Flow Measurement
Special Interest Group

Flow Measurement Horizon Scan-
A Review of Publicly Funded Research

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EXECUTIVE SUMMARY

This report sets out the methodology and findings arising from a review of UK publicly funded research over the period January 2000 – April 2019. The review sought to identify areas where complex flow measurement was significant, with a view to identifying priorities and indicators of need for development of new capability. The principal source was UK Research and Innovation (UKRI), but much of the data derived from its precursors: the UK Research Councils and the UK Technology Strategy Board. The principal European sources of research funding open to UK institutions were also reviewed. This review also examined the priority areas addressed by the UK Catapult Centres, to identify areas where flow measurement may be a priority.

The review was performed under the aegis of the Institute of Measurement and Control's (InstMC) Flow Measurement Special Interest Group and was funded by BEIS (the Department for Business, Energy and Industrial Strategy). The review draws on earlier work carried out for Coventry University by Measurement Matters Ltd in 2018.

Here, flow measurement encompasses all aspects of the subject, not just quantity (including patterns, structures, quality, etc.). This wider definition provides a more comprehensive picture of activity in the field, and the likely need for new standards infrastructure, knowledge and techniques to support this.

In the period 2000-2019, there were 344 funded research grants with a total value of £174m where complex flow measurement was a key component of the research project. In addition, a further 69 projects had no declared monetary value. The bulk of the projects reviewed were academic projects. Many of these are at a very early stage of development, but some are near market ready, particularly those funded by Innovate UK.

Figure 1 Publicly funded measurement research projects identified from public databases, with start years from 2000 to 2019

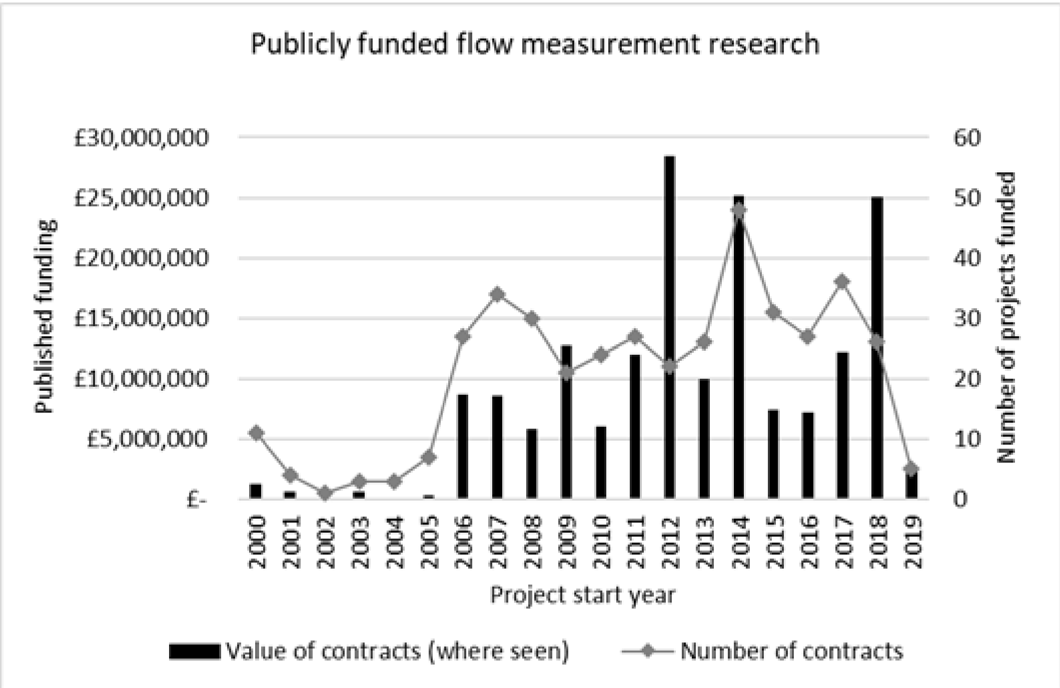

Figure 1 shows the pattern of public funding (number of grants, plus total value) of such research during the period under review. At the start of the millennium, there were relatively few projects and the level of public funding for these was very low. There was a significant increase in funded projects in 2006, after which activity has held broadly steady with over twenty funded projects each year. There are three significant spikes, reflecting major Infrastructure and Consortium grant awards to Universities in years 2012, 2014 and 2018 (e.g. an upgraded Positron Centre to examine complex multiphase and multiscale flows in aqueous systems).

Grant award recipients (i.e. the researchers) are obliged to self-declare the industrial sectors that they believe will benefit from the impact of their project. There is more detail in the main text but it is clear that flow measurement advances will have a positive impact on every industry sector. There will also be a positive impact upon aspects related to Quality of Life (a key market failure aspect addressed by government intervention) for example: environmental protection; natural resource management; and medicine, as well as enabling the uptake of new developments such as Hydrogen as a direct energy source. This suggests a mismatch between actual and potential needs, and the UK Government's pattern of flow measurement standards support, which has focused on the needs of the Oil and Gas industry. This situation has been exacerbated by significant reductions to NMS Flow Programme funding, which have severely inhibited the Programme's ability to diversify to address wider needs.

Analysis also highlights a number of areas that need new approaches to flow measurement capability. For example, the suggested **Fluid Surface Interaction Theme** (defined as an area where '***drag, collision of particles, or surface friction has an important bearing on the processes under observation***'), has a strong bearing on various micro-fluidic application areas. This implies the need for a multidisciplinary approach to the development of novel techniques and capabilities. It also implies the need for new fundamental science to underpin these new techniques and capabilities.

The analysis reveals new patterns of research activity in response to novel socio-economic activity. For example, a cluster of flow research projects related to 'Fracking' first appear in the data relating to 2018/2019. It is too early to draw any conclusions about the likely need for new flow standards or infrastructure to support this new field. However, we are now well placed to track the pattern of developments in order to be able to respond to need for new capability. The pool of data gathered here lends itself well to future longitudinal studies.

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1 SCOPE and OBJECTIVES

The scope of this review was to identify the need for new Flow Measurement Standards and/or Infrastructure arising from publicly funded research activity in the UK Science base. In order to assess this, we reviewed the activity of all the UK Research Funding bodies, as well as European Programmes open to UK Institutions.

A further strand of the review analysed the research priorities of the UK Catapult Centres.

The principal objectives were to:

1. establish the extent of public research involving complex flow measurement
2. identify any priority areas for action
3. identify any UK Flow Measurement Research Centres of Excellence
4. make recommendations for future action

2 METHODOLOGY

2.1 Direct Research Funding

The first task was to identify all the funding bodies likely to fund projects where there was a flow measurement component.

2.1.1 Data Gathering

The UK's principal research funding bodies make all their grant awards public and this is searchable using respective 'Grant Finder' tools. Details of the websites searched is at Annex 10. The information available is a written abstract, which describes the research project, and a number of other facts:

- Grant value
- Date of award
- Other key dates
- Name of organisation receiving the award
- Lead investigator (i.e. person directing the research)
- Organisation employing the Lead Investigator
- Grant type (e.g. facilities, equipment, research personnel)
- Sectors impacted*
- Key technologies impacted*

*Lead Investigators are required to assess and identify the industry sectors and key technologies likely to benefit from their research. All of this data was the basis of our analysis.

The methodology involved creating a set of search terms that would target research projects where complex Flow Measurement issues had a bearing on the outcome of the project. The word “measurement” appears in very many project abstracts. The word “flow” less so, but even when they appeared together in an abstract, this did not guarantee that there was any flow metrology aspect. The search terms selected were:

- flow measurement;
- flow measur*;
- flow AND measurement; and
- multiphase

Search terms such as ‘complex flow’ did not increase the overall pool of projects and produced smaller sub-sets of non-unique (I.e. already captured by the main search terms) results. The optimal search terms were then applied using the search features of the ‘Grant Finder’ functions of the various research funding bodies. The resulting data was then imported into a spreadsheet, for further analysis.

It bears mention that there were variances between the different organisations’ search tools and, in a few cases, data import was a painstaking process.

2.1.2 Data Analysis

Every abstract was read to ensure that there was a genuine flow metrology component to each project. Once that was established, it was possible to cluster data and draw inferences from the results.

2.2 UK Catapult Centre Priorities

The UK Catapult Centres were established in 2011 by Innovate UK. They promote business-led research and development to exploit market opportunities in key priority areas. Catapult Centres are Government funded but do not award grants in their own right, their role is to catalyse and support partnerships between scientists and engineers working on projects within the key priority areas.

Analysis of the Catapult Centres was through desk-based research of their individual websites and key documents. Everything else was determined by further desk-based research, for example to explore wider evidence of trends, and through conversations (either face to face, or via electronic communication) with experts (see Annex 9 for list of the experts consulted).

3 FINDINGS

3.1 The extent and nature of public research involving complex flow measurement

3.1.1 Number of research projects

Over the period reviewed 344 research projects were funded with a total contract value of £174m. There were a further 69 projects where the awarding body did not declare the contract value (in general these bodies did not declare which sectors or technologies were impacted). In addition, some projects (principally those funded by EURAMET) are not categorised. Figure 1 shows the number and monetary value of projects receiving grant awards/contracts per year. This does not mean that this amount was actually spent in the given year. Most of the grant awards span several years of activity.

3.1.2 Declared Sector Impact

Researchers are required to self-declare which sectors will be impacted by the results emerging from their project. Researchers are not limited to selecting just one sector classification, and most choose several. A result of this is that, when aggregated, every sector is shown to benefit in some way from flow measurement research. Reading the project abstracts it is always clear which is the primary sector for impact. For the purpose of this analysis that is the sole sector used here, as that is likely to be a more accurate reading of the chief sectors impacted by such research.

The number and value of projects that impact on individual sectors is, at best a proxy measure of significance - it cannot be taken as absolute proof of importance, nor is there any guarantee that impact will be realised. That said areas with higher level of research activity are intuitively more likely to deliver some impact. In the case where research results in new applications, it is a reasonable assumption that full commercialisation will require new standards, to ensure repeatability, interoperability, and customer confidence. On that basis, it is reasonable to assume that the greater the volume of research directed at a sector, or technology area, the greater the likelihood of a need for new measurement standards, techniques and knowledge.

The Industry Sectors most frequently identified by researchers as priority impact areas within their projects are set out in the following table:

Table 1: Sector Classification (as seen in the application record, July 2019), ranked by value*

Sector Classification (as seen in the application record*, July 2019), ranked by value		
Category	**Number**	**Value (£)**
Aerospace, Defence & Marine/ Mechanical Engineering	74	£ 60,085,184
Chemicals/ Process Engineering/ Catalysis & Surfaces/ Chemical Measurement	96	£ 42,077,158
Energy	87	£ 31,730,339
Tools, technologies & methods/ Instrumentation/ Systems engineering	101	£ 27,452,624
Environment/ Environmental Risks & Hazards/ Geosciences/ Environmental engineering	95	£ 25,721,687
Natural Resource Management/ Terrestrial & freshwater environments/ Marine environments	85	£ 22,607,769
Manufacturing	21	£ 20,040,189
Healthcare/ Medical science/ Medical & health interface	27	£ 16,621,562
Pharmaceuticals and biotechnology/ Immunology/ Biomolecules & biochemistry	11	£ 11,122,884

Sector Classification (as seen in the application record*, July 2019), ranked by value		
Category	**Number**	**Value (£)**
No relevance to underpinning sectors	31	£ 10,595,852
R&D	44	£ 9,004,289
Transport systems and vehicles	32	£ 7,534,631
Construction/ Built environment	11	£ 6,864,592
Global change/ Climate change	23	£ 5,865,281
Food and drink	16	£ 4,795,485
Water	34	£ 4,678,956
Pollution and waste	18	£ 2,931,215
Mechanical Engineering	6	£ 2,484,740
Information Technologies	6	£ 1,648,022
Electronics	4	£ 660,813
Biodiversity	2	£ 579,552
Atmospheric phys. & chemistry	2	£ 375,804
Atomic & molecular physics	1	£ 19,285
Not provided	*151*	*£ -*

** The categories for UK Research Council records are taken from the UK Research and Innovation database as of July 2019. The allocations are not the same as those shown in the individual Research Councils' databases as some have been consolidated here.*

Table 2 is drawn from the UK Office for National Statistics (ONS) report: Gross domestic expenditure on research and development, UK:2017 (the latest published report on this subject) (www.ons.gov.uk/economy/governmentpublicsectorandtaxes/researchanddevelopmentexpenditure/bulletins/ukgrossdomesticexpenditureonresearchanddevelopment/2017)

Which lists the following sectors as the most research-intensive sectors (these are the only sectors highlighted in the ONS report) by spend on R&D:

Table 2: Most R&D Intensive Sectors (as identified by the ONS)

Sector	**Spend (£)**
Pharmaceuticals	£ 4.3bn
Vehicles and parts	£ 3.6bn
Computer programming and information service activities (excluding software development)	£ 1.9bn
Aerospace	£ 1.5bn
Miscellaneous business activities; technical testing and analysis	£ 1.5bn
Software development	£ 1.4bn

The definitions and terms used by ONS and the various Research Councils may differ, however it is clear that public R&D spend does not mirror the wider national R&D spend. In our data 'Vehicles and parts' (which maps to: Transport systems and vehicles) is 12th in significance, based on spend/projects, rather than second, as per the ONS Report. Also, whilst Pharmaceuticals has a reasonable amount of spend and research project activity in our data, it does not dominate in the way that it does in the ONS Report. A reasonable interpretation of the differences is that publicly funded flow measurement research does not mirror national R&D spend trends. Where our data suggests that flow measurement has specific importance to any given sector, we can see that this is not simply because that sector spends a great deal on R&D. We can reasonably infer that flow measurement research is more important to the Aerospace Sector, than it is to the Pharmaceuticals Sector. We can also reasonably infer that the nine areas shown on the following table are the most research intensive for flow measurement purposes and are probably the ones most likely to require new Flow Measurement Standards and Infrastructure.

Table 3: Sectors with the most academic Flow R&D activity

Sectors with the most academic Flow R&D activity		
Sector Category	**No of Projects**	**Value (£)**
Aerospace, Defence & Marine/ Mechanical Engineering	74	£ 60,085,184
Chemicals/ Process Engineering/ Catalysis & Surfaces/ Chemical Measurement	96	£ 42,077,158
Energy	87	£ 31,730,339
Tools, technologies & methods/ Instrumentation/ Systems engineering	101	£ 27,452,624
Environment/ Environmental Risks & Hazards/ Geosciences/ Environmental engineering	95	£ 25,721,687
Natural Resource Management/ Terrestrial & freshwater environments/ Marine environments	85	£ 22,607,769
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This list is at marked contrast to historic UK Government support for Flow Measurement Standards and Infrastructure. This was previously almost exclusively concentrated on the needs of the Oil and Gas, and Energy and Utilities (Water and Natural Gas). The flow measurement needs of sectors such as Aerospace, Chemicals/Process Engineering, Manufacturing and Healthcare need to be addressed also. These important areas are sufficiently distinctive to require their own flow measurement techniques, protocols, standards and standards infrastructure. Even within the traditionally supported Energy sector, there has been significant evolution, resulting in new needs within the Nuclear area (plasma flows) and sustainable Energy sources such as Hydrogen and Shale Gas. Looking just at Hydrogen (as an energy source), it embrittles many metals and alloys, and is a very fast-moving molecule. There are therefore some significant questions about the applicability of conventional instrumentation and methods, so it may not be safe to assume that existing techniques, protocols, standards and standards infrastructure will be effective.

The technology areas most frequently identified by researchers as priority impact areas are listed in Annex 1. Interpreting that data required the creation of new theme categories to help 'brigade' specific areas of focus. Some projects inevitably had aspects of more than one Research Theme. As with the assignment of Sectors (where only the principal sector focus was assigned), only the principal technology focus was assigned. The seven Research Themes (the definitions are italicized) shown in Table 4 capture the essence of the flow measurement aspects within the wide pool of projects:

Table 4: Suggested Research Themes based on the assessment of publicly funded research projects

1) Complex Open Channel Flow Measurement	*Large area open channel flow, e.g. river systems, estuaries and ocean currents*
2) Dynamic Flow Measurement	*Real time measurement where conditions are constantly changing*
3) Experimental Flow Measurement Techniques	*Use of novel techniques and technologies to address the need for greater accuracy, or to measure flow in more demanding conditions*
4) Flow Modelling and Analytics	*New modelling techniques and analysis of very large data sets*
5) Fluid/Surface Interaction	*Drag, collision of particles, or surface friction has an important bearing on the processes that are being measured.*
6) Measurement of Complete Flow Systems	*Simultaneous measurement of flow at multiple points in a distributed system*
7) Miscellaneous	*Projects falling outside classifications 1-6*

The volume of research projects (and contract/grant value) in each of the suggested Research Theme Classifications is set out in Table 5.

Table 5: Projects assigned by suggested Research Theme Classification

Projects Assigned by Suggested Research Theme Classification		
Theme	**Count by Theme**	**Value by Theme (where given)**
Experimental Flow Measurement Techniques	132	£ 54,941,420
Dynamic Flow Measurement	59	£ 37,905,878
Flow Modelling & Analytics	59	£ 22,434,305
Complex Open Channel Flow Measurement	60	£ 18,985,096
Miscellaneous	31	£ 18,210,865
Fluid/Surface interactions	51	£ 15,392,520
Measurement of Complete Flow Systems	21	£ 6,473,646

It is interesting to consider the percentage of the UK Research Council's Technology category: 'Tools technologies and methods/ Instrumentation/ Systems engineering' in each Theme, see Table 6. This category is indicative of the new underpinning instrumentation and tools required for exploitation of knowledge. Instrumentation has always had a direct association with flow measurement as it includes the metering technologies required to make accurate measurements.

Table 6: Distribution of Sector category 'Tools technologies and methods/ Instrumentation/ Systems engineering across the research themes

Research Theme	**% of projects assigned as: Tools technologies and methods/ Instrumentation/ Systems engineering**
Experimental Flow Measurement Techniques	22%
Dynamic Flow Measurement	16%
Measurement of Complete Flow Systems	13%
Fluid/Surface interactions	10%
Miscellaneous	4%
Flow Modelling and Analytics	3%

It is possible to interpret the pattern represented in Table 6 in a number of ways:

a) The needs coming out of the Experimental Flow Measurement Techniques Theme were always likely to be statistically well represented, given the similarities between the Theme and Category titles. That does not invalidate the fact that this is a strong area for focus, with likely emerging standards and infrastructure needs.
b) The needs coming out of projects in the *Miscellaneous* and *Flow Modelling and Analytics* Themes are either limited, because they are already well catered for. On the other hand (and particularly with *Miscellaneous*), they may be so niche, varied and early stage that the need for new standards and infrastructure have yet to crystallise. This does not mean that they never will, or that it will be a long time into the future. It is more the case that these are areas to monitor.
c) All of four Themes with over 10% (Tools/Instrumentation, etc.) are sufficiently well represented to suggest that they are the most likely to require new flow measurement standards and infrastructure. At first sight, these Themes are the recommended priority areas.

What

Table 6, and indeed this review itself, does not do, is identify whether Themes have any common standards or infrastructure needs, i.e. where one new development meets multiple varied needs. To explore that we need to look at the individual Research Theme classifications in turn.

3.1.2.1 Complex Open Channel Flow Research Theme

Projects falling within this Theme (see Annex 2) will overwhelmingly have an impact on Environmental and Natural Resource Management related sectors and issues. These projects were primarily funded through the former Natural Environment Research Council (NERC) and are of great interest to Regulators working for the Department for Environment, Food and Rural Affairs (DEFRA). They address market failures related protecting citizens against pollution, flooding and coastal erosion. Such issues would typically score highly in assessments for government intervention (i.e. funding for knowledge and infrastructure). The facilities at HR Wallingford are genuinely World leading and appear capable of meeting the infrastructure needs of this Research Theme. Given that, there appears to be no basis for suggesting any additional flow measurement infrastructure needs to support this Theme. There may be a need for documentary measurement standards development activity but, on balance, this does not appear to be an area for prioritisation.

3.1.2.2 Dynamic Flow Measurement Research Theme

The projects within this Theme (see Annex 3) will make an impact upon the Process Industries, but also other, largely Engineering-led, sectors such as Aerospace and Transport and Instrumentation. There is no clear definition of state of the art in terms of proven methods for Dynamic Flow Measurement. That may partly be a function of the distinctiveness of Dynamic Flow Measurement within the different application areas. Addressing the measurement standards needs arising from these projects is likely to require the development of new measurement infrastructure. Given the diversity of industrial applications, this might imply a need for multiple facilities, which in practical terms would require very significant investment. There are alternative mechanisms to metrologically robust new laboratory standards, which could temporarily meet diverse industry needs suggested by analysis of the data in this report, until the point we can very clearly identify a common infrastructure to meet such needs. One such mechanism is a Publicly Available Specification, or PAS, which is a standardization document closely resembling a formal standard in structure and format but which has a different development model. According to the IEC the objective of a PAS is to speed up standardization in areas of rapidly evolving technology. There are several different forms of PAS, to meet differing needs, but the appropriate one to consider here is as a *Method of Test*, i.e. to provide repeatable and reproducible procedures with consistent outcomes for the assessment of material, product or process performance.

An experimental flow facility at The Centre for Process innovation (CPI) indicates a theoretical next step. The CPI facility was developed to study scale-up dynamics in chemical formulation processes and validate new sensor technologies and process analytics capabilities. The equipment supports rapid learning of how formulated product properties, discovered at the laboratory scale, can be manufactured economically and flexibly. It also enables predictive scale-up of batch formulation processes and the development of automated monitoring and control schemes. The CPI facility, which is the physical interface to a Digital Twin, is experimental and bears no comparison with a National Standard. However, if it proves to be a success it will drive improvements and positive measurement and control behaviours in the Process Industries Sector. If we could analyse the components of CPI's system (respecting intellectual property), we might create a case study setting out the fundamental principles of a Dynamic Flow Measurement

System. These theoretical principles can be enshrined in a new Dynamic Flow Measurement PAS to serve as a flexible, but robust model for other industry sectors to follow. This approach is very much at the 'thought leadership' end of a Designated Institute's role. It is a pragmatic and useful means of influencing something urgent, but so diverse, that one piece of infrastructure could not meet all needs. Eventually a position might be reached where there is significant overlap between the Dynamic Flow Measurement needs of multiple relevant sectors, justifying creation of new standards infrastructure that, ultimately, supplants the PAS.

3.1.2.3 Experimental Flow Measurement Techniques Research Theme

Projects within this Theme (see Annex 4) will have an impact on the traditional users of Flow Measurement Infrastructure such as Energy and Utilities, but it is broader and affects other, distinctly varied industry sectors. Many of the projects for Instrumentation, Energy and Water involve multiphase flow. Given the recent construction of an Advanced Multiphase Flow facility at NEL, which includes experimental research facilities it is difficult to imagine any immediate need for any further measurement infrastructure at this stage. By contrast, the needs of Aerospace address issues such as the measurement of air intake flow into engines (i.e. large volume), and understanding changes brought about by rain, mist and condensation. Addressing such measurement issues would deliver high impact, in one of the Government's priority sectors. This would require new-large scale experimental facilities and would be unlikely to come about without a partnership with an Aerospace engine manufacturer. If such a partnership can be established, (it falls outside the scope of this review) then this would be a high priority area for action. If not, then overall there is no need for new measurement infrastructure to address projects in this Theme.

3.1.2.4 Flow Modelling and Analytics Research Theme

Projects within this Theme (Annex 5) primarily address needs within Chemicals; the Process Industries; Aerospace; Energy; and Transport Systems. For such an industrially focussed Theme there is an extremely low level of academic research relating to the Instrumentation sector. This reflects the nature of these projects, which relate to CFD and other analytical methods including Big Data. The need for new Standards arising from this Theme is unlikely to require significant standards infrastructure, other than access to a supercomputer and the development of 'Digital Twin' capability. Digital Twins and Internet of Things (IoT) are a potentially a disruptive technology in the field of measurement standards infrastructure, and calibration. There are many definitions of what a Digital Twin is but, in this context, it is a digital replica of the physical assets, processes, systems and devices used within a flow measurement standard. The digital representation provides both the elements and the dynamics of how the 'physical twin' operates and lives throughout its life cycle and this is underpinned by real-time data using sensors. Digital Twins integrate IoT devices, artificial intelligence, machine learning and software analytics to create living digital simulation models that update and change as their physical counterparts change. A Digital Twin continuously learns and updates itself from multiple sources to represent its near real-time status and working conditions. It learns from itself, using sensor data that represents its operating conditions; from human experts; and from its larger system and environment. A digital twin may also integrate historical data from past machine usage to factor into its digital model. It can be used for monitoring, diagnostics and prognostics to optimize asset performance and utilisation. Deployment of IoT devices in a range of high value manufactured products, such as Automotive has radically changed the vehicle maintenance model. Improved diagnostic systems, using very large data sets are used to predict the need for very specific corrective maintenance. This approach could readily transfer to the world of the calibration laboratory. It could radically change the existing model of large-scale measurement and calibration facilities in laboratory conditions to something near instantaneous supported by live data feeds in well-characterised field conditions in the future. Enabling this future requires preparedness now. The projects within this Theme are a very strong fit for the Government's various Big Data initiatives, so this Theme should be a priority for focus.

3.1.2.5 Fluid/Surface Interactions Research Theme

Projects within this Theme (Annex 6) primarily relate to Environmental and Natural Resource Management issues. However, there are a number of more industrially focussed projects within the Chemicals; Process Industries; Instrumentation; Aerospace; Manufacturing; and various Health/Medicine sectors/application areas. The theme is quite distinctive to Microfluidics, a search term that was initially considered but dismissed, as it produced no evidence of discernible patterns or volumes of flow measurement activity. An interpretation of the evidence is that better understanding and control of friction, drag and other surface effects are now high priorities for the further development and exploitation of microfluidic devices. These are significant across a wide range of applications (e.g. 'lab on a chip' medical diagnostic devices). The type of measurement infrastructure is likely to be bench scale, rather than factory scale, so the likelihood is that new measurement standards will be realised through programmes of research activity, rather than through the creation of large facilities. The nature of the subject, involving Chemistry, Physics and Mechanical Engineering lends itself to multidisciplinary approaches. This Theme should be seen as an area of an area for priority focus as the research projects discussed in the report begin to crystallise and have an impact on the market.

3.1.2.6 Measurement of Complete Flow Systems Research Theme

Projects within this Theme (Annex 7) address a range of sectors but are primarily in the Environmental and Natural Resource Management field. By its very definition '*Simultaneous measurement of flow at multiple points in a distributed system',* this Theme addresses flow within large-scale distributed systems. The areas under investigation could be applied in managing (through accurate measurement), an entire oilfield, chemical plant, or a drinking water distribution system at city scale, etc. These aspirations are not new, but they are now more realisable, with the advent of cheaper, faster computer processing and greater prevalence of IoT devices in manufactured goods. Given the scale and nature of the activities related here, it is unlikely that significant large-scale standards infrastructure would be required to develop new measurement standards. A possible approach might be to test different combinations of instruments and relate these to Digital Twins (see 4.1.2.4), which could develop, over time, into one or more National Standards. This Theme also looks suitable for the development of one or more Publicly Available Specifications. This Theme offers impact in a range of areas prioritised by Government, so should be a priority area for standards development focus as more of the research projects begin to crystallise and have an impact on the market.

3.1.2.7 Miscellaneous Research Theme

Projects within this Theme (Annex 8) have a very diverse spread, partly evidenced by the fact that they do not fit into any of the other categories. Whilst the greatest number of projects within the Theme have a medical focus, they are very small scale and extremely diverse. A reasonable interpretation of the projects in this Theme is that they are extremely early stage and probably a considerable time away from a need for new measurement standards or infrastructure. The projects in this Theme should not be prioritised for infrastructure development, or at this stage, any Publicly Available Specifications.

3.1.3 Catapult Centre Findings

The UK's Catapult Centres are fully described at https://catapult.org.uk/. They include a combination of knowhow, established networks and specialist scientific facilities. A general point, the Catapults are intermediaries through which developers of new technology, including measurement technology, infrastructure and standards ought to be working. This will help draw a wider pool of capability into setting the requirement (i.e. capturing the voice of the customer) and developing the necessary outcomes.

A small number of references to flow measurement were found on the websites and key documents of the various Catapult Centres:

3.1.3.1 High Value Manufacturing (HVM) Catapult

Within their **High Temperature Processing** theme, the HVM Catapult has interests in Viscoelastic Flow. HVM's specific application area is "forming of metallic components by use of carefully controlled combinations of temperature and pressure to effect viscoelastic flow and/or plastic deformation". Viscoelastic fluids are non-Newtonian fluids. They can exhibit a response that resembles that of an elastic solid under some circumstances, or the response of a viscous liquid under other circumstances. Typically, such fluids are macromolecular in nature (i.e. they have a high molecular weight), such as polymeric fluids (melts and solutions) used to make plastic articles, food systems such as dough used to make bread and pasta, and biological fluids such as synovial fluids found in joints. HVM's specific application is arguably more materials science, than flow measurement science. There were four Research Grant awards in this field (totalling £1.7m: with projects in 2006/7, 2014 and 2017), the pattern of these suggests that Viscoelastic Flows are a mature area of knowledge. The field appears to be of relevance to industry across a number of possible application areas and is possibly one to watch. It also appears to tie in well with a number of the suggested new areas for capability development, notably '**Fluid-Surface Interaction'** and **'Experimental Flow Measurement Techniques'**.

The second area of interest is CPI (The Centre for Process Innovation, a partner and component of the HVM Catapult) who have developed a physical rig to study scale-up dynamics in formulation processes, and advance and validate new sensor technologies and process analytics capabilities. This state-of-the-art equipment is intended to support rapid learning of how formulated product properties, discovered at the lab scale, can be manufactured economically and flexibly. It will also enable predictive scale-up of batch formulation processes and the development of automated monitoring and control schemes. The facility's flow loop consists of two main parts; four vessels increasing in size from one litre to 1,000 litres and a flow skid comprising pumps and additional instrumentation. Flow measurement control for the process industries is closely aligned to flow measurement control in the Energy Industry. Partnership opportunities should be explored to identify opportunities for knowledge exchange and collaborative development.

3.1.3.2 Energy Systems Catapult (ESC)

There were no specific Flow Measurement references on the ESC website, however it did highlight the International Energy Agency's (IEA) 2015 'Hydrogen and Fuel Cells Technology Roadmap'. This called for "Hydrogen metering regulation" and a range of other standards to enable the widespread adoption of Hydrogen. The IEA subsequently issued a report 'The Future of Hydrogen' in June 2019 to the G20 meeting in Japan. In this, their recommendation 5 was for Governments to: "Eliminate unnecessary regulatory barriers and harmonise standards". The European Commission's February 2019 'Hydrogen Roadmap Europe' describes how very near market ready Hydrogen and similarly calls for action from regulators. Hydrogen cannot be exploited or commercialised without the standards (both measurement standards and documentary standards) necessary to underpin regulations, consumer confidence, trade, and environmental impact. Currently there are no specific hydrogen Documentary Standards anywhere worldwide. Considering physical primary reference Standards for hydrogen, only France and Switzerland have a working portable hydrogen standard for light vehicle refuelling. By their very nature, portable test rigs used in varying conditions out in the field are no substitute for the type of reference standard needed to underpin regulations and provide consumer confidence. This is an area of the highest priority for immediate action.

3.1.3.3 Other Catapults

There were no other significant references to flow measurement within the key documents of the other Catapult Centres.

3.2 Priority areas for action

The following list identifies priority areas for action, with a summary rationale:

a. The highest priority is the need to develop flow measurement standards infrastructure for Hydrogen (coupled with Carbon Dioxide, given that Hydrogen production currently generates vast quantities of CO_2). That a significant global influencer such as the International Energy Agency (IEA) entreats the G20 to accelerate a range of actions, including new regulation related to Hydrogen is a signal that should not be ignored. Hydrogen is a relatively mature technology, so there was relatively little publicly funded research within the period under review. Hydrogen has moved beyond the 'discovery' stage and is now in the realm of application development and user-acceptance testing. Hydrogen is being deployed in trains (in Germany) as a replacement for diesel. It is being used in fuel cell operated vehicles and the various utility operators are exploring its use as a direct replacement for natural gas for domestic cooking and heating. The EU also posits the use of Hydrogen for Industrial use as a direct replacement of natural gas. The principal barriers to wider exploitation are infrastructure (such as refuelling stations, although the UK has seen a progressive increased rollout of these), and regulations and standards to facilitate interoperability; customer confidence; quality; and trade, etc. The development of new flow measurement standards would underpin the creation of new documentary standards and regulations. Considerable first mover advantages will accrue to whichever nation first develops credible Hydrogen Flow Measurement Standards. This is likely to be in the form of increased new product development, and consultancy services to international markets.

b. The second major priority is to develop Digital Twin capability within the UK's suite of Flow Measurement Standards. This is described in sections 3.1.2.4 and 3.1.2.6 Adoption of this capability will have a direct bearing on ability to satisfy existing and future industry needs in the fields of *Flow Modelling and Analytics;* and *Measurement of Complete Flow Systems.*

c. The areas of *Dynamic Flow Measurement; Fluid/Surface Interactions; Flow Modelling and Analytics;* and *Measurement of Complete Flow Systems* are all likely to become priorities as the academic research projects discussed in this report are realised and bring new technologies and techniques to the market. However, these Themes and definitions are not currently recognised beyond the pages of this report. Thought needs to be put into determining what the components of an appropriate Flow Measurement System might comprise. This should initially be done at high level, rather than at individual application area level, given the multiplicity of potential application areas. Greater and timelier impact might be achieved through the development of Publicly Available Specifications, to provide core principles and guidance on the fundamentals of flow measurement systems falling within the two suggested Themes. This is preferable and more fiscally realistic than attempting to build a new national measurement standard facility for each Theme at such a relatively early stage of development. It is also likely that IoT devices will have a very strong bearing in three of these Themes. Given what has been said elsewhere in the report, this needs to be done in partnership with respected intermediaries such as the Catapults and the various named UK Centres of Excellence.

d. A large amount of flow measurement related academic research is addressed to a wide range of industry sectors. This is likely to be more significant than previously thought and suggests some need for diversification of the National Measurement System Flow Programme. Thought should be given about how best to broaden the Flow Measurement Standards Portfolio to be able to address these needs. This is likely to be best achieved by working in partnership with others, as suggested with CPI (paragraph 4.1.2.2), other Centres of Excellence, and direct with industry itself.

3.2.1 Centres of Excellence (CoE)

Analysis of what constitutes a Flow Measurement Centre of Excellence was judged by the degree and nature of research grant awards, and a review of other public information. Where a grant was awarded for a Centre of Doctoral Training, it was easy to define the institution as a CoE, equally so if it was for a significant facility. A high volume (or indeed cumulative value) of grant awards is not a good indicator. Some institutions have high numbers and high values of grant awards, but awards were dispersed across the institution, rather than concentrated on individuals working within recognisable Flow Teams, or Research Groups. The Flow Centres of Excellence determined through the nature of primarily capital grant awards is set out at Table 7. It covers a wide range of sectors, technologies and application areas. As with Catapult Centres, these COE should be drawn into dialogue (where the context is pertinent) when new measurement standards infrastructure is required.

Table 7: Suggested Centres of Excellence, location, focus and key personnel

Nature of Centre of Excellence Focus	Institution	Key Individual
National Wind Tunnel Facility	Imperial College London	Professor Morrison
Positron emission particle tracking of complex multiphase flows	University of Birmingham	Professor Barigou
Multi-scale exploration of multiphase physics in flows	Imperial College London	Professor Matar
Carbon Capture and Utilisation	University of Sheffield	Professor Allen
Multiscale turbulent dynamics of tokamak plasmas	University of York	Professor Wilson
Centre for Doctoral Training in Fluid Dynamics	University of Leeds	Professor Jimack
Mathematical underpinnings of stratified turbulence	University of Cambridge	Professor Linden
Stratified turbulence and mixing processes	University of Cambridge	Chancellor's Office
Aircraft noise system	Rolls Royce Plc	Undeclared
Multiscale analysis of complex interfacial phenomena	Imperial College London	Professor Kalliadasis
Modelling mixing mechanisms in 1D water network models	University of Sheffield	Professor Guymer
Multi-phase Flows at High Pressure and Temperature	University of Edinburgh	Professor Linne

Nature of Centre of Excellence Focus	Institution	Key Individual
Steerable Air-Coupled Ultrasonic Technology for Flow Measurement	University of Warwick	Professor Dixon
Multi-scale modelling for particulate Flow	Heriot-Watt University	Professor Ocone
Fuel control system sensors and effectors	Rolls Royce Plc	Not declared
Biosurfactant process engineering	University of Manchester	Dr Martin

3.3 Observations on the methodology and findings

This methodology offers a reasonable proxy view of developments that are likely to require flow measurement standards and infrastructure both now and in the near future. The dataset created and analysed here reveals a range of interesting trends that might otherwise not have come to the fore. It can be analysed further, for example specific to a single technology area, and that may be appropriate as a preliminary step for those areas where the UK's Designated Institute for Flow decides to develop new capability arising from this and the complementary reviews of the needs of the Water Industry and Life Sciences sectors. As an exercise, it is relatively easy to update the data annually and this merits consideration to help ensure that any future Flow Programme addresses priority needs in multiple sectors.

4 RECOMMENDATIONS

The rationale for these recommendations is set out in section 3.2 (Priority areas for action) and within the individual sections describing the various suggested Research Themes (3.1.2.1 - 3.1.2.7). They are primarily directed at NEL, the UK's Designated Institute for Flow Measurement Standards, but also to the team within BEIS responsible for the UK's National Measurement System.

Recommendation 1: The UK should lead the development of Hydrogen flow measurement standards to underpin development of the documentary standards and regulations required for the wide-scale exploitation of Hydrogen as a replacement to petroleum-based fuels and natural gas.

Recommendation 2: The UK should incorporate Digital Twin (linked with IoT technology) capability within the National Flow Measurement and Density Standards.

Recommendation 3: The UK should develop fundamental principles (and related guidance) for *Dynamic Flow Measurement* Systems for development and use by industry and academia in the form of one or more Publicly Available Specifications.

Recommendation 4: The UK should develop fundamental principles (and related guidance) for *Measurement of Complete Flow Systems* for development and use by industry and academia in the form of one or more Publicly Available Specifications.

Recommendation 5: The UK Designated Institute for Flow Measurement should expand its capability in *Flow Modelling and Analytics.* As an early stage, this should involve access to a Supercomputer.

Recommendation 6: The UK should develop capability in measurement of *Fluid/Surface Interactions* in Flow.

Recommendation 7: BEIS should consider extending the funding available to the NMS Flow Programme to facilitate development of the required new capability identified in this report.

Recommendation 8: The UK Designated Institute for Flow Measurement, in developing the new capability described in this report, should work with a wide range of sector intermediaries; the Catapult Centres and known Centres of Excellence.

Annex 1. Full Research Classification List

Table 8: Research categories (as seen in application record, July 2019), ranked by value

Category (as seen in application record, July 2019), ranked by value	No of projects	Value (where given)
Fluid dynamics	73	£ 49,929,562
Multiphase flow	103	£ 49,598,066
Aerodynamics	50	£ 40,563,237
Instrumentation Engineering & Development / Sensors & detectors	87	£ 27,920,729
Combustion	36	£ 24,109,400
Energy - Marine & Hydropower	13	£ 16,182,644
Continuum mechanics	10	£ 11,784,053
Particle Technology	13	£ 10,910,169
Sediment/ Sedimentary Processes/ any other sediment related topic	44	£ 9,165,171
Wind Power	10	£ 8,785,041
Oil & Gas extraction/ shale gas	32	£ 8,678,350
Heat & Mass Transfer	10	£ 8,072,670
Separation Processes	7	£ 6,932,623
Complex fluids & soft solids	15	£ 6,743,117
Fluid flow/ Flow modelling	33	£ 6,550,510
Materials processing	4	£ 5,820,963
Numerical Analysis	9	£ 5,755,342
Gas & Solution Phase Reactions	5	£ 5,704,396
Design of Process systems	2	£ 5,595,789
Earth Surface Processes/ Crustal processes	36	£ 5,510,537
Coastal & Waterway Engineering	22	£ 5,502,346
Geohazards/ Faults (various types)/ Earthquakes	27	£ 5,496,088
Acoustics	9	£ 5,416,845
Microsystems	11	£ 5,371,719
Tidal Currents/ Tidal Farms	9	£ 4,867,288
Reactor Engineering	2	£ 4,815,054
Catalysis & Applied Catalysis	1	£ 4,559,973
Rheology	14	£ 4,476,207
Fusion	1	£ 4,349,472
Plasmas - Laser & Fusion	1	£ 4,349,472
Plasmas - Technological	1	£ 4,349,472
Technology & Method Development	76	£ 4,146,509
Quantum Fluids & Solids	5	£ 3,853,563
Hydrogeology/ Hydrogeological processes/ Hydrological processes/ Reservoir technology	19	£ 3,688,424
Earth Resources	14	£ 3,430,830
Non-linear Systems Mathematics	18	£ 3,414,360
Water Engineering	7	£ 3,202,014
Carbon capture & storage / Carbon dioxide injection/ Geostorage/ Subsurface injection	7	£ 2,699,741
Survey & Monitoring	10	£ 2,640,554
Cells	6	£ 2,314,741
Properties of Earth Materials	8	£ 2,219,994

Category (as seen in application record, July 2019), ranked by value	No of projects	Value (where given)
Energy - Conventional	7	£ 2,172,472
Ecosystem Scale Processes	10	£ 1,952,177
Remote sensing & Earth Observation	11	£ 1,884,348
Mathematical sciences/ Mathematical & Statistic Psych/ Mathematical Analysis/ Mathematical physics	10	£ 1,833,509
Water Quality	15	£ 1,553,663
Ocean Circulation	8	£ 1,543,331
Medical Imaging	2	£ 1,503,186
Organic carbon	4	£ 1,480,598
Submarine landslides/ Tsunamis	5	£ 1,457,317
Volcanic Processes	5	£ 1,376,111
Bioprocess Engineering	2	£ 1,275,888
Earth & environmental	3	£ 1,263,049
Lasers & Optics	4	£ 1,263,043
Gravity flows/ Gravity Currents	6	£ 1,255,201
Coal Technology	4	£ 1,209,089
Turbidity currents	4	£ 1,198,058
Medical science & disease	3	£ 1,061,558
Analytical biosensors	2	£ 964,794
Technology for environmental applications	4	£ 950,212
Bioenergy	3	£ 850,951
Electric Motor & Drive Systems	1	£ 837,467
Microbiology	1	£ 824,266
Animal & human physiology	1	£ 673,877
Mining & minerals extraction	3	£ 641,841
Software Engineering	3	£ 631,319
Debris flows	2	£ 618,659
Quaternary science	2	£ 618,659
Energy - Nuclear	3	£ 613,770
Geomechanics/Geomechanical models	2	£ 586,644
Image & Vision computing	3	£ 570,226
Biological membranes	1	£ 569,187
Biophysics	1	£ 569,187
Structural biology	1	£ 569,187
Theoretical biology	1	£ 569,187
Tools for the biosciences	1	£ 569,187
Environment & Health	2	£ 568,458
Eng. Dynamics & Tribology	1	£ 538,609
Earth Engineering	2	£ 533,647
Medical Instruments, devices & equipment	2	£ 524,716
Land-ocean interactions	4	£ 517,057
Drug Formulation & Delivery	2	£ 496,002
Climate & Climate Change	3	£ 489,831
Tectonic processes	1	£ 471,774
Glacial & Cryospheric Systems	4	£ 406,075
Mantle & Core Processes	2	£ 388,876

Category (as seen in application record, July 2019), ranked by value	No of projects	Value (where given)
Statistics & Appl. Probability	4	£ 355,153
Waste Minimisation	3	£ 348,207
Control Engineering	1	£ 273,131
Computer Graphics & Visual.	1	£ 205,545
Design & Testing Technology	2	£ 202,262
Optoelectronics Devices & Circuits	1	£ 193,778
Analytical Science	2	£ 181,046
Building Ops & Management	2	£ 181,042
Management & Business Studies	2	£ 181,042
Biomedical sciences	1	£ 169,831
Boundary layer meteorology	2	£ 168,999
Pollution/ Diffuse Pollution/ Pollution Pathways/ Pollutant Transport/ Water Pollution	4	£ 156,645
Bioinformatics	1	£ 150,562
Cell cycle	1	£ 147,921
Stem cell biology	1	£ 147,921
Animal organisms	1	£ 146,151
Scattering & Spectroscopy/ UV & visible spectroscopy	1	£ 140,528
Ocean Modelling	2	£ 131,640
Shelf Ocean Dynamics	2	£ 131,640
Ocean-Atmosphere Interactions	3	£ 131,115
Land-Atmosphere Interactions	2	£ 131,115
Tropospheric Processes	2	£ 131,115
Design Engineering	1	£ 119,810
Design of Built Infrastructure	1	£ 119,810
High Performance Computing	2	£ 118,077
Electromagnetics	1	£ 110,620
Wave Action/ Wave Energy/ Wave Turbines	5	£ 109,667
Algebra & Geometry	1	£ 101,150
Quantum Optics & Information	1	£ 100,798
Electronic Devices & Subsystems	1	£ 99,787
Surfaces & Interfaces	1	£ 98,126
Shoreline Wave Devices	4	£ 88,565
Energy Efficiency	1	£ 81,227
Information & Knowledge Management	2	£ 56,670
Complexity Science	1	£ 56,670
Data fusion	1	£ 56,670
Data Mining	1	£ 56,670
Intelligent Measurement Systems	1	£ 52,750
Agricultural systems/ Agri-environmental science	1	£ 48,420
Aquaculture	1	£ 48,420
Coastal Hydrodynamics	1	£ 48,420
Chemical Structure	1	£ 40,518
Materials Synthesis & Growth	1	£ 40,518
Transport Ops & Management	1	£ 24,525
Cold Atomic Species	1	£ 19,285

Category (as seen in application record, July 2019), ranked by value	**No of projects**	**Value (where given)**
Soil conservation	2	£ 16,117
Soil science	2	£ 16,117
Composition	1	£ 5,000
Not provided	*150*	*£ -*

Annex 2. Complex Open Channel Flow Measurement

Table 9: Number of projects by sector allocated to research Theme, Complex Open Channel Flow Measurement

Complex Open Channel Flow Measurement	
Sector (where provided)	**Count of Theme and Sector**
Environment/ Environmental Risks & Hazards/ Geosciences/ Environmental Engineering	44
Natural Resource Management/ Terrestrial & freshwater environments/ Marine environments	39
Global change/ Climate change	10
Tools, technologies & methods/ Instrumentation/ Systems engineering	7
Water	7
Chemicals/ Process engineering/ Catalysis & surfaces/ Chemical measurement	4
Aerospace, Defence & Marine	3
Energy	3
Pollution and waste	3
Construction/ Built environment	2
Healthcare/ Medical science/ Medical & health interface	2
Atmospheric phys. & chemistry	1
Biodiversity	1
Food and drink	1

Annex 3. Dynamic Flow Measurement

Table 10: Number of projects by sector allocated to research Theme, Dynamic Flow Measurement

Dynamic Flow Measurement	
Sector (where provided)	**Count of Theme and Sector**
Chemicals/ Process engineering/ Catalysis & surfaces/Chemical measurement	22
Aerospace, Defence & Marine	16
Tools, technologies & methods/Instrumentation/Systems engineering	15
R&D	8
Environment/ Environmental Risks & Hazards/ Geosciences/ Environmental Engineering	5
No relevance to underpinning sectors	5
Transport systems and vehicles	5
Energy	4
Natural Resource Management/Terrestrial & freshwater environments/ Marine environments	4
Mechanical Engineering	3
Global change/Climate change	2
Information Technologies	2
Atomic & molecular physics	1
Construction/ Built environment	1
Electronics	1
Manufacturing	1

Annex 4. Experimental Flow Measurement Techniques

Table 11: Number of projects by sector allocated to research Theme, Experimental Flow Measurement Techniques

Experimental Flow Measurement Techniques	
Sector (where provided)	**Count of Theme and Sector**
Tools, technologies & methods/Instrumentation/Systems engineering	57
Energy	43
Water	25
Aerospace, Defence & Marine	21
Chemicals/ Process engineering/ Catalysis & surfaces/ Chemical measurement	20
Environment/ Environmental Risks & Hazards/ Geosciences/ Environmental Engineering	15
No relevance to underpinning sectors	13
Manufacturing	11
R&D	10
Healthcare/ Medical science/ Medical & health interface	9
Natural Resource Management/ Terrestrial & freshwater environments/ Marine environments	9
Food and drink	8
Pollution and waste	5
Construction/ Built environment	4
Pharmaceuticals and Bio technology/ immunology/ biomolecules & biochemistry	4
Electronics	3
Transport systems and vehicles	2
Agriculture	1
Global change/ Climate change	1
Mechanical Engineering	1

Annex 5. Flow Modelling & Analytics

Table 12: Number of projects by sector allocated to research Theme, Flow Modelling & Analytics

Flow Modelling & Analytics	
Sector (where provided)	**Count of Theme and Sector**
Chemicals/Process engineering/Catalysis & surfaces/Chemical measurement	31
Aerospace, Defence & Marine	23
Energy	23
R&D	20
Transport systems and vehicles	18
Tools, technologies & methods/ Instrumentation/ Systems engineering	4
Environment/Environmental Risks & Hazards/Geosciences/Environmental Engineering	3
Natural Resource Management/ Terrestrial & freshwater environments/ Marine environments	3
No relevance to underpinning sectors	3
Pharmaceuticals and Bio technology/immunology/biomolecules & biochemistry	3
Construction/ Built environment	2
Healthcare/ Medical science/ Medical & health interface	2
Manufacturing	2
Pollution and waste	2
Global change/ Climate change	1
Information Technologies	1
Water	1

Annex 6. Fluid/ Surface Interactions

Table 13: Number of projects by sector allocated to research Theme, Fluid/Surface Interactions

Fluid/Surface interactions	
Sector (where provided)	**Count of Theme and Sector**
Environment/ Environmental Risks & Hazards/ Geosciences/ Environmental Engineering	22
Natural Resource Management/ Terrestrial & freshwater environments/ Marine environments	18
Chemicals/Process engineering/Catalysis & surfaces/Chemical measurement	10
Aerospace, Defence & Marine	9
Tools, technologies & methods/ Instrumentation/ Systems engineering	9
No relevance to underpinning sectors	7
Manufacturing	5
Healthcare/ Medical science/ Medical & health interface	4
Food and drink	3
R&D	3
Pollution and waste	2
Transport systems and vehicles	2
Global change/ Climate change	1
Mechanical Engineering	1
Water	1

Annex 7. Measurement of Complete Flow Systems

Table 14: Number of projects by sector allocated to research Theme, Measurement of Complete Flow Systems

Measurement of Complete Flow Systems	
Sector (where provided)	**Count of Theme and Sector**
Energy	12
Natural Resource Management/ Terrestrial & freshwater environments/ Marine environments	10
Tools, technologies & methods/ Instrumentation/ Systems engineering	7
Global change/ Climate change	6
Environment/ Environmental Risks & Hazards/ Geosciences/ Environmental Engineering	4
Pollution and waste	4
Chemicals/ Process engineering/ Catalysis & surfaces/ Chemical measurement	2
Transport systems and vehicles	2
Aerospace, Defence & Marine	1
Atmospheric physics & chemistry	1
Construction/ Built environment	1
No relevance to underpinning sectors	1
R&D	1

Annex 8. Miscellaneous

Table 15: Number of projects by sector allocated to research Theme, Miscellaneous

Miscellaneous	
Sector (where provided)	**Count of Theme and Sector**
Healthcare/ Medical science/ Medical & health interface	10
Chemicals/ Process engineering/ Catalysis & surfaces/ Chemical measurement	7
Food and drink	4
Pharmaceuticals and Bio technology/ immunology/ biomolecules & biochemistry	4
Information Technologies	3
Transport systems and vehicles	3
Energy	2
Environment/ Environmental Risks & Hazards/ Geosciences/ Environmental Engineering	2
Global change/ Climate change	2
Manufacturing	2
Natural Resource Management/ Terrestrial & freshwater environments/ Marine environments	2
No relevance to underpinning sectors	2
Pollution and waste	2
R&D	2
Tools, technologies & methods/ Instrumentation/ Systems engineering	2
Aerospace, Defence & Marine	1
Biodiversity	1
Construction/ Built environment	1
Mechanical Engineering	1

Annex 9. Experts Consulted

Table 16: Experts consulted

Name	Organisation
Professor Mostafa Barigou	University of Birmingham
Dr Peter Cowley	Quarndon Cognition Ltd
Dr Norman Glenn	TUV-NEL
Professor Manus Henry	Oxford University
Professor Andy Hunt	iPhase Ltd
Dr James Johnstone	Centre for Process Innovation (CPI)
Pete Loftus	Independent Consultant
Professor David Robinson	Psi-Tran Ltd
Dr Seyed Shariatipour	Coventry University
Dr Janet Townsend	Measurement Matters Ltd

Nb. Information extracted from this review was passed to the experts leading separate reviews of flow measurement needs within the Water Industry, and the Medical/Biosciences area. The names of people consulted in those studies are not included in the list above.

Annex 10. Databases Reviewed

BBSRC	Biotechnology and Biological Sciences Research Council
Cordis	European Commission
EPSRC	Engineering and Physical Sciences Research Council
ESA	European Space Agency
NERC	Natural Environment Research Council
RCUK Gateway	(Research Councils and Innovate UK) later called UK Research and Innovation

Nb. Project research and sector classifications are not 100% consistent between 'Gateway to Research' codes used in July 2019 by ukri.org and the original individual Research Council research finder tools.