APPENDIX B

U.S. Test Facilities

Table B.1
U.S. Subsonic WTs

Name	Test Section	Mach Number	Rn (per ft × 10^6)	Organization	Web Site
National Full-Scale Aerodynamics Complex (NFAC) 80×120-Foot	80H×120W (ft)	0–100 knots	0–1.2	NASA Ames Research Center	windtunnels.arc.nasa.gov/
NFAC 40×80-Foot	39H×79W×80L (ft)	0–300 knots	0–3	NASA Ames Research Center	windtunnels.arc.nasa.gov/
Unitary 12-Foot Pressure Wind Tunnel	11.3H×11.3W×28L (ft)	0.05–0.55	0.1–12	NASA Ames Research Center	windtunnels.arc.nasa.gov/
9×15-Foot Low-Speed Wind Tunnel	9H×15W×28L (ft)	0–0.2	0–1.4	NASA Glenn Research Center	facilities.grc.nasa.gov/9x15/index.html
Icing Research Tunnel (IRT)	6H×9 W×20L (ft)	50–395 mph		NASA Glenn Research Center	facilities.grc.nasa.gov/irt/index.html
14×22-Foot Subsonic Tunnel	14.5H×21.75W×50L (ft)	0–0.3	0–2.1	NASA Langley Research Center	wte.larc.nasa.gov/facilities/aerodynamics/14X22.cfm?field=1&id=2&fac=1
Low-Turbulence Pressure Tunnel (LTPT)	7.5H×3W×7.5L (ft)	0.05–0.5	0.4–15	NASA Langley Research Center	wte.larc.nasa.gov/facilities/aerodynamics/low.cfm?field=3&id=2&fac=1
12-Foot Low-Speed Tunnel	12H×15W (ft)	0–77 ft/sec	0–0.5	NASA Langley Research Center	wte.larc.nasa.gov/facilities/facilities_type.cfm?id=2&fac=4
20-Foot Vertical Spin Tunnel	20 diameter × 25H (ft)	0–85 ft/sec	0–0.15	NASA Langley Research Center	wte.larc.nasa.gov/facilities/flight_dynamics/20foot.cfm?field=7&id=2&fac=1
Subsonic Aerodynamic Research Laboratory (10×7-Foot)	10×7 (ft)	0.2–0.5		Air Force Research Laboratory	www.wrs.afrl.af.mil/infores/facilities/fac_102.htm
Vertical Wind Tunnel	12 diameter (ft)	0–0.14	0–0.91	Air Force Research Laboratory	www.wrs.afrl.af.mil/infores/facilities/fac_101.htm

Table B.1—continued

Name	Test Section	Mach Number	Rn (per ft 10^6)	Organization	Web Site
Army Aeromechanics Lab	7×10 (ft)	0–0.33	0–2.1	Army Aeromechanics Lab (at NASA Ames Research Center)	www.worthey.net/windtunnels/
8×10-Foot Subsonic Wind Tunnel	8H×10W×14L (ft)	10–275 ft/sec		Naval Surface Warfare Center–Carderock Division	www50.dt.navy.mil/facilities/data/swtdata.html
Low-Speed Wind Tunnel	8H×12W×15L (ft)	0.04–0.36	0.25–2.5	Allied Aerospace (Microcraft)	www.alliedaerospace.com/Wind%20Tunnel%20Testing.htm
20×20-Foot Subsonic Wind Tunnel	20H×20W×45L (ft)	0–215 knots	0–2.3	Boeing	www.boeing.com/assocproducts/techsvcs/boeingtech/bts_aeroe.html
9×9-Foot Subsonic Propulsion Wind Tunnel	9H×9W×19.5L (ft)	0–200 knots		Boeing	www.boeing.com/assocproducts/techsvcs/boeingtech/bts_aerod.html
Boeing Research Aero/Icing Tunnel	4×6 (ft)	0–250 knots		Boeing	www.boeing.com/assocproducts/techsvcs/boeingtech/bts_aerof.html
BTS-Low Speed Aeroacoustic Facility	9×12 (ft) 7×10 (ft)	0.25 0.32		Boeing	www.boeing.com/assocproducts/techsvcs/boeingtech/bts_acoub.html
John J. Harper Low-Speed Wind Tunnel	7×9 (ft)	10–220 ft/sec	0–1.6	Georgia Institute of Technology	www.ae.gatech.edu/research/windtunnel/expaero/jjht.html
Low-Speed Wind Tunnel #1	30×26 (ft)	14–146 ft/sec	0–1	Lockheed Martin	www.worthey.net/windtunnels/
Low-Speed Wind Tunnel #2	16×23 (ft)	29–293 ft/sec	0–2	Lockheed Martin	www.worthey.net/windtunnels/
8×12-Foot	8×12 (ft)	0–293 ft/sec	0–1.7	Lockheed Martin	www.worthey.net/windtunnels/
Wright Brothers Wind Tunnel	7.5 × 10 elliptical × 15L (ft)	0–0.25	0–1.8	Massachusetts Institute of Technology	web.mit.edu/aeroastro/www/labs/WBWT/wbwt_industry_info.doc (download)
7×10-Foot Low-Speed Wind Tunnel	7H×10W×20L (ft)	0–300 mph	1.8	Northrop Grumman	www.is.northropgrumman.com/test/test_capabilities/wind_tunnel/wind_tunnel.html
Langley Full-Scale Tunnel	30H×60W×56L (ft)	13–80 mph	0.73	Old Dominion University	www.lfst.com

Table B.1—contined

Name	Test Section	Mach Number	Rn (per ft × 10^6)	Organization	Web Site
Oran W. Nicks Low-Speed Wind Tunnel	7H×10W×12L (ft)	0–0.25	0–1.9	Texas A&M	wind.tamu.edu/facility.htm
Large Subsonic Wind Tunnel	8 octagonal × 16L (ft)	0–0.9	4.5	United Technologies	www.worthey.net/windtunnels/
	10×15×31 (ft)	0–0.45	2.6		
	18 octagonal × 40L (ft)	0–0.26	1.6		
Acoustic Research Tunnel	5 diameter (ft)	0–0.65	4.6	United Technologies	www.worthey.net/windtunnels/
	50D(in)×8L(ft)	0–0.35	4.6		
Pilot Wind Tunnel	4×6×8 (ft)	0.12	0.90	United Technologies	www.worthey.net/windtunnels/
Glenn L. Martin Wind Tunnel	7.75H×11.04W (ft)	0–0.3		University of Maryland	www.aero.umd.edu/research/gmwt.html
F. K. Kirsten Wind Tunnel	8H×12W×10L (ft)	0–250 mph	0–1.8	University of Washington	www.uwal.org
Stability Wind Tunnel	6H×6W×24L (ft)	275 ft/sec	0–1.66	Virginia Polytechnic Institute and State University	www.aoe.vt.edu/research/facilities/stab/
Walter H. Beech Memorial Wind Tunnel	7×10 (ft)	5–160 mph	0–1.5	Wichita State University	www.niar.twsu.edu/niar/aerolab/

Table B.2
U.S. Transonic WTs

Name	Test Section	Mach Number	Rn (per ft × 10^6)	Organization	Web Site
Unitary 11-Foot Transonic Wind Tunnel	11H×11W×22L (ft)	0.2–1.5	0.3–9.6	NASA Ames Research Center	windtunnels.arc.nasa.gov/
8×6-Foot Supersonic Wind Tunnel	8H×6W×23.5L (ft)	0.25–2.0	3.6–4.8	NASA Glenn Research Center	facilities.grc.nasa.gov/8x6/index.html
16-Foot Transonic Tunnel (16TT)	15.5 (octagonal) ×22L (ft)	0.2–1.25	1–4	NASA Langley Research Center	wte.larc.nasa.gov/facilities/aerodynamics/16foot.cfm?field=2&id=2&fac=1
National Transonic Facility (NTF)	8.2H×8.2W×25L (ft)	0.1–1.2	4–146	NASA Langley Research Center	wte.larc.nasa.gov/facilities/aerodynamics/national.cfm?field=4&id=2&fac=1
Transonic Dynamics Tunnel (TDT)	16H×16W×17L (ft)	0.1–1.2	0.03 (in air) 0.2–10 (in R-134a)	NASA Langley Research Center	wte.larc.nasa.gov/facilities/aeroelasticity/transonic.cfm?field=14&id=2&fac=1
16-Foot Propulsion Wind Tunnel (16T)	16H×16W×40L (ft)	0.06–1.6	0.1–6.0	Air Force Arnold Engineering Development Center	www.arnold.af.mil/aedc/factsheets/pwt/PWT.pdf
4-Foot Propulsion Wind Tunnel (4T)	4H×4W×12.5L (ft)	0.2–2.0	~2–6	Air Force Arnold Engineering Development Center	www.arnold.af.mil/aedc/factsheets/pwt/PWT.pdf
Channel 10	66H×66W (in)	0–1.15	4.2 at Mach 1	Aero Systems Engineering	www.aerosysengr.com/Aero_Test_Services/ATCapabilities/Channel_6_and_10/channel_6_and_10.html
Boeing Transonic Wind Tunnel (BTWT)	8×12×14.5 (ft)	0–1.1	0–4	Boeing	www.boeing.com/assocproducts/techsvcs/boeingtech/bts_aerob.html
Veridian Transonic Wind Tunnel	8H×8W×18.75L (ft)	0.2–1.35	0–5 (conventional) 0–12.5 (ejector augmentation)	Veridian	www.veridian.com/offerings/suboffering.asp?offeringID=360&historyIDs=0,227,360

Table B.3
U.S. Supersonic WTs

Name	Test Section	Mach Number	Rn (per ft × 10^6)	Organization	Web Site
Unitary 9×7-Foot Supersonic Wind Tunnel	7H×9W×11L (ft)	1.5–2.55	0.5–5.7	NASA Ames Research Center	windtunnels.arc.nasa.gov/
Abe Silverstein Supersonic Wind Tunnel (10x10-Foot)	10H×10W×40L (ft)	0–0.4 2.0–3.5	0.2–3.5 2.1–3.0	NASA Glenn Research Center	facilities.grc.nasa.gov/10x10/index.html
Unitary Plan Wind Tunnel (UPWT)	4H×4W×7L (ft)	1.5–2.9 2.3–4.6	0.5–6 0.5–11	NASA Langley Research Center	wte.larc.nasa.gov/facilities/aerodynamics/unitary.cfm?field=5&id=2&fac=1
Trisonic Gas-dynamics Facility	2×2 (ft)	0.23–0.8, 1.5, 1.9, 2.3, 3.0	0.5–7	Air Force Research Laboratory	www.wrs.afrl.af.mil/infores/facilities/fac_100.htm
16-Foot Propulsion Wind Tunnel (16S)	16H×16W×40L (ft)	1.5–4.75[a]	0.1–2.6	Air Force Arnold Engineering Development Center	www.arnold.af.mil/aedc/factsheets/pwt/PWT.pdf
Trisonic Wind Tunnel	7H×7W (ft)	0.3–3.5	2–19	Allied Aerospace (GASL)	www.alliedaerospace.com/Wind%20Tunnel%20Testing.htm
Polysonic Wind Tunnel	4H×4W (ft)	0.30–5.05	1–48	Boeing	www.boeing.com/assocproducts/techsvcs/boeingtech/bts_aeroh.html
Lockheed Martin Missile and Fire Control (Dallas) High Speed Wind Tunnel	4H×4W×5L (ft)	0.4–4.8	4–34	Lockheed Martin	www.worthey.net/windtunnels/

[a] The Mach range has been limited to 1.6–2.2. An upgrade to extend the range to 1.5–4.75 is in progress with an initial operating capability scheduled for March 2004.

Table B.4
U.S. Hypersonic WT/PT Facilities

Name	Test Section	Mach Number	Rn (per ft × 10^6)	Organization	Web Site
Hypersonic Tunnel Facility (HTF)	42 diameter (in) 10–14 ft	5, 6, 7		NASA Glenn Research Center	http://facilities.grc.nasa.gov/htf/index.html
8-Foot High Temperature Tunnel (HTT)	8 diameter × 12L (ft)	4, 5, 7	0.3–5.1	NASA Langley Research Center	http://wte.larc.nasa.gov/facilities/hypersonic/8ft.cfm?field=10&id=2&fac=1
Arc-Heated Scramjet Test Facility	4 diameter × 11L (ft)	4.7–8.0	0.04–2.2	NASA Langley Research Center	http://wte.larc.nasa.gov/facilities/hypersonic/arc-heated.cfm?field=11&id=2&fac=1
Combustion-Heated Scramjet Test Facility	42H×30W×96L (in)	3.5–6.0	1.0–6.8	NASA Langley Research Center	http://wte.larc.nasa.gov/facilities/hypersonic/combustion.cfm?field=12&id=2&fac=1
NASA HYPULSE		5–30		NASA; Allied Aerospace (GASL)	www.alliedaerospace.com/Wind%20Tunnel%20Testing.htm
Mach 6, High Rn	12 diameter (in)	6	30	Air Force Research Laboratory	www.wrs.afrl.af.mil/infores/facilities/fac_97.htm
20-Inch Hypersonic Wind Tunnel	20 diameter (in)	12, 14	1	Air Force Research Laboratory	www.wrs.afrl.af.mil/infores/facilities/fac_98.htm
von Karman Gas Dynamics Facility (VKF) Hypersonic Wind Tunnel A	40 (in sq.)	1.5–5.5		Air Force Arnold Engineering Development Center	www.arnold.af.mil/aedc/factsheets/vkf/VKF.pdf
VKF Hypersonic Wind Tunnel B	50 (in)	6, 8		Air Force Arnold Engineering Development Center	www.arnold.af.mil/aedc/factsheets/vkf/VKF.pdf
VKF Hypersonic Wind Tunnel C	25 diameter (in) 50 diameter (in)	4, 6, 10		Air Force Arnold Engineering Development Center	www.arnold.af.mil/aedc/factsheets/vkf/VKF.pdf
Hypervelocity Wind Tunnel 9	5 diameter × 12L (ft)	7, 8, 10, 14, 16.5	0.072 at M14 55.7 at M8	Air Force Arnold Engineering Development Center	www.arnold.af.mil/aedc/tun9ov.htm
Channel 9	20 diameter (in)	7, 11, 14		Aero Systems Engineering	www.aerosysengr.com/Aero_Test_Services/ATCapabilities/Channel_9/channel_9.html
B30 Hypersonic Shock Tunnel (B30 HST)	12-inch diameter nozzle 30-inch nozzle	5–8 8–20		Boeing	www.boeing.com/assocproducts/techsvcs/boeingtech/bts_aerog.html
Large Energy National Shock Tunnel–Leg I (LENS I)	8 diameter × 28L (ft)	8–18	0.001–100	Calspan–University of Buffalo Research Center (CUBRC)	www.cubrc.org/aerospace/index_selectfacility.html
Large Energy National Shock Tunnel–Leg II (LENS II)	8 diameter × 41.7L (ft)	4.5–8	0.05–30	CUBRC	www.cubrc.org/aerospace/index_selectfacility.html

APPENDIX C

Foreign Test Facilities

Table C.1
Foreign Subsonic WTs

Name	Test Section	Mach Number	Rn (per ft × 10^6)	Country	Organization	Web Site
9×9 Low Speed Wind Tunnel	9.1H×9.1W×22.9 L (m)	0–55 m/sec		Canada	National Research Council, Institute for Aerospace Research	iar-ira.nrc-cnrc.gc.ca/aero_6.html
2×3 Wind Tunnel	1.9×2.7×5.2 (m)	0–140 m/sec		Canada	National Research Council, Institute for Aerospace Research	iar-ira.nrc-cnrc.gc.ca/aero_7.html
5m Vertical Wind Tunnel	5 diameter (m) 3×3 (m)	0–28 m/sec		Canada	National Research Council, Institute for Aerospace Research	iar-ira.nrc-cnrc.gc.ca/aero_9b.html
Filton 12×10	12×10×25 (ft)	0.25	1.4	United Kingdom	BAE	www.sata.aero/members/tunnels/9.html
Avro Low-Speed Closed Return Tunnel	2.75×2.23×5.5 (m)	0–70 m/sec		United Kingdom	Flow Science—Goldstein Research Laboratory	www.flow-science.eng.man.ac.uk/avro.htm
Environmental Wind Tunnel	4.57×1.52×9.14 (m)	0–20 m/sec		United Kingdom	Flow Science—Goldstein Research Laboratory	www.flow-science.eng.man.ac.uk/et.htm
5 Metre Low Speed Wind Tunnel	4.2×5.0×6.0 (m)	0.05–0.34	7.6	United Kingdom	QinetiQ	www.sata.aero/members/tunnels/21.html
DA-LSWT	2.1×2.1×4.3 (m)	6–75 m/sec	0.08–1.0	Germany	Airbus Deutschland GmbH	www.aa.washington.edu/sata/members/tunnels/17.html
Icing Wind Tunnel				Italy	Italian Aerospace Research Center (CIRA)	www.cira.it/mezzidiprova/M002_eng.htm
Large, Low-Speed Facility	6.0×6.0×15 (m) 8.0×6.0×20.0 (m) 9.5×9.5×20.0 (m)	0–152 m/sec 0–116 m/sec 0–60 m/sec	6.0 5.3 3.9	The Netherlands	German-Dutch Wind Tunnels (DNW)	www.dnw.aero/facilities/index.htm
Low-Speed Tunnel	3H×2.25W×8.75L (m)	0–80 m/sec	1.4	The Netherlands	DNW	www.dnw.aero/facilities/index.htm
Low-Speed Wind Tunnel Braunschweig (NWB)	3.25×2.80 (m)	0–90 m/sec	1.8	Germany	DNW	www.dnw.aero/facilities/index.htm
Cryogenic Wind Tunnel Köln (KKK)	2.4×2.4×5.4 (m)	0–0.38	9.5	Germany	DNW (DLR)	www.dnw.aero/facilities/index.htm
Low-Speed Wind Tunnel LT1	3.6 (diameter) ×8L (m)	0–80 m/sec		Sweden	FOI (Swedish Defence Research Agency)	www.foi.se/english/activities/983971605.html/

Table C.1—Continued

Name	Test Section	Mach Number	Rn (per ft × 10^6)	Country	Organization	Web Site
F1	3.5H×4.5W×11L (m)	0.05–0.36	8	France	ONERA (National Aerospace Studies and Research Office)	www.onera.fr/gmt-en/table.html
F2	1.8H×1.4W×5L (m)	≤100 m/sec	1.1	France	ONERA	www.onera.fr/gmt-en/table.html
S1MA	8(diameter) ×14L (m)	0.05–1		France	ONERA	www.onera.fr/gmt-en/table.html
Large Subsonic Wind Tunnel Emmen	5H×7W (m)	0–68 m/sec	0–4.5	Switzerland	RUAG Aerospace	www.sfaerospace.ch/pdf/LWTE_scrn.pdf
L-1B	2H×3Wx20L (m)	2–50 m/sec		Belgium	Von Karman Institute for Fluid Dynamics	www.vki.ac.be/facilities/index.html
IAI-LSWT	3.66×2.59×6 (m)	0–100 m/sec	6	Israel	Israel Aircraft Industries	www.aa.washington.edu/sata/members/tunnels/35.html
Open-Circuit Low-Speed Wind Tunnel	4.25×2.75 (m)	0–70 m/sec		India	Indian Institute of Science	aero.iisc.ernet.in/facilities/aerodyn_facilities.html
National Wind Tunnel Facility	3×2.25×8.75 (m)	0–80 m/sec	6	India	Indian Institute of Technology Kanpur	www.iitk.ac.in/nwtf/
Low-Speed Wind Tunnel	6.5×5.5 (m)	1–70 m/sec		Japan	National Aerospace Laboratory of Japan	www.nal.go.jp/eng/research/wintec/000.html
Low-Speed Wind Tunnel	3×3×12 (m)	10–100 m/sec		China	Beijing Institute of Aerodynamics	www.bia701.com/html/e_15_fd09_07.htm
T-101	24×14 (elliptical) (m)	5–55 m/sec	3.3	Russia	Central Aerohydrodynamic Institute (TsAGI)	www.tsagi.ru/eng/areas/test_facilities/
T-102	4×2.33 (m)	5–55 m/sec	3.3	Russia	TsAGI	www.tsagi.ru/eng/areas/test_facilities/
T-103	2.33×4 (m)	5–110	7	Russia	TsAGI	www.tsagi.ru/eng/areas/test_facilities/
T-104	7 (diameter) (m)	15–125	8	Russia	TsAGI	www.tsagi.ru/eng/areas/test_facilities/
T-107	2.7 (diameter) (m)	0.15–0.90	14.5	Russia	TsAGI	www.tsagi.ru/eng/areas/test_facilities/

Table C.2
Foreign Transonic WTs

Name	Test Section	Mach Number	Rn (per ft × 10^6)	Country	Organization	Web Site
Transonic Wind Tunnel	2.74×2.44 (m)	0.2–1.4		United Kingdom	Aircraft Research Association	www.ara.co.uk/facilities%20frames%20page.htm
PT-1 Transonic Wind Tunnel		0.1–1.1, 1.4		Italy	CIRA	www.cira.it/mezzidiprova/M003_eng.htm
High-Speed Tunnel	2.0×1.8 (m)	0.1–1.35	9	The Netherlands	DNW NLR	www.dnw.aero/facilities/index.htm
European Transonic Windtunnel (ETW)	2.0H×2.4W×9.0L (m)	0.15–1.35	0–50 (full-span aircraft model) 0–85 (wall-mounted semi-span model)	Germany (European Union)	European Transonic Windtunnel GmbH	www.etw.de/windtunnel/windtunnel.htm
Transonic Wind Tunnel	2H×2W (m)	0.4–1.4		Japan	National Aerospace Laboratory of Japan	www.nal.go.jp/eng/research/wintec/000.html
T-106	2.48 diameter round (m)	0.15–1.1	35	Russia	TsAGI	www.tsagi.com/areas/test_facilities/

Table C.3
Foreign Supersonic WTs

Name	Test Section	Mach Number	Rn (per ft × 10^6)	Country	Organization	Web Site
Trisonic Blowdown Wind Tunnel	1.5×1.5 (m) or 0.38×1.5 (m)	0.1–0.75 0.7–1.4 1.1–4.25	80 160	Canada	National Research Council, Institute for Aerospace Research	iar-ira.nrc-cnrc.gc.ca/aero_8.html
Supersonic Wind Tunnel	0.69×0.76 (m)	1.4–3.0	20 (at Mach 1.4)	United Kingdom	Aircraft Research Association	www.ara.co.uk/facilities%20frames%20page.htm
Transonic Wind Tunnel Göttingen	1H×1W (m)	0.3–0.9 0.5–1.2 1.3–2.2	1.8	Germany	DNW DLR	www.dnw.aero/facilities/index.htm
Supersonic Tunnel	1.2H×1.2W (m)	1.2–4.0	15	The Netherlands	DNW NLR	www.dnw.aero/facilities/index.htm
High-Speed Wind Tunnel T1500	1.5H×1.5W×4.0L (m)	0.2–1.25 0.2–0.8, 1.3–2.0	0–80	Sweden	FOI	www.foi.se/english/activities/983966301.html
S4	0.92×0.90 (m) 0.92×1.15 (m)	0.5–2.0	0–13	Sweden	FOI	www.foi.se/english/activities/983970586.html
S2MA	1.77H×1.75W (m) (transonic) 1.935H×1.75W (m) (supersonic)	0.1–3.1	5.4 (transonic) 4.0 (supersonic)	France	ONERA	www.onera.fr/gmt-en/table.html
S3MA	0.76×0.8 (m)	0.1–5.5		France	ONERA	www.onera.fr/gmt-en/table.html
Trisonic Wind Tunnel	4H×4W×5L (ft)	0.5–2.0 1.6–5.0	38	Israel	Israel Aircraft Industries	www.aa.washington.edu/sata/members/tunnels/35.html
Supersonic Wind Tunnel	1H×1W (m)	1.4–4.0		Japan	National Aerospace Laboratory of Japan	www.nal.go.jp/eng/research/wintec/000.html
Trisonic Wind Tunnel	0.6H×0.6W×1.575L (m)	0.4–4.5		China	Beijing Institute of Aerodynamics	www.bia701.com/html/e_17_fd06_02.htm
T-108	1×1 (m)	0.2–1.7	11–20	Russia	TsAGI	www.tsagi.com/areas/test_facilities/
T-109	2.25×2.25 (m)	0.4–4.0	60	Russia	TsAGI	www.tsagi.com/areas/test_facilities/
T-112	0.6×0.6 (m)	0.6–1.8	15	Russia	TsAGI	www.tsagi.com/areas/test_facilities/
T-114	0.6×0.6 (m)	0.3–4.0	20	Russia	TsAGI	www.tsagi.com/areas/test_facilities/
T-128	2.75H×2.75W (m)	0.15–1.7	41	Russia	TsAGI	www.tsagi.com/areas/test_facilities/
T-33	0.8(diameter) (m)	3.0 . . . 5.0	70	Russia	TsAGI	www.tsagi.com/areas/test_facilities/
TPD	4.0(diameter) (m)	0.3–4.0	60	Russia	TsAGI	www.tsagi.com/areas/test_facilities/

Table C.4
Foreign Hypersonic WT/PT Facilities

Name	Test Section	Mach Number	Rn (per ft × 10^6)	Country	Organization	Web Site
Hypersonic Wind Tunnel (HWT) 1 of 2	0.3×0.4 (m)	4.0–5.0	40–60	United Kingdom	Aircraft Research Association	www.ara.co.uk/facilities%20frames%20page.htm
HWT 2 of 2	0.3 diameter (m)	6.0 7.0 8.0	70 50 30	United Kingdom	Aircraft Research Association	www.ara.co.uk/facilities%20frames%20page.htm
SCIOROCCO Plasma Wind Tunnel	5 diameter × 9.6H (m)			Italy	CIRA	www.cira.it/mezzidiprova/M001_eng.htm
Rohrwindkanal Göttingen (RWG)	0.5H×0.5W (m) 0.5 diameter (m)	3, 4 5, 6, 6.8	3.5 2.2	Germany	DNW DLR	www.dnw.aero/facilities/index.htm
HYP500	500 diameter (mm)	4 7.15		Sweden	FOI	www.foi.se/english/activities/983971979.html
S4MA	0.68 diameter (m) 1 diameter (m) 1 diameter (m)	6.4 10 12	1.7 0.9 0.35	France	ONERA	www.onera.fr/gmt-en/table.html
F4	670 diameter (mm) 670 diameter (mm) 430 diameter (mm) 930 diameter (mm)	8–17 7–13 6–11 9–21	2 3 5 1	France	ONERA	www.onera.fr/gmt-en/table.html
Hypersonic Wind Tunnel	1.27 diameter (m)			Japan	National Aerospace Laboratory of Japan	www.nal.go.jp/eng/research/wintec/000.html
Hypersonic Wind Tunnel	0.5 (m)	5–8, 10–12		China	Beijing Institute of Aerodynamics	www.bia701.com/html/e_18_f500_04.htm
T-113	0.6×0.6 (m)	1.8–6.0	43	Russia	TsAGI	www.tsagi.com/areas/test_facilities/
T-116	1×1 (m)	1.8–10	47	Russia	TsAGI	www.tsagi.com/areas/test_facilities/
T-117	1 diameter (m)	10–18	4	Russia	TsAGI	www.tsagi.com/areas/test_facilities/
IO-2	0.2 (m) 0.9 (m)	16.3–17.9 10–22	40	Russia	TsAGI	www.tsagi.com/areas/test_facilities/
ST-1	0.3 (m) or 0.5 (m)	5–10	5.3 at Mach 6	Russia	TsAGI	www.tsagi.com/areas/test_facilities/
VAT-3	1 (m)	12–18 12–20	0.03–1.5	Russia	TsAGI	www.tsagi.com/areas/test_facilities/
T-131	1.2 diameter × 2.0L (m)	5–7	10	Russia	TsAGI	www.tsagi.com/areas/test_facilities/
T-313	0.6H×0.6W (m)	1.8–6.0	60	Russia	Institute of Theoretical and Applied Mechanics	

Table C.4—Continued

Name	Test Section	Mach Number	Rn (per ft × 10^6)	Country	Organization	Web Site
UT-302	0.3 diameter (m)	5–15	10	Russia	Institute of Theoretical and Applied Mechanics	
AT-303	0.3H×0.3W (m) 0.6H×0.6W (m)	10–20	100	Russia	Institute of Theoretical and Applied Mechanics	

APPENDIX D

Questionnaires

To gather necessary baseline information, members of the RAND Corporation visited facilities and organizations across the country and overseas, not only to assess capabilities but also to identify programs and research efforts that are likely to require such facilities in the future. RAND used an interview protocol consisting of an initial list of questions to support the gathering of data and information for the study.

Subsequent to this protocol, RAND requested user community representatives in December 2002 to complete a spreadsheet indicating anticipated user occupancy hours (UOH) for wind tunnels and engine-on hours (EOH) for propulsion test facilities. Additional sets of questions were sent in March and April of 2003 to aeronautic design experts to explore deeper questions regarding user needs, aerodynamic issues, and facility issues.

The questions used in these queries are included below.

Interview Protocol Questions

Please generate answers to the following questions as a way of collecting the type of information that will inform our analysis. Please include any official program test documentation that you might deem appropriate (e.g., Integrated Test Plans) with your response. The following stepwise approach may be helpful in generating your answers:

Step 1: Provide detailed information on current programs.
Step 2: Provide detailed information on possible "block upgrades" to current programs, with as much detailed information as possible.
Step 3: Provide as much detailed information as possible on future programs and base the estimate of testing hours at the appropriate level of granularity (category, subcategory) using test requirements of past programs as the baseline.

(a) What aerospace programs or areas (including research, development, and operation) should need the use of wind tunnels or propulsion test facilities in the next 10–25 years? What other programs are you aware of?

- Description of program
- Program stakeholders?
- Relationship to:
  - Higher-level planning guidance (e.g., national strategy, aeronautic capabilities planning documents)?
  - Other programs?
- Probability of execution (*definite*, *likely*, *uncertain*)
- Supporting milestones (planned? budgeted?)
- Please provide detailed information on programs or potential future needs with respect to schedule, amount of testing hours by category (rough estimates or range of estimates by sub-, trans-, super-, and hypersonic), subcategory (specific experimental conditions), and time frame, including any of the following that are pertinent:
  - Type of testing: research, development, or validation/test and evaluation (T&E)
  - Critical considerations (e.g., cost, availability, lead time in scheduling, scheduling confidence, speed of acquiring data, analysis support)

Interview Protocol Questions—Continued

–Subsonic, transonic, supersonic, hypersonic, propulsion test, propulsion integration
–Mach number (range)
–Critical associated needs (e.g., instrumentation, computational fluid dynamics [CFD], model building, sensors)
–Reynolds number (range)
–Reynolds number per foot for facility
–Pressure effects
–Cryogenics effects
–Tunnel size (cross-sectional area, height, width, length of test section)
–Model characteristics
–Scale of model (lowest acceptable)
–Physical dimensions of model (smallest acceptable)
–Model fabrication technology advances needs
–Data collection of key testing parameters and related instrumentation requirements
–Anticipated instrumentation technology improvements
–Flow characteristics
–Steady-state flow quality (acceptable turbulence levels in the tunnel), dynamic flow, aeroelastics (flutter, buffeting, etc.), spin control (normal and recovery)
–Acoustic characteristics
–Propulsion testing needs
–Productivity needs
–Vitiated/non-vitiated flow needs
–Dynamics testing needs
–Temperature needs
–Relationship to flight test and CFD.

Other important aspects not listed above:

- To what extent do you foresee computational fluid dynamics satisfying your research and development needs? How do you utilize CFD with other test capabilities (e.g., do you integrate CFD and simulations to direct when and where you need to conduct ground or flight tests)?
- Do you find difficulties in relying on different facilities as a result of facility owner prioritization processes? Are you satisfied with the prioritization process? What changes, if any, would you prefer? What effect (e.g., meeting mission, cost, schedule, deadlines) do such uncertainties have on your program?
- How does Technology Readiness Level (TRL) or technology maturity (research, development, or acquisition) affect the type of needs? Is there more flexibility at earlier levels?

(b) What advantages do the facilities you use offer? What disadvantages?

(c) Are there any proprietary data, ITAR (International Traffic in Arms Regulations), or other data protection concerns or issues that need to be addressed by the T&E facilities? Do NASA or DoD facilities meet those needs?

(d) From one view, each class of test facility has instantiations that have different scale and capability aspects (e.g., in a flight analogy, there are Boeing 747s, small business jets, and Piper personal planes, each with different capabilities and costs). Can you explain the effect on your program if you did not have such a range of options to choose from? Can you quantify those costs?

(e) For recent large programs (e.g., F15, F16, F22, JSF, C5, 777, 767, Space Shuttle, National Aerospace Plane), can you provide a facility need and utilization profile that shows the types of facilities needed, overall schedule (including time, facility, and specific reason why that facility was chosen), the magnitude of use across those facilities, and explanation of whether a fewer number of facilities could have met your needs? What would have been the cost and schedule effects if fewer facilities were available? Were there facilities or types of capabilities that you needed but were unable to obtain for any reason (e.g., did not exist; not technically feasible; not able to obtain time at the facility; unable to afford the facility)? How did you determine the level of acceptable risk in not performing more tests or in selecting alternate test methods? When the program was originally conceived and cost estimated, how did you forecast your testing needs?

(f) What kind of general database or records (if any) do you have that describing historical needs and usage?

Hypersonics
(g) What concepts for hypersonics programs are envisioned for the next 10–25 years? What is the probability that one or more of those programs will come through? Do you foresee the commercial sector trailing military and space sectors in the utilization of hypersonics technology? What level and types of hypersonic facilities do you foresee the nation needing in the next 10–20 years? What levels of utilization might those facilities see if a large hypersonic development and acquisition program arises? What would the effect be on hypersonics if we lost the remaining facilities (through either mothballing and loss of technical workforce or having to build new facilities)? Are new hypersonic ground test facilities needed (what type, when, cost estimates, etc.)?

Quantitative Survey of Anticipated Facility Use Hours

The quantitative survey conducted in December 2002 asked user community representatives to complete the spreadsheet shown in the following table (next page) for each type of testing they anticipate needing in the future. We also asked the users to describe the pros and cons of the facilities they are familiar with and to describe any future needs that cannot be met with existing facilities.

Table D.1
Anticipated Testing Spreadsheet Used in the December 2002 Queries

Projected Wind Tunnel Needs (Test Hours)
Preliminary Organization Input

Discipline

Name	
Organization code	
Phone	
Email	

Subsonic Wind Tunnels (Mach range 0–0.6 and ≥ 6 ft test section)
Test Description (e.g., force and moment testing; spin; icing; flutter; dynamic control, store separation)

			Estimated/Projected Test Hours in 100s								
Program	Facility Requirements	Specific Tunnel Required (if known)	FY03	FY04	FY05	FY06–07	FY08–09	FY10–14	FY15–19	FY20–24	FY25–29
		Totals	0	0	0	0	0	0	0	0	0

Transonic Wind Tunnels (Mach range 0.6–1.5 and ≥ 4 ft test section)
Test Description (e.g., force and moment testing; spin; icing; flutter; dynamic control, store separation)

			Estimated/Projected Test Hours in 100s								
Program	Facility Requirements	Specific Tunnel Required (if known)	FY03	FY04	FY05	FY06–07	FY08–09	FY10–14	FY15–19	FY20–24	FY25–29
		Totals	0	0	0	0	0	0	0	0	0

Table D.1—Continued (landscape)

Supersonic Wind Tunnels (Mach range 1.5–5.0 and ≥ 2 ft test section) Test Description (e.g., force and moment testing; spin; icing; flutter; dynamic control, store separation)											
			Estimated/Projected Test Hours in 100s								
Program	Facility Requirements	Specific Tunnel Required (if known)	FY03	FY04	FY05	FY06–07	FY08–09	FY10–14	FY15–19	FY20–24	FY25–29
		Totals	0	0	0	0	0	0	0	0	0

Hypersonic Wind Tunnels (Mach range > 5.0 and ≥ 1 ft test section) Test Description (e.g., force and moment testing; spin; icing; flutter; dynamic control, store separation)											
			Estimated/Projected Test Hours in 100s								
Program	Facility Requirements	Specific Tunnel Required (if known)	FY03	FY04	FY05	FY06–07	FY08–09	FY10–14	FY15–19	FY20–24	FY25–29
		Totals	0	0	0	0	0	0	0	0	0

Air-Breathing Propulsion Test Description (e.g., force and moment testing; spin; icing; flutter; dynamic control, store separation)											
			Estimated/Projected Test Hours in 100s								
Program	Facility Requirements	Specific Tunnel Required (if known)	FY03	FY04	FY05	FY06–07	FY08–09	FY10–14	FY15–19	FY20–24	FY25–29
		Totals	0	0	0	0	0	0	0	0	0

Caveats

Questions on Facility Needs and Capabilities

These are the questions sent to representatives of the design community in March and April of 2003.

Subsonic Wind Tunnel Questions

(1) For each vehicle, aircraft, missile, etc., class or type that you are now, or expect to be, involved with, what subsonic tunnels do you (or will you) mainly rely on for your technology- and product-development and testing needs?
- NASA?
- DoD?
- Non-U.S. (Canadian, European, other)?
- Private?
- University?

(2) Are there alternatives and/or backups to these primary facilities available that would allow you to fulfill your testing needs if any of the NASA and DoD (and other) tunnels were not available to you? If so:
- What are they?
- What technical risk factors would be involved?
- What cost and scheduling risks might having to use these alternatives entail?

(3) What facility/testing capability voids exist today that would/might limit your ability to incorporate some of the advanced technology concepts that are being proposed such as advanced flow (separation) control concepts, laminar flow control (passive and active), noise reduction concepts, vehicle geometry simplification concepts, morphing, etc.?
- What new facilities would be necessary to permit incorporation of these advanced technologies into viable new products?
- What thoughts do you have regarding the economic benefits versus costs of such new facilities?

(4) For each vehicle/aircraft class or type that you are now or expect to be involved with, what are representative *flight* Reynolds numbers (based on wing MAC or other) at important/critical subsonic low-speed conditions (e.g., takeoff, landing)?
- What are the corresponding Mach numbers?
- What Reynolds numbers are you able to attain with sensibly sized models in the various subsonic wind tunnels that you currently utilize, or plan to utilize?
- What Reynolds numbers do you need/require in order to effectively manage development risk, i.e., preclude significant surprises in flight with existing technologies? With new technologies?
- Do you consider the use of semi-span models as an effective means of increasing attainable wind tunnel test Reynolds numbers for your important/critical subsonic low speed testing needs?

(5) With existing air vehicle aerodynamic technologies, how do wind tunnel flow quality (free-stream turbulence and noise levels, flow angularity, etc.) characteristics influence your determination of what is an acceptable or nonacceptable test facility?
- For general aerodynamic configuration development, especially for smaller vehicles that may have some run/extent of laminar flow in flight?
- For noise reduction concept development studies?
- What tunnels do you use when excellent tunnel flow quality is necessary?
- Do you think the United States is lacking in wind tunnels with the flow quality needed for some applications? If so, what would you suggest for new facilities? What do you think the technical versus economic arguments would be for such facility developments?

(6) How do you balance flow quality requirements versus Reynolds number requirements if you can't get both?
- For general aerodynamic configuration development?
- For noise reduction concept development?
- If you have to sacrifice Reynolds numbers for flow quality in noise reduction studies, is that acceptable to you?

(7) When is having both the necessary flow quality *and* Reynolds number capability an enabling requirement?
- What potentially valuable new technology concepts are having their development and implementation held back by the lack of adequate test facilities that can provide the needed flow quality, Reynolds numbers, etc.?

(8) Is the representative modeling of jet engine (inlet and exhaust) characteristics and/or propeller effects at low speeds in the wind tunnel an important or critical element in your vehicle development efforts?
- If so, which subsonic tunnels have unique/essential capabilities in this regard?

- Which ones are not really useable/reliable in this regard?
- Do you encounter situations where you have to trade Reynolds numbers, flow quality, etc., capabilities in order to simulate power effects? Or vice versa? What development risks does this impose? Any examples of where this has led to "problems"?

- What advanced technology implementations are being curtailed by engine and/or propeller simulation shortfalls?
- What new capabilities (wind tunnel and engine/propeller simulations) do you need to efficiently and effectively develop any potentially promising new concepts/technologies? Any ideas on how these new capabilities could be achieved technically?
- Does the simulation of heat transfer effects (other than for ice accretion effects) ever enter into your choice of acceptable/adequate subsonic wind tunnels?
- Is the inability to simulate/determine heat transfer effects ever a limitation or risk to you?

(9) Considering the numerous "novel" new flow control (e.g., separation onset and progression) concepts under "development," are existing wind tunnel capabilities in the United States adequate to enable the effective and low-risk development and incorporation of these concepts into a range of air vehicle types?

- If not, for which class(es) of vehicles do serious shortcomings exist? What are these deficiencies?
- Is scaling the efficiency of such devices possible, or do you need facilities where full-scale designs can be tested at flight Reynolds numbers with the necessary tunnel flow quality?
- Do you feel that the development of any new subsonic facilities to enable the effective and low-risk development and incorporation of these technologies would be economically justified? Why?

(10) Answer questions in (9) but with regard to the effective and low-risk incorporation of laminar flow control technology, either active or passive, for a range of air vehicle classes.

(11) Is the representative modeling of steady and/or unsteady ground effects in subsonic wind tunnel testing critical to the success of your designs?

- If so, which wind tunnels have the required capabilities (such as moving ground belt)?
- Do such facilities also have adequate Reynolds number and other required/needed capabilities? If not, what compromises/risks are taken to get the ground effects data? How does this impact development risk?
- Are additional capabilities required in this area for the incorporation of any promising new technologies?

(12) What other unsteady flow phenomena (other than flow separation) need to be addressed in subsonic wind tunnel testing of existing and new technologies?

- What capabilities/facilities are needed/required to satisfactorily address flutter, spin characteristics, store and stage separation characteristics, etc., for your product line?
- Are there any documented cases where existing facilities have yielded results not representative of flight? If so, could you give us examples?

(13) How have current state-of-the-art computational fluid dynamics capabilities (e.g., Reynolds Averaged Navier Stokes [RANS] with state-of-the-art turbulence models) allowed you to reduce the amount of subsonic wind tunnel test time needed for the development of the low-speed configuration (e.g., takeoff and landing geometries) of the vehicles you develop and build?

- A feel for about how much?
- What kind of testing has it reduced the need for?
- Can you do some effective screening of concepts prior to testing?
- Does the (generally accepted) inability of current RANS technology to reliably predict flight separation onset and progression characteristics effectively minimize the amount of subsonic wind tunnel testing that you can replace with CFD?
- Do you feel you have adequate access to the latest and best CFD capabilities developed by NASA? DoD (where applicable)?
- Are current CFD limitations (in conjunction with facility limitations) an important obstacle standing in the way of the effective implementation of (separation) flow control, laminar flow control, and other promising new technology concepts? Why?
- What do you think is needed before CFD will permit a significant reduction in the amount of subsonic low speed wind tunnel testing needed for vehicle development?
- Do you believe that emerging large-eddy simulation (LES) or detached-eddy simulation (DES) technologies will eventually allow you to make meaningful reductions in the amount of subsonic wind tunnel testing you need, for either technology- or product-development efforts? Or, do you believe the direct numerical simulation (DNS) will be needed before you can make any further significant reductions in the amount of subsonic wind tunnel testing required?
- What areas, or types of testing, do you believe LES, DES, and/or DNS would allow significant reductions in the amount of subsonic wind tunnel testing required? Any estimates on how long it might be before any of these new technologies are ready and available?

- How would you prioritize needed CFD technology developments versus building any new subsonic tunnels? Or making improvements to existing ones?

(14) Is the NASA Glenn Icing Research Tunnel (IRT) an important/required facility for your vehicle developments?
- If so, would you have problems in going elsewhere (e.g., such as the new CIRA icing tunnel in Italy, private/industry icing tunnels in the United States) if the IRT were not available?
- How do you use icing tunnels such as the IRT in your vehicles development programs? To define the most critical ice shapes? Or for the development and/or validation of your ice protection system?
- How important do you believe improvements to the IRT would be to permit testing of supercooled large droplet (SLD) conditions? For your vehicles?

(15) Do you make a concerted effort to thoroughly document the lessons learned (often the hard way) regarding subsonic (and other) wind tunnel test successes and failures that guide new engineers in selecting appropriate test facilities for current issues/problems associated with either existing or new technology implementations? Are these continually updated? Typically, what form are these in?

Transonic Wind Tunnel Questions

(1) For each vehicle, aircraft, missile, etc., class or type that you are now, or expect to be, involved with, what transonic tunnels do you (or will you) mainly rely on for your technology- and product-development and testing needs?
- NASA?
- DoD?
- Non-U.S. (Canadian, European, other)?
- Private?
- University?

(2) Are there alternatives and/or viable backups to these primary facilities available that would allow you to fulfill your testing needs if any of the NASA and DoD (and other) tunnels were not available to you? If so:
- What are they?
- What technical risk factors would be involved?
- What cost and scheduling risks might having to use these alternatives entail?

(3) What facility/testing capability voids exist today that would/might limit your ability to incorporate some of the advanced technology concepts that are being proposed such as advanced flow (separation) control concepts, laminar flow control (passive and active), vehicle geometry simplification concepts, morphing, etc.?
- What new facilities would be necessary to permit incorporation of these advanced technologies into viable new products?
- What thoughts do you have regarding the economic benefits versus costs of such new facilities?

(4) For each vehicle/aircraft class or type that you are now or expect to be involved with, what are representative *flight* Reynolds numbers (based on wing MAC or other) at important/critical transonic conditions?
- What are the corresponding Mach numbers?
- What Reynolds numbers are you able to attain with sensibly sized models in the various transonic wind tunnels that you currently utilize, or plan to utilize?
- What Reynolds numbers do you need/require in order to effectively manage development risk, i.e., preclude significant surprises in flight with existing technologies? With new technologies?
- Do you consider the use of semi-span models as an effective means of increasing attainable wind tunnel test Reynolds numbers for your important/critical transonic testing needs?

(5) With existing air vehicle aerodynamic technologies, how do wind tunnel flow quality (free-stream turbulence and noise levels, flow angularity, etc.) characteristics influence your determination of what is an acceptable or nonacceptable test facility?
- For general aerodynamic configuration development, especially for smaller vehicles that may have some run/extent of laminar flow in flight?
- What tunnels do you use when excellent tunnel flow quality is necessary?
- Do you think the United States is lacking in wind tunnels with the flow quality needed for some applications? If so, what would you suggest for new facilities? What do you think the technical versus economic arguments would be for such facility developments?

(6) How do you balance flow quality requirements versus Reynolds number requirements if you can't get both?
- For general aerodynamic configuration development?
- Other?

(7) When is having both the necessary flow quality *and* Reynolds number capability an enabling requirement?
- What potentially valuable new technology concepts are having their development and implementation held back by the lack of adequate test facilities that can provide the needed flow quality, Reynolds numbers, etc.?

(8) Is the representative modeling of jet engine (inlet and exhaust) characteristics and/or propeller effects at transonic conditions in the wind tunnel an important or critical element in your vehicle development efforts?
- If so, which transonic tunnels have unique/essential capabilities in this regard?
- Which ones are not really useable/reliable in this regard?
- Do you encounter situations where you have to trade Reynolds numbers, flow quality, etc., capabilities in order to simulate power effects? Or vice versa? What development risks does this impose? Any examples of where this has led to "problems"?
- What advanced technology implementations are being curtailed by engine and/or propeller simulation shortfalls?
- What new capabilities (wind tunnel and engine/propeller simulations) do you need to efficiently and effectively develop any potentially promising new concepts/technologies? Any ideas on how these new capabilities could be achieved technically?
- Does the simulation of heat transfer effects ever enter into your choice of acceptable/adequate transonic wind tunnels?
- Is the inability to simulate/determine heat transfer effects ever a limitation or risk to you?

(9) Considering the numerous "novel" new flow control (e.g., separation onset and progression) concepts under "development," are existing wind tunnel capabilities in the United States adequate to enable the effective and low-risk development and incorporation of these concepts into a range of air vehicle types?
- If not, for which class(es) of vehicles do serious shortcomings exist? What are these deficiencies?
- Is scaling the efficiency of such devices possible, or do you need facilities where full-scale designs can be tested at flight Reynolds numbers with the necessary tunnel flow quality?
- Do you feel that the development of any new transonic facilities to enable the effective and low-risk development and incorporation of these technologies would be economically justified? Why?

(10) Answer questions in (9) but with regard to the effective and low-risk incorporation of laminar flow control technology, either active or passive, for a range of air vehicle classes.

(11) What unsteady flow phenomena (other than flow separation) need to be addressed in transonic wind tunnel testing of existing and new technologies?
- What capabilities/facilities are needed/required to satisfactorily address flutter, store and stage separation characteristics, etc., for your product line?
- Are there any documented cases where existing facilities have yielded results not representative of flight? If so, could you give us examples?

(12) How have current state-of-the-art computational flight dynamics capabilities (e.g., Reynolds Averaged Navier Stokes [RANS] with state-of-the-art turbulence models) allowed you to reduce the amount of transonic wind tunnel test time needed for the development of the transonic configuration of the vehicles you develop and build?
- A feel for about how much?
- What kind of testing has it reduced the need for?
- Can you do some effective screening of concepts prior to testing?
- Does the (generally accepted) inability of current RANS technology to reliably predict flight separation onset and progression characteristics effectively minimize the amount of subsonic wind tunnel testing that you can replace with CFD?
- Do you feel you have adequate access to the latest and best CFD capabilities developed by NASA? DoD (where applicable)?
- Are current CFD limitations (in conjunction with facility limitations) an important obstacle standing in the way of the effective implementation of (separation) flow control, laminar flow control, and other promising new technology concepts? Why?
- What do you think is needed before CFD will permit a further significant reduction in the amount of transonic wind tunnel testing needed for vehicle development?
- Do you believe that emerging large-eddy simulation (LES) or direct-eddy simulation (DES) technologies will eventually allow you to make meaningful reductions in the amount of transonic wind tunnel testing you need, for either technology- or product-development efforts? Or, do you believe the direct numerical simulation (DNS) will be needed before you can make any further significant reductions in the amount of transonic wind tunnel testing required?
- What areas, or types of testing, do you believe LES, DES, and/or DNS would allow further significant reductions in the amount of transonic wind tunnel testing required? Any estimates on how long it might be before any of these new technologies are ready and available?
- How would you prioritize needed CFD technology developments versus building any new transonic tunnels? Or making improvements to existing ones?

(13) Do you make a concerted effort to thoroughly document the lessons learned (often the hard way) regarding transonic (and other) wind tunnel test successes and failures that guide new engineers in selecting appropriate test facilities for current issues/problems associated with either existing or new technology implementations? Are these continually updated? Typically, what form are these in?

Supersonic Wind Tunnel Questions

(1) For each vehicle, aircraft, missile, etc., class or type that you are now, or expect to be, involved with, what supersonic tunnels do you (or will you) mainly rely on for your technology- and product-development and testing needs?

- NASA?
- DoD?
- Non-U.S. (Canadian, European, other)?
- Private?
- University?

(2) Are there alternatives and/or backups to these primary facilities available that would allow you to fulfill your testing needs if any of the NASA and DoD (and other) tunnels were not available to you? If so:

- What are they?
- What technical risk factors would be involved?
- What cost and scheduling risks might having to use these alternatives entail?

(3) What facility/testing capability voids exist today that would/might limit your ability to incorporate some of the advanced technology concepts that are being proposed such as advanced flow (separation) control concepts, laminar flow control (passive and active), reduced sonic boom, vehicle geometry simplification concepts, morphing, etc.?

- What new facilities would be necessary to permit incorporation of these advanced technologies into viable new products?
- What thoughts do you have regarding the economic benefits versus costs of such new facilities?

(4) For each vehicle, aircraft, missile, etc., class or type that you are now or expect to be involved with, what are representative *flight* Reynolds numbers (based on wing MAC or other) at important/critical supersonic conditions?

- What are the corresponding Mach numbers?
- What Reynolds numbers are you able to attain with sensibly sized models in the various supersonic wind tunnels that you currently utilize, or plan to utilize?
- What Reynolds numbers do you need/require in order to effectively manage development risk, i.e., preclude significant surprises in flight with existing technologies? With new technologies?

(5) With existing air vehicle aerodynamic technologies, how do wind tunnel flow quality (free-stream turbulence and noise levels, flow angularity, etc.) characteristics influence your determination of what is an acceptable or nonacceptable test facility?

- For general aerodynamic configuration development, especially for smaller vehicles that may have some run/extent of laminar flow in flight?
- What tunnels do you use when excellent tunnel flow quality is necessary?
- Do you think the United States is lacking in wind tunnels with the flow quality needed for some applications? If so, what would you suggest for new facilities? What do you think the technical versus economic arguments would be for such facility developments?

(6) How do you balance flow quality requirements versus Reynolds number requirements if you can't get both?

- For general aerodynamic configuration development?
- Others?

(7) When is having both the necessary flow quality *and* Reynolds number capability an enabling requirement?

- What potentially valuable new technology concepts are having their development and implementation held back by the lack of adequate test facilities that can provide the needed flow quality, Reynolds numbers, etc.?

(8) Is the representative modeling of jet engine (inlet and exhaust) characteristics and effects at supersonic speeds in the wind tunnel an important or critical element in your vehicle development efforts?

- If so, which supersonic tunnels have unique/essential capabilities in this regard?
- Which ones are not really useable/reliable in this regard?
- Do you encounter situations where you have to trade Reynolds numbers, flow quality, etc., capabilities in order to simulate power effects? Or vice versa? What development risks does this impose? Any examples of where this has led to "problems"?
- What advanced technology implementations are being curtailed by propulsion system simulation shortfalls?
- What new capabilities (wind tunnel and propulsion system simulations) do you need to efficiently and

effectively develop any potentially promising new concepts/technologies? Any ideas on how these new capabilities could be achieved technically?
- Does the simulation of heat transfer effects ever enter into your choice of acceptable/adequate supersonic wind tunnels?
- Is the inability to simulate/determine heat transfer effects ever a limitation or risk to you?

(9) Considering the numerous "novel" new flow control (e.g., separation onset and progression) concepts under "development," are existing wind tunnel capabilities in the United States adequate to enable the effective and low-risk development and incorporation of these concepts into a range of air vehicle types?
- If not, for which class(es) of vehicles do serious shortcomings exist? What are these deficiencies?
- Is scaling the efficiency of such devices possible, or do you need facilities where full-scale designs can be tested at flight Reynolds numbers with the necessary tunnel flow quality?
- Do you feel that the development of any new facilities to enable the effective and low-risk development and incorporation of these technologies would be economically justified? Why?

(10) Answer questions in (9) but with regard to the effective and low-risk incorporation of laminar flow control technology, either active or passive, for a range of air vehicle classes.

(11) What unsteady flow phenomena (other than flow separation) need to be addressed in supersonic wind tunnel testing of existing and new technologies?
- What capabilities/facilities are needed/required to satisfactorily address flutter, store and stage separation characteristics, etc. for your product line?
- Are there any documented cases where existing facilities have yielded results not representative of flight? If so, could you give us examples?

(12) How have current state-of-the-art computational fluid dynamics capabilities (i.e., Reynolds Averaged Navier Stokes [RANS] with state-of-the-art turbulence models) allowed you to reduce the amount of supersonic wind tunnel test time needed for the development of the supersonic configuration characteristics of the vehicles you develop and build?
- A feel for about how much?
- What kind of testing has it reduced the need for?
- Can you do some effective screening of concepts prior to testing?
- Does the (generally accepted) inability of current RANS technology to reliably predict flight separation onset and progression characteristics effectively minimize the amount of supersonic wind tunnel testing that you can replace with CFD?
- Do you feel you have adequate access to the latest and best CFD capabilities developed by NASA? DoD (where applicable)?
- Are current CFD limitations (in conjunction with facility limitations) an important obstacle standing in the way of the effective implementation of (separation) flow control, laminar flow control, and other promising new technology concepts? Why?
- What do you think is needed before CFD will permit a further significant reduction in the amount of supersonic wind tunnel testing needed for vehicle development?
- Do you believe that emerging large-eddy simulation (LES) or detached-eddy simulation (DES) technologies will eventually allow you to make meaningful reductions in the amount of supersonic wind tunnel testing you need, for either technology- or product-development efforts? Or, do you believe the direct numerical simulation (DNS) will be needed before you can make any further significant reductions in the amount of supersonic wind tunnel testing required?
- What areas, or types of testing, do you believe LES, DES, and/or DNS would allow further significant reductions in the amount of supersonic wind tunnel testing required? Any estimates on how long it might be before any of these new technologies are ready and available?
- How would you prioritize needed CFD technology developments versus building any new supersonic tunnels? Or making improvements to existing ones?

(13) Do you make a concerted effort to thoroughly document the lessons learned (often the hard way) regarding supersonic (and other) wind tunnel test successes and failures that guide new engineers in selecting appropriate test facilities for current issues/problems associated with either existing or new technology implementations? Are these continually updated? Typically, what form are these in?

Hypersonic Wind Tunnel Questions

(1) Which NASA space access and exploration programs have you either been involved with, are presently involved within, or plan to be involved with?
- Shuttle enhancements and safety upgrades?
- Alternate access to Space Station, such as Orbital Space Plane?

- 2nd-generation reusable launch vehicles (RLVs)?
- 3rd-generation RLVs?
- Hypersonic cruise?
- Hyper-X?
- X-30, X-33, X-34, X-37, X-38, X-40, X-43?
- Two-stage to orbit?
- Others?

(2) Similar questions (1) for DoD and DARPA space/hypersonic vehicles, missiles, etc.?
- Hypersonic Deep Attack?
- DARPA Hy-Fly?
- Are there others that you can talk about?
- Others that you can't talk about?

(3) What are the primary vehicle (and other) aerodynamic requirements for ground-based testing (i.e., hypersonic wind tunnel) for the aforementioned air vehicles, missiles, etc.?
- In the research phase?
- In the (preliminary) development phase?
- In the production design stage?

(4) What are the critical "flow physics" characteristics that you need to (or certainly would like to) simulate in ground test facilities and/or flight test in order to achieve the desired aerodynamic and aerothermodynamic flight characteristics for the aforementioned air vehicles, missiles, etc.?
- Boundary layer transition characteristics?
  - –Determination and control?
- Shockwave-viscous and/or shock-shock interactions?
- Viscous layer separation and reattachment?
  - –Flow control?
- Boundary layer diversion characteristics?
- Interacting flow fields (e.g., stage separation)?
- Aero heating characteristics (ascent and reentry)?
- Chemically reacting or nonreacting?
- Base flow (and other separated flow) regions?
- Aero/aeropropulsion interaction?
- Enthalpy levels?
- Radiation and ionization effects?
- Various molecular regimes (rarified, transitional, continuum)?
- Other?

(5) Which "absolute" quantities are important to simulate in order to effectively capture the controlling "flow physics"?
- Reynolds number?
- Free-stream disturbance/noise levels?
- Temperature levels?
- Molecular regimes?
- Enthalpy levels?
- Others?

Why? Or why not?

(6) Which existing *hypersonic* wind tunnels do you deem essential for providing the (best currently available) simulation capabilities needed for the successful development of the previously listed vehicle, missile, etc., programs/categories?
- NASA Langley
  - –8-Foot High Temperature Tunnel (M = 4, 5, 7)?
  - –20-Inch Mach 6 Air Tunnel?
  - –Mach 6 Quiet Tunnel?
  - –15-Inch Mach 6 Hi Temp Air?
  - –31-Inch Mach 10 Air Tunnel?
  - –20-Inch CF_4 Tunnel (M = 13–18)?
  - –22-Inch Mach 15/20 Helium Tunnel (mothballed)?
  - –Hypersonic Pulse Facility?
  - –Others?
- NASA Glenn
  - –Plum Brook Hypersonic Tunnel Facility?
- Arnold Engineering and Development Center
  - –Hypervelocity Wind Tunnel 9?

  - –Von Karman Gas Dynamics Facility Hypersonic Wind Tunnel A?
  - –Von Karman Gas Dynamics Facility Hypersonic Wind Tunnel B?
  - –Von Karman Gas Dynamics Facility Hypersonic Wind Tunnel C?
- Private
  - –Aero Systems Engineering Channel 9?
  - –Boeing B30 Hypersonic Shock Tunnel?
  - –Allied Aerospace (GASL) NASA HYPULSE?
  - –Calspan Large Energy National Shock Tunnel?
- Foreign
  - –ARA Hypersonic Wind Tunnel?
  - –ONERA S4MA?
  - –ONERA F-4?
  - –DNW/DLR RWG?
  - –Various TsAGI Facilities (T-113, 116, 117, IO-2, ST-1, VAT-3, T-131)?

(7) What are the critical advantages of these hypersonic wind tunnels that you have considered, and, also, what are the critical limitations?

- Do you consider some of these as having redundant capabilities, and, if so, which are your preferred facilities? Why?

(8) What new hypersonic wind tunnel testing capabilities are necessary to enable the low-risk development of noted programs/concepts?

- What additional "flow physics" simulation capabilities do you require?

(9) What hypersonic wind tunnel testing capabilities are lacking that necessitate flight-test development programs (prior to commitment)?

(10) Which subsonic, transonic, and supersonic wind tunnels do you deem as essential for the low-risk development of the programs/concepts identified in (1) and (2)? Why?

- What are the important "flow physics" simulations needed?
- What did the NTF testing of the Shuttle ascent configuration tell us in terms of the need for flight–Reynolds number simulation?

(11) What role do current state-of-the-art computational fluid dynamics capabilities presently play in the development of (successful) hypersonic air vehicles, missiles, etc.?

- Have CFD development to date enabled any significant reductions in the amount of ground testing requirements? How?
- What important "flow physics" characteristics can you adequately predict or account for now, and which ones remain elusive? Attached flows, separated flows, etc.?
- What important/critical CFD developments are needed to permit further significant reductions in the amount of ground (and flight) testing required?
- What new technology is likely required for these, and how long do you believe it may take to develop such capabilities? Years? Decades?
- How would you prioritize new/improved facility development efforts versus the development of new/advanced CFD capabilities?

Hypersonic Propulsion Integration Questions

(1) For each vehicle, missile, etc., class or type that you are now, or expect to be, involved with, what specific test facilities do you (or will you) mainly rely on for your technology- and product-development and testing needs?

- NASA?
- DoD?
- Private?

(2) Are there alternatives and/or viable backups to these primary facilities available that would allow you to fulfill your testing needs if any of the NASA and DoD (and other) test facilities were not available to you? If so:

- What are they?
- What technical risk factors would be involved?
- What cost and scheduling risks might having to use these alternatives entail?

(3) What facility/testing capability voids exist today that would/might limit your ability to incorporate some of the advanced technology concepts?

- What new facilities would be necessary to permit incorporation of these advanced technologies?

(4) What are the critical "flow physics" characteristics that you need to (or certainly would like to) simulate in ground test facilities and/or flight test in order to achieve the desired aerodynamic and aerothermodynamic flight characteristics for the aforementioned air vehicles, missiles, etc.?

- Boundary layer transition characteristics?
  - Determination and control?
- Shockwave-viscous and/or shock-shock interactions?
- Viscous layer separation and reattachment?
- Aeroheating characteristics?
- Chemically reacting or nonreacting?
- Enthalpy levels?
- Real gas effects?
- Other?

(5) Which "absolute" quantities are important to simulate in order to effectively capture the controlling "flow physics"?

- Reynolds number?
- Free-stream disturbance/noise levels?
- Temperature levels?
- Enthalpy levels?
- Others?

Why? Or why not?

(6) Which existing hypersonic propulsion-system development facilities do you deem essential for providing the (best currently available) simulation capabilities needed for the successful development of the propulsion systems required for the initially listed vehicle, missile, etc., programs/categories?
For turbojets, ramjets, scramjets, and combined/combination cycle?

- NASA Langley
  - 8-Foot High Temperature Tunnel?
  - Arc-Heated Scramjet Test Facility?
  - Combustion-Heated Scramjet Test Facility?
  - Others?
- NASA Glenn
  - Plum Brook Hypersonic Tunnel Facility?
  - Propulsion Systems Laboratory?
  - Others?
- Arnold Engineering and Development Center
  - Aero Propulsion Test Unit?
  - G-range (scramjet projectile testing)?
  - Others?
- NASA Ames
  - High Speed Arc Tunnel
  - Other?
- Private?
- Foreign?

(7) What role would current state-of-the-art computational fluid dynamics capabilities play in the development of (successful) propulsion integration concepts?

- What important "flow physics" characteristics can you adequately predict or account for now, and which ones remain elusive?
- What important/critical CFD developments are needed to permit reductions in the amount of ground (and flight) testing required?
- What new technology is likely required for these, and how long do you believe it may take to develop such capabilities? Years? Decades?
- How would you prioritize new/improved facility development efforts versus the development of new/advanced CFD capabilities?

(8) Overall, what would be your general strategy for employing a combination of hypersonic test facilities, computational fluid dynamics, flight test, or other means to develop a hypersonic propulsion integration vehicle/missile?

Direct-Connect Propulsion Facility Questions

Assumptions/Exclusions

- Hypersonic propulsion integration test facilities are a separate category and are not to be addressed here.
- Issues associated with what NASA Glenn research center often refers to as its propulsion wind tunnels, i.e.,

the 10×10-Foot Supersonic Wind Tunnel and the 8×6-Foot Transonic Wind Tunnel, are presumed to have been addressed in responses to the subsonic, transonic, and supersonic wind tunnel questionnaires.

- Inlet and nozzle development in wind tunnels are assumed to be addressed in the appropriate wind tunnel categories.

Facilities Included in This Air-Breathing Propulsion Test Facilities Category

- Engine test cells/stands such as the NASA Glenn Propulsion System Lab, AEDC C, J, SL, and T facilities, industry facilities, and European facilities.
- Engine component test facilities such as NASA Glenn Engine Component Research Laboratories and the Advanced Subsonic Combustion Rig.
- Acoustic test facilities/anechoic chambers such as NASA Glenn Aero-Acoustic Propulsion Laboratory and Edwards AFB Chamber.
- Vectored-thrust engine/nozzle test stands, etc., for STOVL applications, including MATS (Multiaxis Test Stand), NASA Glenn Powered Lift Rig, European facilities, etc.
- Other?

Questions

(1) For each vehicle, aircraft, missile, etc., class or type that you are now, or expect to be, involved with, which air-breathing propulsion test facility types do you require and/or rely on for your technology- and product-development testing needs?

(2) For each facility type that you require for your technology- and product-development efforts (for each vehicle and/or missile type or class), which facilities (that exist today or are planned) will you mainly rely on?

(3) Are there alternatives and/or backups to these “primary” facilities available to you that would allow you to fulfill your testing needs if any of the primary facilities (NASA, DoD, or others) that you identified become unavailable to you?

- What are they?
- What technical risk factors would be involved?
- What cost and scheduling risks might having to use these alternatives entail?

(4) What are critical facility/testing limitations or voids that exist today in facilities that you currently use, or plan to use, that would seriously hinder your ability to incorporate (identified) advanced technology concepts?

- What modified or new facilities would be necessary to permit incorporation of these advanced technologies into viable new products?
- Do any of these capabilities exist anywhere else (in the world) that you could use?
- Any thoughts on how to justify the costs associated with identified new facility requirements?

(5) Have current state-of-the-art computational fluid dynamics capabilities (i.e., Reynolds Averaged Navier Stokes with state-of-the-art turbulence models) allowed you to reduce the amount of air-breathing propulsion system testing needed for the development of the vehicle and/or missiles you develop and build?

- A feel for about how much?
- What kind of testing has it reduced the need for?

(6) Do you make a concerted effort to thoroughly document lessons learned regarding air-breathing propulsion test facility successes and failures that guide new engineers in selecting appropriate test facilities for current issues/problems associated with either existing or new technology implementations? Are these continuously updated? Typically, what form are these in?

APPENDIX E

Construction Times and Costs for Major Test Facilities

Facility investments and shared support must reflect the dynamics of aeronautics research and development and the possible role of test technologies and facilities as enablers. Major test facilities such as wind tunnel and propulsion test facilities are major investments (ranging from hundreds of millions to billions) and long lead times.

We identified 26 of the 31 NASA facilities that fall within the scope of this study in the NASA Real Property Database. The book value of these test facilities, that is, the simple sum of unadjusted dollars invested in past years in facility construction or modernization, amounted to about \$0.9 billion dollars. Because, in many cases, decades have past since construction, the book value is significantly lower than the cost it would take to build the facilities today.

The current replacement value (CRV) of these 26 test facilities totaled about \$2.5 billion in the NASA Real Property Database. The CRV is derived by looking at similar types of buildings (e.g., usage, size) within the Engineering News Magazine's construction economics section. The magazine uses a 20-city average to produce rough estimates of how much a building would cost to replace. Most NASA finance and facilities people believe that this average underestimates the actual cost of replacing WT/PT facilities, since they are more complex buildings than the "similar" building types available through engineering economics. Unfortunately, NASA has not found a better metric to compare buildings across the various field centers

Finally, the construction estimates for the large subsonic and transonic facilities proposed in the National Facility Study (1994) ran in the \$2–3 billion range (depending on the exact configuration being discussed).

Construction time for a major test facility has averaged more than 10 years in the past[1] (see, for example, AEDC [Arnold Engineering and Development Center] data in Figure E.1)—not counting the years it takes to develop the facility technology, defend the program, and acquire funding from Congress.

As a result, there are significant risks associated with premature decisions regarding research, development, test, and evaluation (RDT&E) test facilities. Building a new facility before having thoroughly analyzed the needs justification or knowing the right design to pursue can result in problems exemplified by the Ames 12-Foot.

Conversely, closing a facility without sufficient long-range planning that will survive the natural budgetary ebbs and flows from current administrations, congressional leadership,

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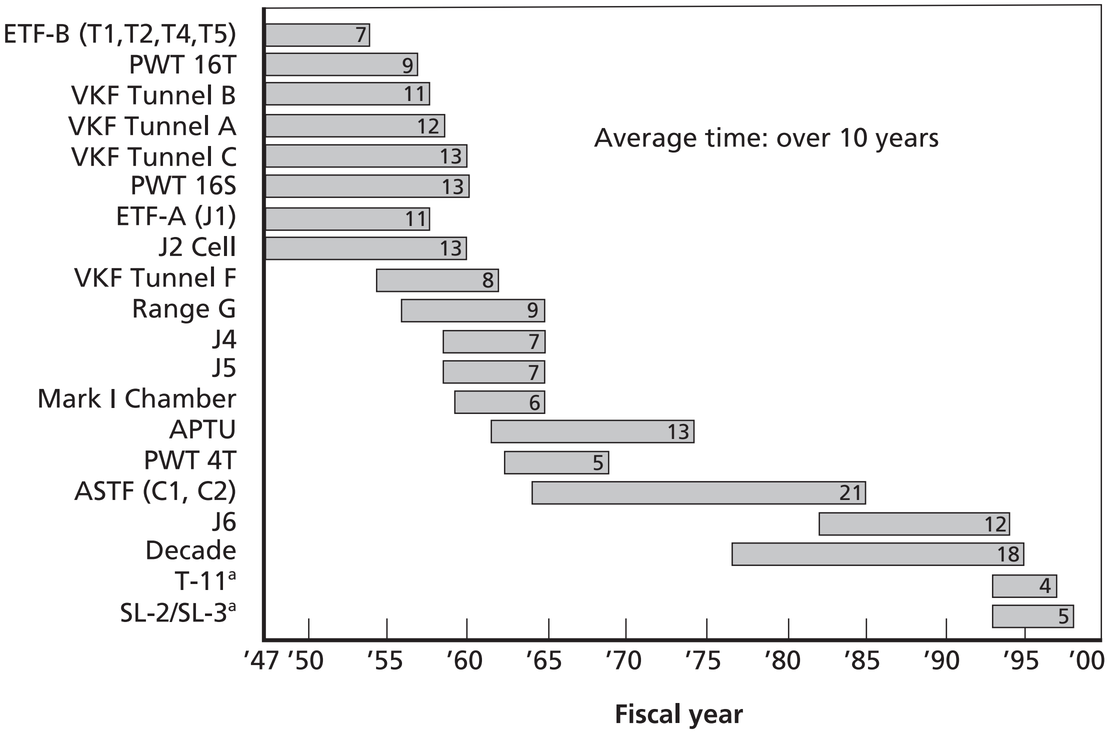
[1] It is unclear, however, to what extent construction time can be compressed for high-priority facilities in a crisis or how much additional funds would be required.

Figure E.1
Major Test Facility Construction Times at AEDC



[a] Acquired through FY03 BRAC
SOURCE: AEDC.
RAND *TR134-E.1*

and vehicle constructions and needs (let alone the uncertainty surrounding research breakthroughs) requires careful planning and long-term support for RDT&E tools despite the attractiveness of short-term gains from closing facilities.

Previous calls for new large, productive, high-Rn facilities (subsonic and transonic) do not match current market drivers of low utilization because of high costs.