Ground Testing as Part of Vehicle Development: Some Concepts for an Overall Strategy

- No single tunnel can simulate all aspects of hypersonic flight: Mach number, Reynolds number, enthalpy, ablation and heat soak, wall roughness and temperature, freestream disturbances, etc.
- No simulation can fully account for all aspects of flight either, all must make assumptions
- Mechanism-based simulations must be used to compare ground-test results from different facilities. The sims must also be compared to existing flights, and then used to <u>extrapolate</u> estimates of performance in new flights
- Cooperatively develop best combination of ground experiments, simulations and flight tests
- Efforts must be focused on the particular issues that appear most critical to prospective vehicles of current interest.

Major Hypersonic Ground Test Facilities

- The following brief summary is mostly taken from “Advanced Hypersonic Test Facilities”, edited by Frank Lu and Dan Marren, AIAA Progress in Astronautics and Aeronautics, v. 198, 2002.
- See also Kingsbury, “Aerospace Technology: Technical Data and Information on Foreign Facilities”, GAO report NSIAD-90-71FS, June 1990.
- Also Penaranda and Freda, “Aeronautical Facilities Catalog, Vol 1, Wind Tunnels”, NASA RP-1132, 1985.
- Also Anton et al., “Wind Tunnel and Propulsion Test Facilities, Supporting Analyses to an Assessment of NASA’s Capabilities to Serve National Needs”, RAND report, 2004.
- See also Goodrich et al., “Wind Tunnels of the Eastern [and Western] Hemisphere”, U.S. Library of Congress, Aug. 2008, slides in PDF at http://www.loc.gov/rr/frd/ Nontechnical descriptions, sketchy, but useful.
- Best overall description of facility types can be found in Lukasiewicz, “Experimental Methods of Hypersonics”, Marcel-Dekker, 1973. No more recent overall summary at an introductory level.
- Many facilities were closed during the 70’s, 80’s, and 90’s. U.S. industry has closed (nearly) all their facilities.

see also the Appendix on High Enthalpy Facilities in Hypersonic Nonequilibrium Flows: Fundamentals and Recent Advances, ed. by Josyula, AIAA Progress in Astro. and Aero., v. 247, 2015.

Major Hypersonic Shock Tunnels

- GASL, HYPULSE, shock-expansion tunnels and reflected shock tunnels. Detonation driver. Core flow of 10-18 in. dia.
- CUBRC shock tunnels: LENS I, LENS II are reflected shock tunnels Mach 3-14, nozzle exits to 5-ft dia., vel. to 15 kft/s. LENS-XX is a new large expansion tunnel, seems to achieve high enthalpy with minimal contamination (e.g. AIAA 2013-2837, 2011-0626).
- U-12 shock tube at TSNIIMASH near Moscow. Nozzle with 3 m diameter.
- Combustion-driven shock tunnel at Beijing, JF-12, new ca. 2012, nozzles for Mach 5-9, diam. to 2.5m, length of 260m, runtime 100ms. So far, only website information, no technical papers found. However, seems to follow smaller facilities of a similar type, some technical papers seem to exist. see aiaa 2014-1012
- Other detonation-driven shock tunnels at Aachen, and UT Arlington.
- Free-piston shock tunnels at Australia (T3 and T4), Caltech (T5), Germany (HEG, 0.44m exit dia., P0 to 900 atm., T0 to 8100K, H0 to 22MJ/kg, Re to 6.7e5/m), and Japan (HIEST, piston to 780 kg, 1 m nozzle, H0 to 25MJ/kg, P0 to 1500 atm.).
- Chemistry is a major issue; nice summary by Hans Hornung in "Experimental Hypervelocity Flow Simulation, Needs, Achievements and Limitations, presented at the 1st Pacific Int'l Conf. on Aerospace Sci. and Tech., Taiwan, 1993. 10 pages incl. 12 figures.

Specialized Hypersonic Blowdown Tunnels

- Moscow, TSNIIMASH, piston gasdynamic unit, opposing pistons, P0 to 2500 atm., T0 to 4000K, runtimes to 1 sec.
- Arcjets at AEDC, NASA Ames, SCIROCCO in Naples, Italy, LBK at Cologne in Germany, high enthalpies and long run times, poor flow quality, used to test TPS materials.
- 8-ft high-temperature tunnel at NASA Langley, vitiated air system, used to test scramjet propulsion systems. Burns methane. 8-ft. test section. To 200 atm. at 3000F.
- NASA Glenn hypersonic tunnel at Plum Brook, T0 to 2200K, P0 to 80 atm. Nitrogen with graphite heater.
- French ONERA F4 hot-shot tunnel. Nozzles to 0.9m dia. Arc driven by energy stored in a 15-ton flywheel.
- AEDC Tunnel 9 at White Oak. Nozzles of Mach 7-14, Re to 48 million per foot, P0 to 1000 atm., cold nitrogen with graphite heater.
- Other large blowdown tunnels in Germany, France, Japan, Russia, probably China.

Hypersonic Tracks and Ballistic Ranges

- Test track at Holloman AFB in New Mexico. Speeds to 3 km/s on rails in the desert. Rocket-boosted sleds.
- Ballistic ranges shoot projectiles out of light-gas guns into long tubes with controlled atmospheres:
- Track G at AEDC in Tullahoma has 8 and 14-in. guns, 1000 ft. of range, roughly 4-7 km/s and seeking 10 km/s.
- NASA Ames has a smaller range, but this one can fire counterflow into a shock tunnel to increase the relative velocity.
- Ballistic ranges also exist elsewhere, at ISL in France, Eglin AFB in Florida, etc.

See also "The Optimum Hypersonic Wind Tunnel", by Trimmer, Cary, and Voisinet, AIAA Paper 86-0739CP, March 1986. This paper has a nice discussion of various types of hypersonic wind tunnels and also shock tunnels, as of 1986.