The 21st Century Renaissance of the Transonic Wind Tunnel

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Presentation Overview

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1. **The Transonic Wind Tunnel**
   – definitions
   – examples → *focusing on industrial-scale facilities*
2. **Demand & Supply**
   – tunnel usage
   – tunnel populations
3. **What About Europe & the UK?**
   – tunnel population
4. **Who's Doing What and When?**
   – new-built and reactivated high-speed tunnels
   – funding programs and upgrades
5. **Final Remarks**

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SURVEY

Transonic industrial wind tunnel testing in the 2020s

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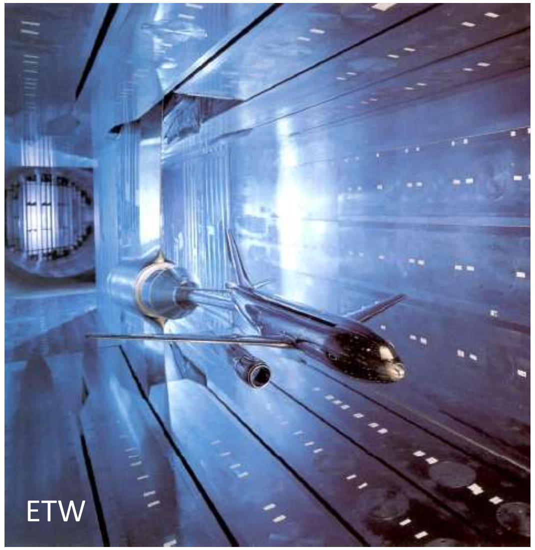
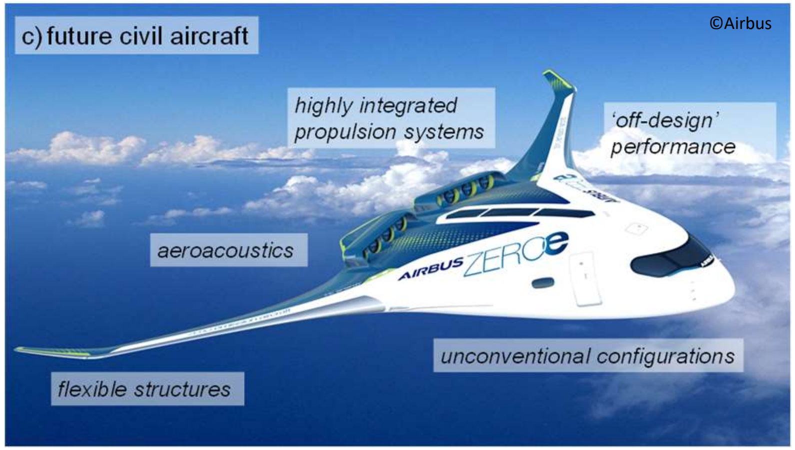
1. The Transonic Wind Tunnel

What is a ‘Transonic’ Wind Tunnel?

- **a tunnel capable of operating in the transonic range → M = 0.7-1.4**
  - still the most challenging flight vehicle flow regime for both CFD and EFD
- **the defining feature of a transonic tunnel is a <u>ventilated</u> test section**
  - *perforated* walls → normal holes, or 60° inclined holes
  - *slotted* walls → profiled slots, or straight slots with internal baffles
  - 3-22% porosity depending on age, wall configuration, and test type
  - backed by a closed plenum chamber surrounding the test section
- **why ventilated?**
  1. to prevent *choking* (shock formation) in the test section at transonic conditions,
  2. to set or adjust freestream *Mach number* at low supersonic conditions,
  3. to reduce or eliminate wall *corrections* at subsonic conditions, and
  4. to reduce or eliminate *wave reflections* at low supersonic conditions
- **in/out-flow controlled by the plenum pressure (and the porosity distribution)**
  - *passive*, using diffuser suction (e.g. re-entry flaps at the test section exit)
  - *active*, using a Plenum Exhaust System compressor



Ongoing Aeronautical Applications of Transonic Wind Tunnels



- **spacecraft also a major application**
- **<u>all</u> of these would have been familiar to test engineers 30+ years ago**
  - *but emphasis has shifted away from aero/S&C database building*
  - high data productivity
  - impact of improved instrumentation
  - complementary nature of EFD and CFD
- ***loss or degradation of existing capabilities is a major challenge***

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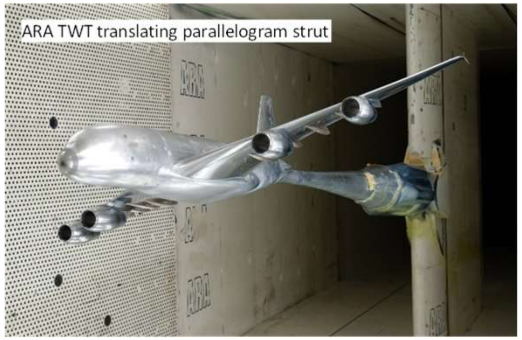
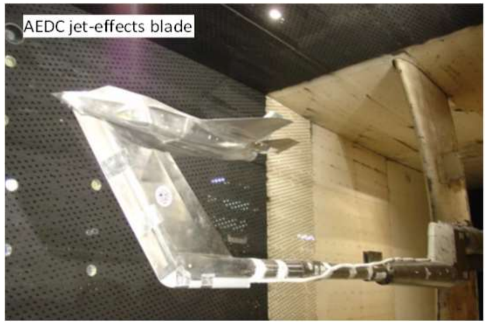
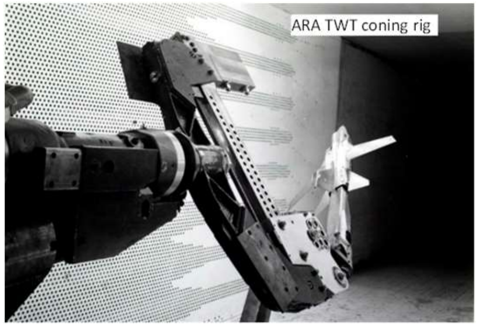
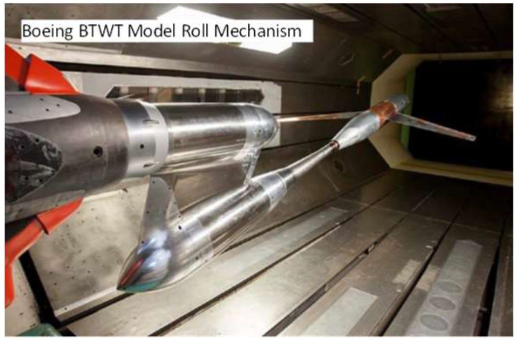
Examples of Transonic Wind Tunnel Test Rigs

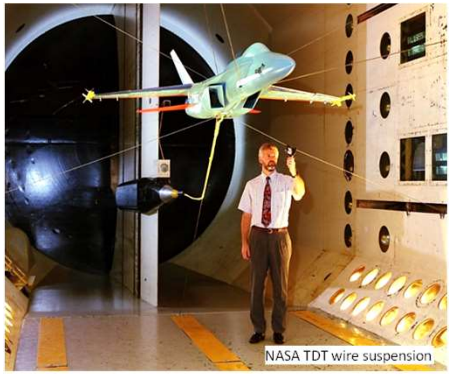

ARA TWT translating parallelogram strut


AEDC jet-effects blade

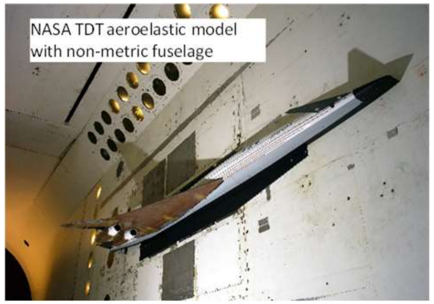

ARA TWT coning rig


ARA TWT propulsion integration model


Boeing BTWT Model Roll Mechanism

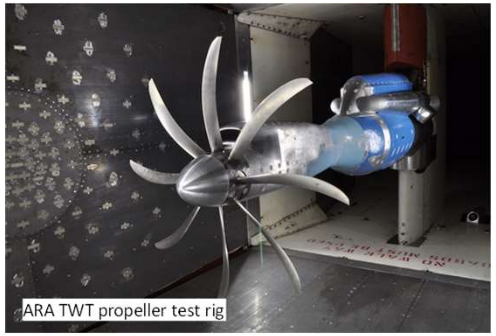

NASA TDT wire suspension

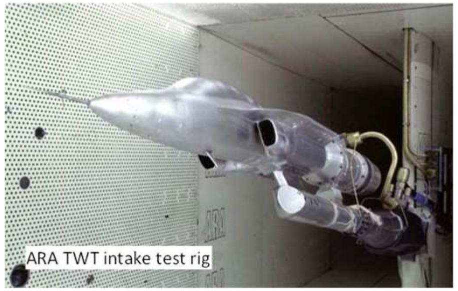

ARA TWT 'Two Sting Rig' CTS


NASA TDT aeroelastic model with non-metric fuselage


ARA TWT 'Twin Sting Rig'

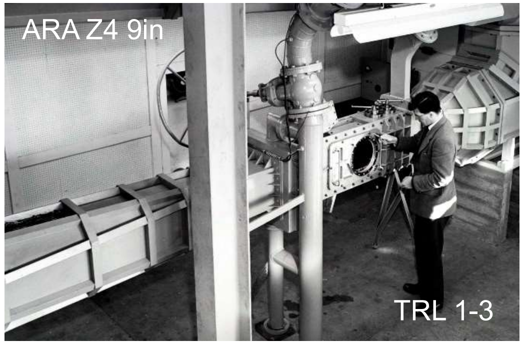

ARA TWT cranked sting


ARA TWT propeller test rig


ARA TWT intake test rig

Classification of Transonic Wind Tunnels

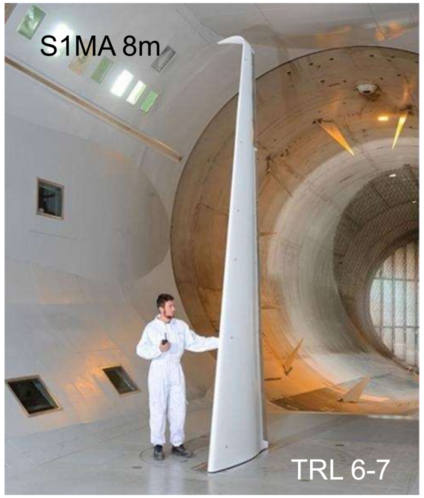
- **I prefer to classify transonic tunnels by test section ‘size’ √A rather than by the more usual Reynolds or Mach number capability**
  - Re/M envelopes messy to plot, and not always well defined
  - size translates directly to cost and complexity of the tunnel and its associated plant
  - also correlates with typical test TRLs



a) ‘small research’ tunnel

b) ‘mid-range industrial’ tunnel

c) ‘large industrial’
(or production) tunnel

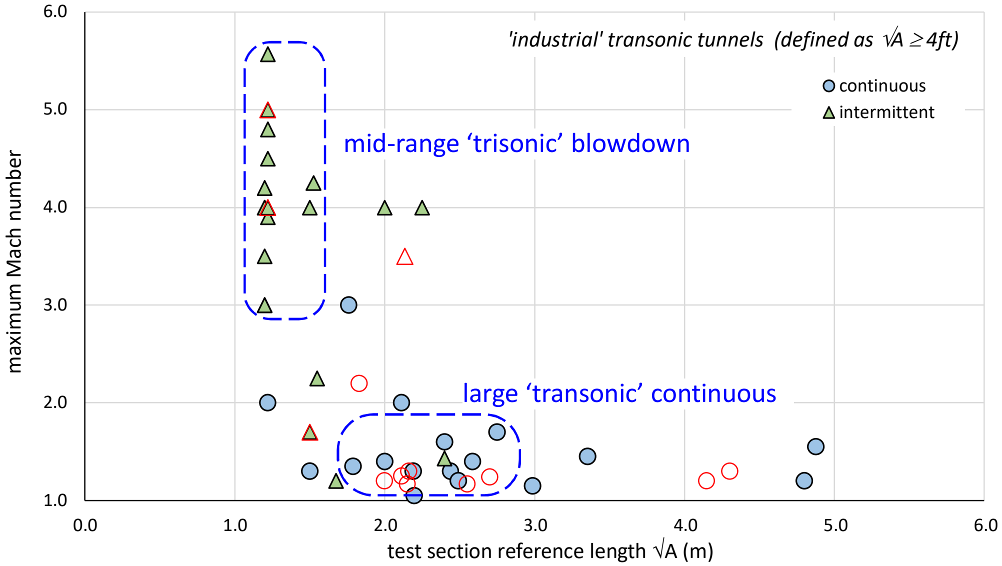


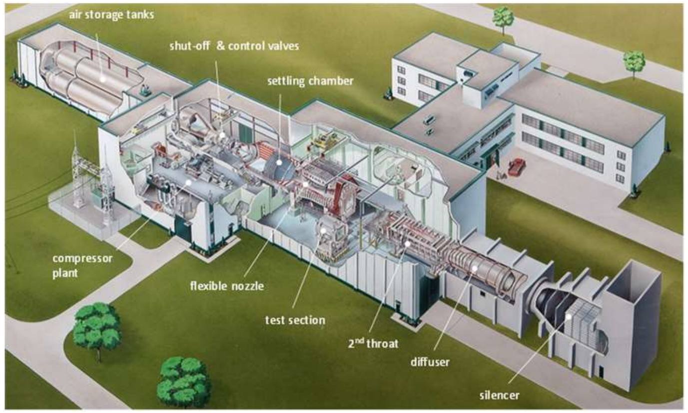
d) ‘very large industrial’ tunnel

- **the ‘test engineer’ is a physically significant reference length …**
  - if you can get into the test section it’s an *industrial* tunnel
  - if you can stand up in the test section it’s a *large industrial* tunnel

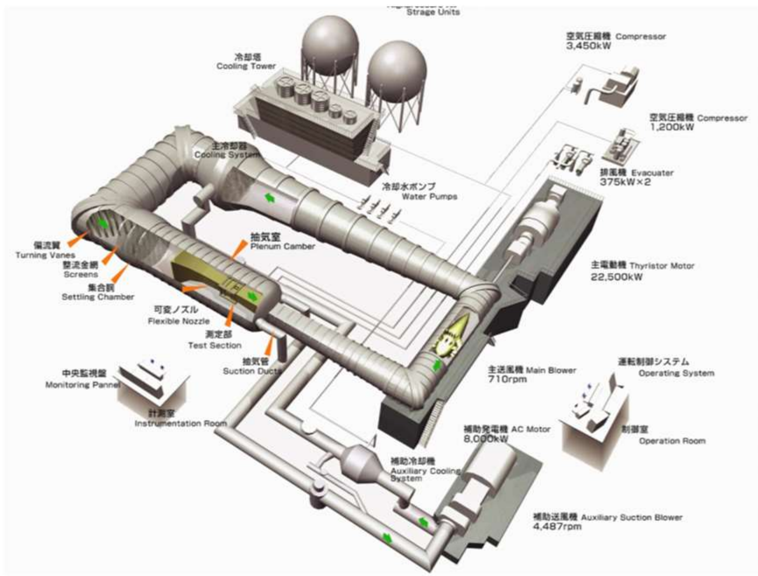
Typical Industrial Facilities

- **a pragmatic definition of 'industrial' → √A ≥ 4ft/1.2m**
- **M vs √A plot → two classes of 'work-horse' tunnels:**
  1. mid-range *trisonic* blowdown
     → M_{max} = 3-5, √A = 1.2-1.5m (4-5ft)
  2. large *transonic* continuous
     → M_{max} = 1.1-1.7, √A = 1.8-2.8m (6-9ft)





NRC 1.5m

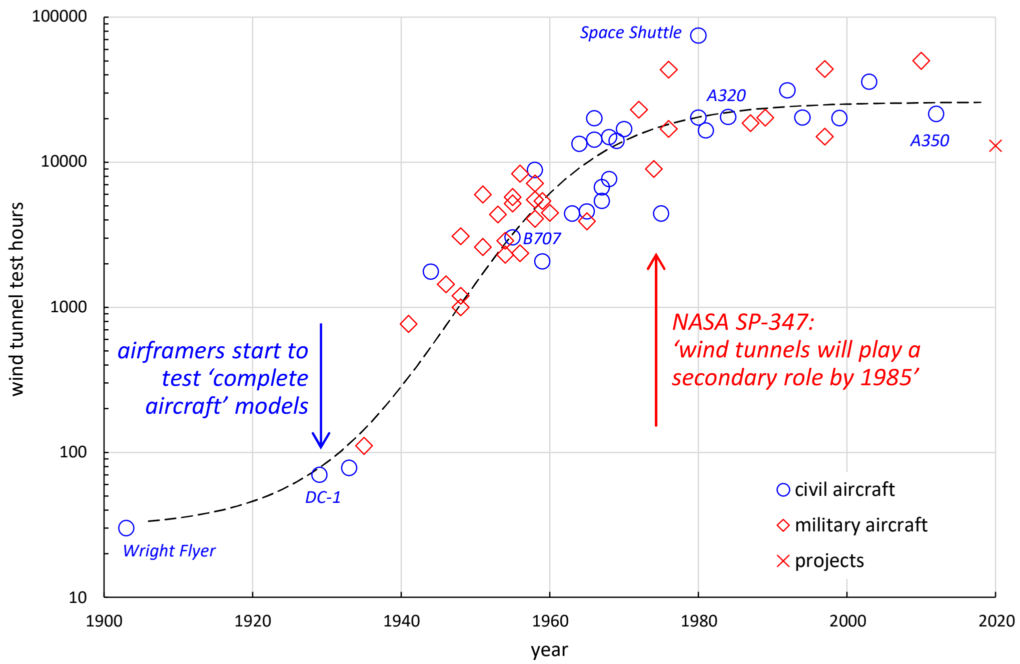


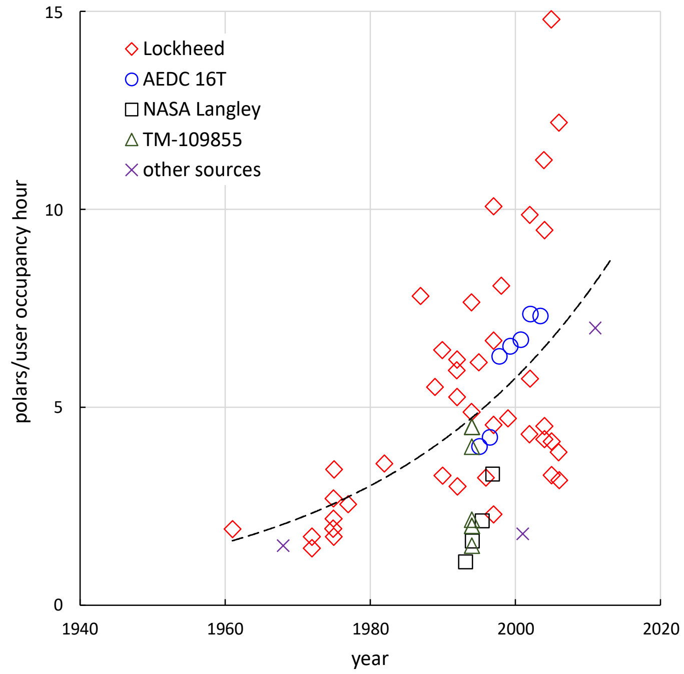
JAXA 2m

2. Demand & Supply

Wind Tunnel Usage and Productivity

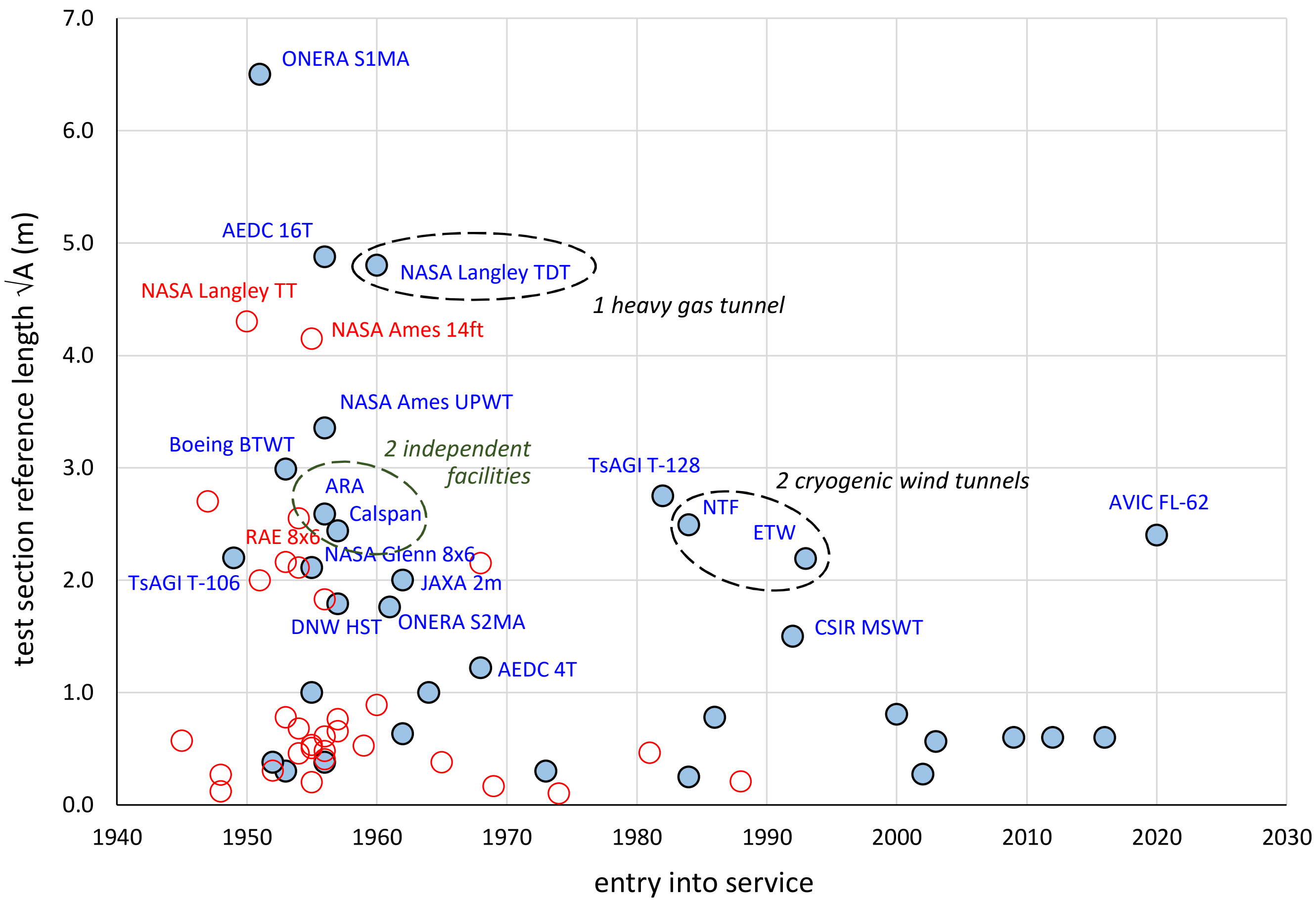
- **tunnel User Occupancy Hours (UOH) per aircraft program, and polars or traverses per UOH**
- **rapid increase in usage in WW2 and early years of the Cold War**
- **hours per program levels off in the 1970s, but data productivity starts to increase around the same time**
  - also about the time that CFD starts to become a useful tool
    … and when the 1st predictions of the demise of the wind tunnel were made …





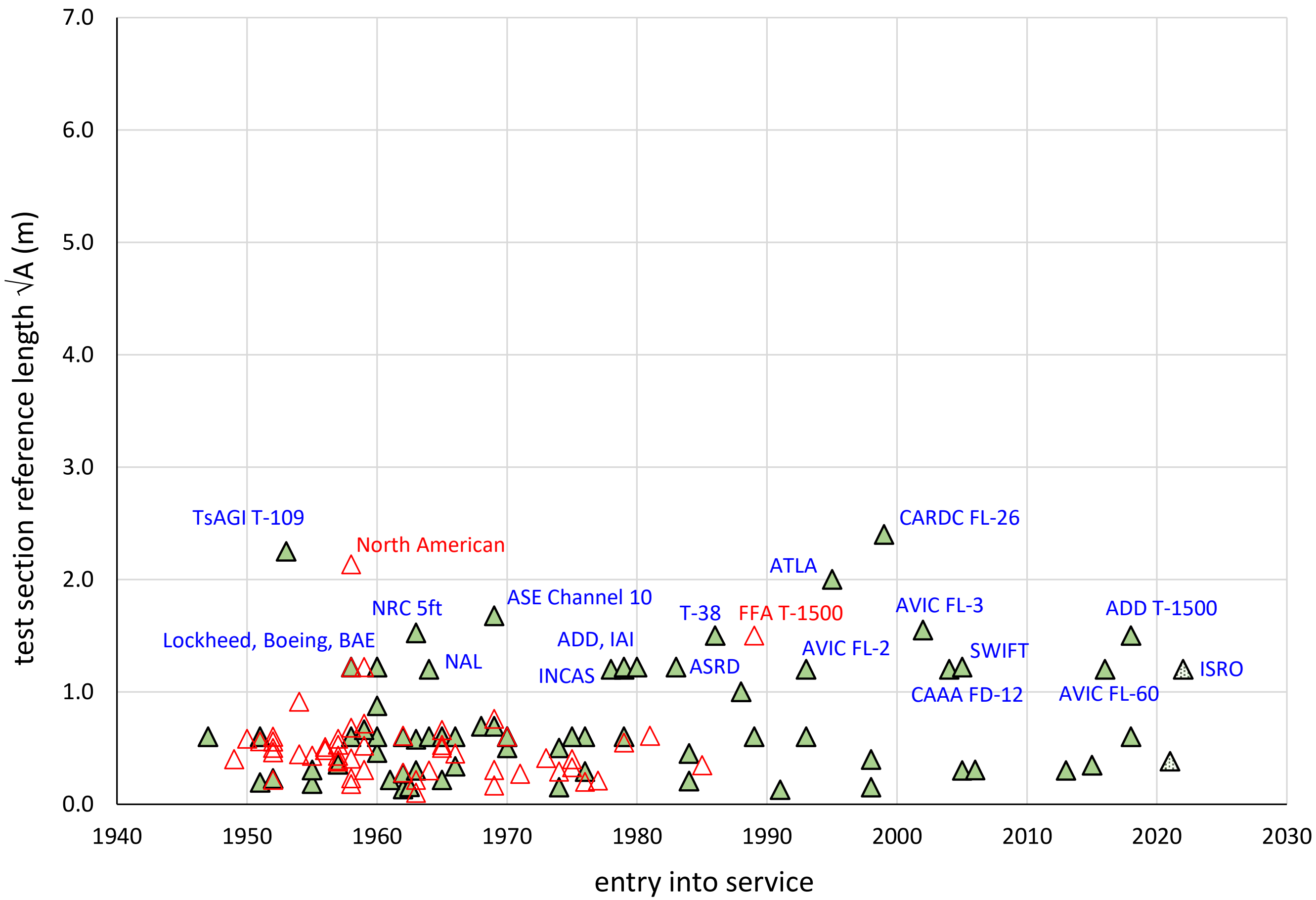
Transonic Wind Tunnels of the World - *Continuous*

- **facilities capable of continuous running**
  - run times measured in hours
  - closed return circuits
  - high levels of installed power
  - generally transonic and low-supersonic ($M_{max} < 2$)
  - mostly operated by national research organisations
- **excludes purely supersonic tunnels**
  - i.e. tunnels with solid wall test sections
- **test section size plotted vs entry into service date**
  - filled/blue = operational
  - open/red = closed



Transonic Wind Tunnels of the World - *Intermittent*

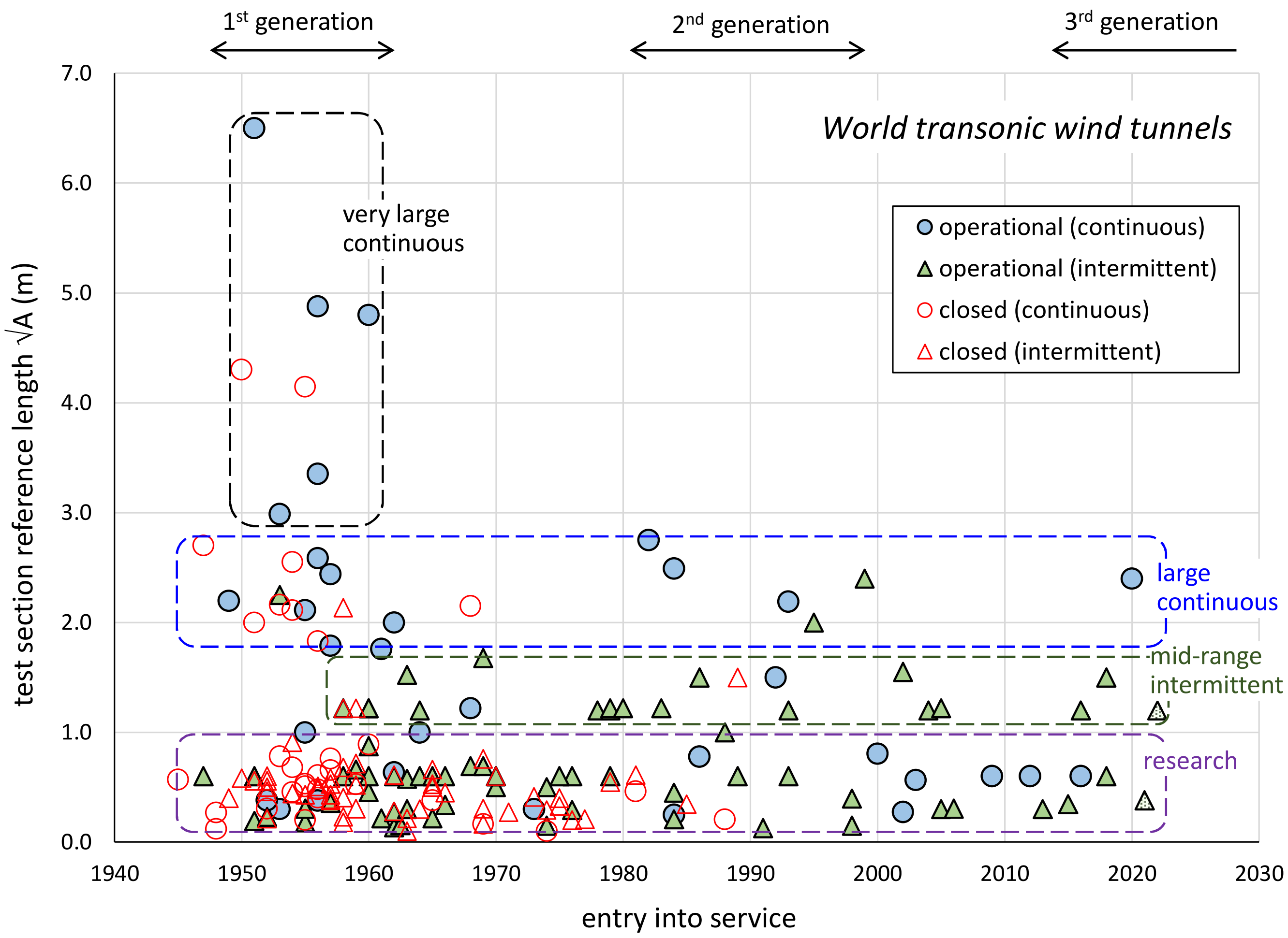
- **facilities only capable of intermittent operation**
  - run times measured in minutes, or even seconds
  - usually open return circuits
  - usually 'blowdown' operation, from high-pressure storage tanks
  - generally trisonic ($M_{max} \approx 3\text{-}5$)
  - operated by a mix of research organisations and airframers



Transonic Wind Tunnels of the World

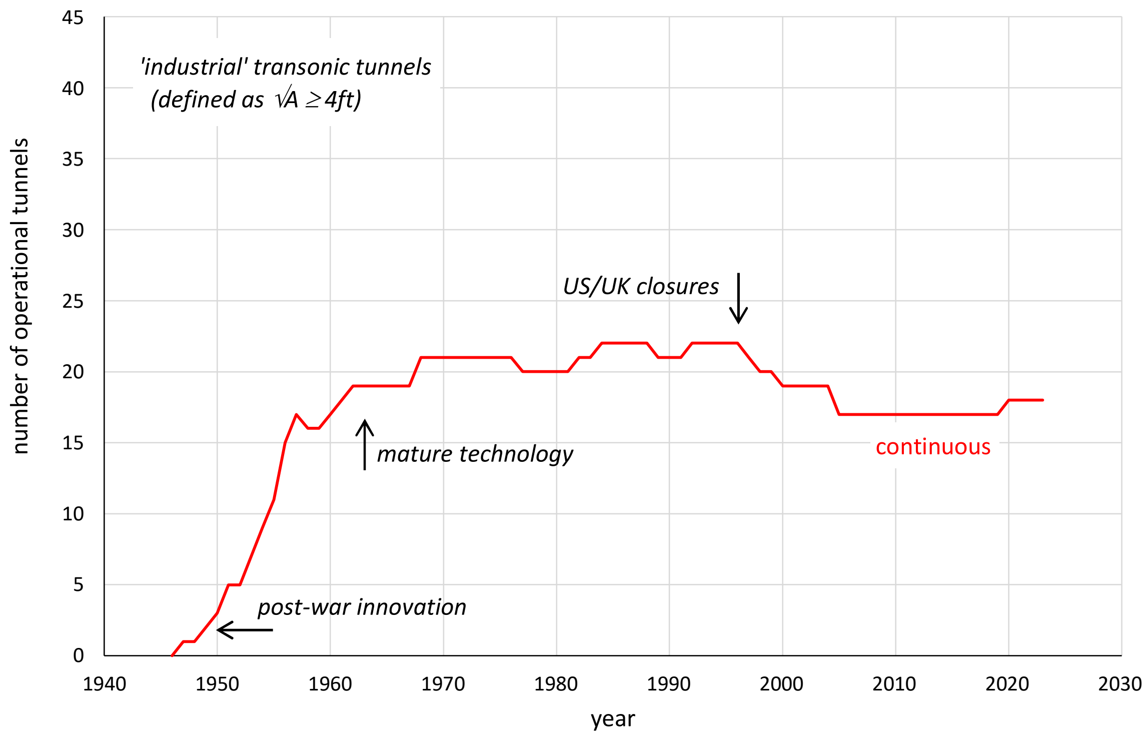
- **four main categories of tunnels:**
  - small research $\sqrt{A} \geq 0.1$m
  - mid-range intermittent ≥ 1.2m
  - large continuous ≥ 1.8m
  - very large continuous ≥ 3.0m
- **three generations of industrial tunnels:**
  1. post-war pioneers 1945-1965
  2. new technology designs 1980-2000

     ... (interregnum) ...
  3. 21st century renaissance 2010-
- **most mid-range to very-large tunnels are still running**
  - only one built after 1960 has closed permanently



World Population of Industrial Transonic Tunnels

- **numbers of transonic/trisonic industrial-scale tunnels in operation over the last 70 years**
  - natural split into continuous (mostly large transonic), and intermittent (mostly mid-range blowdown)
  - difficult to do the same for small research tunnels – closure dates almost impossible to find for university facilities
- **this was a bit of a surprise … !**
- **continuous tunnels:**
  - rapid early growth in numbers in the 50s
  - numbers stable from 1960 to 1995
  - US & UK closures 1995-2005



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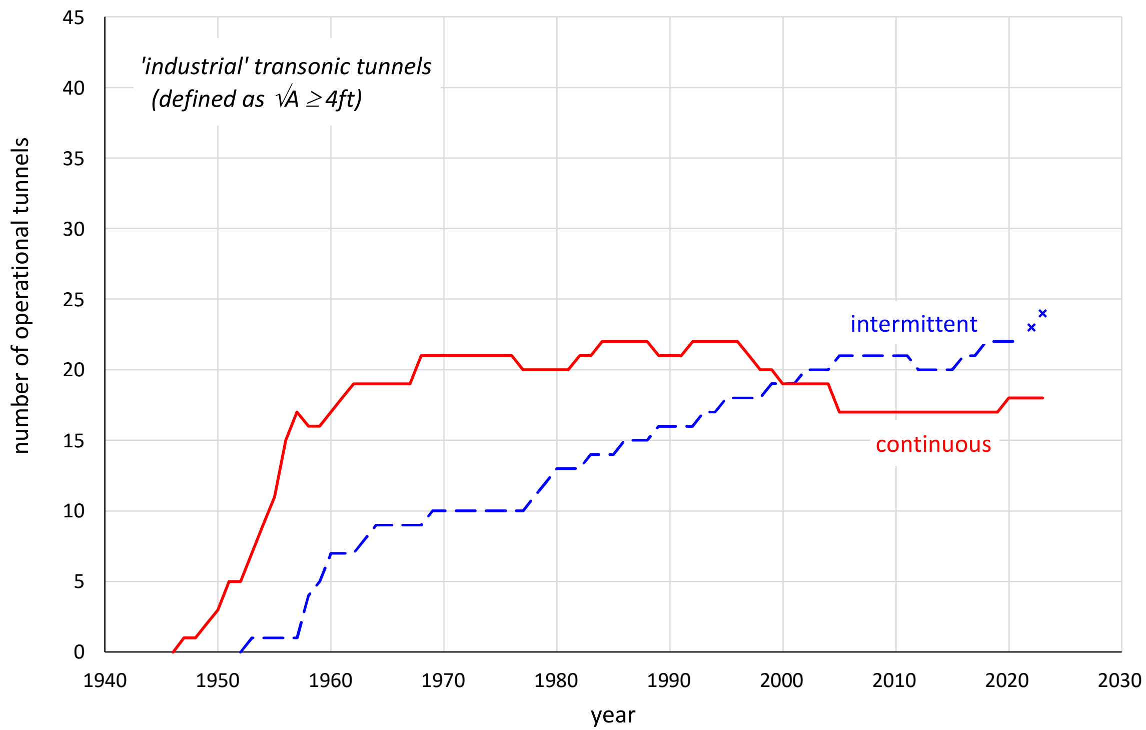
- **intermittent tunnels:**
  - 5-10 years behind continuous tunnels
  - second growth spurt in the late 70s
    → many built by Fluidyne and DSMA/Aiolos
  - *only one trisonic tunnel has ever closed permanently*



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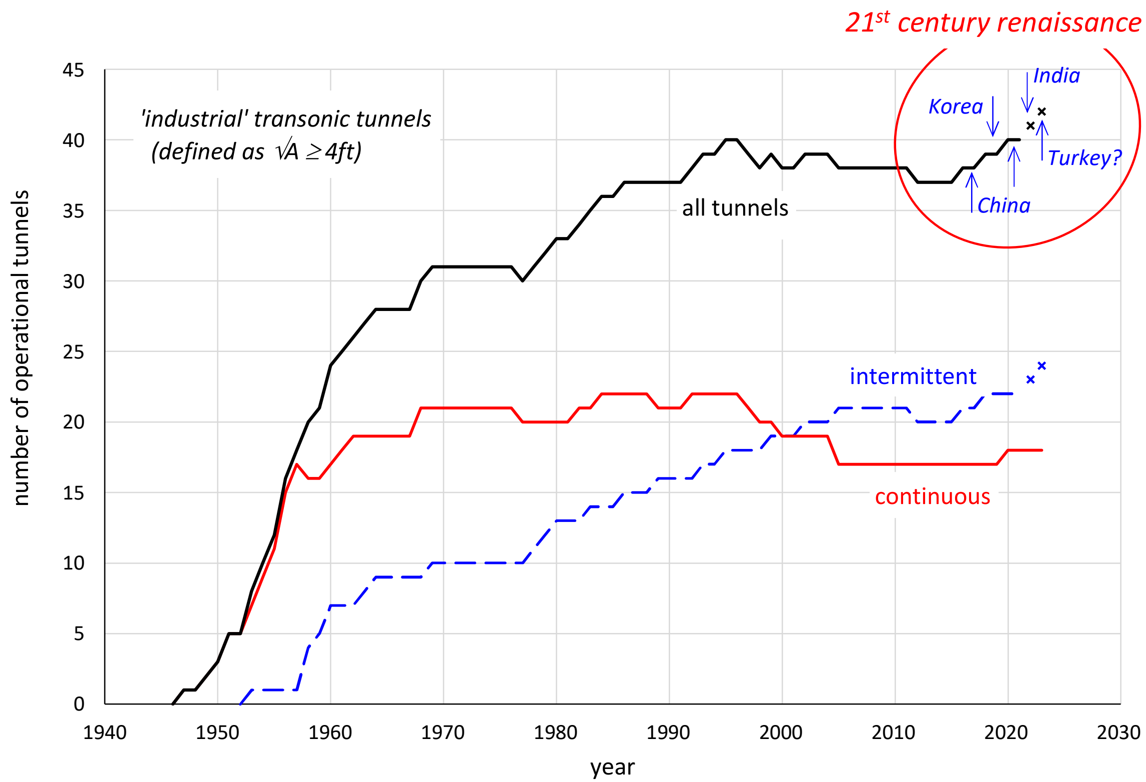
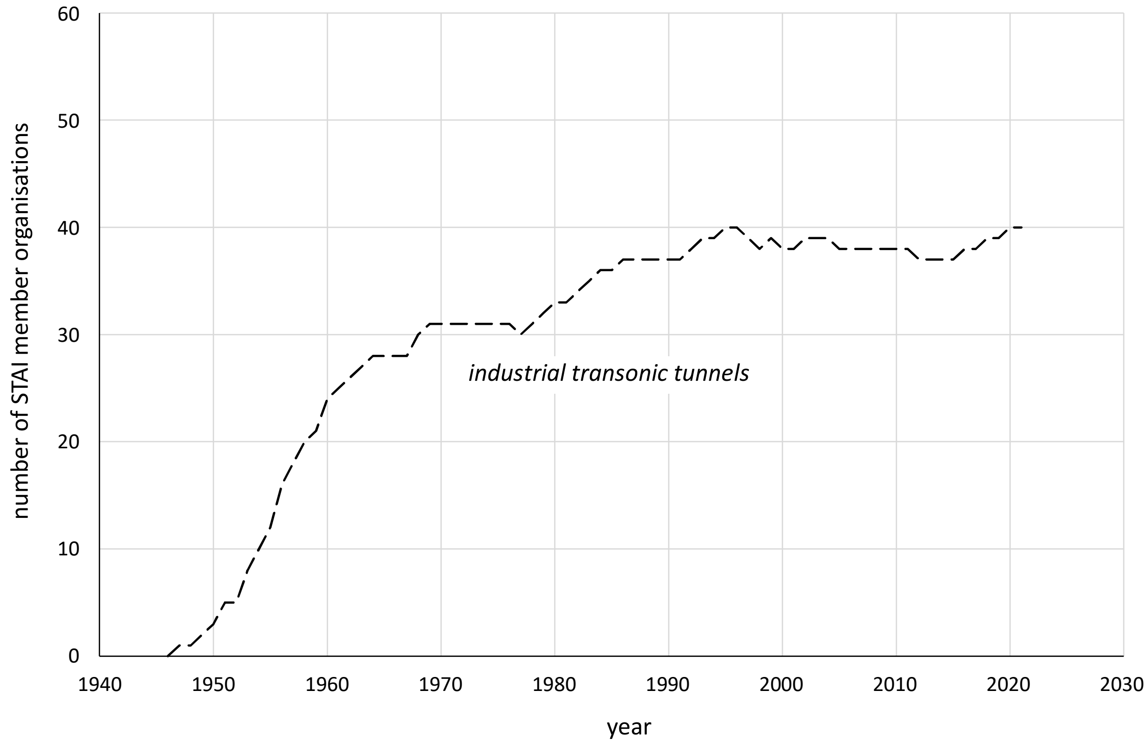
    → many built by Fluidyne and DSMA/Aiolos
  - *only one trisonic tunnel has ever closed permanently*
- **in 2022 total numbers will exceed the 1995 peak**
  - 1.2m blowdown tunnel currently under construction for the Indian space agency ISRO



STAI Membership

- **The "Supersonic Tunnels Association, International"** [**http://fsu-stai.org/**](http://fsu-stai.org/)
  - an organization for operators of high-speed aerodynamic and compressible fluid mechanics testing facilities
  - primary purpose is the sharing of information concerning facility operation, instrumentation and test techniques

- *starting with industrial facility numbers as a baseline*
- *then adding STAI membership …*



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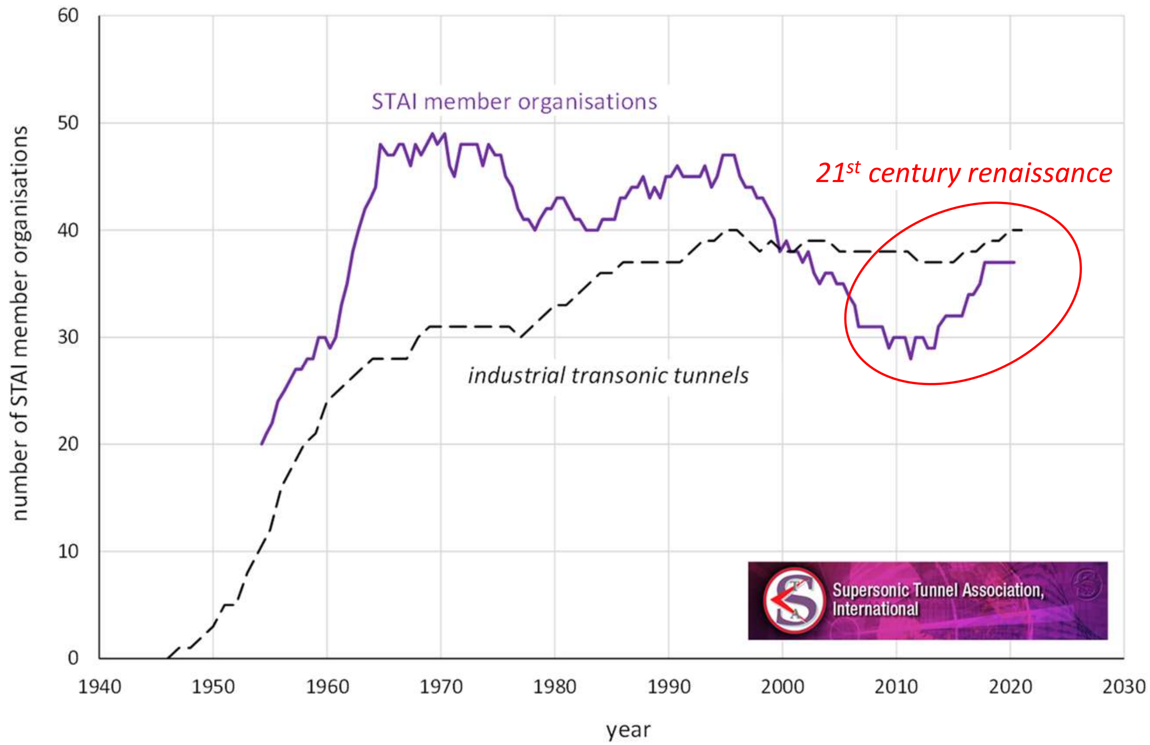
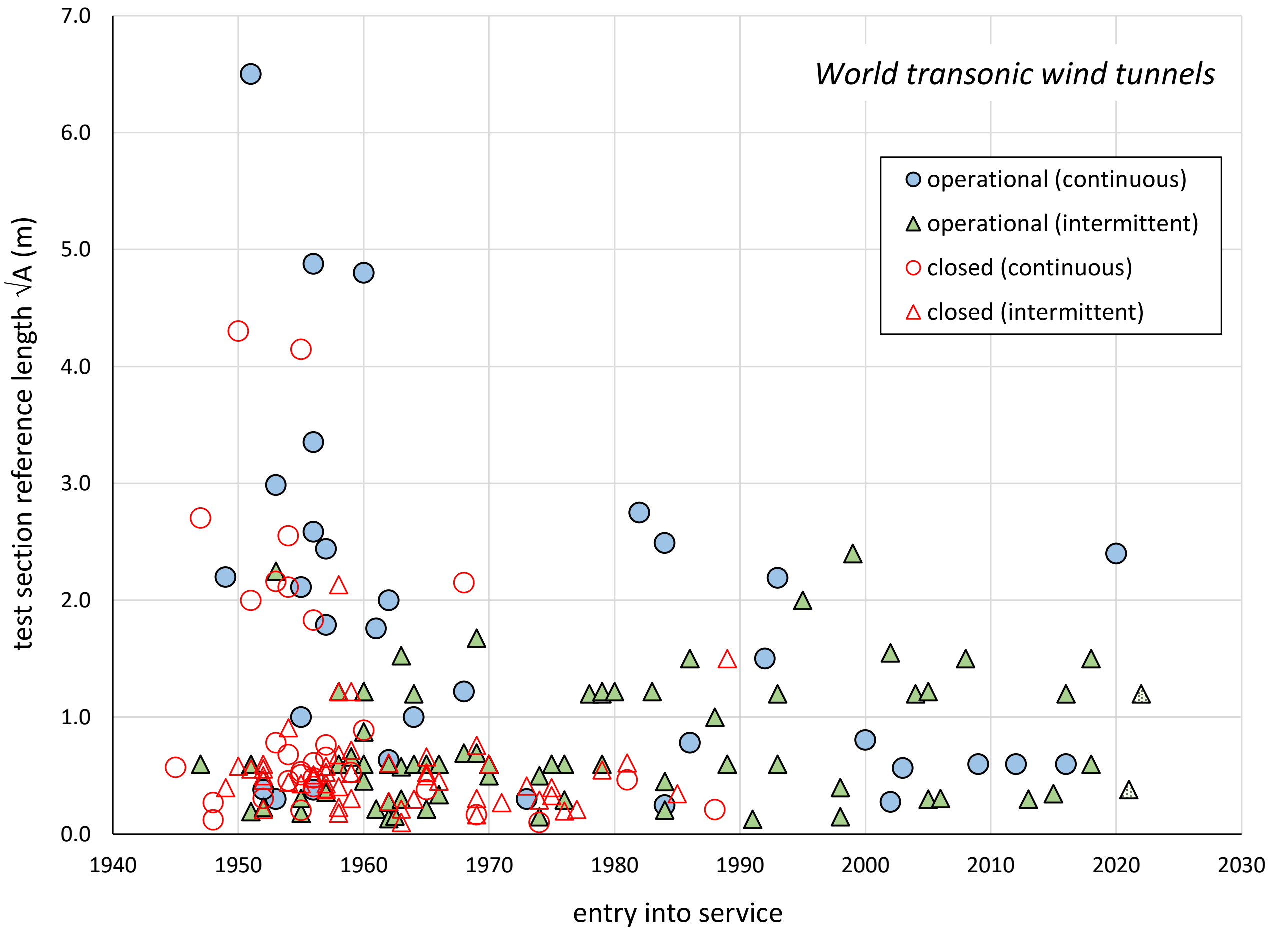
  - an organization for operators of high-speed aerodynamic and compressible fluid mechanics testing facilities
  - primary purpose is the sharing of information concerning facility operation, instrumentation and test techniques
- **rather more volatile than facility numbers**
  - universities and companies come and go
- **1990s were a bad time …**
  - tunnel closures just one aspect of this
  - fewer members than tunnels?
- **but something clearly changed 10 years ago**
  - increase in facility numbers more than matched by increase in STAI membership
- **ARA is currently the only UK member**
  - DERA left in 2001, BAe left in 2010
- **European members are CIRA, DNW, ETW, INCAS, IOA, ONERA, & VKI**



3. Where are UK & Europe in this 'Renaissance' ?

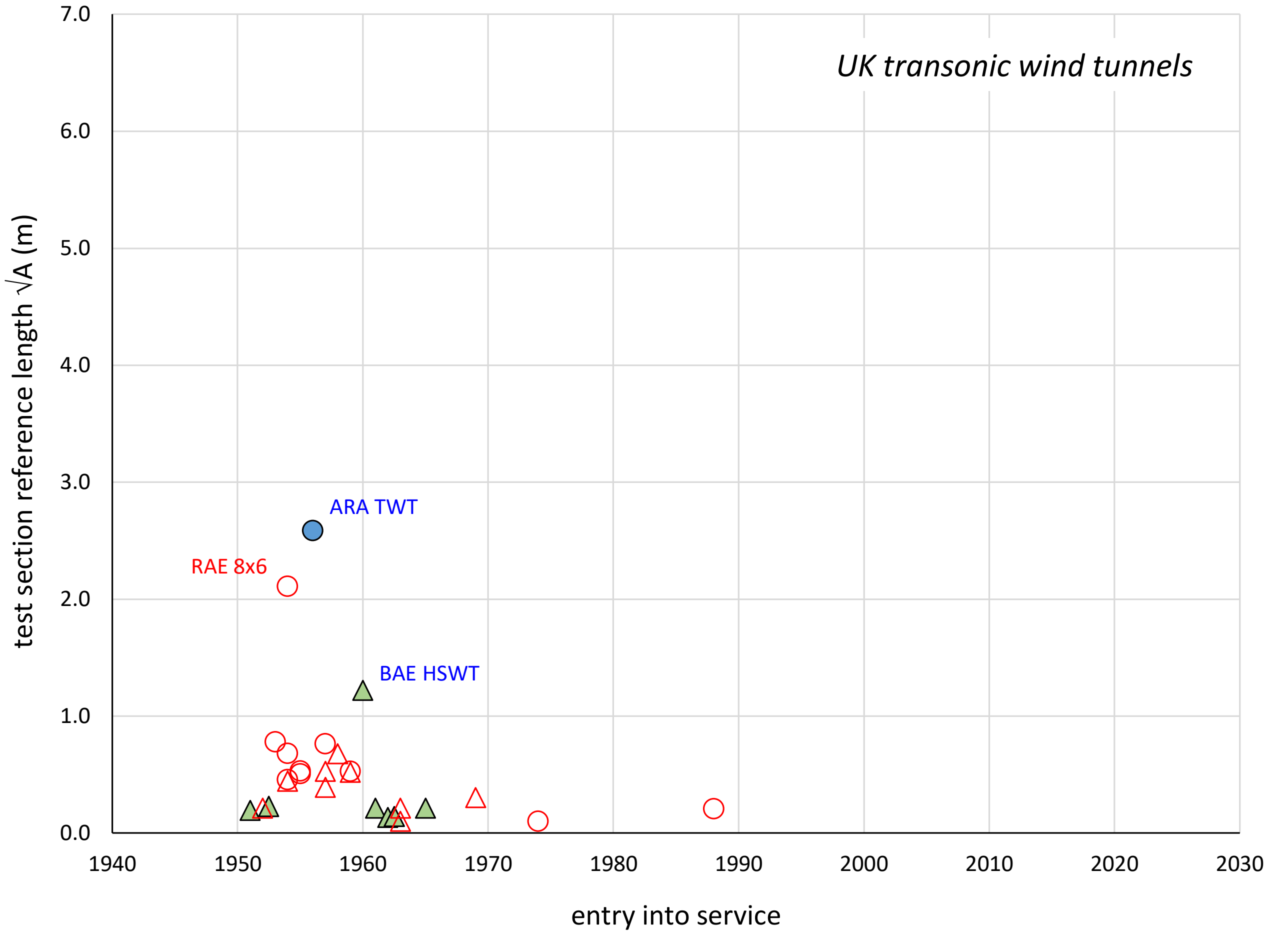
Transonic Wind Tunnels in the UK & Europe

- **back to the 'tunnels of the world' slide …**
- **UK & European facilities are hidden away in this plot**
  - *let's pull them out …*



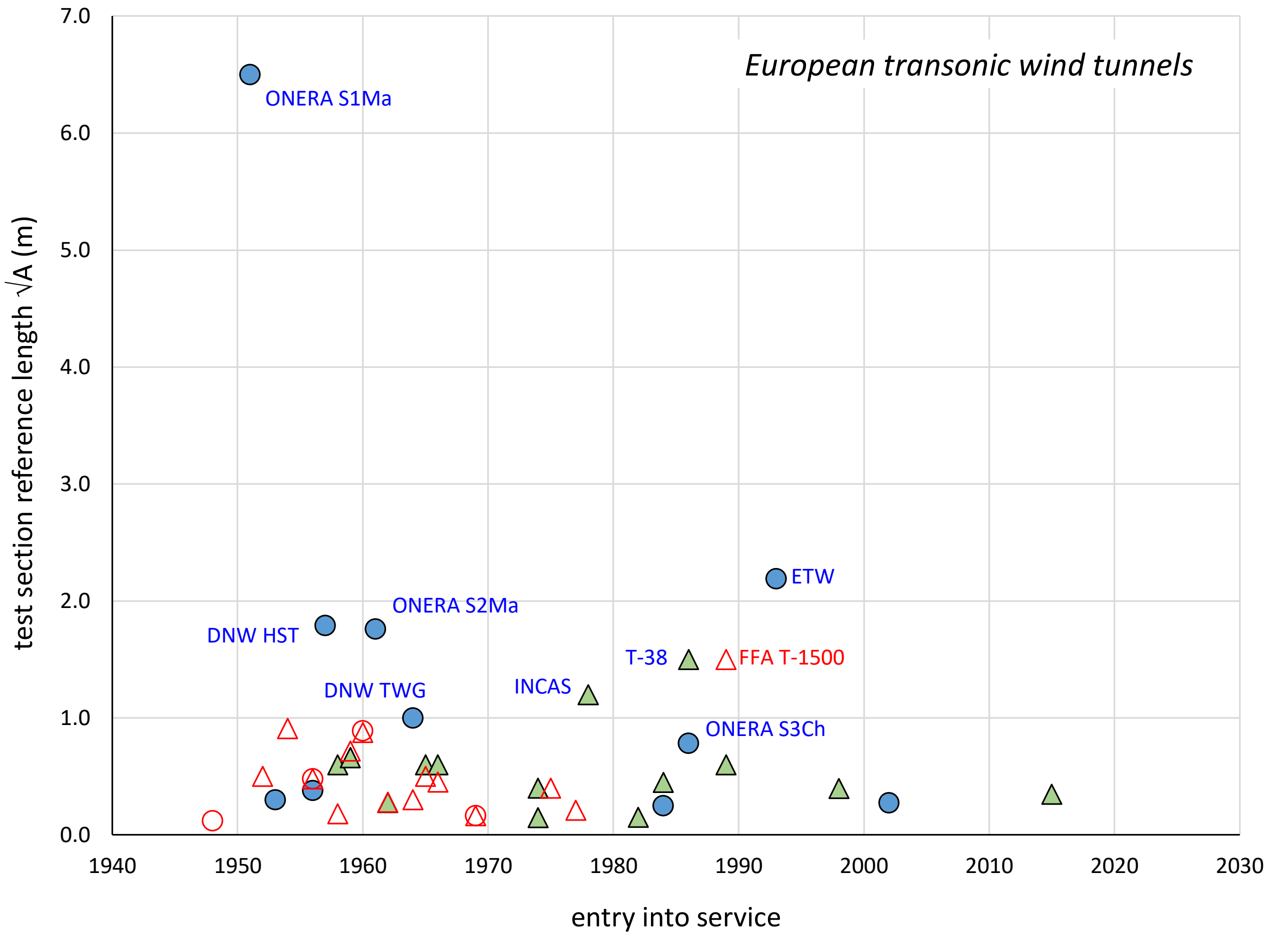
Transonic Wind Tunnels in the UK

- **no ‘very large’ tunnels**
  - but only the US and France/Germany ever built these
- **no large state facilities**
  - only a few small university tunnels
- **two commercial tunnels**
  - ARA TWT, Bae HSWT
- **no ‘research’ tunnels of a significant size or capability**
  - 9” is as large as a UK university tunnel gets
  - NPL, RAE, and airframer R&D facilities all long gone
- **all operational UK tunnels are 1st generation, essentially ‘as-built’**
  - newest tunnel left running in the UK is 55 years old



Transonic Wind Tunnels in Europe

- **one ‘very large’ tunnel**
- **one ‘large production’ tunnel**
- **all operational tunnels are state facilities**
  - national research organisations
  - universities
- **no commercial tunnels**
  - but ETW is a special case?
- **good supporting infrastructure of ‘research’ tunnels**
- **European tunnels are a mix of 1st and 2nd generation designs**
  - most 1st generation tunnels have been significantly upgraded
  - ETW could be considered an early 3rd generation tunnel?



4. Who’s Doing What and When ?

Industrial Transonic Wind Tunnels by Country

- ***listing covers operational + current projects***
  - *see my Aeronautical Journal paper for details …*

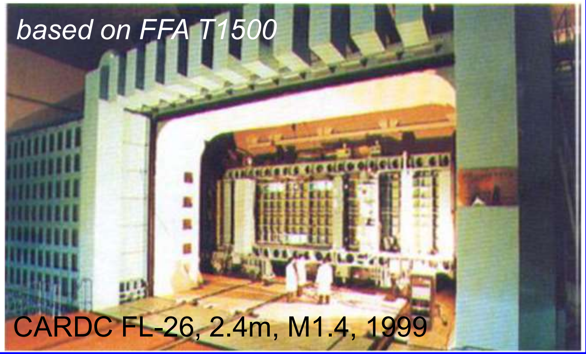
- **US still in the lead, but China catching up fast**
- **most countries with active military aircraft projects have:**

  (a) 2 industrial-scale transonic tunnels
  - with the exception of India and Turkey
  - but both nations have ongoing projects for 2m+ supersonic tunnels

  (b) a supporting ecosystem of supersonic tunnels, and smaller research facilities
  - with the exception of Turkey, South Korea, and the UK
- **most countries have a national aerospace research organization operating or supporting their transonic test capabilities**
  - with the exception of Israel (?) and the UK
  - *DSTL, ATI, and EPSRC have not replaced the RAE or DERA in this respect*

country	operating organisation	supporting national research organisation	tunnel designation	date in service (at current location)	continuous ?	reference length √A (m)	maximum M
Canada	NRC	NRC	1.5m Trisonic	1963	×	1.52	4.25
China	AVIC	CARDC	FL-2	1993	×	1.20	3.00
			FL-60	2016	×	1.20	4.20
			FL-3	?	×	1.55	2.25
			FL-62	2020	✓	2.40	1.60
	CAAA		FD-12	?	×	1.20	4.00
	CARDC		FL-24	1979	×	1.20	3.00
			FL-26	1999	×	2.40	1.43
France	ONERA	ONERA	S2MA	1961	✓	1.76	3.00
			S1MA	1951	✓	6.50	1.00
Germany	ETW	DLR, NLR	ETW	1993	✓	2.19	1.30
India	CSIR-NAL	CSIR	1.2m Trisonic	1964	×	1.20	4.00
	ISRO		*Trisonic*	*2022+*	×	*1.2*	*4.0*
Israel	IAI	×	Trisonic	1980	×	1.22	5.00
Japan	ATLA	JAXA	Trisonic	1995	×	2.00	4.00
	JAXA		2m	1962	✓	2.00	1.40
Netherlands	DNW	NLR	HST	1957	✓	1.79	1.35
Pakistan	DESTO	DESTO		2008	×	1.50	
Romania	INCAS	INCAS	Trisonic	1978	×	1.20	3.50
Russia	TsAGI	TsAGI	T-106	1949	✓	2.20	1.05
			T-109	1953	×	2.25	4.00
			T-128	1982	✓	2.75	1.70
Serbia	VTI	VTI	T-38	1986	×	1.50	4.00
Singapore	DSO	DSO	SWIFT	2005	×	1.22	4.00
South Africa	CSIR	CSIR	MSWT	1992	✓	1.50	1.40
South Korea	ADD	ADD	Trisonic	1979	×	1.22	4.00
			T1500	2018	×	1.50	1.70
Taiwan	ASRD	NCSIST	Trisonic	1983	×	1.22	4.50
Turkey	*Tubitak*	*Tubitak*	*TSTT*	*2023+*	×	*1.2*	*4.0*
UK	ARA	×	TWT	1956	✓	2.59	1.40
	BAE		HSWT	1960	×	1.22	3.90
USA	AEDC	NASA AEDC	4T	1968	✓	1.22	2.00
			16T	1956	✓	4.88	1.55
	Boeing		PSWT	1960	×	1.22	5.57
			BTWT	1953	✓	2.99	1.15
	Calspan		Channel 10	1969	×	1.68	1.20
			TWT	1957	✓	2.44	1.30
	Lockheed		HSWT	1958	×	1.22	4.80
	NASA Ames		11ft	1956	✓	3.35	1.45
	NASA Glenn		8x6	1955	✓	2.11	2.00
	NASA Langley		NTF	1984	✓	2.49	1.20
			TDT	1960	✓	4.80	1.20

New Transonic Facilities in the 21st Century - China



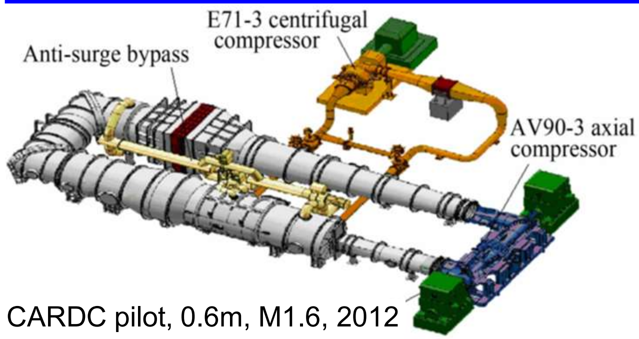
CARDC FL-26, 2.4m, M1.4, 1999

AVIC FL-3, 1.5m, M2.2, *~2002*

NWPU NF-6, 0.6m, M1.2, 2003

1st continuous Chinese transonic tunnel

CAAA FD-12, 1.2m, M4.0, *~2004*

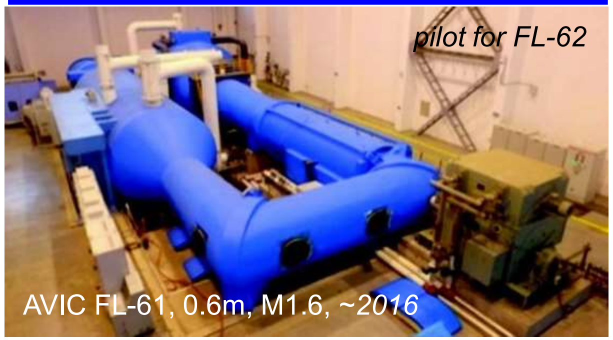


CARDC pilot, 0.6m, M1.6, 2012

AVIC FL-60, 1.2m, M4.2, *~2016*

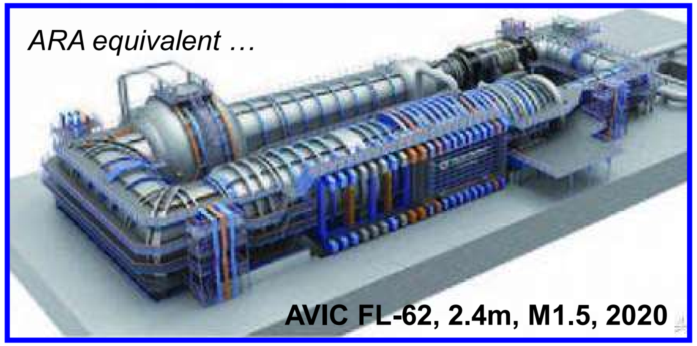
5 industrial scale tunnels

+ 4 mid-range research tunnels



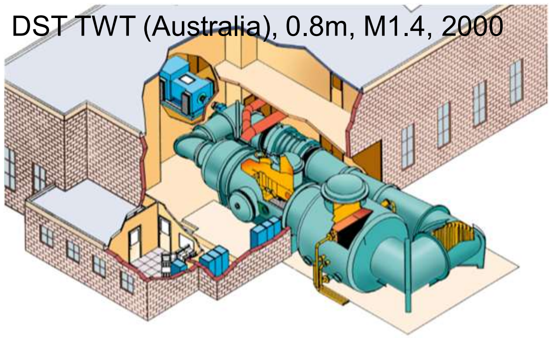
AVIC FL-61, 0.6m, M1.6, *~2016*

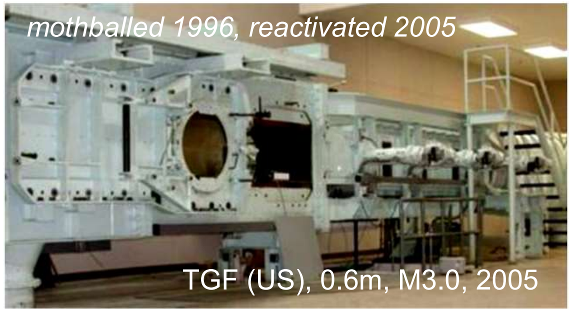
CARDC FL-32, 0.6m, M4.5, *~2018*



AVIC FL-62, 2.4m, M1.5, 2020

‘New’ Transonic Facilities in the 21st Century – Rest of the World



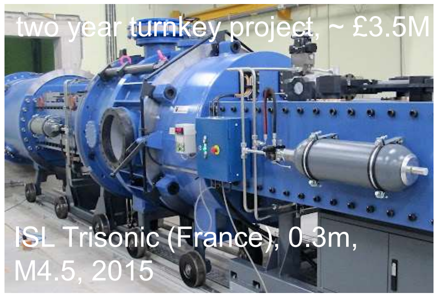


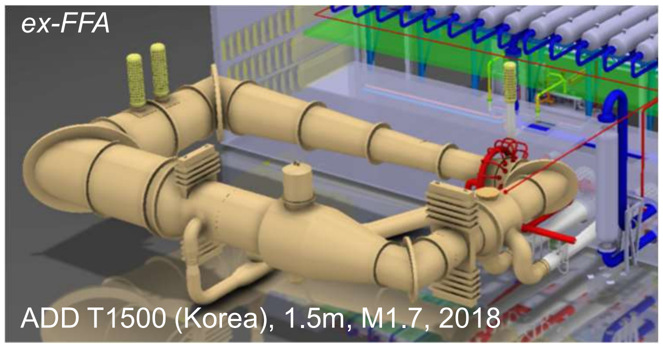
Trisonic (Pakistan), 1.2m? M?, 2008?

4 industrial scale tunnels

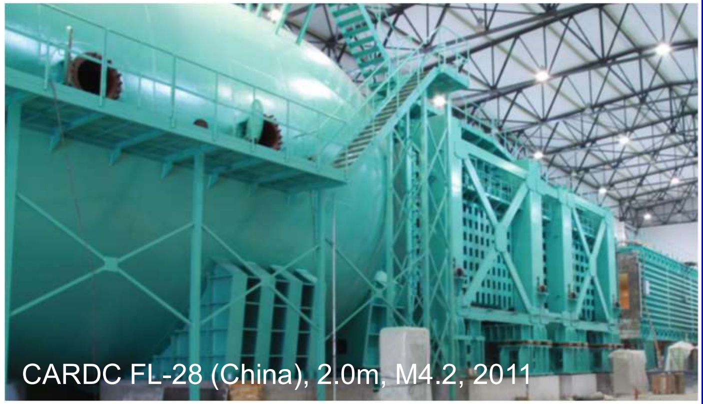
+ 3 mid-range research tunnels

+ upgrades, e.g. DNW HST





‘New’ Supersonic Wind Tunnels in the 21st Century



3 industrial scale tunnels

21st Century Wind Tunnel Investments & Upgrades – NASA

AeroDynamiQ

- **multiple tunnel closures at the end of the 20th century**
  - Ames 6ft (1988), LARC 8ft TPT (1996), NSRDC 7ft×10ft (1997), Ames 14ft (1999), LARC 16ft (2004)
- **multiple capability reviews**
  - NASA (1988), National Facilities Study (1994), RAND (2004), NSTC Plan (2008), RAND (2009), RDT&E plan (2011)
- **multiple grand initiatives**
  - NAFP (1977), NWTA (1998) → NATA (2000) → NPAT (2007), ATP (2006) → AETC Project (2015) → AETC Portfolio (2017)

the US see facilities as worth arguing about!

- **culminating with NASA Aerosciences Capability 'New Funding Model' for the AETC Portfolio in 2017**
  - national recognition of strategic nature of NASA facilities, need to maintain existing core capabilities, etc …
  - 2016: 50% of fixed costs → 2017: 100% of fixed costs → **2019: 100% of fixed costs + consumables** (for NASA users)
- ***this is leading to investment in operations, maintenance, capability enhancements, and test technologies***


Ames UPWT 11'x11'


Glenn 8'x6'


Langley Transonic Dynamics Tunnel


Langley National Transonic Facility

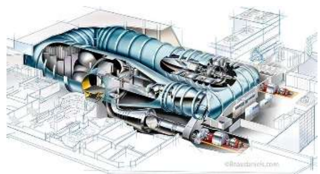
21st Century Wind Tunnel Investments & Upgrades – Commercial

independent operators

- **ARA TWT**
  - compressor replaced in 2000, *plans for test envelope expansion to M = 1.7 shelved in 2007*
  - £15M from ATI in 2012-18, for specific test capabilities
- **Calspan TWT**
  - significant recent investment in complementary capabilities → Triumph, ASE (ex-Fluidyne), ACEnT
  - new data reduction code in 2019, $6M for CTS, compressors, air storage, cooling, balances, systems in 2020

airframers

- **BAe HSWT**
  - repair and refurbishment of flexible nozzle, test section, and model cart
- **Lockheed HSWT**
  - new compressor in 2018, new data acquisition & control systems in 2019
- **Boeing BTWT**
  - new heat exchanger & circuit upgrade in 2001, new model mounting system in 2017
- **Boeing PSWT**
  - extensive renovation 2000-10 → nozzle, compressor, control system, instrumentation

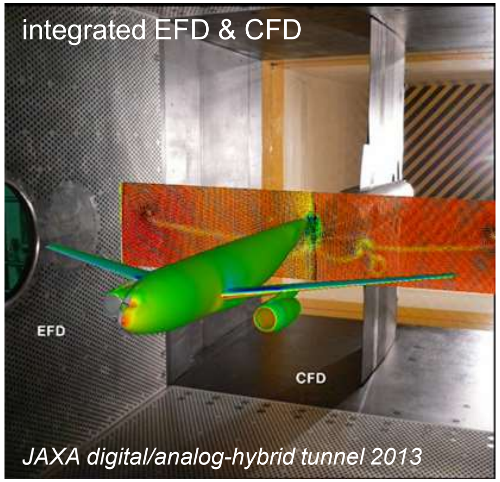


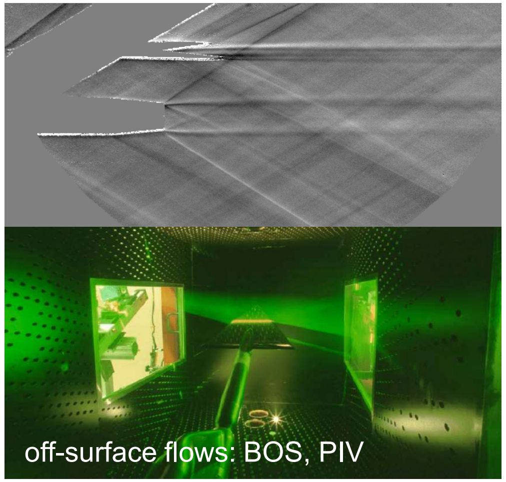
21st Century Wind Tunnel Investments & Upgrades – Europe

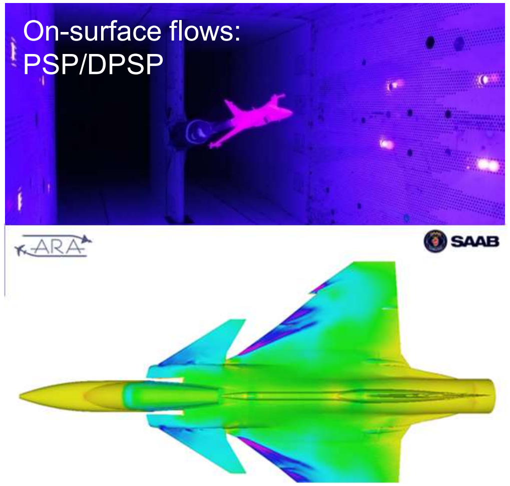
- **ETW**
  - a modern cryogenic tunnel, with a steady flow of facility and instrumentation system upgrades
  - ESWIRP (*European Strategic Wind tunnels Improved Research Potential*) 2009-2014
  - GADE (*Green-Aircraft Design Enabler*) 2014-
- **DNW HST**
  - an older tunnel, with two major facility upgrade programmes in 1994-1997 and 2019-2023
  - new dryer, refurbished compressors & new missile model support system in 2005
  - perforated wall test section, model and Mach number control system upgrades in 2021, main drive upgrade in 2023
- **ONERA S1Ma**
  - a unique facility, in respect of both size and of drive system …
  - new fan in 2009, laminar flow test section in 2017
  - ESWIRP (*European Strategic Wind tunnels Improved Research Potential*) 2009-2014
- **ARA TWT**
  - a 1st generation transonic tunnel, largely in original condition
  - last significant upgrade was a new flow conditioning system in 1991
  - £15M from ATI in 2012-18, for specific test capabilities → *rather limited success, no further government funding*

New and Improved Capabilities

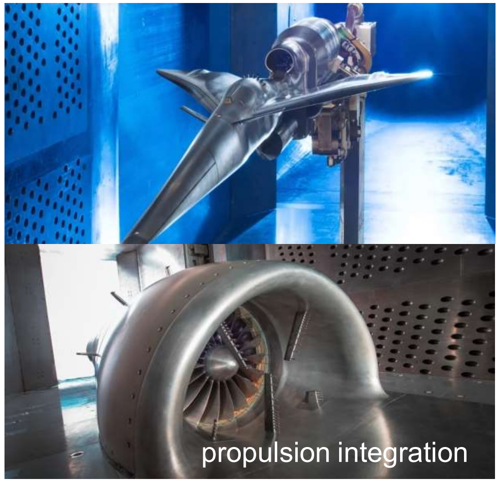
AeroDynamiQ



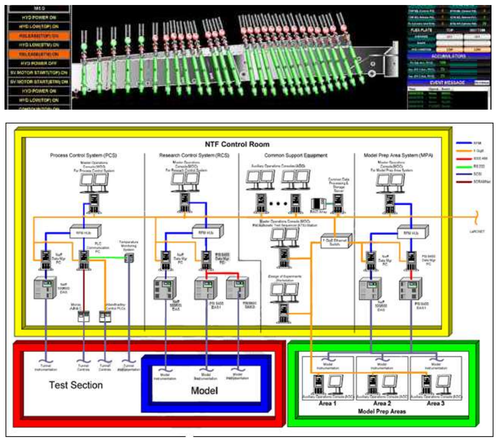




COTS miniature pressure
scanners & probes



control and data acquisition systems

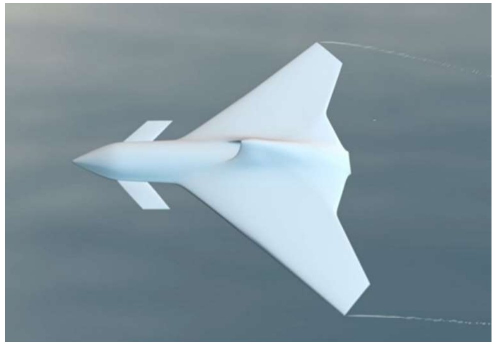


5. Final Remarks

Why is 'The Transonic Renaissance' Happening?

- **there is clearly a continuing need for a range of transonic (and supersonic) ground-test capabilities**
  - plenty of current and future civil and military flight vehicle projects where effective transonic operations are key
    → in the UK alone we have Tempest, LANCA, Aeralis, CRANE, FlyZero, FC/ASW, Spear
    + assorted projects from Airbus, Leonardo, Dowty etc
  - but CFD still not adequate for 'edge-of-the-envelope' flight, or for unconventional high-speed configurations
    → for the next decade at least, 'digital twinning' will still need analogue and well as digital elements





Why Isn't It Happening in the UK?

1. **we have no over-arching long-term national vision for *strategic* aerospace ground test capabilities**
   - fragmented planning and funding organisations
     → DSTL has no money, ATI & EPSRC not very interested, very little direct financial support from industry
   - technical needs lost in the politics → e.g. the early days of the UK Aerodynamics Centre
   - *contrast this with NASA AETC, AEDC, DNW, DLR, ONERA, EU, CARDC/AVIC*
     → *and historically in the UK … the ARC, NPL, RAE, NAE, and CoA*
2. **we are plagued by short-term management thinking**
   - early ATI/UKAC focus on one-off, set-piece, high-pressure, 'headline' projects
   - 1 year at a time funding horizons, focused on spend profiles and 'box ticking' milestones
   - underlying blame culture → *if you can't admit failure then you won't learn from your mistakes …*
3. **we have an inadequate supporting research 'ecosystem'**
   - no national aerospace research organization
     → ATI, EPSRC, DSTL, MoD, QinetiQ have failed to replace RAE and DERA
   - no mid-range transonic/supersonic research facilities in academia or industry
     → a handful of very small tunnels with rather limited test envelopes, NWTF focused on low-speed & hypersonic
   - *contrast this with every other significant 'aerospace nation' !*

Q: is it too late to catch up?

Summary

- ***but on a more positive note for the rest of the world …***
- **this is a really good time to be a high-speed wind tunnel test engineer**
  - there is currently a very high demand for industrial testing in transonic, supersonic, and hypersonic wind tunnels
  - CFD developments have not (as yet) had a significant impact on high-speed wind tunnel usage
  - basic test types have changed relatively little in the last 40 years,
    … but have become significantly more complex (and therefore more interesting …)
- **globally, the industrial-scale transonic wind tunnel is undergoing somewhat of a renaissance**
  - 'new-build' tunnels in China, South Korea, India, Turkey, and …
- **numbers of high-speed tunnels in-service are increasing**
  - as of 2022 there are 40 industrial transonic and trisonic wind tunnels operational around the world
  - these are supported by a floating population of around 60-70 smaller research facilities.
  - of the 20 industrial-scale trisonic blowdown tunnels built since the 1950's, only one has ever closed permanently
- **investment levels are rising, calibrations are being done again, test capabilities are being enhanced**
  - most major industrial facilities have had significant refurbishments and/or upgrades in the last 20 years
  - recent advances in instrumentation are having a major effect on test productivity and data quality

Thanks for listening – any questions?