Aerocapture, Entry, Descent and Landing (AEDL) Human Planetary Landing Systems
Section 10, AEDL Analysis, Test and Validation Infrastructure

Presented by J. O. Arnold for the

APIO Human Planetary Landing System Study Team

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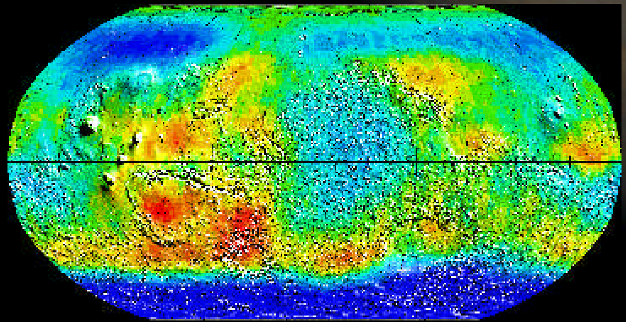
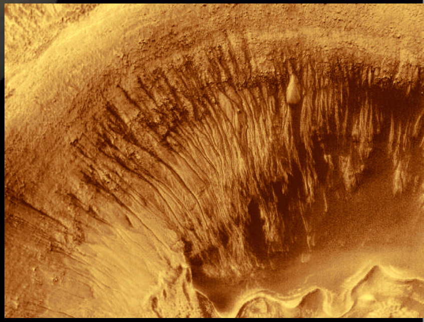


May 4, 2005



Words of Wisdom

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"Test as you fly, fly as you test[1]"

"Train as you fly, fly as you Train[2]"

"If you are not ready, do not fly[1]"

"Mars Exploration program strategy must account for a reasonable number of failures and be robust against their happening[1]"

"Programs have the responsibility to ensure that projects provide data/information for the health of future projects, e.g. flight instrumentation to understand failures and performance[1]"

[1] Tom Young/Mars Program Independent Assessment Team (MPIAT)

[2] Harrison Schmitt, Apollo Astronaut

"No ground facility can simultaneously duplicate the altitude, velocity and scale of human flight vehicles/systems[3]"

"You told the boss (1st president Bush) what it cost ($400 B) to do the human Mars mission and it cost you the program, plus there was no congressional support[4]"

"A sustained Mars Program must sustain public interest[4]"

"I wish I had come to the NASA Ames and Langley Research Centers earlier[5]"

"One strike, and you are out[1]"

[3] Dean R. Chapman/NASA Ames/Stanford

[4] Hans Mark

[5] Tony Spear, Mars Pathfinder Project Manager

Outline

- Listing of critical capabilities (knowledge, procedures, training, facilities) and metrics for validating that they are mission ready
- Examples of critical capabilities and validation metrics: ground test and simulations
- Flight testing to prove capabilities are mission ready
- Issues and recommendations

Capabilities

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Knowledge Model/codes Ground
Facilities* Metrics***

10.1 Systems Engineering 1-6 — **Physics based/cost** — **- Intercenter teams*,+**
Industry + Academia

10.2 G,N & Control (flexibles) 1-5 — **Real time code** — **- Simulation**

10.3 Aerodynamics 1-5 — **Aero databases;** — **- Wind tunnels: (Hyper/**
10.3.1 Aeroelasticity for flexibles — **Thermo-chemical noneq CFD codes; Coupled CFD/Finite Element Analysis** — **super/trans/sub sonic with (forced oscillation)**
- Ballistic range. Quiet tunnels
- Low density tunnels**

10.3.2 Aero + Propulsion 1-5 (retro and reaction control system) — **Real-Gas Aero + Propulsion CFD; Ground effects** — **- Wind tunnel with combined propulsion**

.

* Red colored text: critical issue under threat e.g., potential termination, demolition/ closure / mothballing
**Blue colored text: special issue or no capability

*** Metrics: 1. (code to code or model to model fly-offs), 2. (comparison to ground test) 3. pre/post flight test comparisons, 4. (bi-annual peer review) and 5. Proficiency of existing corps as established from flight test and NRC evaluation of education programs for the next generation of explorers, and 6. Capability to replicate previous "landmark" decisions

Capabilities (cont.)

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Knowledge Facilities* Model/codes Metrics*** Ground

10.4 Aerothermodynamics afterbody heating;

Real-gas/non equ. CFD: Coupled convective and radiative heating: Ionized flow, transition to turbulence models; turbulence models; rarefied flow/transitional codes

- Wind tunnels 1-5
- Shock Tubes
- Shock Tunnels
- Ballistic range
- Rarefied flow tunnels
- Quiet tunnels

10.5 Human Rated Thermal Protection Systems (TPS) Ablators,flexibles;multifunctional (TPS+ space radiation +micrometorite shields) 1-5

Materials specifications; flow/materials coupling (convection/radiation/ unsteady); scalability (e.g gaps bonds; seals, e.g. body flaps to fuselage; manufacturability

- Arc Jets
- Combined (conv. +radiation + unsteady flow)
- Materials labs
- TPS pilot plants with autoclaves
- Full scale TPS manufacture, environments(shake, vac, bake, etc) test capability

Capabilities (cont.)

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Knowledge Model/codes Ground
Facilities* Metrics***

10.6 Engineering Flight 1-5
Sensors

Press, Temp, heat (rad/convect); TPS recession sensors; accelerometers; gyros strain; flutter sensors, flush air data system

- Arc jets
- Wind Tunnels
- Instrument labs

10.7 Terminal descent/land 1-5
10.7.1 Propulsion w/toxics
10.7.2 Aerodynamic decelerators
10.7.3 Hazard avoidance
10.7.4 Touchdown

Engineering models based on physics-based codes and extensive tests for combined effects incl. Cold Soak/start dynamics with correct gravity effects, etc.; Real time hazard recog-, inition, terminal GN & C

- Large wind tunnel (NFAC)
- Large Prop. Test (White Sands)
- Large GRC (Plum Brook)/AEDC
- Helicopter / balloon air drop/ sounding rockets
- China Lake (Rocket sled lidar and radar
- Large Enviromental Test Facility facility (shake, bake, etc.)
- 7'X9' Aero/propulsion tunnel (ARC)

Capabilities (concluded)

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Knowledge Metrics***	Model/codes	Ground Facilities/data source	
10.8 Engineering Model of AEDL Planetary Environment 10.8.1 Atmospheric predictions (structure {Press, Temp.), turbulence, winds) and surface properties (dust, toxicity, strength, slopes, terrain, hazards)	Real time updatable models based on robotic missions: rock distribution models; 30 cm imagery; digitial elevation maps; mesoscale wind models; global circulation models; global dust transport models	- Simulators (ARC) - Mars atm. sim. lab - Odyssey (atm/rocks) - TBD future atm. orbiter.	1-5
10.8.2 Pico/nano satellites and probes to provide just-in-time update information	Pico/nano satellite and atmospheric probes to update models	- None additional for pico/nano sats./probes	
10.9 Astronaut AEDL performance at Mars g-profiles, etc. Human-machine-robotic interface	Human perf. engineering models based on extensive testing.	- China Lake Type rocket sled (with tailored g - profiles) - High performance aircraft - ARC Vertical Motion Simulator - ARC Bed rest facility - ARC Future Flight Central - ARC Vestibular Research Facility	1-5

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Wind Tunnels: Apollo era vs. 2005

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Government (NASA and military)

Year	Transonic	Supersonic	Hypersonic
1965	24	31	40
2005	10	9	7

1965 Government: NASA, Arnold Engineering Development Center, Wright Aeronautical Laboratory, Naval Ordnance Laboratory, Sandia National Laboratories, Ballistic Research Laboratory, David Taylor Model Basin

2005 Government: NASA, Arnold Engineering Development Center, Sandia National Laboratories

Large subsonic tunnels ARC 40'x80' & 30'x60' at LaRC 1965 vs 40x80x120 (NFAC) 2005 (may be needed for parachute tests)

Commercial

Year	Transonic	Supersonic	Hypersonic
1965	10	15	14
2005	7	7	6

1965 Commercial: AVCO, Boeing Aircraft, Cornell Aeronautical Laboratory, Convair, Douglas Aircraft, Fluidyne, General Dynamics, Grumman Aircraft, Lockheed Aviation, Ling-Temco-Vought, McDonnell Aircraft, North American Aviation, Republic Aviation, United Aircraft

2005 Commercial: Aero-Systems Engineering, GASL, Boeing, Lockheed-Martin, Veridian-CUBRC

Quiet tunnels - new capability developed in the 1980/1990's

* Does not include propulsion, arc-jet, or ballistic range facilities

** source for 1965 data: High-Speed Wind Tunnel Testing, Alan Pope and Kennith Goin, Wiley & Sons, 1965

Hypersonic Aero/ Aerothermodynamics Wind Tunnel Testing

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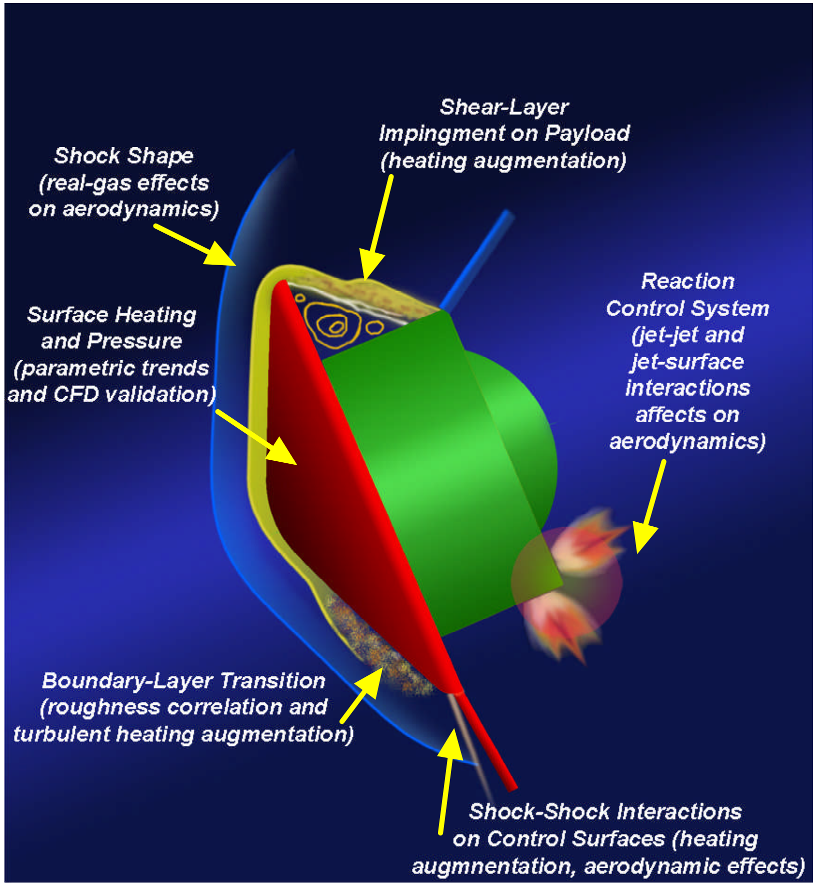
Aerodynamic and Aerothermodynamic phenomena produced in wind tunnel tests

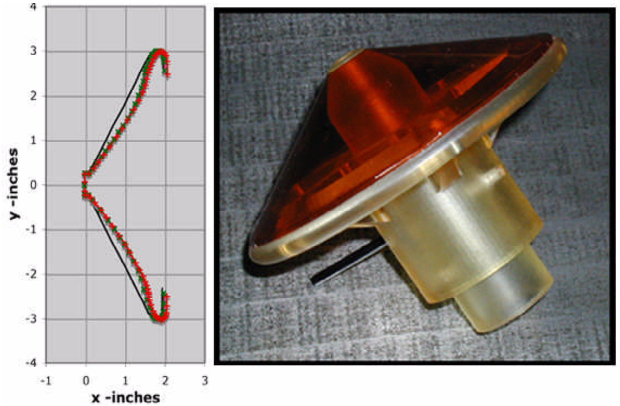


Results of Hypersonic Wind Tunnel Testing:

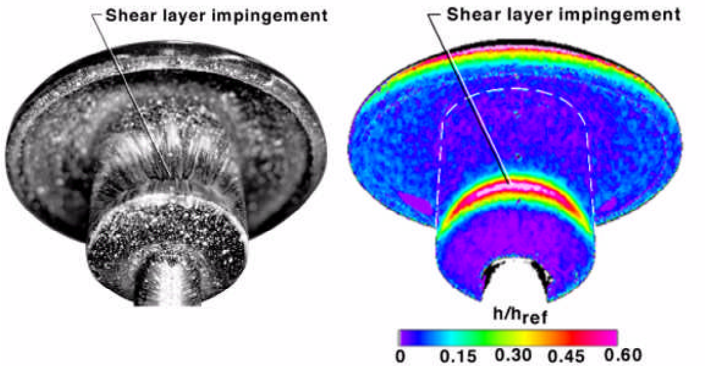
- Aerodynamic forces and moments
- Control surface effectiveness
- Surface pressure distributions
- Laminar and turbulent convective heating distributions
- Boundary-layer and shear-layer transition correlations
- Reaction control system (RCS) jet effectiveness and interactions
- Mach number, Reynolds number, shock-density ratio (real-gas simulation) effects
- Configuration parametric effects
- CFD validation/verification data

Recent Hypersonic W.T. tests

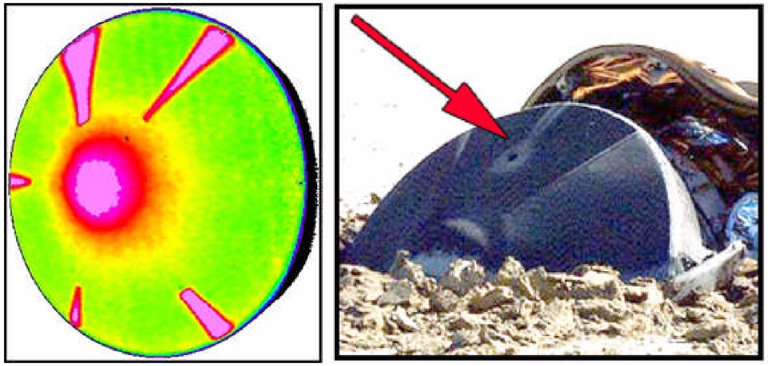
Attached ballute aeroelasticity



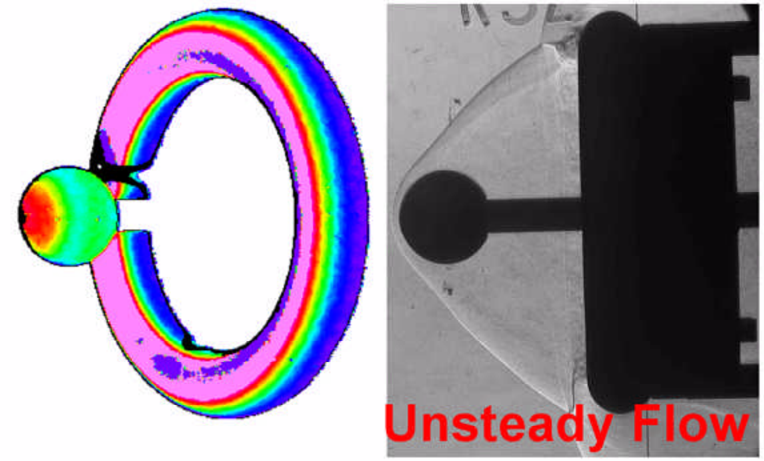
Wake shear layer payload impingement



Heat-shield cavity boundary-layer transition



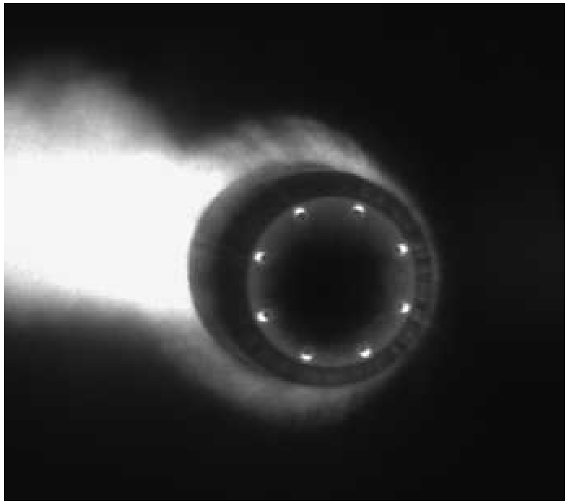
Trailing ballute heating and flow-field

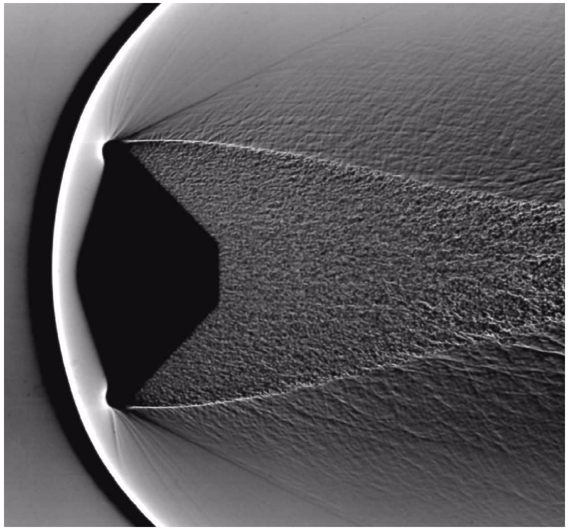


Ballistic Range: Any Test Gas

- Aerodynamic forces and moments in free flight, no sting effects and true real gas effects
- Afterbody flow simulations without sting effects
- Laminar and turbulent convective heating distributions
- Transition to turbulent flow in real gas, on real surfaces in a quiet environment
- Mach number, Reynolds number, shock-density ratio true real gas
- CFD validation/verification data

- **Disadvantage: Small scale models**





Aerodynamics: Example Metrics

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- Every US entry vehicle flown at Mars has used the basic Viking shape, but we do not fully understand its aerodynamic performance. Lack of understanding is disturbing.

  - Lack of adequate engineering flight data clouds this issue

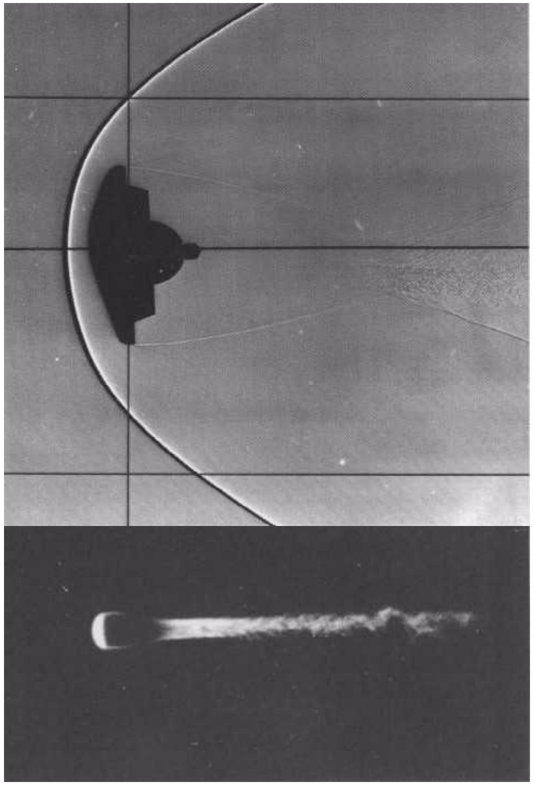
- The Shuttle Orbiter pitching moment was mis-predicted despite thousands of hours of wind tunnel testing and early CFD. With today's CFD and wind tunnel testing can we predict aerodynamic performance for an new shape?

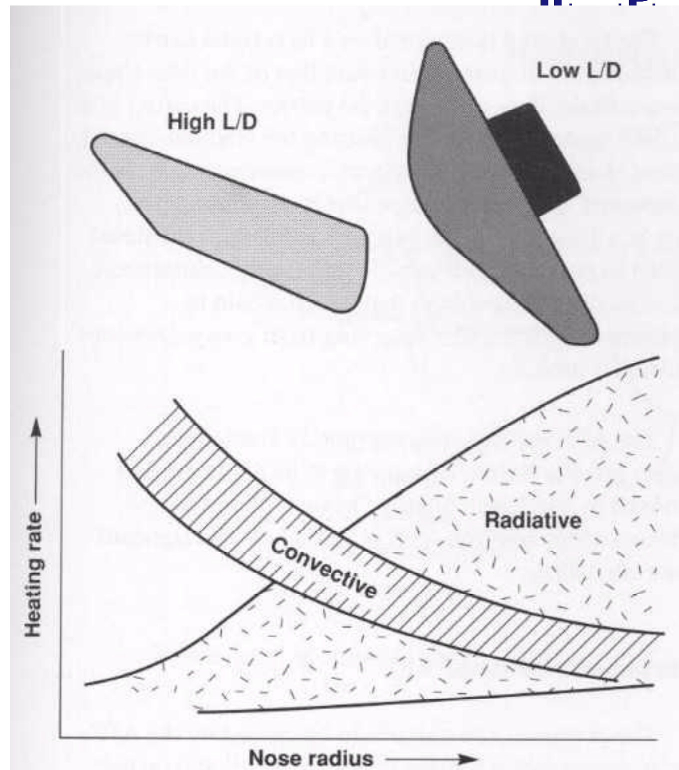
- Grand Aerodynamics Challenge: Choose a likely new shape (based on systems engineering) for a human rigid and flexible Mars aeroshells.
  - With no cross-talk, multiple groups(NASA, academia and industry) predict aerodynamics with emphasis on pitching moment, trim angle of attack and dynamics of the flexible, deformable aeroshell for air and Mars atmosphere.
  - Measure aerodynamics in wind tunnels and ballistic ranges.
  - Conduct balloon/rocket hyper/super/trans/subsonic flight test with a properly instrumented, scaled flight vehicle.
  - Grade teams against pre-determined numerical score

- Properly instrument MSL for 2011 flight. Review Viking aero data base. Examine post-flight data. Grade same teams against pre-determined numerical score.

- Successful efforts on the two prior bullets could make a significant start to validate that our capability is ready for human-critical project development.

Aerothermodynamics
Bow shock layer heating





Apollo peak stagnation point heating

Vel, km/sec	q_c, W/cm^2	q_r, W/cm^2
8.7	39	0.0
11.2	185	336
12.5	241	1283

Radiative heating is an issue for large, blunt bodies at higher velocities for Mars and Earth entry as is the need to develop coupled radiative/convective codes.

Key Aerothermal Gaps

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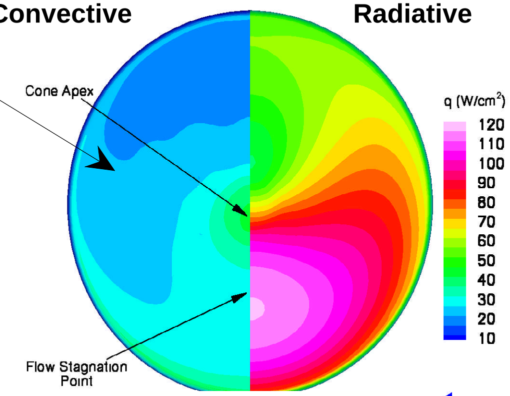
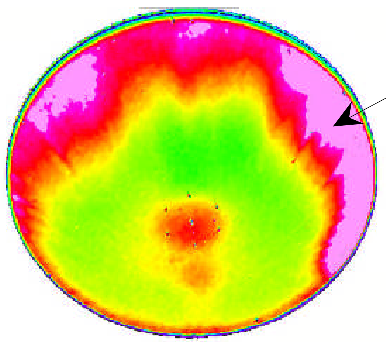
Titan Aerocapture Peak Heating



Transition in Mach 6 Tunnel

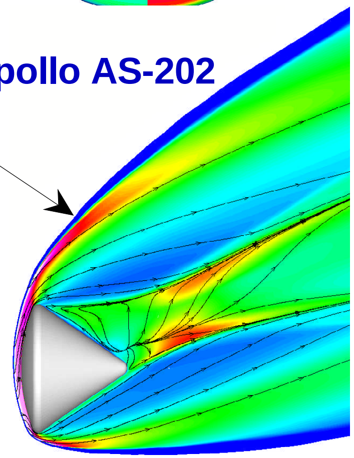


Shock Layer Radiation

Transition to Turbulence

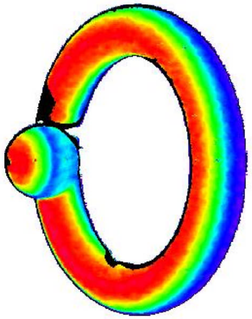
Coupling between radiation/TPS/fluids

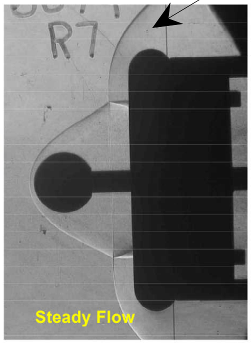
Apollo AS-202



Non-continuum flows and aeroelastic effects for low b entry systems

Trailing Ballute Test

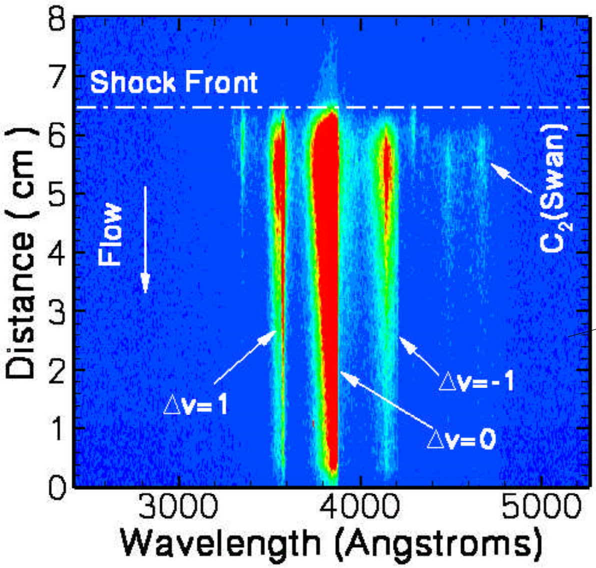


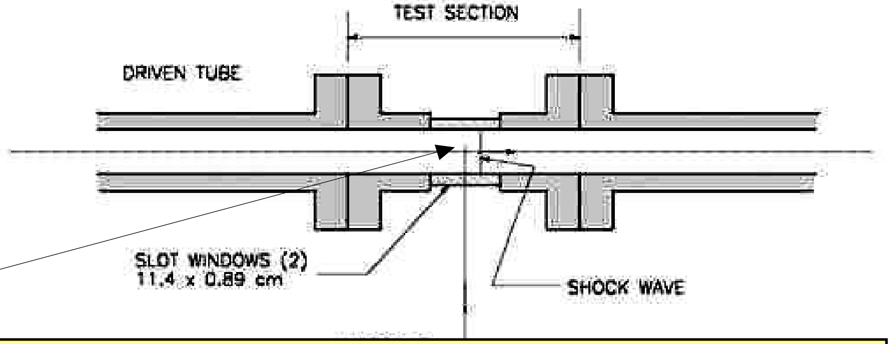


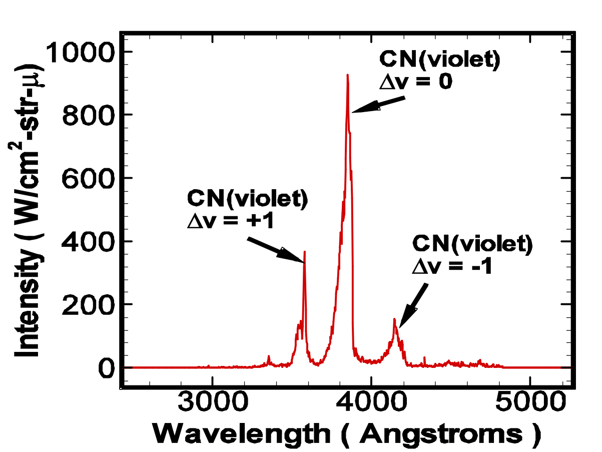
➢ Gaps are addressed via:

- Mission-specific uncertainty analysis to rank importance
- Ground testing *tailored* to reduce key uncertainties
- Model development based on test results
- Model validation with flight instrumentation

Shock Tube Radiation Physics for Huygens Titan Entry







Results of Shock Tube Testing

- Provides nominal 1-Dimensional flow with actual rarefied flow gas kinetics, chemical reactions and radiative properties that occur for flight system at given free stream conditions
- Electric Arc Shock Tube (EAST) can simulate Mars, Earth, Outer Planet and Titan atmospheric gases over all velocity ranges of interest.
- Provides rate constants for basic gas processes and properties needed for real-gas CFD codes

Ablative Thermal Protection System

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Energy management through material consumption

Given: Vehicle environment

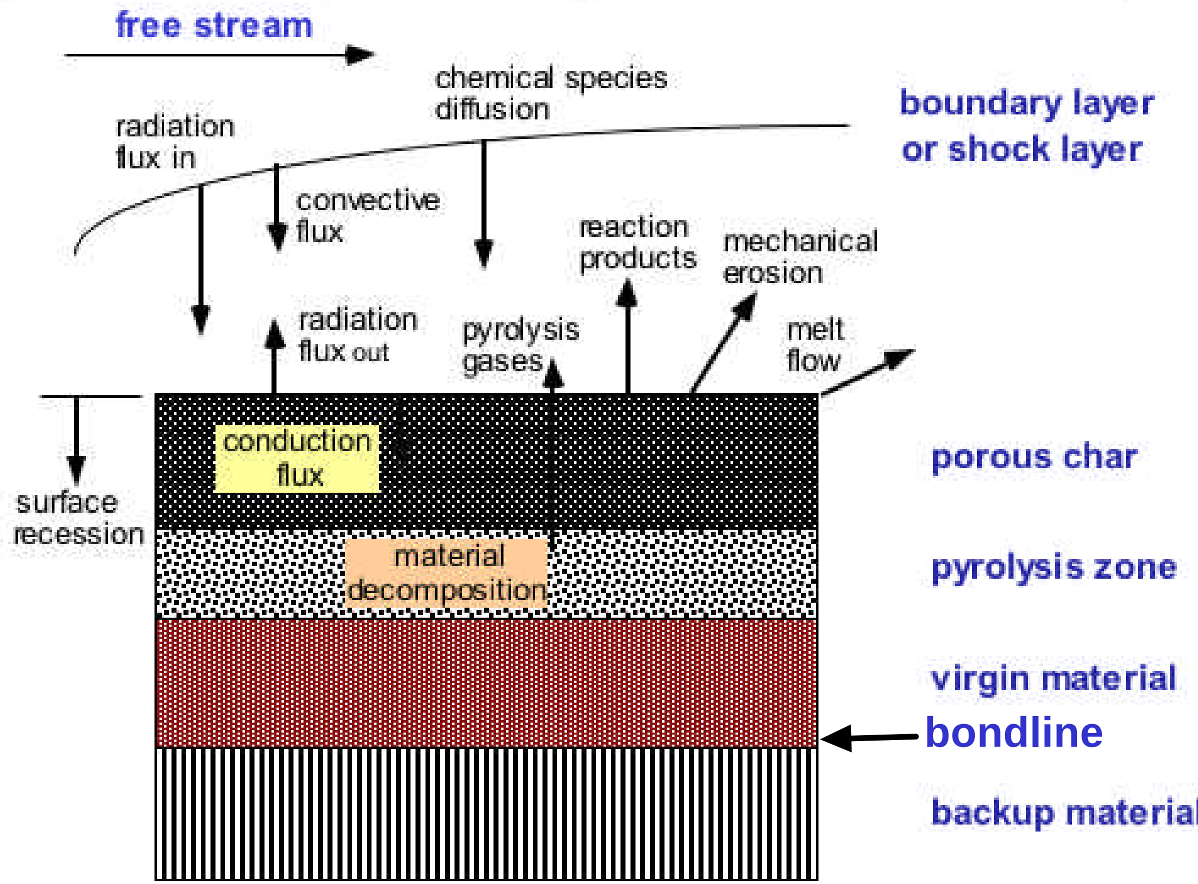
Max. bondline temperature

R & D provides:

- Materials Specification
- Materials response models
- Scalability
- Manufacturability.

Gaps

- Apollo ablator no longer available
- Extremely small No. of researchers available



Ballute Thermal Protection System
using Tailorable, Advanced Blanket Insulation (TABI)

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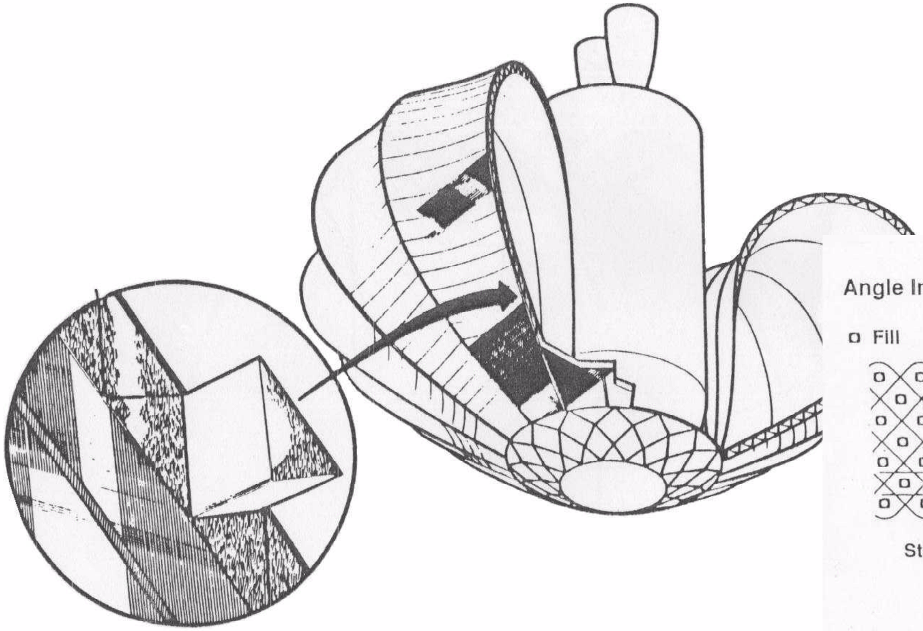
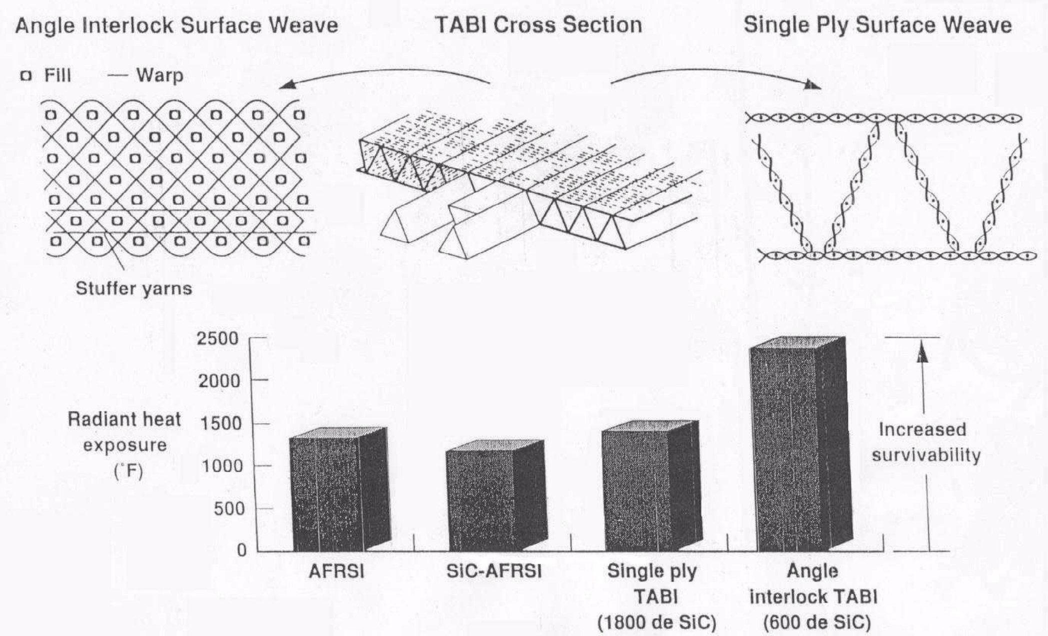
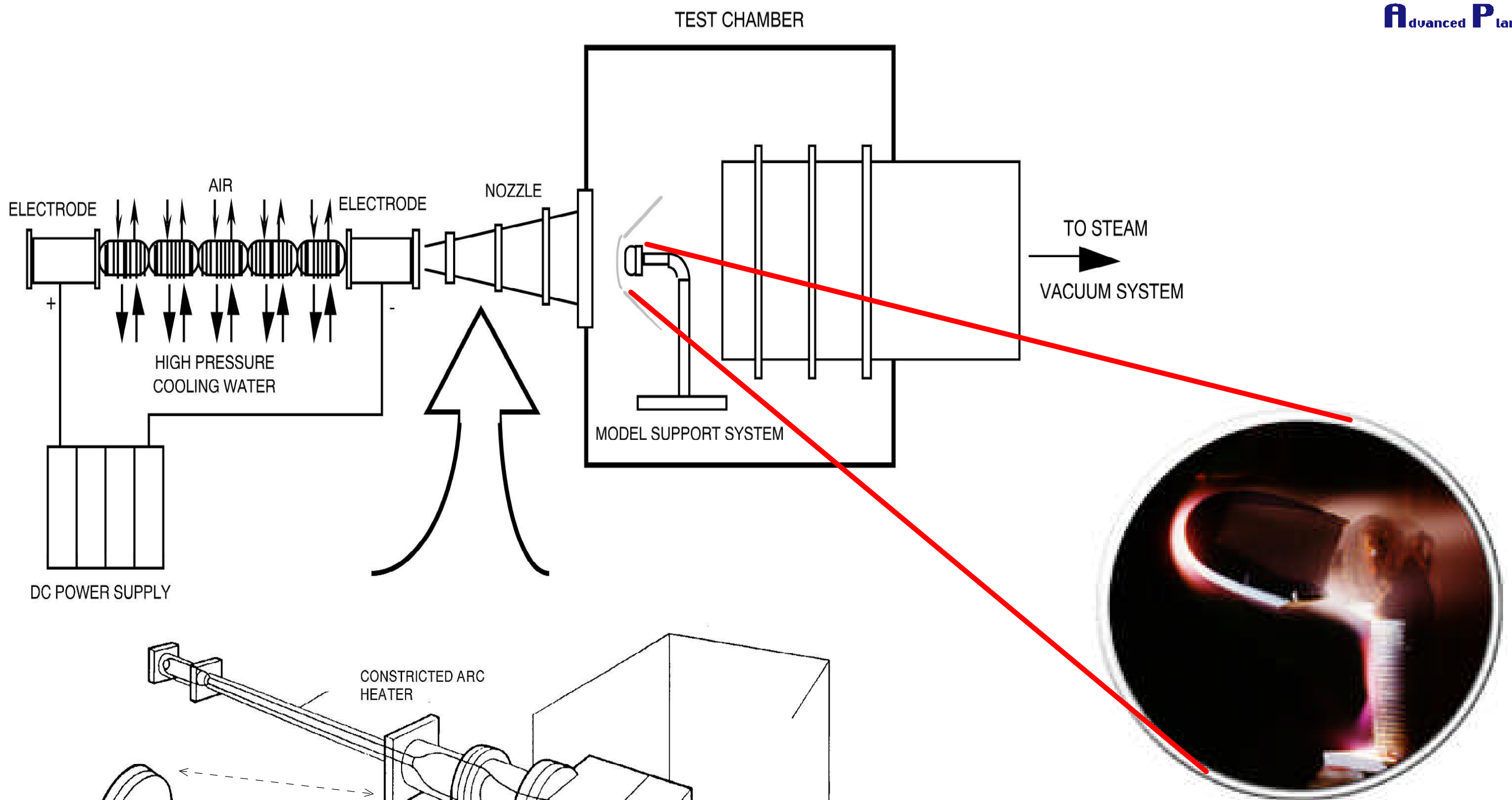
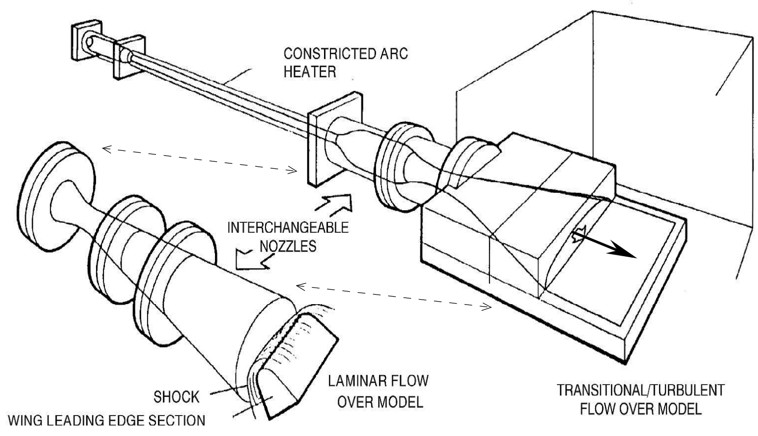




Aeroacoustic survival of flexible TPS after 600 sec at 170 dB (after exposure to radiant heat cycle)

Arc Jet and Test article





Arc Jet Simulation: Missions

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"In the 1960's hundreds of arc jets were operational - this is the remainder" J. Hartman (ARC)

Mission / Gov. Facility	SOMD (Shuttle)	Capsule LEO/Lunar Return	Mars (Viking, Pathfinder, MER)	Mars (Human and cargo)	Venus (Pioneer Venus)	Gas Giants (Galileo, Jupiter Multi-Probe)	Human Mars Return
Heat rate, W/cm^2	20 – 80 (convective)	20 – 350 (convective / combined)	25 – 150 (convective)	Up to approx. 400 for Triconic* (combined)	6,000 – 12,000 (combined)	35,000 – 50,000 (combined)	800– 2,000 (combined)
Pressure, atm	**0.02 – 0.05**	**0.02 – 0.5**	**0.05 – 0.25**	**0.05 – 0.25**	**4 – 10**	**5 – 10**	**0.5 - 1**
ARC	●	D	●	D	○	○	D
JSC	●	D	●	D	○	○	D
AEDC	○	○	○	○	D	○	○
CIRA	◉	◉	◉	○	○	○	○

- ● **Capable of full range with existing facilities**
- D **Capable of partial range with existing facilities**
- ○ **Gap identified: Capability not available**
- ◉ **Potential exists but not demonstrated**

*For Triconic. Much larger for Blunt Ellipseld

Combined = radiative + convective. This is a gap for human missions at both Mars and Earth Return

Langley Drop Research Facility -- to test large landing test articles

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- **Rigorous Landing Test Program Will be Required and Includes tests such as:**
  - **Landing dynamics**
  - **Control system validation**
  - **Pilot training**
  - **Payload egress and deployments**
  - **Emergency procedures**
  - **Simulated ascent vehicle launches**

- ***The gantry built for testing the Apollo lander (Langley's IDRF) is the ONLY existing facility capable of testing future human landers (lunar or Mars).***

- **Little modification or upgrading required to test these systems**
  - **Up to 60,000 kg landers currently envisioned in the reference missions.**
  - **60,000 kg in 1/6 gravity →22,000 lbs**
  - **IDRF could handle up to 60,000 lb**
  - **Customization for vehicle and test specific needs will be required**

Full-Scale Impact Dynamics Research Facility

Advanced Planning & Integration Office

Point of Contact:
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Hampton, VA 23681-2199
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fax: (757) 864-8547

- **Quick Facts**
  - **Length: ~ 400 ft**
  - **Width: ~ 280 ft (at bottom), (100 ft top)**
  - **Height: ~ 240 ft**
- **Originally built for:**
  - **30,000 pound lander, 28 ft/sec (limited by the bridge)**
  - **Bridge upgrade to 60,000 lb ($250k) stopped when facility was closed.**
  - **Each A frame is rated to 100,000 pound load.**
- **Currently "Closed"**
  - **Primarily means no maintenance being done**
  - **$200,000 averaged yearly maintenance cost**
- **Slated for Demolition**
  - **NASA LaRC's Structures and Materials branch has determined that the facility should be demolished.**
  - **It is a National Historic Landmark**
    - **In Sept 04 NASA submitted public notice of demolition intention**
    - **Public hearings being held to approve the demolition plan**
  - **Raytheon has been discussing take-over plans**

- **THIS IS A MUST-HAVE FACILITY FOR HUMAN SURFACE MISSIONS!**

LaRC Full-Scale Impact Dynamics Research Facility

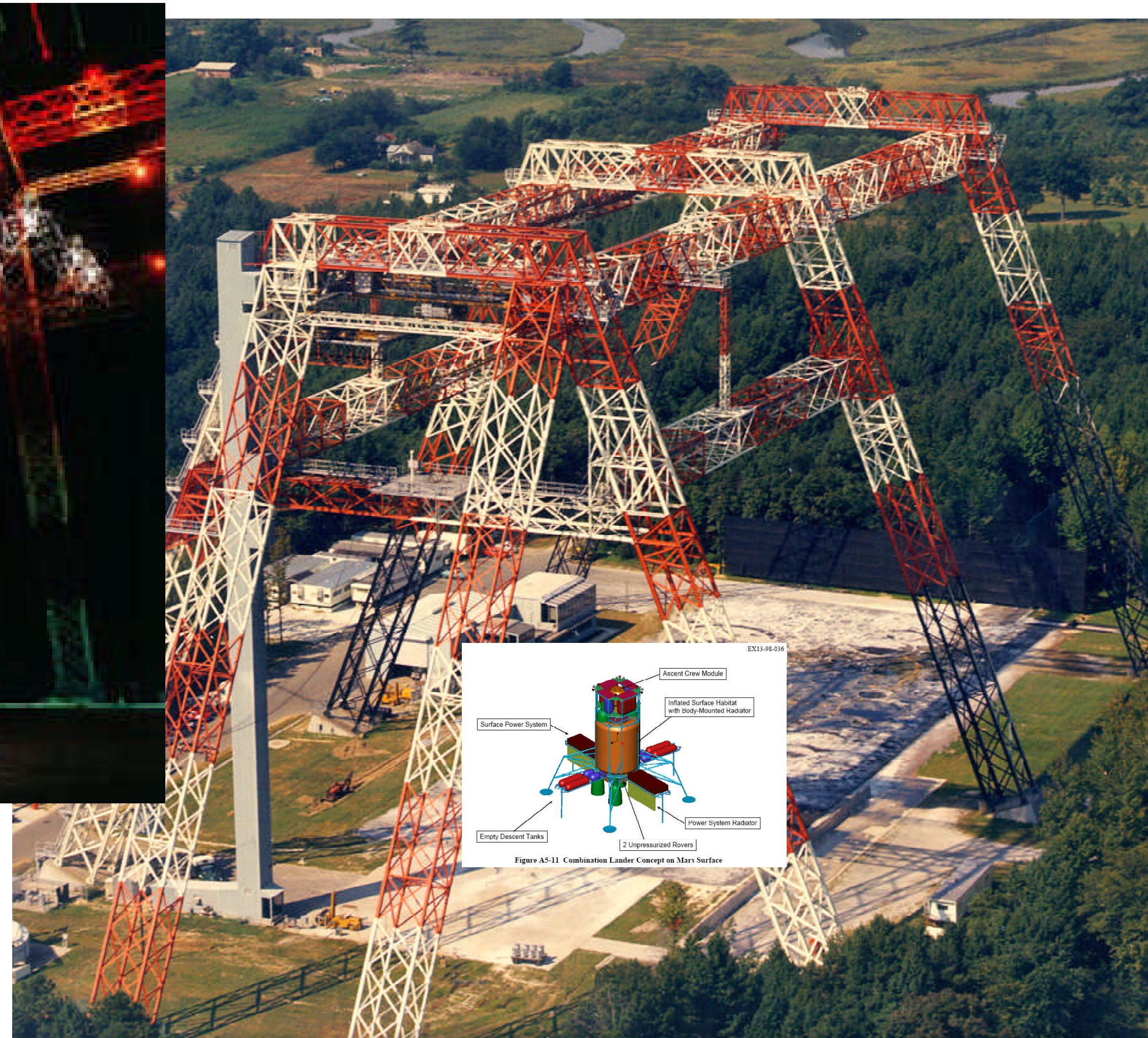

Figure A5-11 Combination Lander Concept on Mars Surface

Outline

- Listing of critical capabilities (knowledge, procedures, training, facilities) and metrics for validating that they are mission ready
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- **Flight testing to prove capabilities are mission ready**
- Issues and recommendations

Flight Tests 2008 - 2015

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Class flights	Validates	No.
Earth, suborbital ballon, ballon + rocket, sounding rocket and piggyback out-of-orbit	- Aerodynamics - Toward human rated TPS - Engineering Sensors - Flexible aeroelasticity/control	Eight
Earth, Shuttle/Station	- Test Human AEDL Perf.	3-4
Mars, Instrumented MSL	- Engineering Sensors / G,N&C - Transition to Turbulence (Mars) - Viking aerodynamics	One
Mars, Robotic scale flights to prove aero. capture when possible/ Affordable - still being discussed	- Aerocapture System	One
Earth, instrumented CEV	- GN & C, aero/aerothermal human rated TPS for Earth orbital entry and engineering inst.	Two

Flight Tests 2015 - 2029

Class	Validates	No. flights
Earth, Instrumented Aero. Capture From Lunar return	Aerocapture into Earth orbit for Mars return to orbiting quarantine station	Two
Mars, Small scale (human configuration) A/C + EDL	Aerocapture System EDL System	Two
Earth, full scale	DL, Super/trans/ subsonic and touchdown systems	Five-Seven
Mars, Instrumented Astrobiology Lab	EDL	One
Moon, CEV Spiral 2 accomplished	DL	All

Example of Properly Instrumented Flight Experiment
Aeroassist Flight Experiment (AFE) :
Vehicle Environment, TPS, GN&C, etc.

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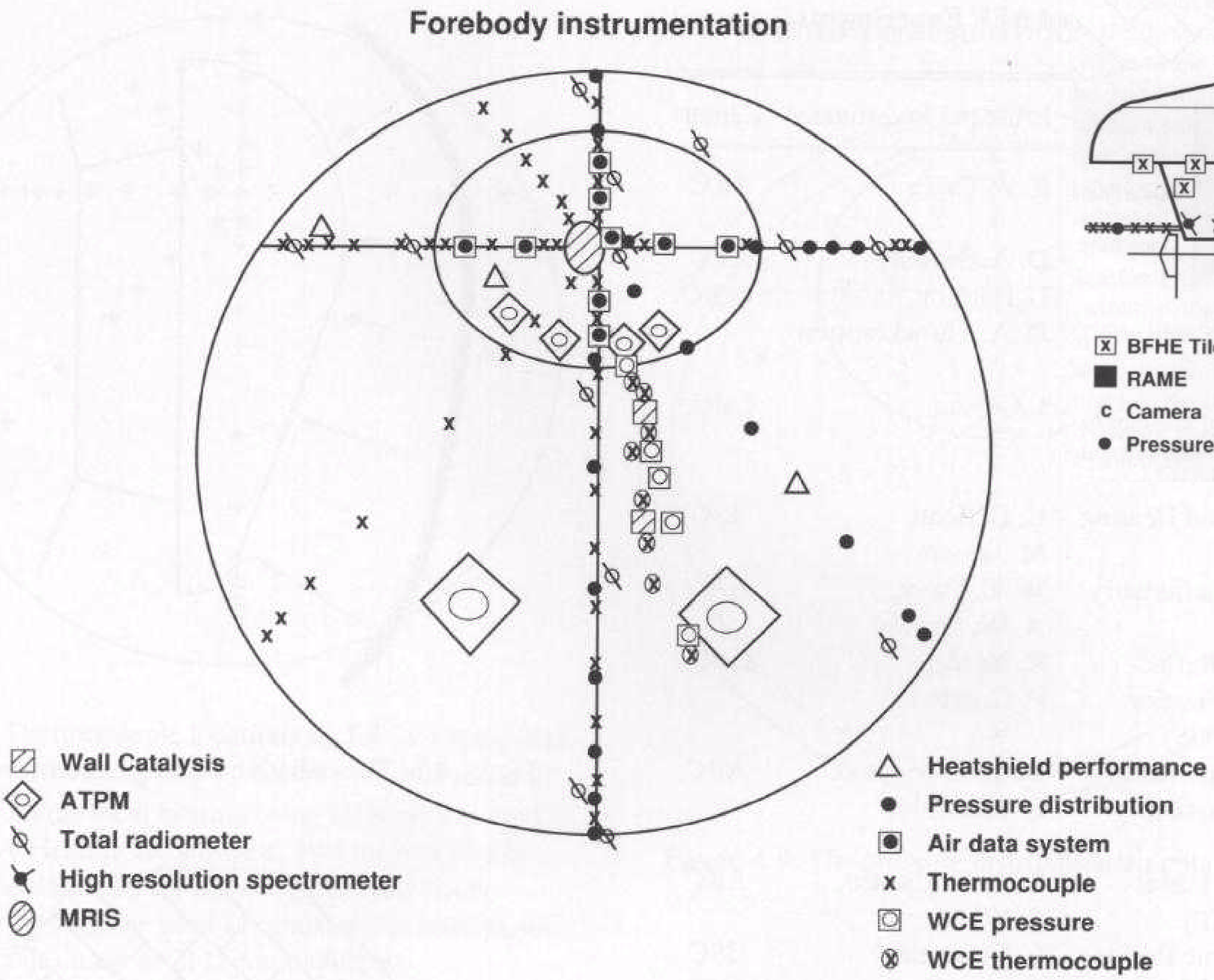
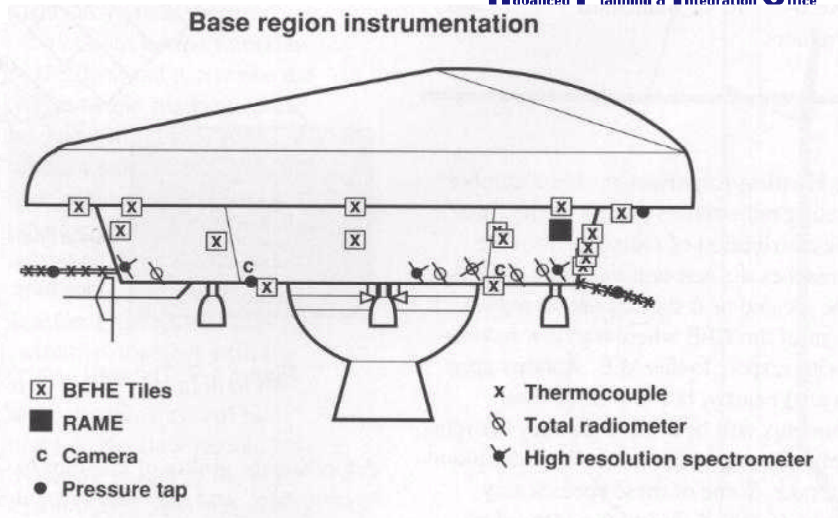
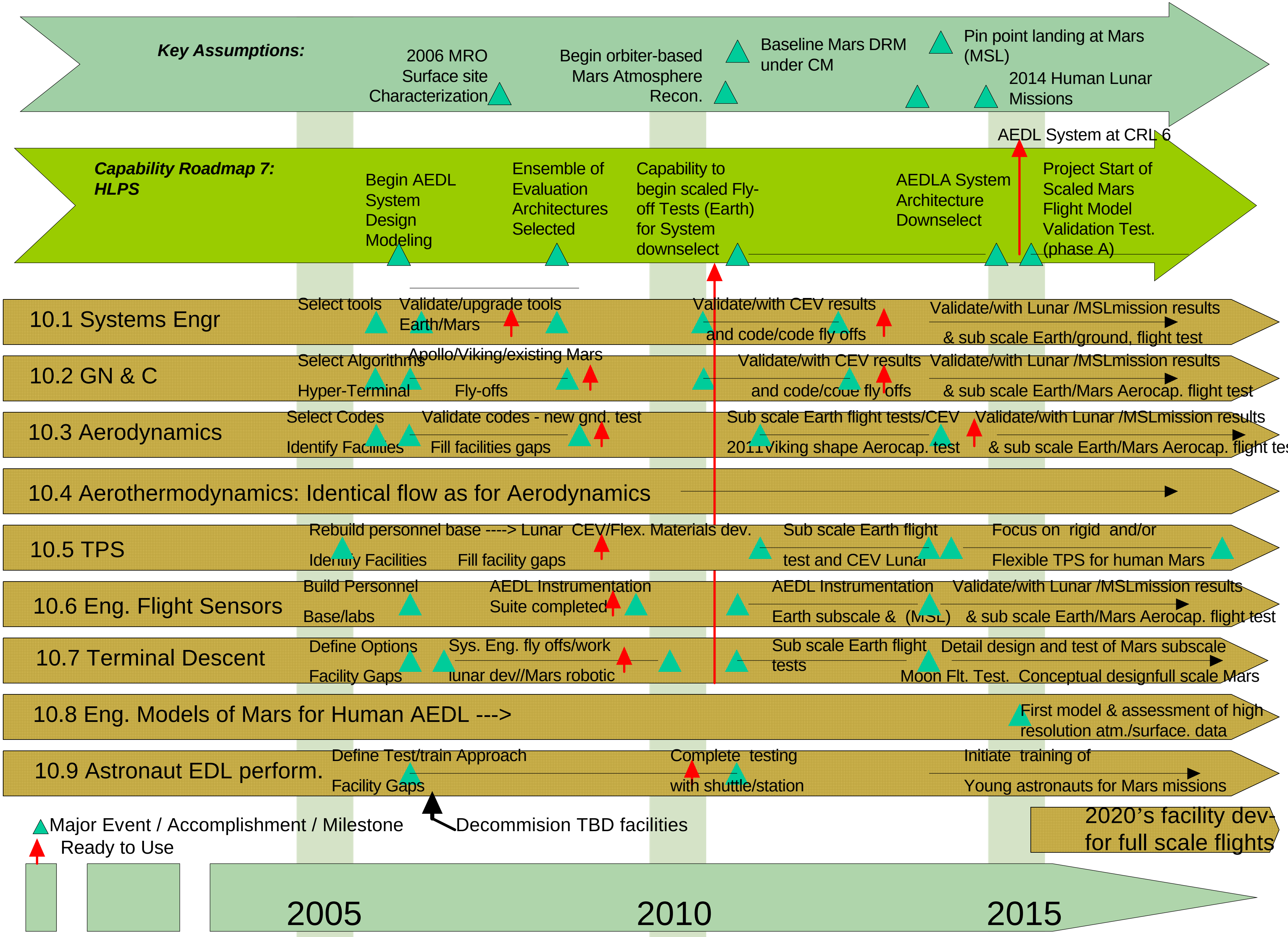




Flight Tests 2020 - 2036

Class	Validates	No. flights
Repeat tests TBD (planned failure and train mission implementers)	Acceptable mission risk	TBD
Mars, Full scale (cargo configuration)	EDL for Mars 1st Crewed Landing	One
First Human Landings	Staggered by 2 years or on same opportunity	Two

Team 7: Human Planetary Landing Systems Section 10.0 Roadmap



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Issues

- Knowledge capture/training across generations of implementers (technologists project/program personnel, leadership, managers, crew {medical, pilot, science: geology, biology, etc.})

- Sustaining/developing facilities, technologies and tools across three decades

- Independent review, analysis and assessment capability

- Early Technical Interchange Meetings (TIMs) and facility review required to ensure that facilities are not closed prematurely and that new facility capabilities are clearly understood during the NASA transformation, e.g. Aerodynamics and Aerothermodynamics CFD validations

Recommendations

- **Review/adopt the best practices/lessons/program funding approaches learned from the Apollo, Viking, Shuttle, ISS and current Mars program as initiated after Mars '98**

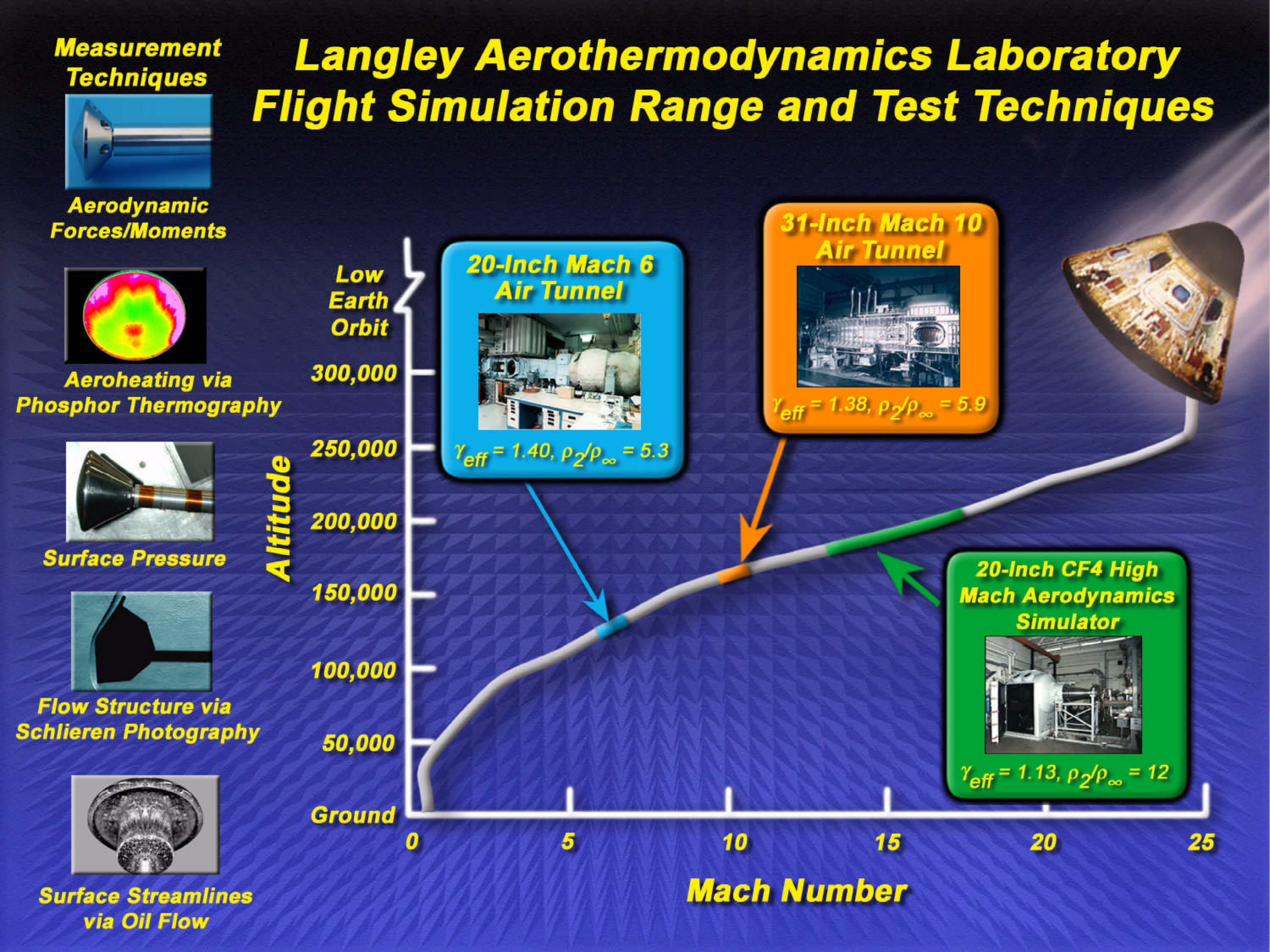
  - Example: in the 60's, 70's and 80's NASA separately (and adequately) funded facilities, technology programs, flight projects and salaries for core compentencies. Flight program/projects only paid facility "occupancy" fees. Technologists were not beholding to projects for funding. Independent, expert opinions were critical for project reviews. New enabling technologies were adopted.

- **In the late 80's/early 90's an ad-hoc "Aeroassist Working Group" was formulated by Langley, Ames, JSC and MCFC, later joined by JPL. Industry/Academia have played roles from time-to-time. In the one-NASA spirit, leadership rotates from center to center. This group has been successful in securing funding for its activity.**

  -This group should be re-invigorated and expanded to include all aspects of AEDL for both human and robotic missions. Its charter should be to facilitate multi-generational knowledge , tools and facilities necessary for agency missions for the next 3-4 generations. It must include early involvement by academia (next generations) and industry (system builders).

- **This expert group should be tasked to conduct TIMs and facilities reviews to understand/advocate for facilities needed by the HPLS for the next 3 decades**

Facility Details


Langley Aerothermodynamics Laboratory
Flight Simulation Range and Test Techniques
Measurement Techniques
Aerodynamic Forces/Moments
Aeroheating via Phosphor Thermography
Surface Pressure
Flow Structure via Schlieren Photography
Surface Streamlines via Oil Flow
20-Inch Mach 6 Air Tunnel
γ_{eff} = 1.40, ρ_2/ρ_∞ = 5.3
31-Inch Mach 10 Air Tunnel
γ_{eff} = 1.38, ρ_2/ρ_∞ = 5.9
20-Inch CF4 High Mach Aerodynamics Simulator
γ_{eff} = 1.13, ρ_2/ρ_∞ = 12
Low Earth Orbit
300,000
250,000
200,000
150,000
100,000
50,000
Ground
Altitude
0
5
10
15
20
25
Mach Number

Human-Rated Vehicle Development Program Test Requirements

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Apollo development (1962-1965)

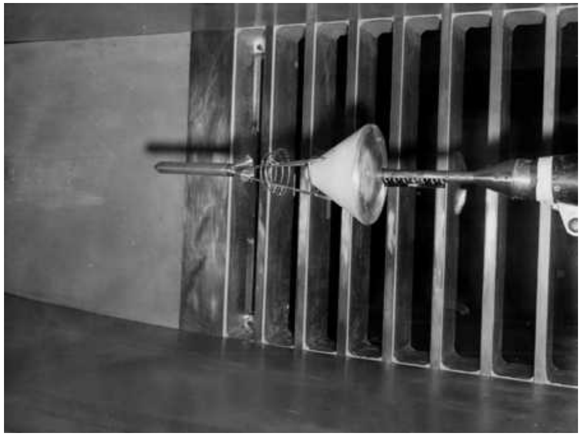
- Estimated 6200+ hours (155 x 40-hour work-weeks or 3 work-years) of wind tunnel testing conducted on Apollo entry and escape configurations.
- Test plan called for use of at least 33 facilities: 22 transonic, supersonic, or hypersonic wind tunnels, 8 high-enthalpy shock tubes or arc jets and 3 free-flight ballistic ranges.
- Ref: Apollo Wind Tunnel Program Report, North American Aviation SID-62-170-5, July 1963).

Space Shuttle (1969 through 1984)

- Shuttle development required over 100,000 hours of wind tunnel testing (2500 x 40-hour work-weeks or 48 work-years) in more than 60 wind tunnels.
- Shuttle was far more complex than Apollo capsule: winged vehicle with external fuel tanks and boosters vs. simple capsule.
- Ref: Romere, P.O, and Brown, S. W., “Documentation and Archiving of the Space Shuttle Wind Tunnel Test Data Base,” NASA TM-104806, Jan. 1995.

Sub / Tran / Supersonic Wind Tunnels

- Robotic exploration programs are more risk tolerant than human-rated programs
- Robotic entry systems are have been simple geometries with no control surfaces
- Every human-rated entry system has been wind-tunnel tested across the speed range
- Many of these tunnels have already vanished
- Remaining tunnels are threatened with closure



Sub / Tran / Supersonic Wind Tunnel Uses

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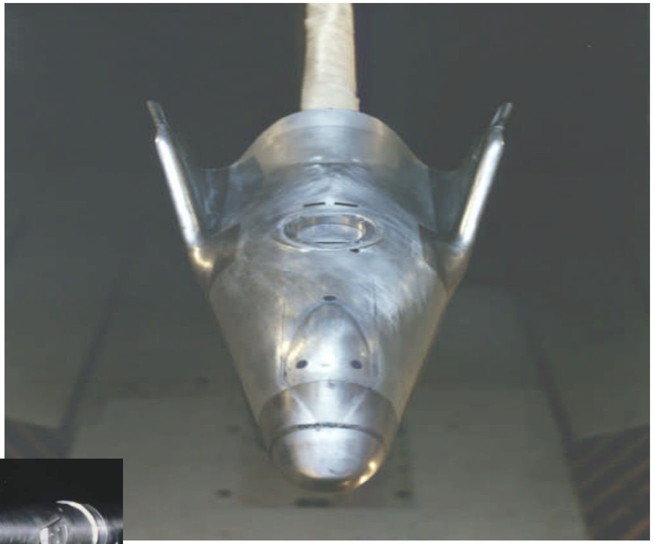
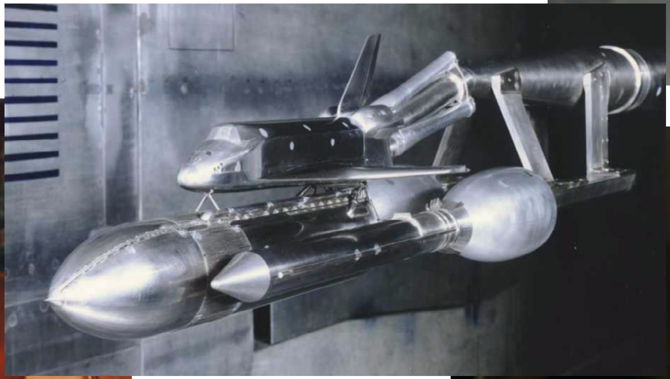
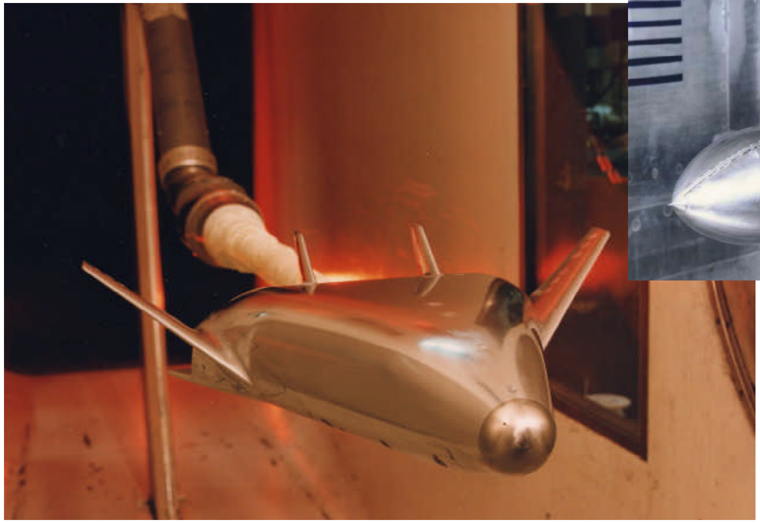
- Configuration development
- Validation of numerical techniques
- Multi-body interactions (launch stack)
- Reaction Control System (RCS) **interactions with flow field**
- Dynamic stability (forced oscillation)

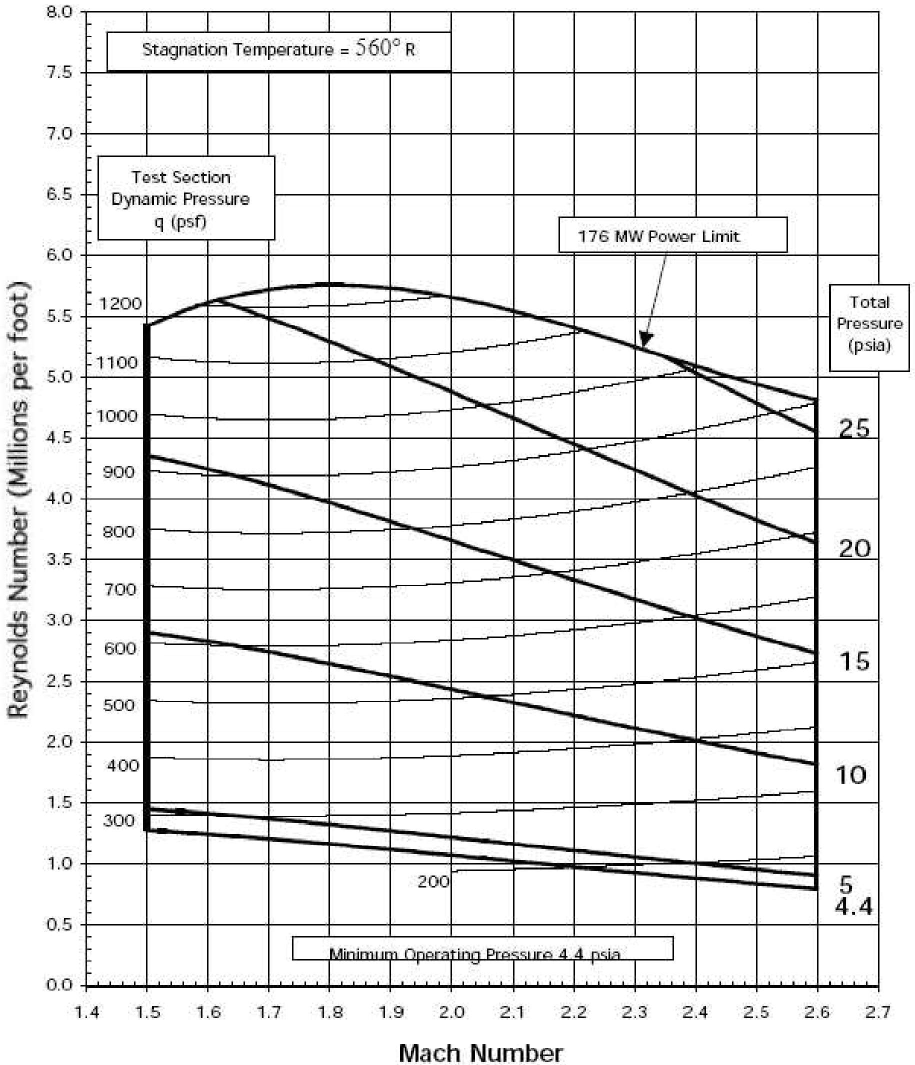


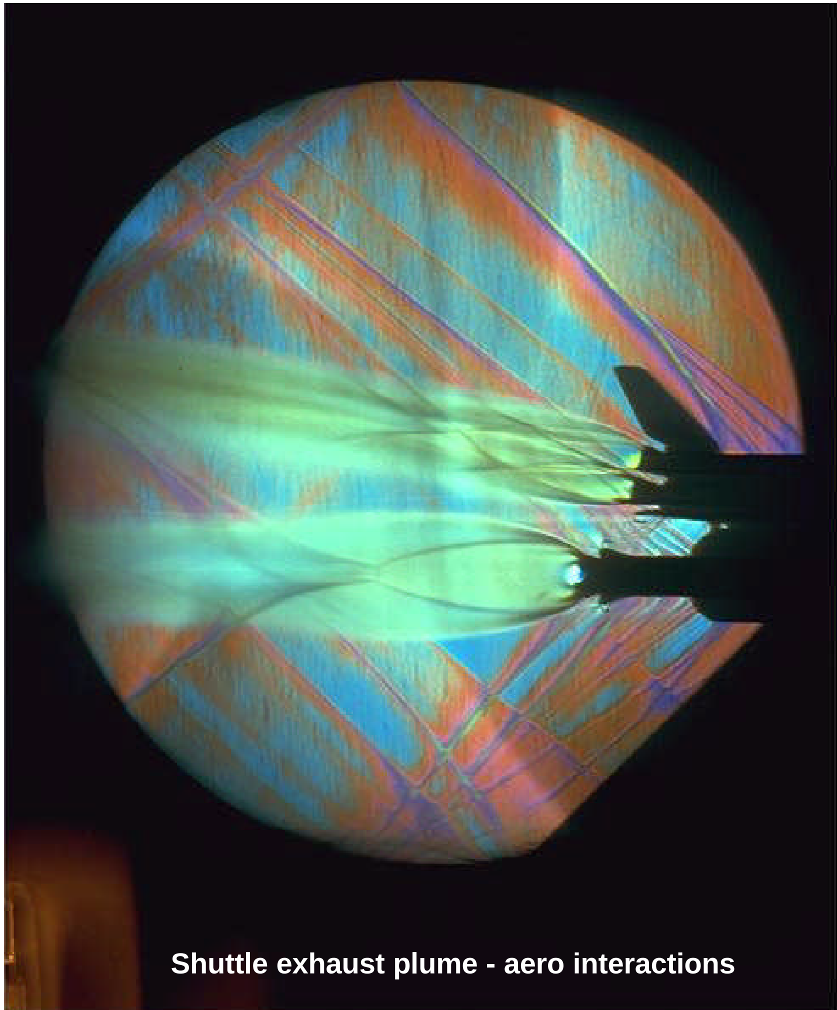




OPERATING CHARACTERISTICS OF THE NASA AMES RESEARCH CENTER 9-BY 7-FOOT SUPERSONIC WIND TUNNEL

Advanced Planning & Integration Office





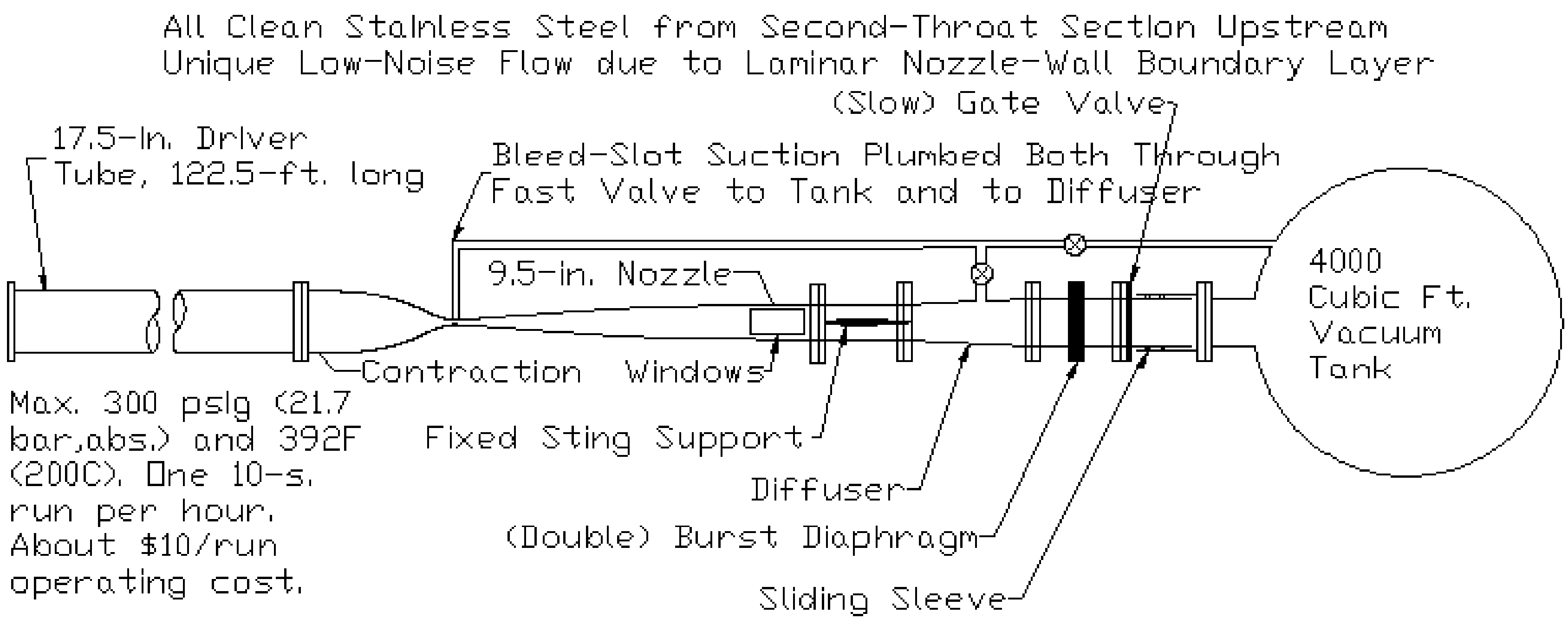
Shuttle exhaust plume - aero interactions

Boeing/AFOSR Mach-6 Quiet Tunnel

- Mach 6 in 9.5-in.-dia. nozzle at $10/shot
- Operates from Re=1E5/ft. to 6E6/ft.
- Quiet flow to about 0.5E6/ft, plans to 3E6/ft
- Usually clean air, could run CO_2

Hot wires (have been calibrated in CO_2), Hot films

Temp. paints, laser differential interferometer, controlled perturbers for stability experiments



Exit of 9.5-Inch Mach-6 Nozzle

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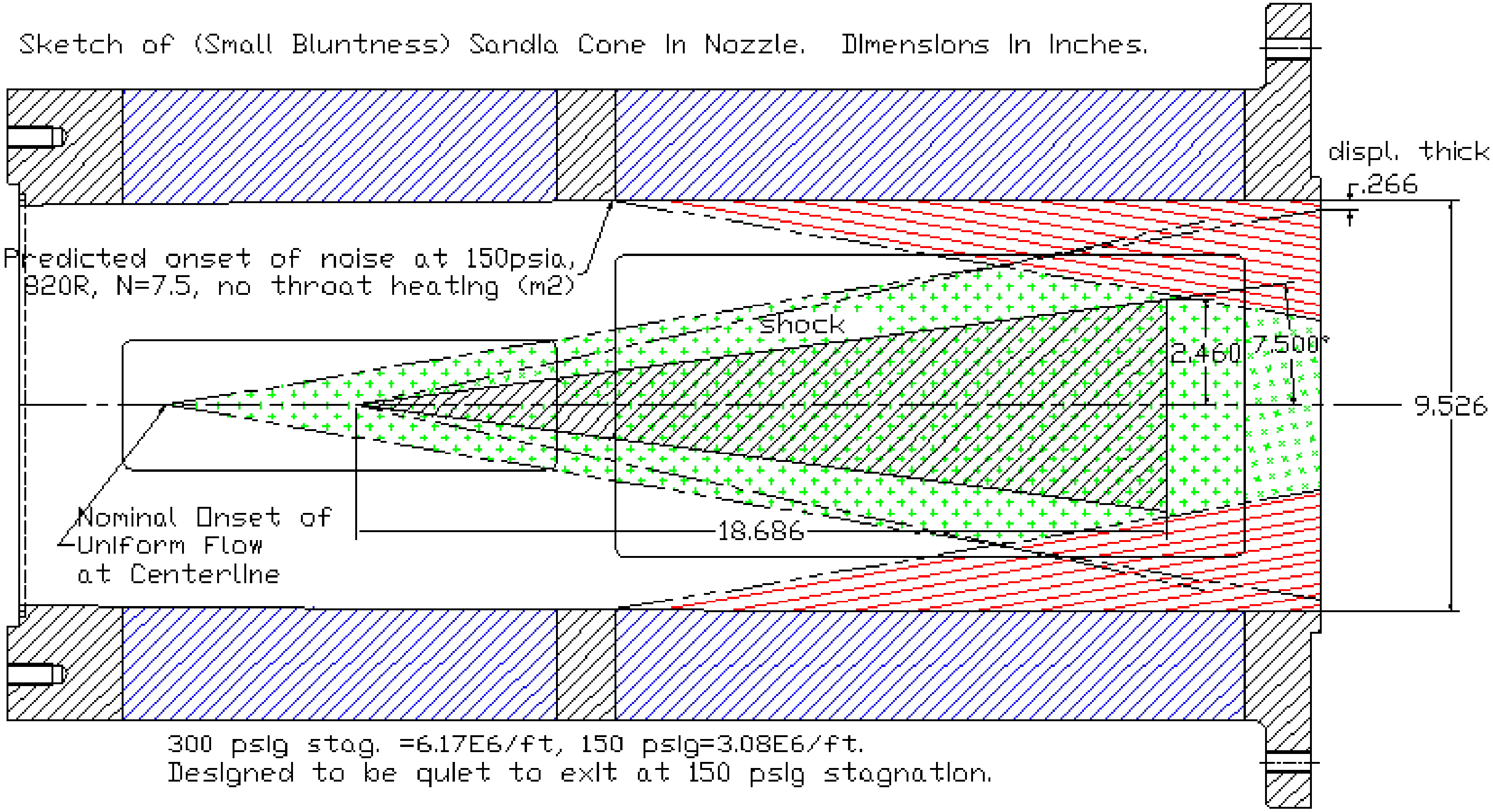
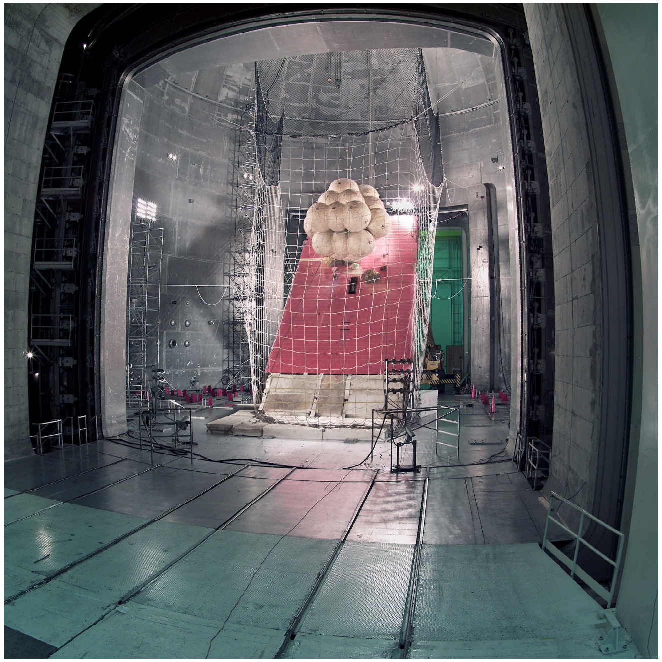
Eight openings for windows (blue), presently one 7x14-inch window and one pair of 5-in.-dia. windows. Auto. traverse in vertical centerplane for wires and pitot probes. Green marks nominal low-noise uniform flow.



GRC Plumbrook Quick Facts

- Overall Functions:
  - **Sustains high vacuum**
  - **Simulates solar radiation (400-kW arc lamp / 4-MW quartz heat lamp array)**
  - **Produces cold environments via cryogenic cold wall (-320 °F)**
  - **Provides a high degree of vibration isolation for sensitive optical tests**
- Test Chamber
  - **100-ft diameter by 120-ft.-tall test area**
  - **Chamber penetrations for power, data acquisition, and high-pressure liquids and gases**



WSTF Overview

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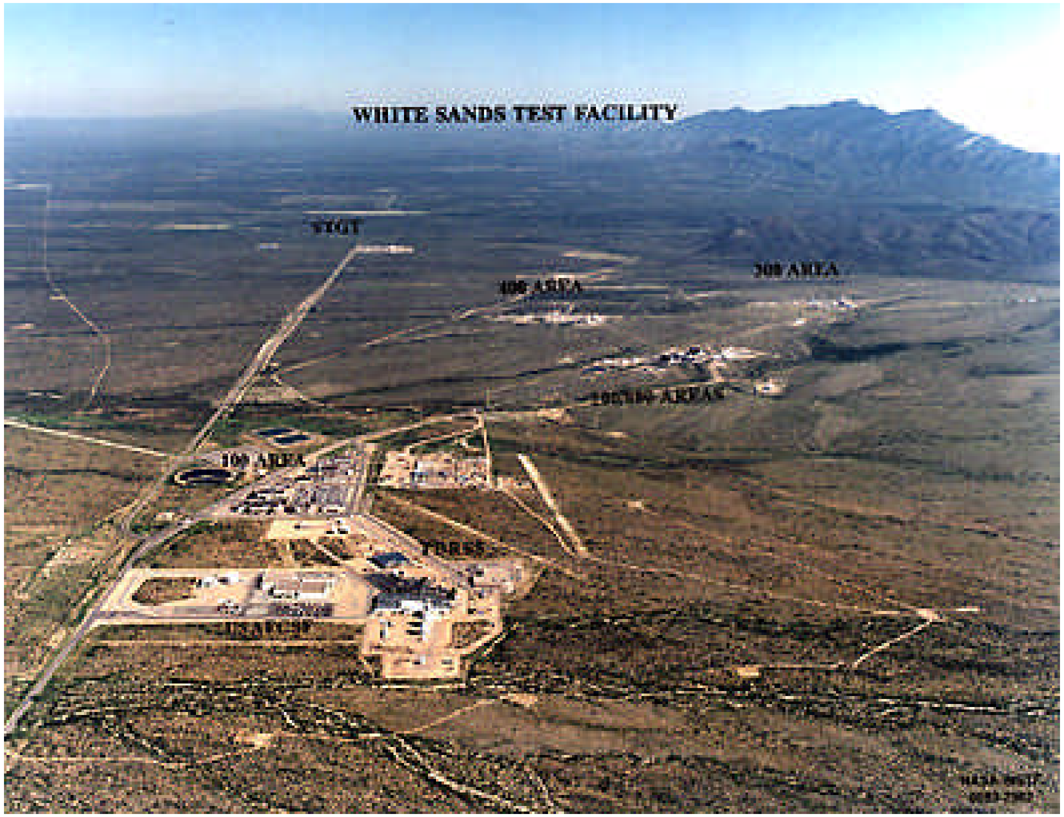
- Constructed in 1962-64 to support project Apollo
- Component of JSC Houston
- Occupies 28 square miles - SW Corner of WSMR



Aerial View Looking North

Unique WSTF Capabilities

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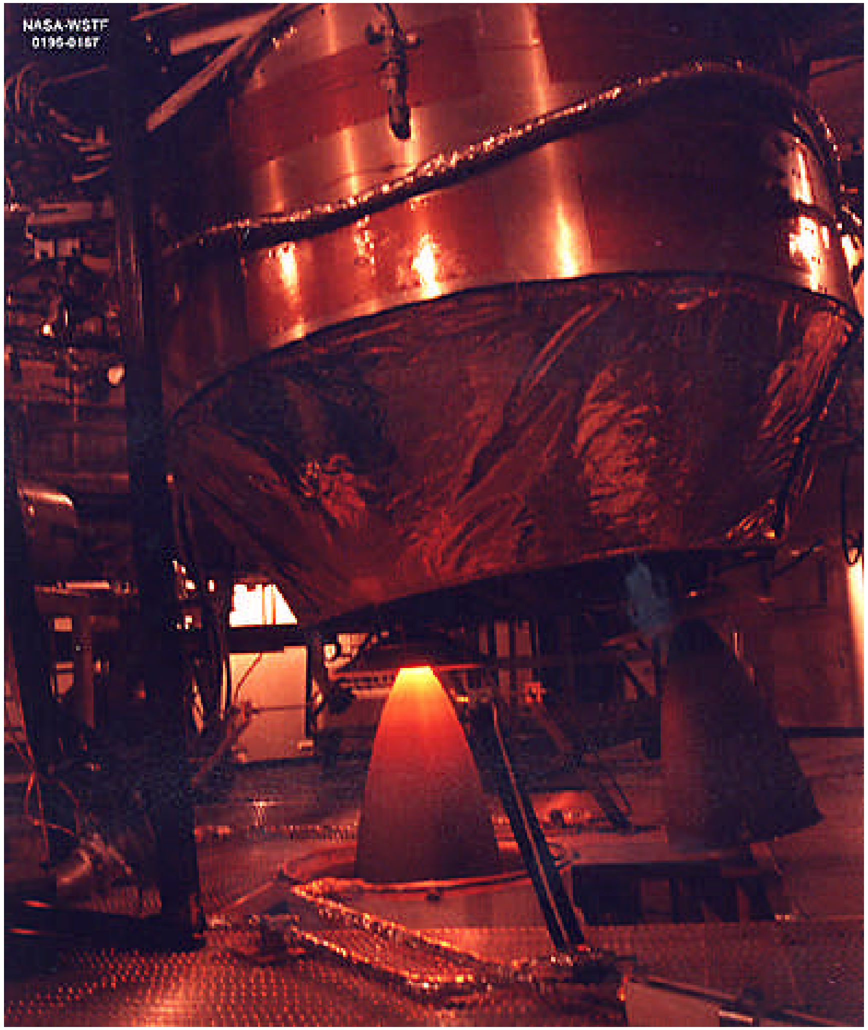
- Simulated altitude testing of full-scale integrated hypergolic propulsion systems
- Agency facility for hypervelocity impact testing, including accommodations for hazardous targets
- Capability for all materials testing defined by NASA Standard 6001 (NHB 8060.1C)
- Design and hazards analysis of oxygen and hydrogen systems
- Large-scale explosion testing of hypergolic, cryogenic, and solid propellants
- Component testing in high temp/high flow gaseous oxygen and hydrogen

Full-scale Shuttle OMS pod installation at vacuum test cell TS-403



Cassini - Saturn orbit insertion engine glows during 3 hr. 20 min. continuous firing

Vestibular Research Facility

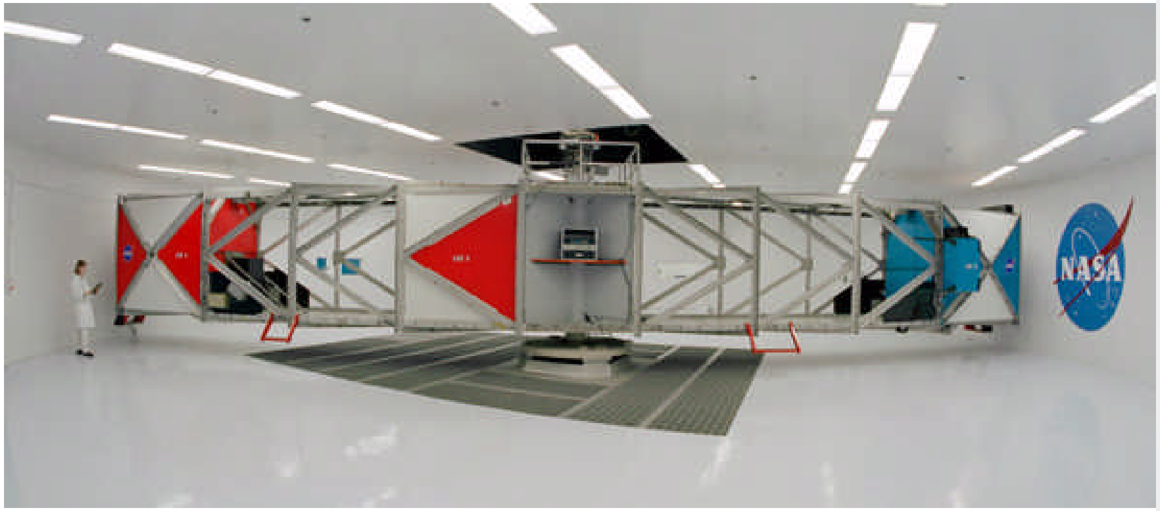
Advanced Planning & Integration Office

The Vestibular Research Facility (VRF) located at NASA Ames Research Center houses approximately 2,000 square feet of laboratory space and 1,000 square feet of office space. The VRF provides a centrifuge and two types of linear sleds for ground-based studies of vestibular function. Support laboratories and office areas complete the facility. Both flight and ground-related science questions may be addressed using either humans or animals as subjects.

30-ft Linear Sled
Vestibular Research Facility

The 30-ft Linear Sled of the Vestibular Research Facility can be used to examine otolith-ocular-perceptual responses humans (the reinterpretation of otolith signals driving both perception and gazer stabilization reflexes is a major component of human adaptation to altered gravity). It consists of a carriage mounted on an ultra smooth horizontal 10-m granite slab. The carriage is supported by low-pressure air bearings that float ~2.5 microns above the granite surface to provide a silent, frictionless linear motion. Artifacts due to mechanical vibration and auditory noise are therefore eliminated. The sled is human-rated and instrumented to deliver visual stimuli in conjunction with the linear-acceleration vestibular stimulus while recording eye movements, arm m

20-G Centrifuge



20-G Centrifuge
Performance limits and specifications:

Radius: 29 ft
Payload: 1,200 lbs
Max G: 20 G (human-rated to 12.5 G)
Max RPM: 50 RPM

The 20-G Centrifuge located at NASA Ames Research Center can be used to evaluate the effects of altered gravity, and G-load transients, and rotational acceleration on humans (in addition to examining G-effects per se, this device can be used to evaluate candidate AG regimes that astronauts may also be exposed to). A cab mounted at the end of the 6.8m-diameter rotating arm contains a modified jet-fighter ejection seat. The centrifuge is human-rated and instrumented to deliver a variety of visual stimuli at a range of possible static g levels (usually up to 3g; capable up to 20g) while recording eye movements, limb movements, and perceptual responses.

Vertical Motion Simulator

Advanced Planning & Integration Office

The Vertical Motion Simulator (*VMS)* , which is located in the Flight and Guidance Simulation Laboratory (SimLab) at *NASA* Ames Research Center, is renowned for its efficient production of high-fidelity, fixed and moving base, real-time, piloted flight simulations of aerospace vehicles. Engineers can customize the system to simulate any aerospace vehicle, whether existing or in the design stage. Existing vehicles that have been simulated include a blimp, helicopters, fighter jets, and the Space Shuttle Orbiter. One aircraft being designed that may be simulated at the *VMS* is a next-generation transport capable of flying in near-earth orbit. Simulations occur with high fidelity; that is, the simulator reproduces flight characteristics with a high degree of accuracy. This entails delivering realistic cues to the astronaut/pilot in real time.

Interchangeable Cab (ICAB) on the VMS Motion Base