Roadmap: Provision of Internationally Leading Wind Tunnel Infrastructure

1 Introduction

There are approximately 180 wind tunnels in the UK of which roughly 150 are in the university sector. Owing to the dual funding structure of research in UK, university tunnels receive government support through a HEFCE teaching budget as well as from funding councils, industry and overseas agencies. This roadmap relates to those facilities funded essentially, but not exclusively by research, and not those retained principally to support the teaching mission of individual universities. Approximately 20 – 30 tunnels are currently used for research: facilities for turbomachinery research are excluded, these being identified in a further ATI road mapping exercise for a "National Propulsion Test Facility". The basis of the National Wind Tunnel Facility (NWTF: http://www.nwtf.ac.uk/html/index.html, https://www.epsrc.ac.uk/research/facilities/access/otherfacilities/national-wind-tunnel-facility-nwtf/) is primarily to focus resource on (1) fewer 'outward-facing' national facilities open to all UK-based researchers; (2) institutions demonstrating a symbiosis of facility and expertise and prepared to demonstrate best practice; (3) institutions that demonstrate a clear, on-going commitment to these national facilities. NWTF presently comprises 17 tunnels across 7 universities subject to a mid-term review in 2016: the tunnels cover a range of sectors, but with an aerospace emphasis. A key precept of NWTF is that facilities and their specific equipment are co-located with the expertise required to maximise the scientific value, and therefore the efficiency of the process. This is consistent with the closure of the EPRSC Engineering Instrument Pool.

The purpose of the roadmap is to define a strategy for further capital investment in facilities that provide further game-changing capabilities that are complementary to those above and are of potential interest to EPSRC, NERC and UK Space Agency. There is a presumption that further investment will lead to an extension of the NWTF model to include further new and refurbished tunnels. As such, NWTF could move to the status of a mid-range facility status before the grant ends in December 2018. The roadmap identifies opportunities in the immediate (<2 years) and near-term (2-5 years) timescales. Prospects for longer-term investments are also included in a more speculative horizon scanning section.

2 Approaches and Mechanisms

The steering group for this exercise comprises:
Professor Jonathan Morrison (Imperial)
Professor Holger Babinsky (Cambridge)
Professor Chris Baker (Birmingham)
Dr Volker Buttgereit (BMT)
Professor Bharath Ganapathisubramani (Southampton)
Dr Kevin Gouder (Imperial)
Professor Peter Ireland (Oxford)
Professor Martin Passmore (Loughborough)
Dr Simon Prince (ATI / Cranfield)
Professor Alan Robins (Surrey)

Two members of this group are able to provide a non-university perspective: Volker Buttgereit has a business perspective in wind engineering. Simon Prince has led the aerospace technology road mapping exercise at the ATI. The group met twice to agree changes to roadmap drafts and also communicated electronically.

3 BIS Consultation

In response to the 2014 BIS consultation process on long-term capital investment in science and research, a review process of wind tunnels initiated by EPSRC identified five grand challenges (§3.1 – 3.5, below), which we take to be the starting point for this roadmap process. They address the aerospace, automotive, wind engineering, and atmospheric sectors (relevant to EPSRC and NERC portfolios) and address the potential for remote access. They are tested against these key considerations:

- investment, current state of the infrastructure: new / existing
- usage & sustainability
- access: unfunded, funded, cross-sectoral, industrial, commercial
- vertical 'integration': pull-through to end user, overlap with industry
- international competitors, primarily EU: e.g. http://www.euhit.org.

3.1 Automotive

The automotive sector is one of the UK's largest high-value manufacturing and exporting industries. The industry's aerodynamics research and development is supported by internationally leading vehicle and applied aerodynamics research groups in a number of Universities including, Cranfield, Durham, Loughborough and Imperial College, working on both fundamental and applied automotive relevant research. The aim of this infrastructure investment is to build a new world-class national aero-acoustic facility. It has an automotive focus but also addresses cross-sectoral needs in aerospace (ACARE targets), rotorcraft and potential wind engineering applications. Capabilities would include full-scale automotive, moving ground, large rotor rig and active turbulence systems. This will put the UK in an internationally leading research position in automotive aerodynamics and aero-acoustics, provide multiple opportunities for cross-sector activity and fulfil an important industrial need. No comparable facilities currently exist in the UK or could be upgraded to meet these requirements. UK provision is very poor compared with France, Italy and Germany.

The facility is proposed as a partnership between industry, research organisations, EPSRC and universities and has the support of UK based vehicle manufacturers including JLR, Bentley and Nissan, the major users of full-scale facilities in the UK. The facility, to be located centrally in the UK would operate on a self-contained sustainable funding model underpinned by the commercial income from the majority of its use. The facility would be operated and managed by an independent operator (e.g. MIRA). The university research element, charged on a marginal cost basis, could be reasonably managed through the NWTF with an EPSRC contribution.

The capability addresses EPSRC priorities in energy, environmental change, and engineering, and addresses major research challenges in aeroacoustics, energy consumption, CO_2 reduction (Worldwide harmonised Light vehicle Test Procedures, WLTP), low carbon vehicles and future cities.

Business Plan

The indicative budget is £100m. The UK Automotive industry accounts for two-thirds of the UK's turnover (£60bn) for the manufacturing sector, with a net value added to the economy of approximately £12bn a year accounting for 10% of total UK exports. The industry employs more than 700,000 people. Current wind tunnel R&D expenditure by the major UK based manufacturers is £3.0m a year in overseas facilities and there will be a step increase in demand with the introduction of the WLTP.

The ATI envisage that such a facility will also have considerable attraction for the wind engineering and aerospace sectors including for the UK National Rotor Rig, being constructed at the ARA, using a £3.6m ATI grant partnered with EPSRC. In addition, the ATI envisages the facility drawing in aeronautical work from BAE, Airbus and others, in areas such as undercarriage noise. Initial aerospace use is estimated at £750k pa. The facility is also likely to attract test work from across Europe.

Access to a local facility will improve efficiency and competitiveness for the UK, protect research and development jobs in high value design and engineering and directly generate highly skilled jobs. The demand for this facility is such that it is expected to operate close to capacity while supporting a marginal cost capability for academic research.

3.2 Wind engineering

The UK has a deserved history of leadership in wind engineering and many leading practitioners are based here (e.g. BMT, BRE, CERC, RWDI), supporting world-wide industries that also have a strong base in the UK (e.g. in architecture, construction, wind energy, meteorology). University research facilities underpin these activities and the UK has established an enviable academic record in wind engineering that has always been based on a healthy balance between fundamental and applied research. The aim of the infrastructure investment is to maintain that capability and its ability to meet future challenges, thereby to ensure its viability over the next 25 years. Four facilities comprise the wind engineering investment:

1. controlled environment facility at the University of Bath that includes a 'wall of wind' and a shallow water wave pool,
2. transient flow laboratory at the University of Birmingham that is capable of simulating the key features of non-synoptic winds,
3. mobile, storm chasing laboratory at the University of Exeter for gathering field data on infrastructure performance pertinent to extreme weather events,
4. stratified flow wind tunnel at the University of Surrey, for generalised stratified atmospheric boundary layer and dispersion modelling.

The combined capability will provide a world-leading, national asset that meets the requirement summarised above and, in doing, addresses EPSRC priorities in energy, environmental change, global uncertainties and engineering, and NERC priorities (through NCAS) in environmental hazards and environmental change. Many of these, for example the future cities and resilience topics, imply long-term challenges with relevance through to 2050 and beyond. The developments link directly to other areas of strength in UK university research in, for example, LES-CFD for environmental fluid mechanics, transport, indoor/outdoor exchange of heat and pollutants, fluid-structure interactions and meteorology (e.g. the urban boundary layer).

Business Plan

The indicative budget is £10m. Based on recent performance, the four university groups involved anticipate annual income running at £0.5-1m per facility, largely from EPSRC but also with large shares from NERC, Industry and the EU. Additional income will derive from third party facility use.

In the 2013 Construction UK Industrial Strategy, the Government set out its vision for ensuring long-term competitiveness and growth of the sector.   A cornerstone of this strategy is for UK industry to lead the world in research and innovation through adoption of digital design, advanced materials and new technologies, and through fully embracing the transition to a digital economy and the rise of smart construction. UK Government has also highlighted, in its National Infrastructure Plan 2014, the need for infrastructure assets to become sufficiently resilient to absorb, adapt to or rapidly recover from disruptive events such as extreme or adverse weather, the total estimated worldwide cost of which has reached $1.4tn (of which only 25% is insured), or simply degradation over time.

The Wind Engineering proposal aligns with these ambitions, focussing on investment in high quality university research facilities to develop greater understanding of environmental fluid mechanics and, in particular, the impact of wind on the urban environment and key infrastructure. Applications extend over a broad range, covering design and construction, resilience to extreme weather, air quality, wind power and urban meteorology. Beneficiaries extend from large-scale industry (e.g. construction) and national bodies (e.g the Met. Office and PHE) to SMEs.

As well as underpinning the resilience of UK critical infrastructure and the well being of UK citizens, advances in wind engineering research are crucial in accelerating innovation towards smarter engineering design of buildings and cities, instrumental to realise the "Future Cities" agenda. This involves not only major construction and engineering organisations but smaller companies involved in sustainable city design – SMEs, architects, small green technology companies - who cannot afford R&D on their own, will also benefit directly and indirectly from this investment. Street/neighbourhood scale modelling will also aid city redevelopment and/or master planning (e.g. by engineering consultancies, local authorities responding to air quality regulations Climate Change Risk Assessments). Environmental research also provides the UK with a sound base in support of international negotiations and provides the information needed to set policy and drive improvements to environmental conditions (through wind loading codes, air quality regulations). Poor air quality persists in a number of UK cities, most notably London, and a substantial research focus addresses traffic and air quality management, as well as emergency response. Air quality impact was also a major factor in deciding whether or not Heathrow could support a further runway. The new and refurbished facilities will target topics that cannot be addressed reliably by numerical simulation alone (e.g. major construction projects, long-span bridges, urban greening, dispersion in complex conditions, off-shore wind power) or where rapid evaluation of response to large-scale design and other changes is crucial.

Wind engineering also has links to the “8 Great Technologies” including Advanced Materials (e.g. through the understanding of the use of advanced materials in the built environment), Big Data (e.g. extract meaningful information and value from CFD models of impact of winds on urban environments) and Synthetic Biology (e.g. potential of Synthetic Biology being used in the built environment to develop novel coatings used for trapping pollutants).

The risk of not investing now is that UK expertise will be lost, with the North American and Chinese universities capturing the entire market and the subsequent drain in financial and intellectual resources that this will have on the UK, which cannot be retrieved in the short or medium term.

3.3 Aerospace

High Reynolds number flows dominate the technological landscape in all engineering sectors, but are most closely identified with aerospace. They pose several key scientific challenges that lie between fundamental physical processes and technological innovation. As computer speed and memory increase, these flows are becoming more approachable with simulation techniques such as large-eddy simulation. However, even full direct simulations cannot fully resolve the microscales appearing at the asymptotically high Reynolds numbers required for probing the fundamental scaling laws that provide the cornerstones to our understanding of fluid dynamics.

Two facilities are proposed to address the grand challenge of fluid behaviour at asymptotically high Reynolds numbers when the effects of viscosity are vanishingly small. They offer the opportunity for real scientific advances in the area of frictionless “superfluids”. They also provide an economical way of addressing the challenges of engineering design of efficient fluid based systems by providing essential design information for the transport sector at full-size conditions.

A medium-scale compressed air tunnel (pressure of up to 400 atmospheres) is proposed that can be used to perform fundamental measurements of flow velocity and pressure at Reynolds numbers of order 10^7 or 10^8. A parallel development of micro instrumentation (point, planar and volumetric measurements of resolution of order 1 – 10 microns) will be required to address fundamental questions concerning the behaviour of turbulence, the most fundamental form of fluid motion. Such a facility would also be used to provide test data of transport vehicles at full-size Reynolds numbers economically, it obviating the need for large-scale test facilities. For example, the drag coefficient of a full-size submarine or an aircraft could be measured at operational Reynolds numbers.

The second facility will use helium superfluids, reaching extreme Reynolds numbers cryogenically by cooling close to absolute zero. Quite small, simple geometries (such as pipes or channels) can be adapted to produce Reynolds numbers of 10^9 or 10^{10}. Sophisticated techniques, such as excimer molecules used as probes will also be developed. As with a compressed air tunnel, a simple channel / pipe flow with a cryostat offers an economic means for performing fundamental science. The sharing of expertise and development of new techniques between engineering and physics communities provides added value.

Current UK experimental expertise in superfluids is at Manchester, Birmingham and Lancaster. There is no compressed air facility in Europe (including the UK), current expertise being almost exclusively at Princeton

University. However, there is current UK-based expertise at Imperial and Southampton through on-going interactions with the Princeton group.

Business Plan

The indicative budget is £20m. The Aerospace Growth Partnership (AGP) has recently established priorities for maintaining the position of UK aerospace, in three stages: protect (0-5 years), sustain (5-10 years) and grow (10+ years). Global air traffic market is set to grow by 4.7% a year from 2013 to 2032, with the number of airline passengers is set to rise from 2.9bn to 6.7bn in 2032. By then, the market will be dominated by Asia-Pacific traffic where increasing urbanization will establish mega-cities and their inter-connection. Hence, the current focus is on civil aerospace, though there is also scope for developing synergies between relevant areas. This has already led to a step change in the working relationships between industry leaders and Government, with companies and academics working closely to maintain the UK's prominent knowledge and capability base.

With UK government committing just over £1bn over the next seven years to aerospace research through the creation of the ATI, with matching funding from industry, the ATI will provide better alignment between early research (e.g. EPSRC) and cross-sectoral R&D innovation delivered through Innovate UK. The ATI has enabling technology streams of aerodynamics, manufacturing, materials, infrastructure and process / tools. The UK is Europe's number one aerospace manufacturer, second only globally to the United States. The significant effect that this has on the national economy through profits and job creation, both directly and indirectly, underscores the importance of this industry. It is therefore an industry that is set to grow; by 2030 there will be an estimated global demand for approximately 27,000 new passenger aircraft potentially worth up to $3.7tn. This figure alone signifies how vital the aerospace sector is to the UK.

3.4 Space

Space is one of the biggest growth sectors, with year on year growth rates of 8% and £10.8bn of contribution to the UK economy[1], and it has been identified as one of the "8 Great Technologies" for investment by BIS. The space transportation sector provides 5% of this contribution[2]. A significant amount of work is being, and will need to be done, in the area of hypersonic aerothermodynamics testing[3], in support of current and emerging ESA projects. This application for investment is timely given ESA's recent progress in new vehicles. For example, the ISV[4] re-usable space plane recently returned from a 412 km altitude trajectory and successfully demonstrated an autonomous atmospheric re-entry system characterised by advanced aerodynamic performance due to its lifting body shape, integrated propulsion and aerodynamic surfaces combined with advanced thermal protection. This spacecraft is a key part of ESA's Future Launchers Preparatory Programme, which is building on the successes of Ariane and Soyuz to ensure Europe's access to space. This programme has identified robust structures and re-usability as key technologies. It is important to note that most UK hypersonic flow research is being outsourced to the US[5] and Australia, due to a gap in testing capability in Europe. In particular there are no facilities in the EU to investigate hypersonic boundary layers at free-stream turbulence levels representative of flight – understanding of which is critical in ensuring acceptable heating rates, control stability and intake flow quality on hypersonic vehicles. There is no experimental EU facility to test materials / configurations in very high Knudsen number flows representative of Low Earth Orbit, where a lack of understanding of the combined effects of surface degradation and molecular slip flow needs to be addressed. Finally, there is no facility outside the US or Japan for free-flight testing of configurations, such as planetary entry bodies, at

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[1] Executive Summary: The Size & Health of the UK Space Industry, UK Space Agency, October 2014

[2] Evaluation of Socio-Economic Impacts From Space Activities in the EU: Study Key Findings and Conclusions. Booz & Company, Amsterdam, 17 March 2014.

[3] The EU, through projects such as LAPCAT, LAPCAT II and ATLLAS spends around €2million per year on basic hypersonics research, much of it on testing. ESA, CIRA (eg: Castor & Pollux), DLR (Eg: SpaceLiner, Shefex) and ONERA, together, spend a similar amount on hypersonics.

[4] Intermediate Experimental Vehicle

[5] The UK government alone is spending, via DSTL, several million pounds a year on hypersonic testing in the US.

representative hypersonic aerothermodynamic conditions, such that experimental data on flight dynamic characteristics can be experimentally acquired.

A major opportunity exists for the UK, via the National Wind Tunnel Facility (NWTF), to capture some of the emerging experimental hypersonic testing work, in these areas and position the UK as a major contributor to future ESA missions. It is proposed to invest £13m to develop three new small-scale test facilities, at the Universities of Cranfield, Glasgow and Oxford, extending the NWTF capability to address research questions in the areas outlined, thereby enabling the UK to maximise its impact on emerging international space programmes, and fill a gap in EU testing capability. Each facility will be designed to ensure low cost operation to maximise utilisation and academic research output.

Business Plan

The indicative budget is £13m. Contract research and design consultancy represented 7% of the UK space industry turnover in 2008[6] and remains at around this level, ie: around £750m today. A £13m investment represents 1.7% of this annual turnover figure. The EC civil funding available for programmes to which these facilities could contribute include space launcher and space science and exploration, of around €120m per year. From this and other sources (US, India, China etc.) it is estimated that the three facilities, together, could draw in around £500k to £1m per year of contract research and development income, and attract many more overseas students and researchers to the UK to study hypersonic aerothermodynamics, thereby amplifying this figure in terms of Gross Value Added to the UK economy.

3.5 Remote Access

Remote access to high specification facilities offers high utilisation but at a reduced cost. It facilitates the use of state of the art wind tunnels to increase further their relevance across sectors with researchers in the UK and beyond. Remote access opens an opportunity for the research community to operate in an integrated, efficient and highly networked manner, facilitating transfer of knowledge and sharing of intellectual capital and best practice.

The framework would strike a balance between commonality and flexibility to meet specific facility requirements. VR technologies enable remote access. Cloud-based computing provides large-scale processing capabilities to users, enabling them to make best use of their data. Real-time communications for visual interactions, system-wide control, and data transfer could be potentially routed through satellite communication, building on technology already employed by live weather forecasting and broadcasting. For short-duration-run facilities, the framework would provide limited operational advantage but a step-change in observer-level experience, with virtually assisted flow, data visualisation and processing. Low-speed tunnels with load, point- and laser-based measurement systems would adopt the above capability and a superimposed user-level with secure, fail-safe, fully remote access. Positioning (static and dynamic) of models, sensors and optics would be remotely operated, and experiments where the model requires multiple geometry changes could benefit from advances in in-situ 3D additive technologies. The proposed system would therefore require investment in robotics and control, autonomous / adaptive systems, smart materials and e-infrastructure, specifically large-scale HPC and robust networking in a big-data-oriented challenge.

Experience suggests that set-up and initial experiments are most effective when fully manned, with full automation and remote access adopted later, once all systems have been shown to be fully operational. Experiments in which a routine set of measurements is required would naturally lend themselves to automation and remote access. However, an experiment where the model requires frequent geometry and configuration changes would have to be assessed for its suitability for automation – and then the optimum level of automation. Instances where each set of measurements is dictated by interpretation of the preceding set are a challenge to automation and remote access,

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[6] The Space Economy in the UK: An economic analysis of the sector and the role of policy. BIS Economics Paper No. 3. February 2010

requiring the development of linked decision making procedures.

Remote access would only be successful if the experimenter is given sufficient sensory inputs and controls, building confidence that nothing out of reach of the experimenter is interfering with the experiment. While working within the limits of available bandwidth, remote access and autonomous systems could provide operational advantage until a sub-system fails beyond remote recovery, when human intervention becomes necessary. The required development in CFD algorithms to augment wind tunnel data, especially in real-time and for complex geometries, is a challenge as well as an opportunity driver.

Business Plan

The indicative budget is £15m. The technology would become a key enabler for strengthening the UK's position as a global exporter of aerodynamic research making NWTF globally accessible, and as an attractor to leverage overseas funding (e.g. Horizon 2020 and EU Structural and Investment funding). Remote access would also open the possibility of hosting larger facilities in locations where space is not at a premium, bringing prosperity through high quality employment opportunities and supply chain provision. In consequence, remote access and control of these facilities inherently reduces the need for travel of support staff, researchers and client teams and should contribute to a reduction of the facilities' carbon footprint. The EPSRC Delivery Plan 2015/2016 seeks pursuit of higher efficiency with one of its key investment priorities aiming to "…work with our university partners to strategically identify further efficiencies in the research ecosystem – such as the shared use of capital equipment." The current focus cuts across four of the "8 Great Technologies" (the majority of which derive from EPSRC-funded research) and therefore promotes cross-disciplinary collaboration. This in turn means that state of the art research in the above technologies can be drawn as part of a holistic and continuous vision-driven development rather than on inefficient and discontinuous project-specific technology evolution, promising better return-on-investment of research funding. BMT Fluid Mechanics has extensive experience in wind tunnel remote operation. Running two consecutive shifts from Teddington and a third shift, remotely, from Kuala Lumpur, tunnel-testing throughput was increased by over 30% and forms a key enabler in maximising utilisation of the facility. In turn, return on assets employed has accordingly increased by approximately 50%.

4 Landscape and Investment

Projected investments from 2010 (2015 values)

	2006-15	**2015**	**2020**	**2020**
	"Wind tunnel" projects capital + resource (RCUK, IUK)	Facilities capital	Facilities capital	Facilities capital (EPSRC)
Automotive	-	£3.0m	£100m	£7m
Wind Engineering	-	£3.3m	£10m	£10m
Aerospace	-	£6.0m	£20m	£20m
Space	-	£2.2m	£13m	£13m
Remote Access	-	-	£15m	£15m
TOTAL	£36.0m	£14.5m	£158m	£65m

4.1 2010 – 2020

The landscape at 2010 is well defined by the ATI survey http://www.ati.org.uk/technology/wind-tunnels, which provided the starting point for NWTF in January 2014. During the period 2010 – 2020, there is likely to be significant changes in the way tunnels are used, with increased numbers of researchers being hosted at NWTF facilities in order to conduct their research programmes. Currently, the visibility of NWTF has stimulated use of these facilities by university-based researchers (e.g. new grants, EP/M028690/1) as well as commercial organisations, the essential point being the engagement by researchers in moving to an NWTF model with facilities sustainably supported by charge-out rates rather than estates rates and operating as cost centres to ensure sound financial management.

An indication of the activity of wind tunnel based research 2006-16 is captured by grant investment of £36m over a ten-year period (capital + resource). While funding was allocated through peer review, little consideration was given to funding efficiency or research productivity. Hence funding followed researchers without any consideration being given to the effectiveness of the investment.

To maximise funding efficiency, investment in facilities during 2010-15 came largely from university infrastructure projects at Oxford, Imperial, Southampton and City, totalling approximately £75m, including some facility investment. It arose either through planned expansion into specific areas (e.g. shipping, through Lloyds Register investment for Boldrewood campus, Southampton), development /modernisation of laboratories (Osney labs, Oxford) or planned refurbishment for space efficiency to include new facilities (e.g. relocation of Aeronautics Department, Imperial College).

In order to rationalise wind tunnel funding, facility investment at 2015 has been principally through the NWTF (EPSRC, £10.4m; ATI, £2.9m) at Cambridge, Cranfield, City, Glasgow, Imperial, Oxford and Southampton. NWTF has been used to leverage some further university investment. In several cases (and especially in the case of large, low-speed facilities), usage is multi-sectoral so that breakdown into the four grand challenges is estimated. Figures for 2020 are specific to the grand challenge themes outlined in §3, where new / enhanced facilities are required to address these. The single automotive facility (§3.1) would require some type of partnership of mixed industry / university usage, where significant infrastructure costs could be offset by use of existing sites with an established operational environment. Such a facility of direct relevance to large-volume road vehicle manufacturers would probably be a separate entity rather than owned by a university (e.g. MIRA). It would therefore require a government / industry collaboration with a long-term industrial commitment to the facilities and to the associated R&D.

The NWTF model maximises research efficiency and cost effectiveness. The 2020 vision comprises, principally, the establishment of NWTF as a mid-range facility (established access protocols, key performance indicators, service level agreements):

- access management board and full-time project manager (ESPRC resource);
- facilities usage subject to periodic, independent review;
- each facility supported by a variable charge-out rate, the baseline rate agreed with EPSRC (assumption of 70% capacity to ensure sustainability);
- each facility generates contingency fund via charge-out rate;
- establishment of ARCHER-like access, allocation of user resource without funding strings, through, for example, CDTs. In some instances, a “loss-leader” approach to stimulate activity might be appropriate.

Owing to the increasing complexity and cost of experiments, the investment per tunnel is bound to rise but with fewer facilities needing to be maintained at the appropriate level of investment. The capital depreciation of a tunnel occurs over $O(10)$ years. The capital depreciation of equipment occurs over $O(1)$ year: therefore tunnels can remain cost effective for several decades if replacement costs of the equipment are budgeted for.

Large facilities such as the European Transonic Wind Tunnel (ETW) constructed to address challenges with specific users in mind run the risk of being uneconomic. For example, a simple rule change by the FIA could suddenly make available a large number of tunnel hours in large low-speed tunnels. Mitigation of this risk requires mechanisms in place to promote accessibility for single users on small-scale projects. This can be done economically by using tunnel hours for both large-scale high TRL testing at the same time as low-TRL research exploiting the special features of a particular facility. Such piggy-backing might not only involve simultaneous use, but also exploit significant turnaround-time that is inevitable in large-scale projects. Such an approach would maximise the benefit of government support of ETW, for example.

Research efficiency for large facilities such as ETW requires:

- UK-based resource funding stream (e.g. CASE awards with facility access credits);
- Development of research equipment at ETW (e.g. thermal, laser-Doppler anemometry, particle imaging);
- Established access protocols, key performance indicators, service level agreements in place.

4.2 2020 – 2050

Fluid mechanics will continue to be a vital science that underpins a range of engineering disciplines, and in which the UK has a prestigious tradition as far back as Newton, with many 20th century giants such as Taylor, Batchelor, Townsend and Lighthill. Cutting-edge experimental fluid mechanics (TRL < 3) will continue to underpin computation and modelling, and will require state-of-the-art facilities with top-end instrumentation for the foreseeable future. Experiments in fluid dynamics will continue to be required at least as far as the 2050 horizon: they respond much more quickly to significant changes in boundary conditions than numerical simulations. Increases in computer speed will not lead to accurate prediction of either complex configurations at large Reynolds numbers without modelling, or to complex multi-variable problems such as the weather prediction more or less indefinitely.

- New facilities described in §3 are likely to have a lifetime of up to 2050, at least, with continued use beyond then being made attractive by the availability of new instrumentation.
- Many experiments will continue to exploit complex phenomena at micro or nano scales ("lab on a chip"). These types of experiments do not scale up, so they are unlikely to require large facilities, but could require new, more sophisticated instrumentation.
- Development of micro-instrumentation and fluid control algorithms will be 'spin-offs'.
- Some experiments developed up to 2020 may require scaled-up, improved new facilities, e.g. CO_2 exchange with simultaneous velocity and species concentration measurements. An 'accelerator' mechanism is required for this to happen effectively.
- In offering efficient, low-cost access to high-specification facilities, remote experimentation is set to grow: remote access will be developed via real-time communication for user / facility interactions and real-time data transfer.
- The development of remote access capabilities will therefore require a much larger budget, £O(10)m beyond 2020. It will underpin almost all access to tunnels, promoting a 'democratisation' of access.
- Remote access will promote synergies with robotics, control, e-infrastructure, large data, HPC and robust networking and therefore offers potentially significant return on all investment in wind tunnels.
- Non-intrusive, laser-based instrumentation will continue to be developed for measurements near surfaces and for mixed-phase flows. The latter will require new facilities for environmental problems.
- Sustainability: more work is required to examine potential synergies on cross-sectorial use, and shared university / industry usage. The latter depends on industry roadmapping such as ATI.
- Facilities for space are sector-specific and will require continued investment at an international level.

5 Key Findings and Recommendations

- The NWTF model enhances research productivity, where fewer facilities are supported at a rate that makes them internationally competitive.
- Changes to shared facility usage are largely a question of culture change for the users.
- NWTF is well placed to become a mid-range facility by the end of the grant period in 2018.

- The grand challenges outlined in §3 address new problems in resilient cities, the environment, transport efficiency and space. They all have clear sector relevance.
- The grand challenge facilities are nearly all new and are required to be operational within the next five years for UK science and technology to remain competitive.
- **Indicative level of capital investment for 2020 is £65m**, with a further £93m industry / government (but non-EPSRC) commitment to a non-university entity for an independent automotive facility.
- To maximise the benefit of this investment, it is crucial that **recurrent resource for NWTF management is supported, of about £200k per year**. Technical support for the facilities (and not a specific experiment) would come from the facility charge-out rate.
- Mechanisms need to be put in place to promote training on large facilities. For example, ETW could be used for fundamental research projects piggy-backing on large test projects. Project-based mechanisms are required for this to happen.
- The remaining grand challenge, remote access, potentially cuts across all of these and is of significant potential impact towards the horizon-scanning end of the roadmap. It would attract the greatest level of investment beyond 2020.
- A process is required to identify benefits and cost-effectiveness in scaling up of specific experiments (an accelerator), or need for international collaboration (e.g. space).
- There needs to be some vertical integration once ATI / other roadmaps for industry have been defined.