)	430	1200	470	1300	520	980
T_∞ (K)	790	1040	550	720	470	480
ρ_∞ (g/m^3)	1.6	3.6	2.8	6.2	3.8	6.9
M_∞	9.7	9.0	10.0	9.5	10.0	10.0
u_∞ (m/s)	5900	6200	4800	5100	4400	4400

HEG standard operating conditions



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.

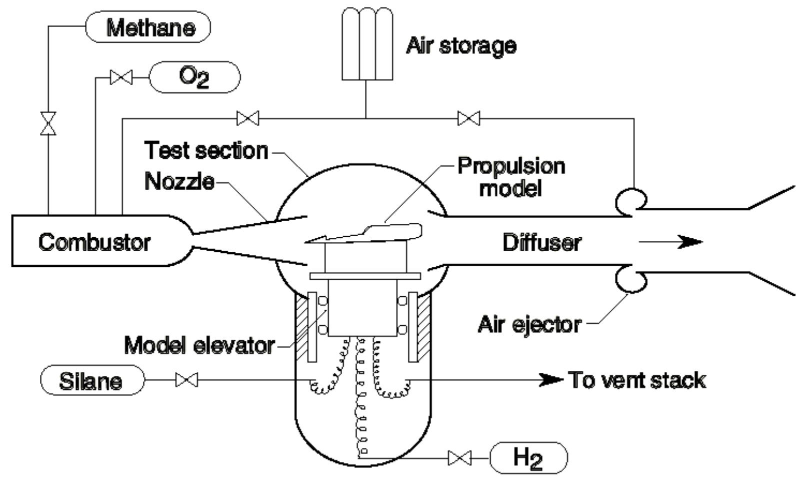


Figure 2. Schematic drawing of the 8' HTT for airbreathing propulsion testing.

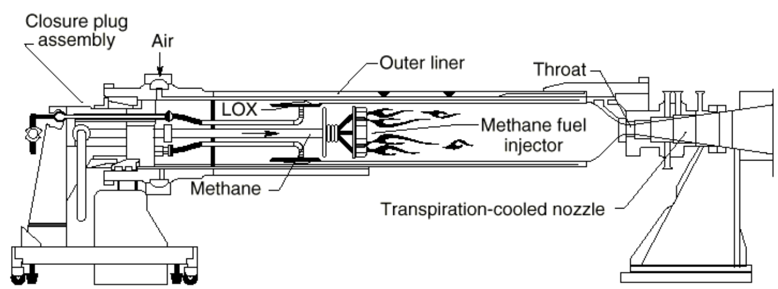
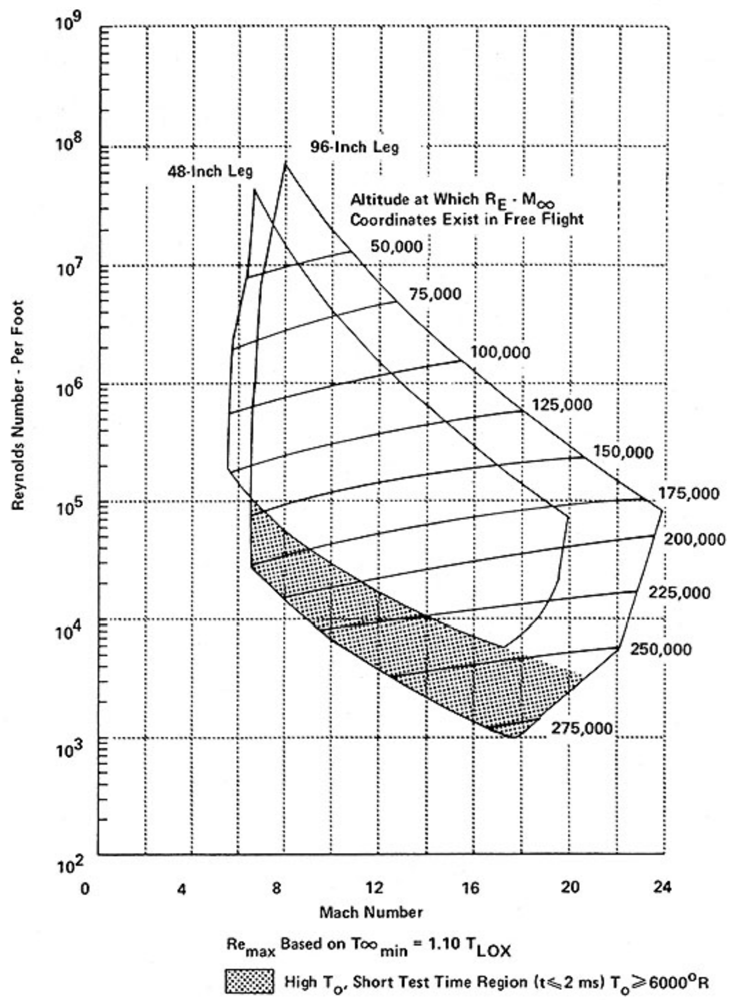


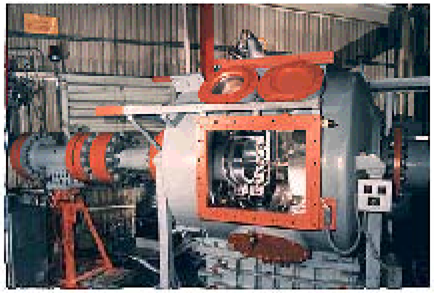
Figure 3. Schematic drawing of the 8' HTT combustor.

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.



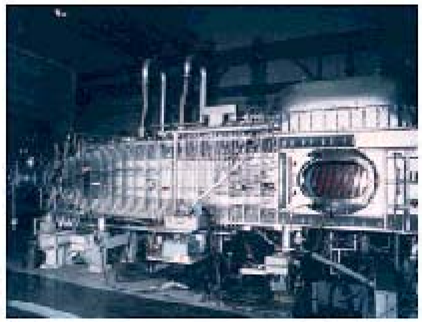
Calspan Hypersonic Shock Tunnel Performance



15-Inch Mach 6 Hi Temp. Air

20-Inch Mach 6 Air

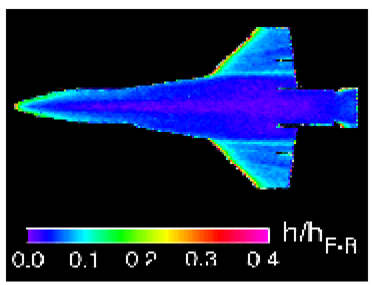
20-Inch Mach 6 CF_4



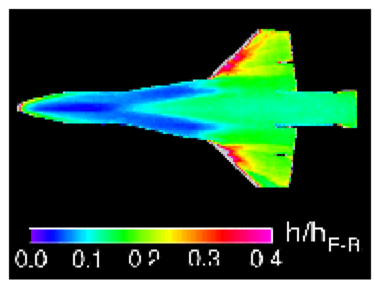
31-Inch Mach 10 Air

22-Inch Mach 15/20 He

Fig. 1 Facilities of the Aerothermodynamic Facilities Complex.

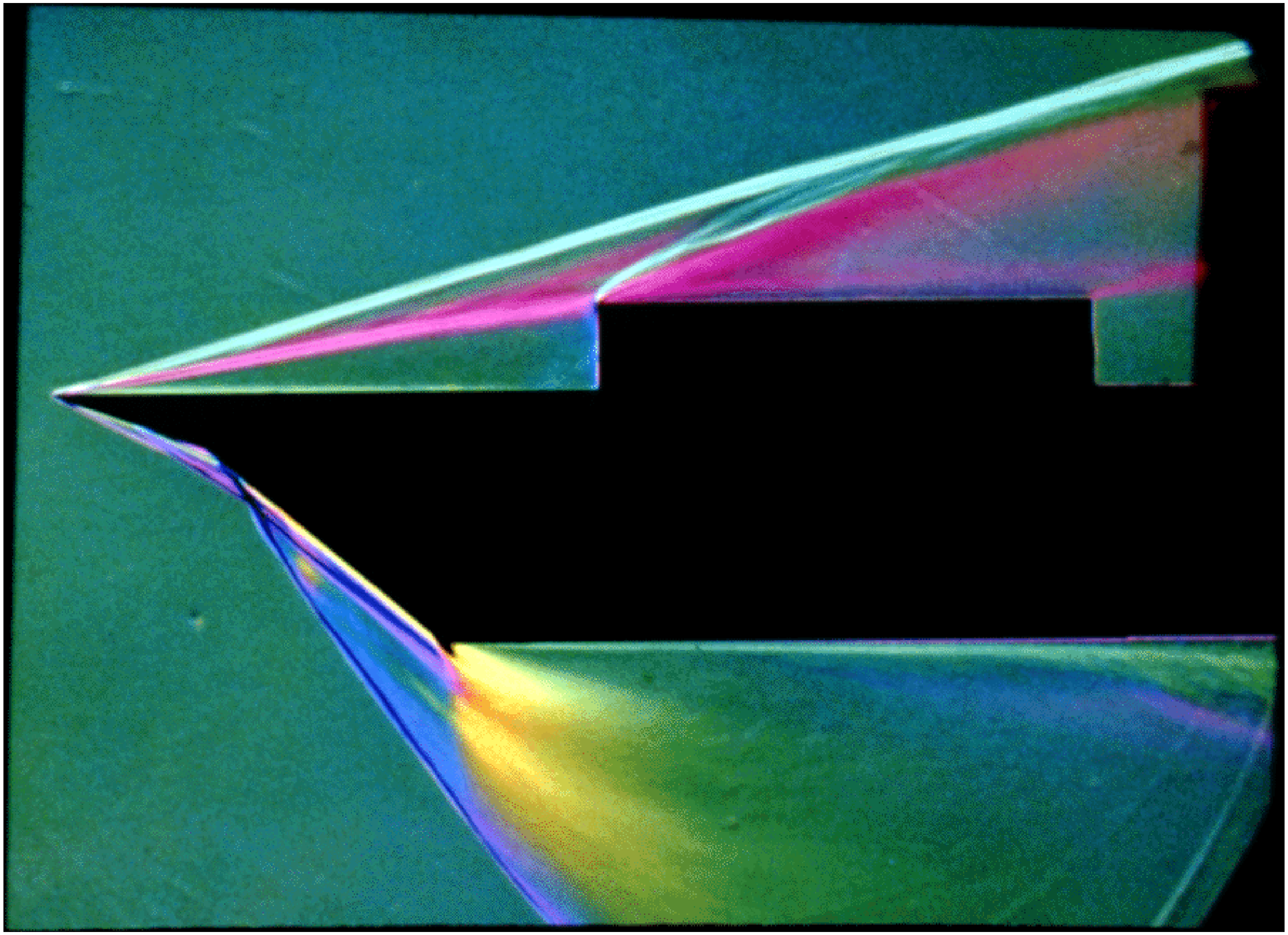


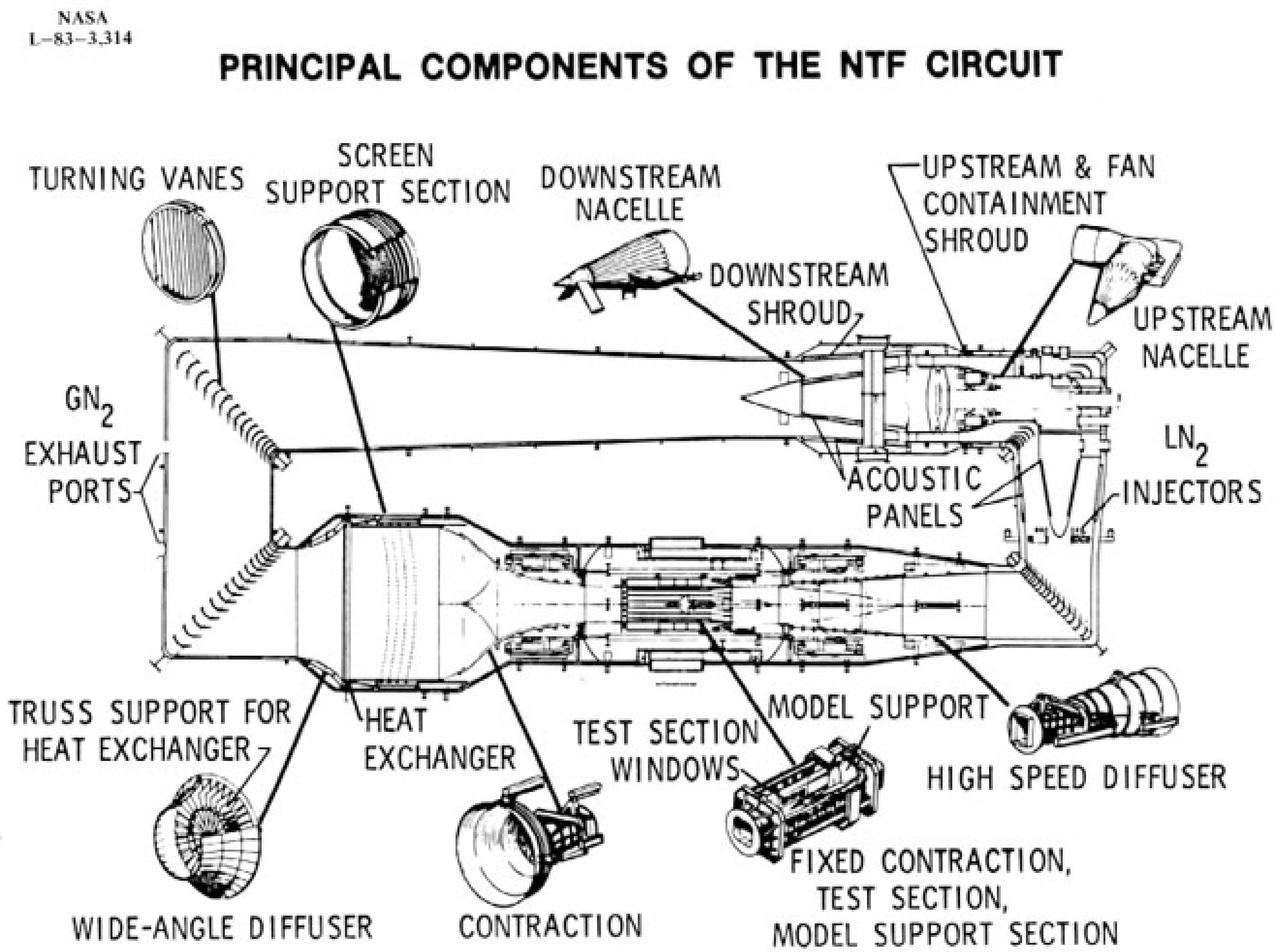
$Re_{\bullet} = 1.1 \times 10^6$/ft



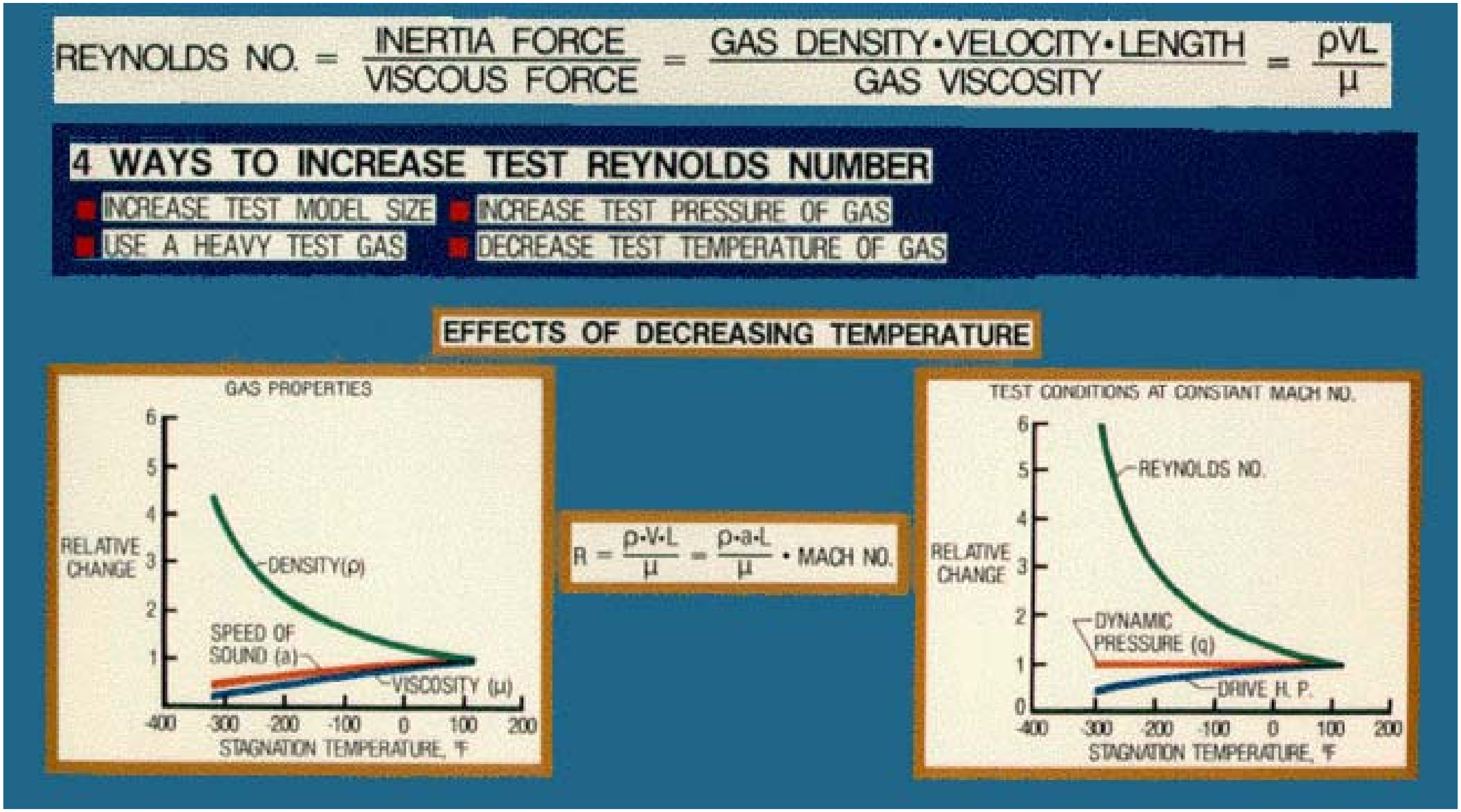
$Re_{\bullet} = 7.9 \times 10^6$/ft

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




NASA
L-83-3,314
PRINCIPAL COMPONENTS OF THE NTF CIRCUIT
TURNING VANES
SCREEN
SUPPORT SECTION
DOWNSTREAM
NACELLE
UPSTREAM & FAN
CONTAINMENT
SHROUD
DOWNSTREAM
SHROUD
UPSTREAM
NACELLE
GN2
EXHAUST
PORTS
LN2
INJECTORS
ACOUSTIC
PANELS
TRUSS SUPPORT FOR
HEAT EXCHANGER
HEAT
EXCHANGER
TEST SECTION
WINDOWS
MODEL SUPPORT
HIGH SPEED DIFFUSER
FIXED CONTRACTION,
TEST SECTION,
MODEL SUPPORT SECTION
WIDE-ANGLE DIFFUSER
CONTRACTION

Cryogenic Wind Tunnels



REYNOLDS NO. = INERTIA FORCE / VISCOUS FORCE = GAS DENSITY•VELOCITY•LENGTH / GAS VISCOSITY = ρVL / μ
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
GAS PROPERTIES
RELATIVE CHANGE
DENSITY(ρ)
SPEED OF SOUND (a)
VISCOSITY (μ)
STAGNATION TEMPERATURE, °F
R = ρ•V•L / μ = ρ•a•L / μ • MACH NO.
TEST CONDITIONS AT CONSTANT MACH NO.
RELATIVE CHANGE
REYNOLDS NO.
DYNAMIC PRESSURE (q)
DRIVE H. P.
STAGNATION TEMPERATURE, °F

NATIONAL TRANSONIC FACILITY

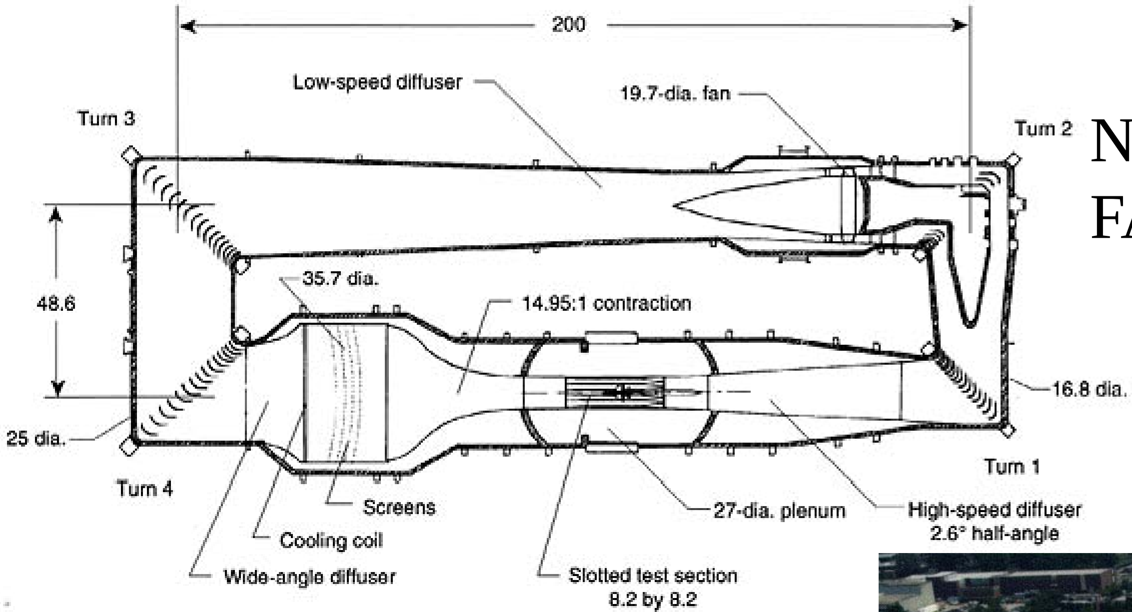
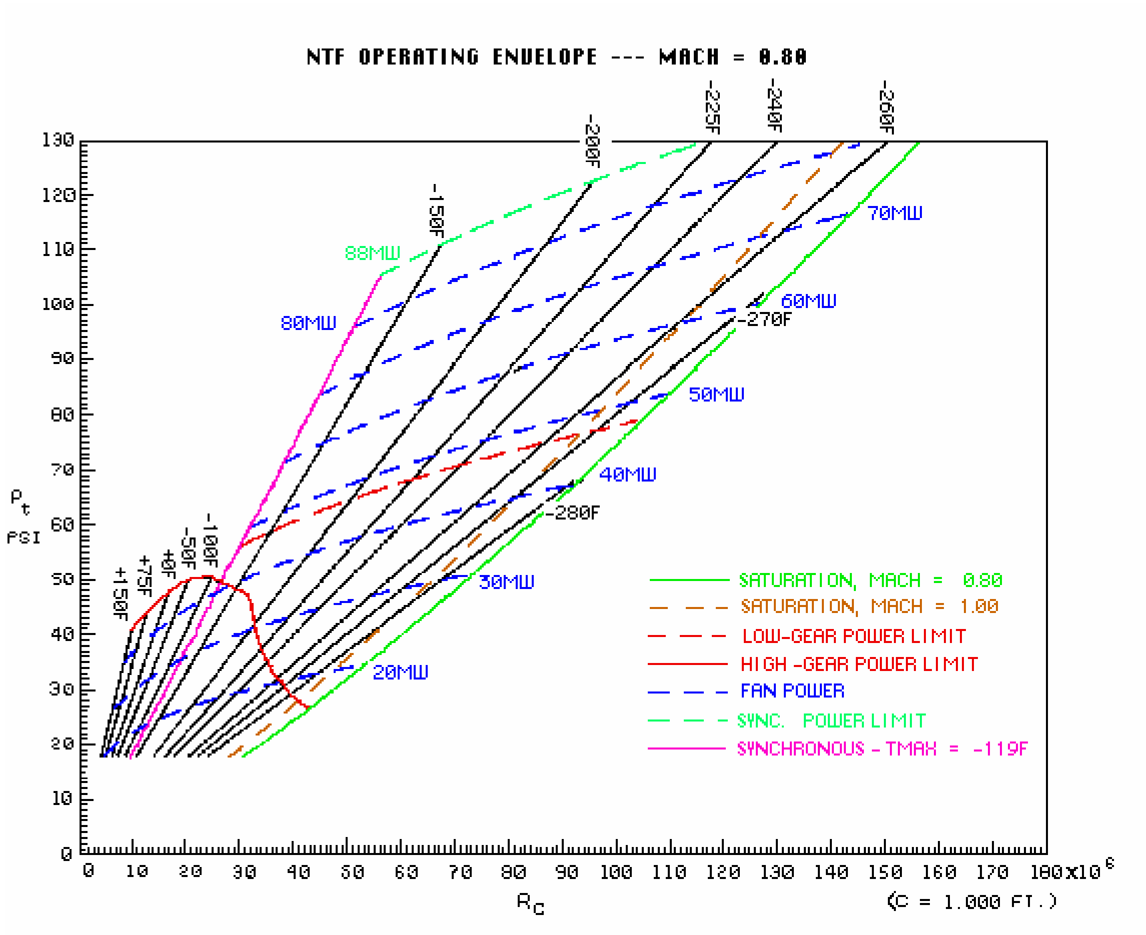
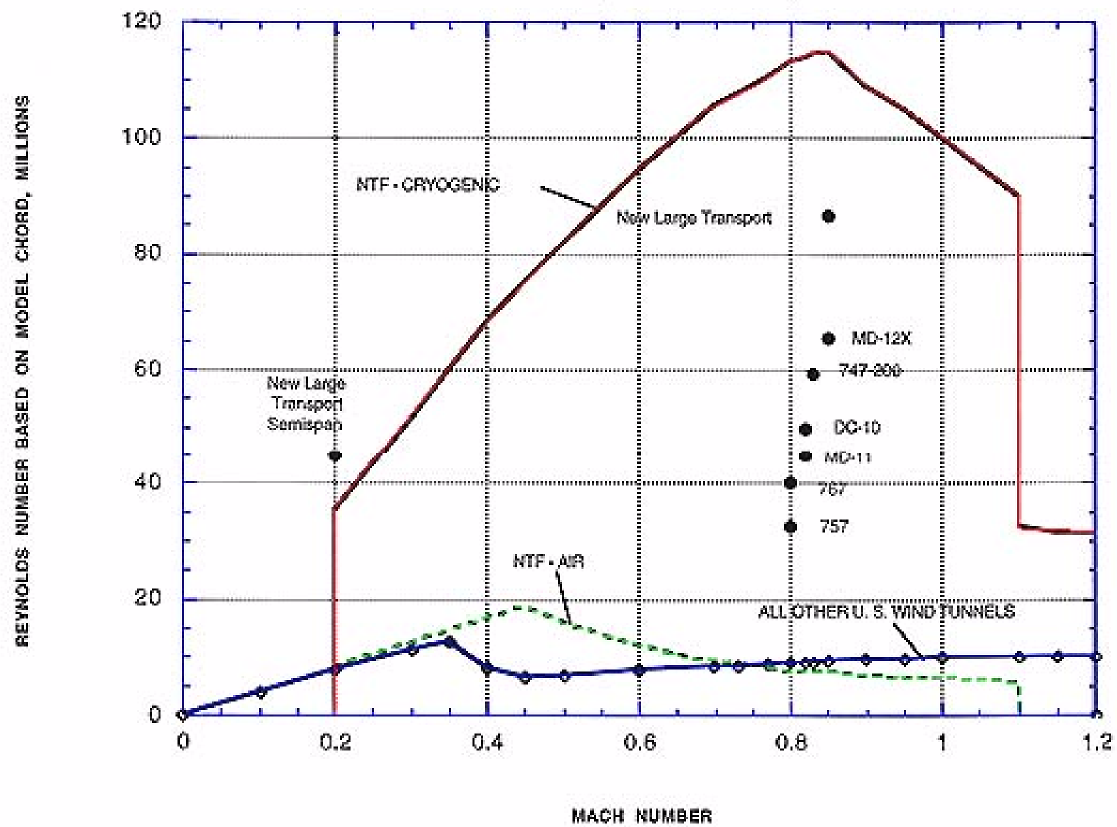


Figure 6. Plan view of NTF tunnel circuit. All linear dimensions are in feet.

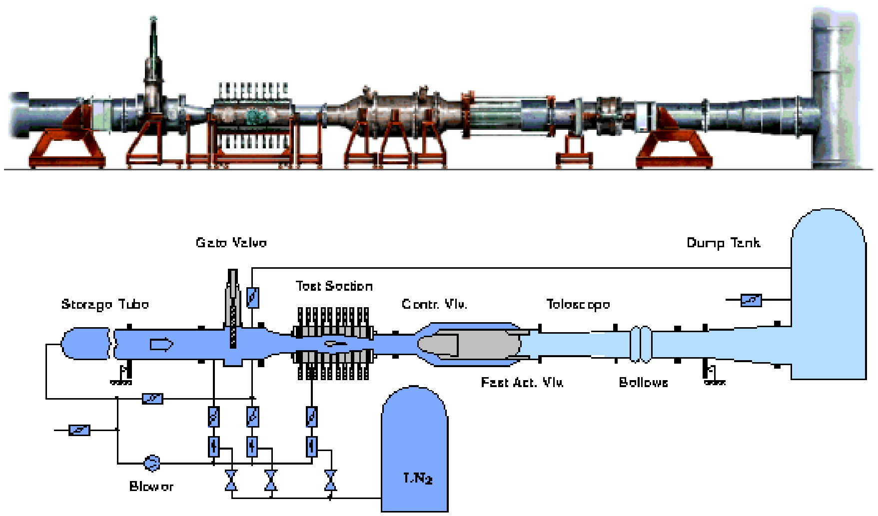


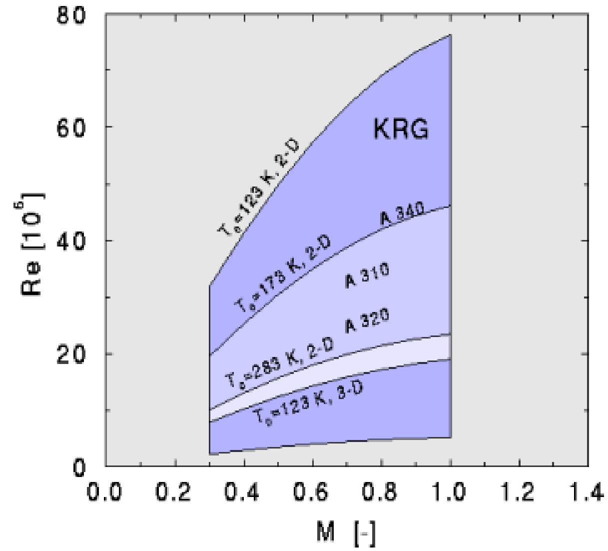
NTF OPERATING ENVELOPE --- MACH = 0.80
Pt PSI
RC
(C = 1.000 FT.)
180x10^6
+150F
+75F
+40F
-50F
-100F
-150F
-200F
-225F
-240F
-260F
-270F
-280F
88MW
80MW
70MW
60MW
50MW
40MW
30MW
20MW
SATURATION, MACH = 0.80
SATURATION, MACH = 1.00
LOW-GEAR POWER LIMIT
HIGH-GEAR POWER LIMIT
FAN POWER
SYNC. POWER LIMIT
SYNCHRONOUS - TMAX = -119F

NTF Capability

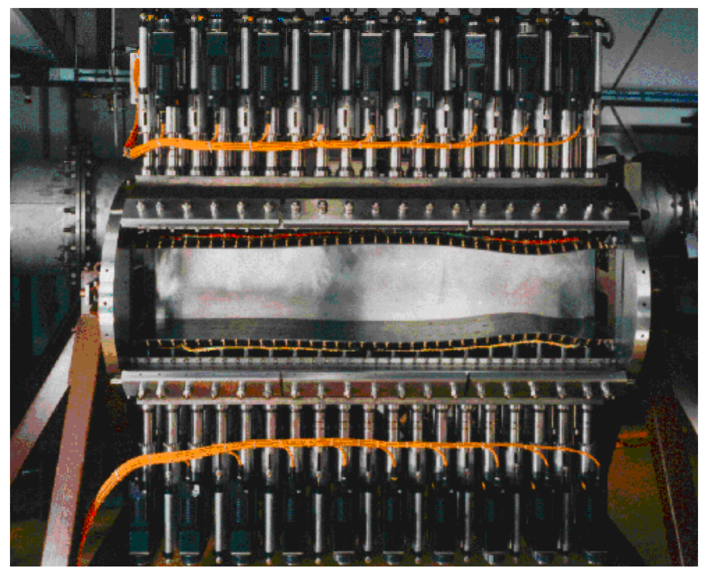


The Cryogenic Ludwieg-Tube at Göttingen (KRG)





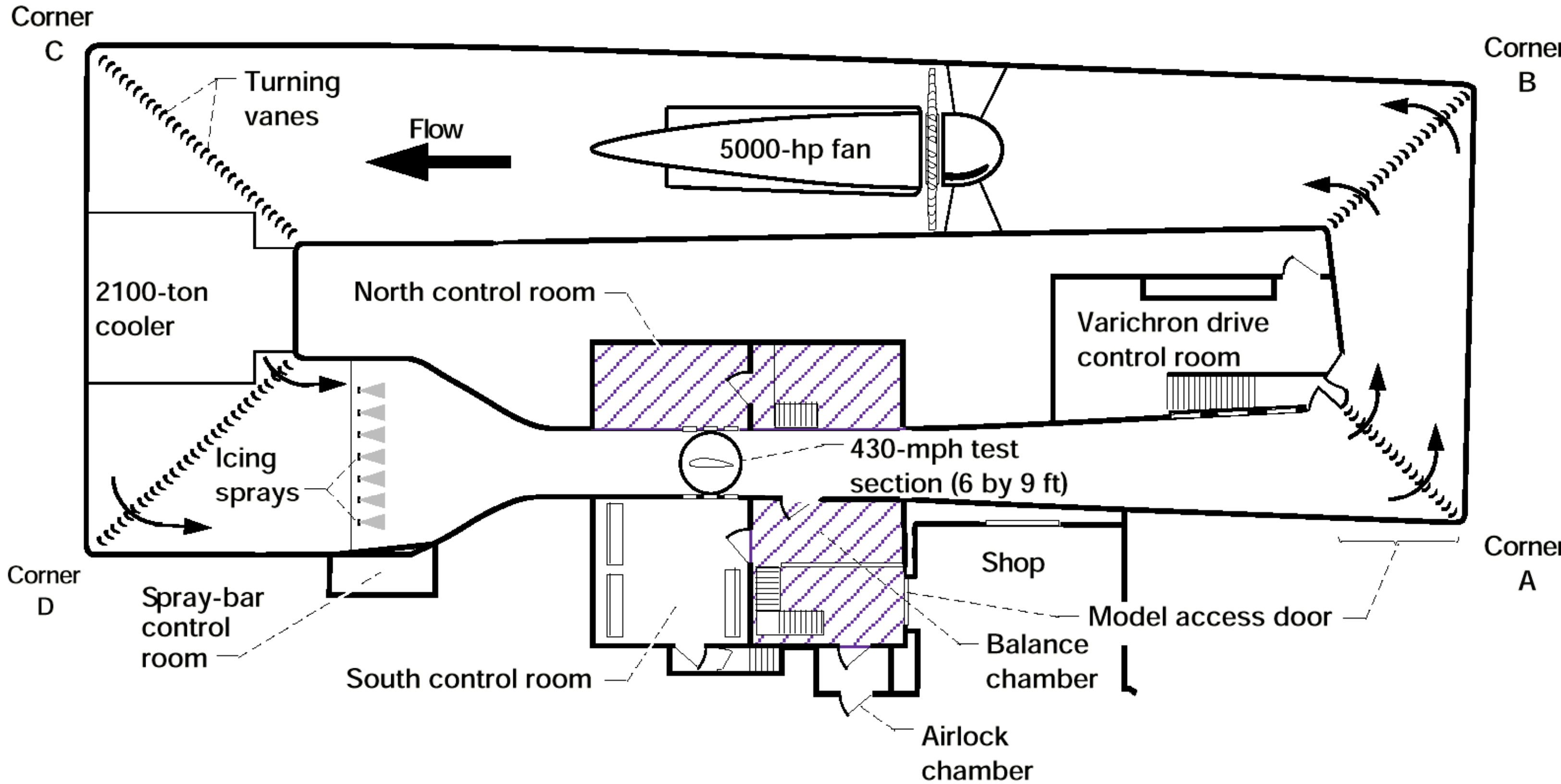
Tube	Diameter	0.8 m	Stag. press. (max.)	10 bar
	Length	130 m	Temperature range	100 to 300 K
	Load. press. (max.)	12.5 bar	Mach number range	0.25 to 0.95
Test Section	Cross section	0.4 x 0.35 m^2	Reynolds no. (max.)	$60 \cdot 10^6$
	Length	2.0 m	Run time	0.6 to 1.0 s
	Model chord (typ.)	0.15 m		

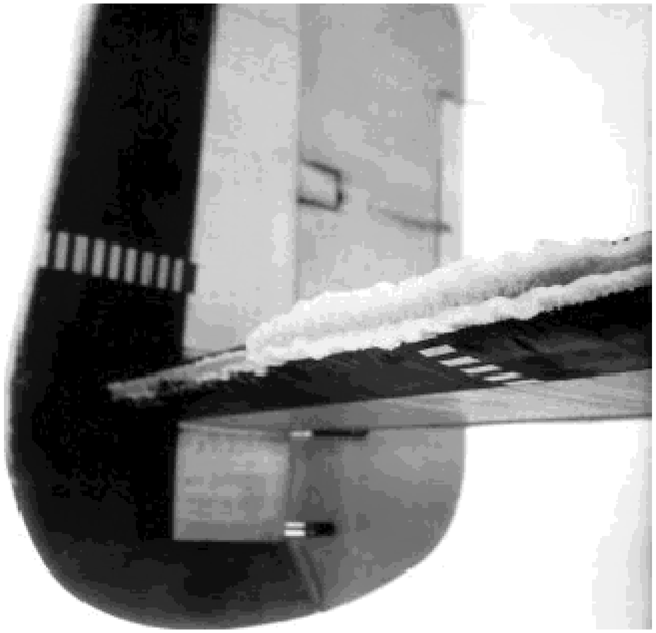


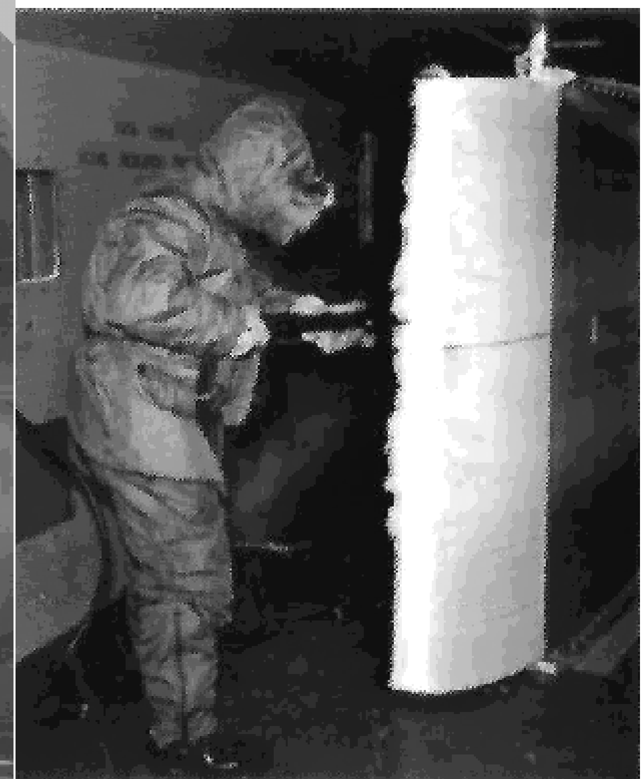
Adaptive wall test section

Icing
Wind Tunnels

Icing Tunnel
NASA Lewis Research Center

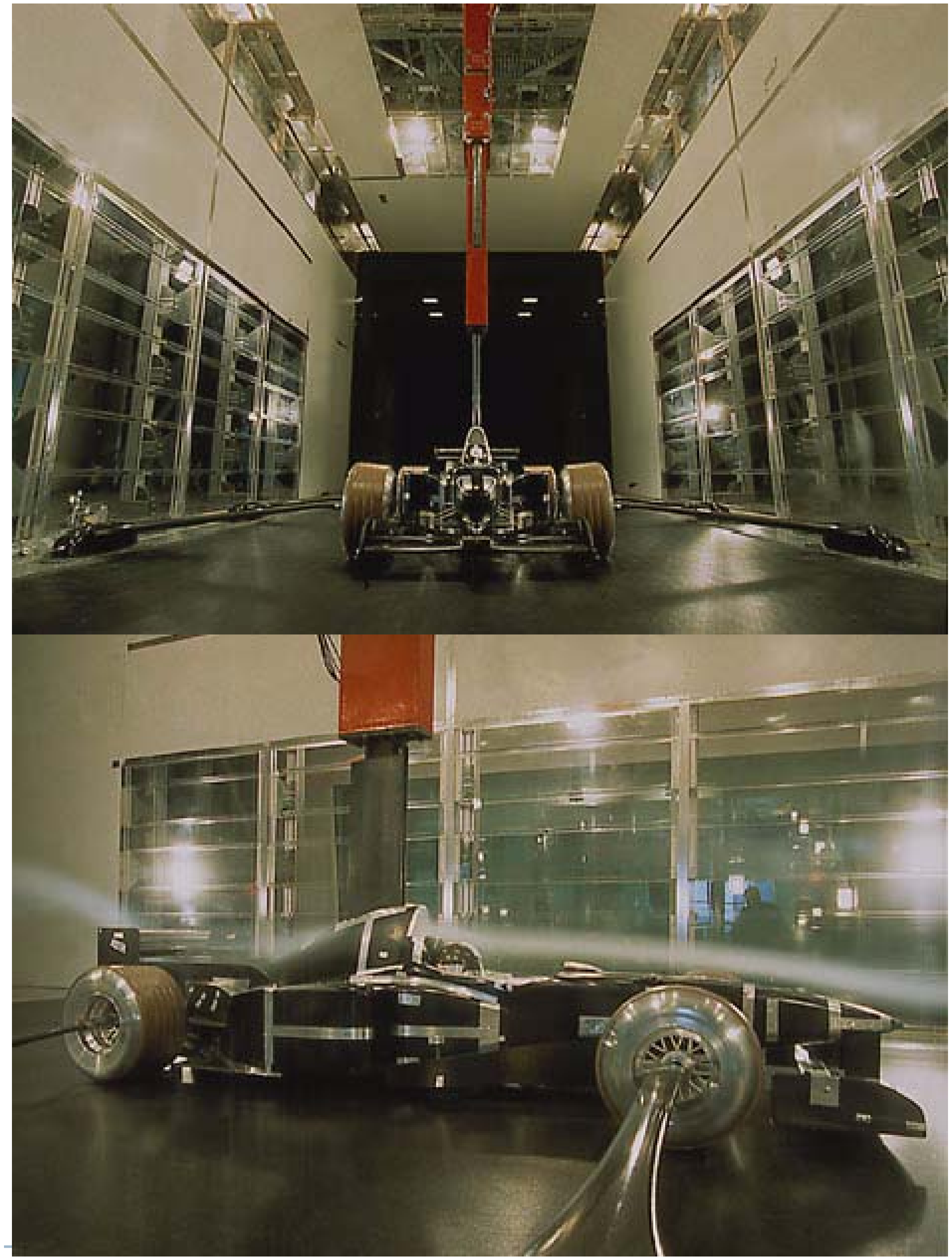


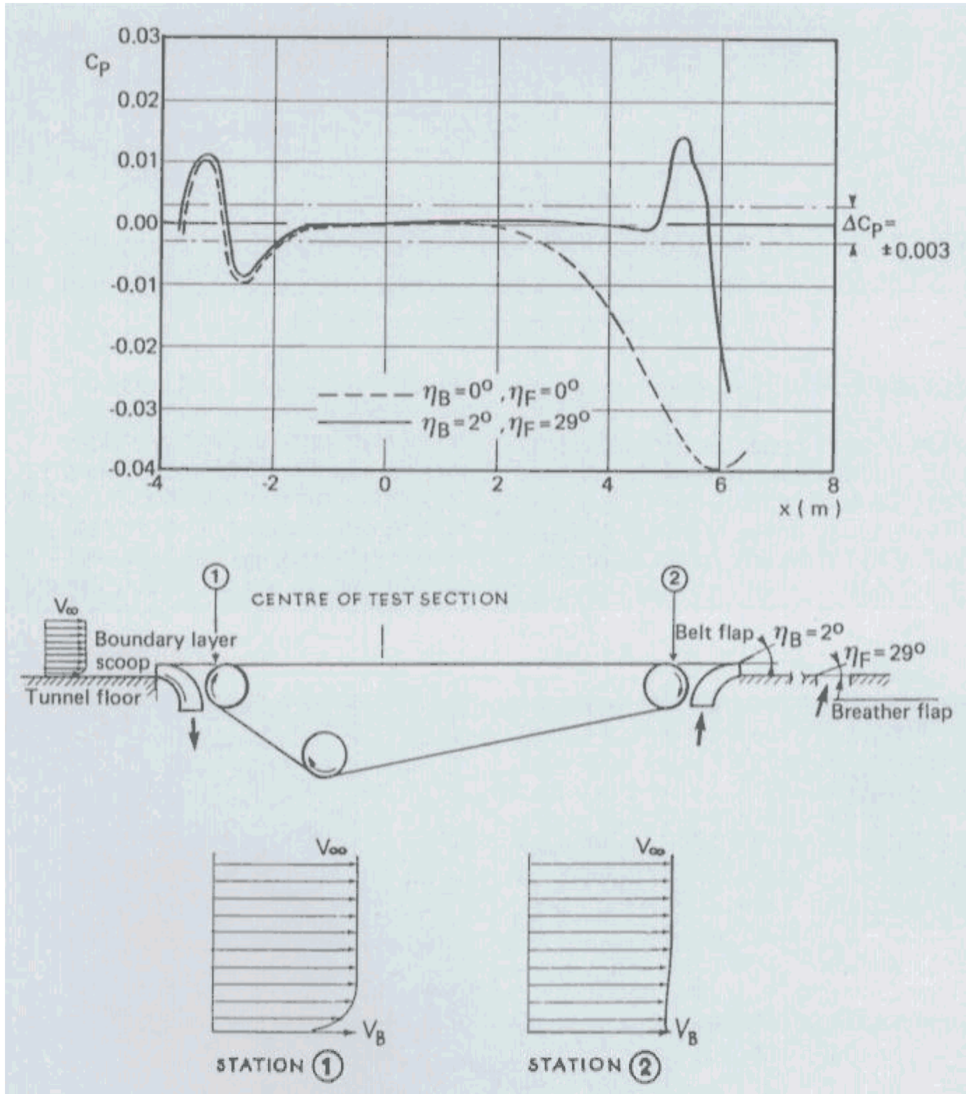




Wings

Automobile Wind Tunnels





0.03
C_P
0.02
0.01
0.00
-0.01
-0.02
-0.03
-0.04
-4
-2
0
2
4
6
8
x (m)
$\Delta C_P =$
±0.003
$\eta_B = 0^o, \eta_F = 0^o$
$\eta_B = 2^o, \eta_F = 29^o$
1
2
CENTRE OF TEST SECTION
V_∞
Boundary layer
scoop
Tunnel floor
Belt flap
$\eta_B = 2^o$
$\eta_F = 29^o$
Breather flap
V_∞
V_B
STATION 1
V_∞
V_B
STATION 2

Wind Tunnel Power Requirements

Energy Ratio

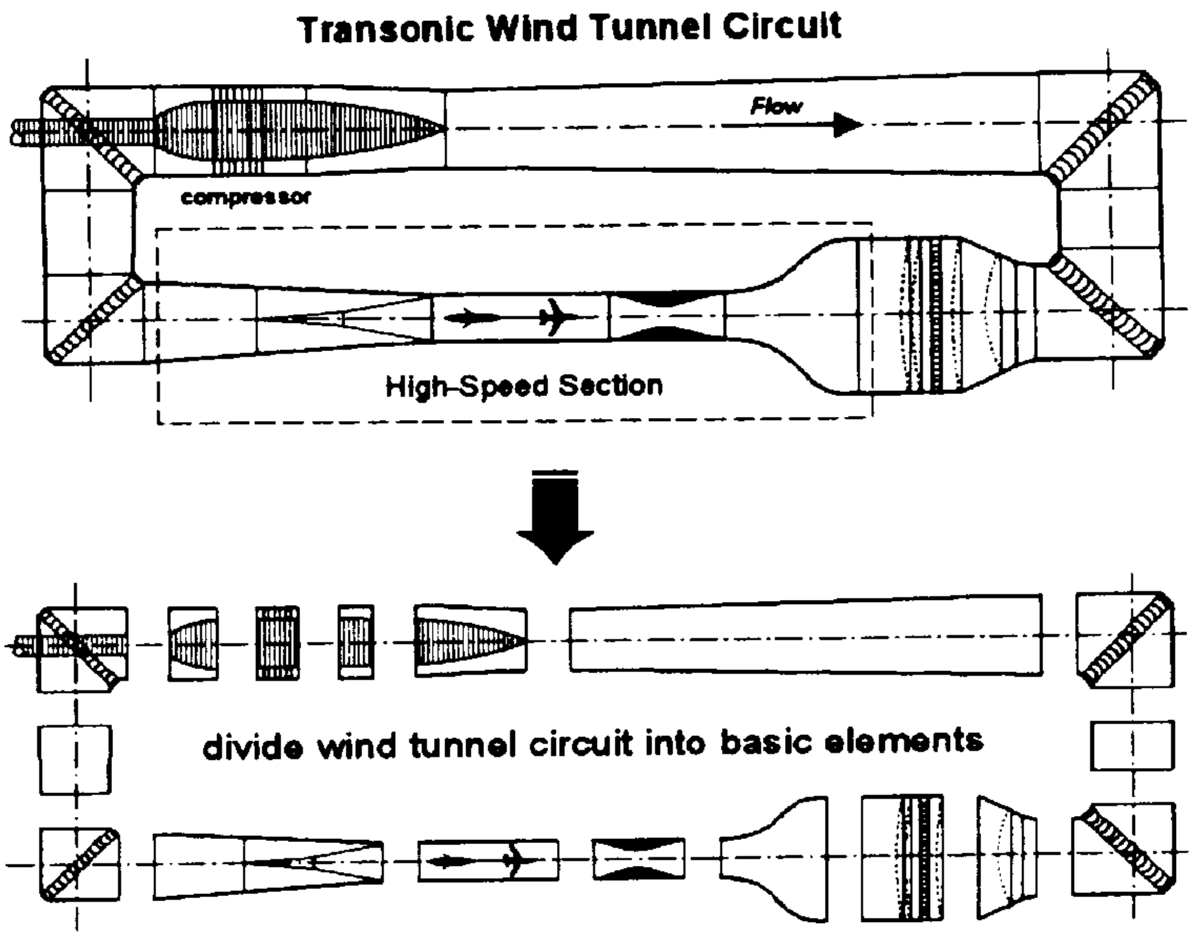
$$(E.R.)_t = \frac{\text{Jet Energy}}{\sum \text{Circuit Losses}} = \frac{1/2\,\rho_0 U_0^3 A_0}{\sum \text{Losses}} = \frac{q_0 U_0 A_0}{\eta\, P}$$

Subscript 0 refers to the test section

P is the motor power

η is the fan efficiency

Wind Tunnel Circuit Elements



Losses

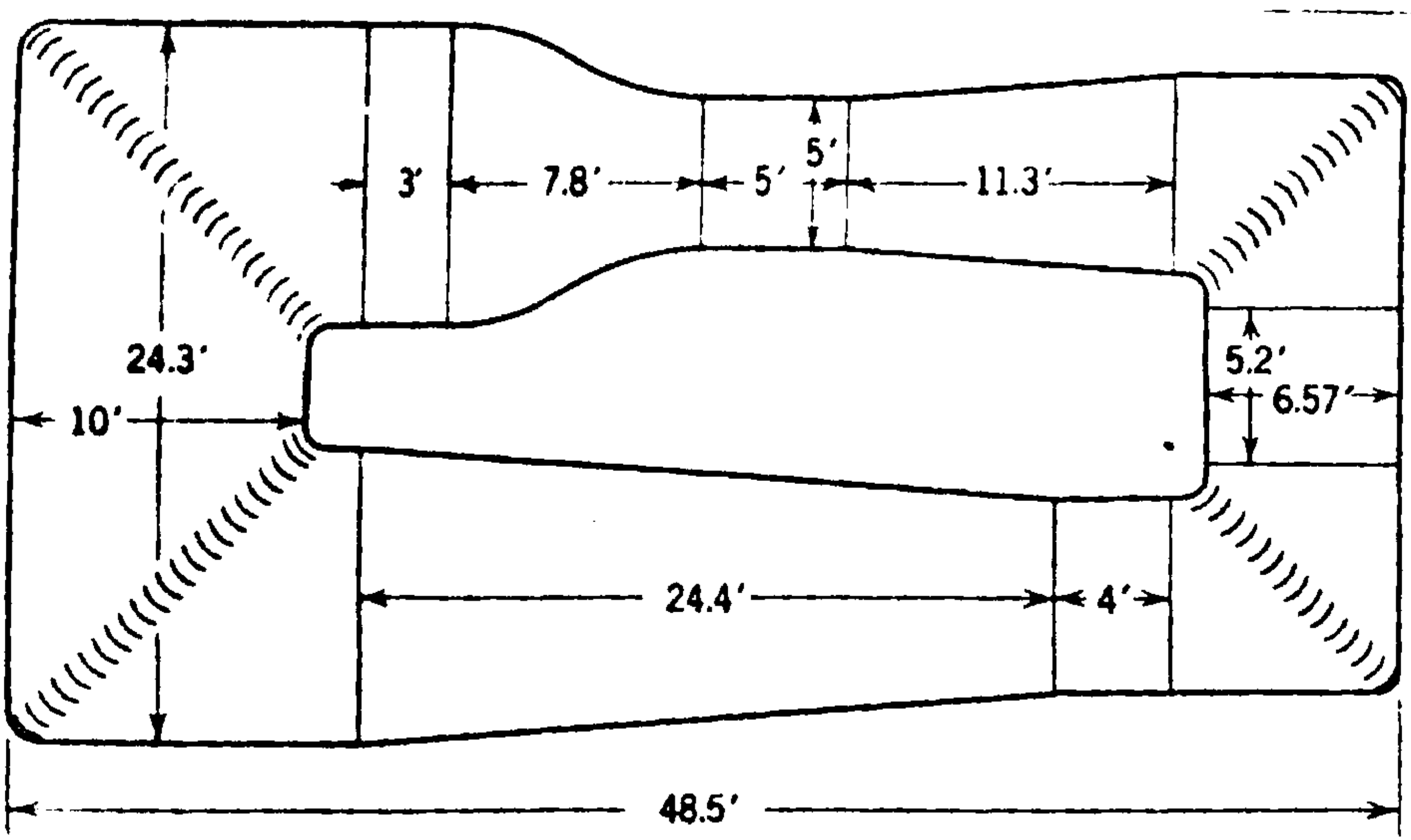
$$K = \frac{p_{t1} - p_{t2}}{q}$$ Local Pressure Loss Coefficient

$$K_0 = \frac{p_{t1} - p_{t2}}{q_0} = K\frac{q}{q_0}$$ Pressure Loss Referred to Test Section

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

$$(E.R.)_t = \frac{\text{Jet Energy}}{\sum \text{Circuit Losses}} = \frac{1/2\rho_0 U_0^3 A_0}{\sum \mathrm{K}_0 1/2\rho_0 U_0^3 A_0} = \frac{1}{\sum K_0}$$

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
	Total	**.1834**	**100.0**

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

Example - Open Return Tunnel

	Section	Ko	% Total Loss
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
	Total	**.150**	**100.0**

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

Turbulence Management System

Stilling Section - Low speed and uniform flow

Honeycomb - Reduces Large Swirl Component of Incoming Flow

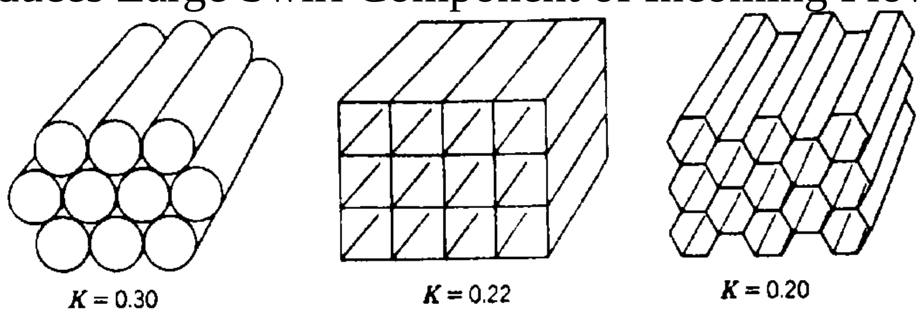


Fig. 2:16 Some honeycombs and their losses.

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 requies power

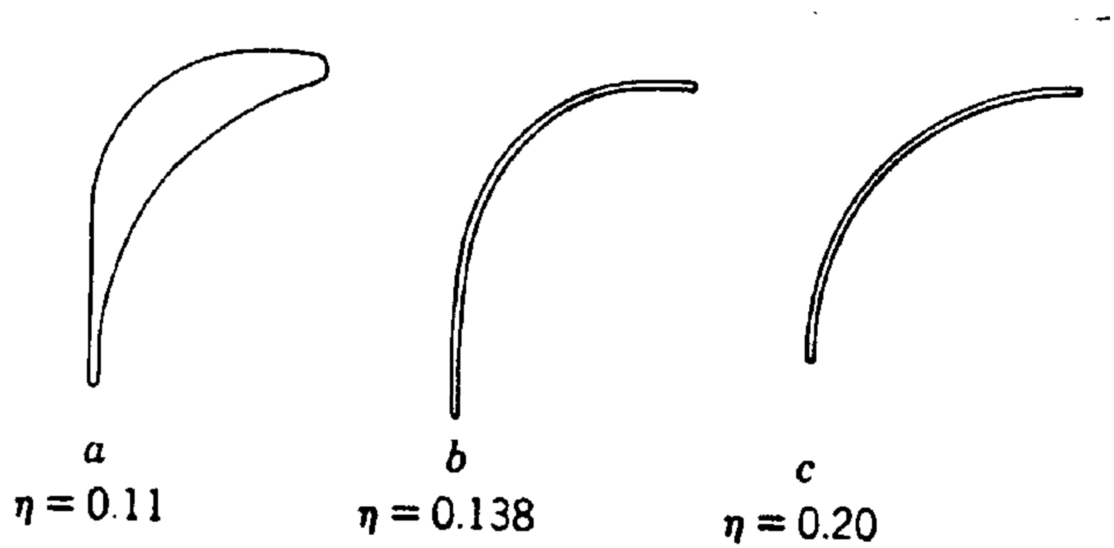
For Aerodynamics Testing 7x10 Height/Width Ratio

Test Section Length - L = (1 to 2)w

Diffuser

Corners

Abrupt Corner without Vanes $\eta = 1.0$



Speed Control

Fan