Building a UK pipeline of research, innovation and technology development for aerosol science

A Report Supported by:

The Aerosol Society

Foreword

Aerosols are a common feature of everyday life. For example, easily recognised visible aerosols include smoke, clouds, fogs, mist, and smog in the atmosphere. However, many aerosols are invisible to the naked eye, and aerosol science is defined more precisely as the scientific investigation of dispersions of particles or liquid droplets dispersed in a gas such as air. Aerosols have come increasingly under media, political and economic scrutiny, with the growing acceptance of the impact of aerosol pollution arising from urbanization on human health, global ecosystems, and patterns of climate modification.

Aerosol science is a core component of a broad range of disciplines and industries, extending from inhaled drug delivery, to combustion science and its health impacts, aerosol assisted routes to synthesis of new materials, climate change, and the delivery of agricultural and consumer products. Estimates of the global aerosol market size suggest it will reach $84 billion/year by 2024 with products in the personal care, household, automotive, food, paints and medical sectors.

Despite the growing interest into the macro-effects and industrial exploitation of aerosols, aerosol science is a relatively young discipline encompassing research topics which can concomitantly be understood as biological, chemical, engineering, environmental, material, medical, pharmaceutical or physical science. Aerosol science emerged as a coherent area of investigation at the centre of these traditional research disciplines in the 20th Century. Aerosol researchers are therefore represented by organizations as diverse as the International Society for Aerosols in Medicine; Institute of Physics Environmental Physics Group: Royal Meteorological Society; British Association for Lung Research; Academy of Pharmaceutical Scientists; or the Royal Society of Chemistry. It was only in 1986 that the UK and Ireland Aerosol Society was constituted. The Aerosol Society provides the only learned society in the UK where the fundamental investigation of aerosols in the many diverse situations they are encountered is unified, regardless of traditional research discipline boundaries.

Research in aerosol science, through the innovative discoveries emerging from these fundamental investigations, is making an increasing contribution to the economic, technological, environmental, health and wellbeing development of the nation. However, as a result of the current structure of research funding across seven research councils and Innovate UK, the development of research capacity in aerosol science remains fragmented with artificial boundaries between multiple traditional disciplines.

The creation of UK Research and Innovation (UKRI) provided the impetus for members of the Aerosol Society to examine the issues arising from the current approach to training and development of the next generation of researchers in aerosol science. This report represents the output of a review which began in July 2017, including a focused workshop in January 2018 involving researchers and senior managers from over 30 UK-based enterprises, industries and public-sector organizations. This was followed by an anonymous online survey, which also extended to invitees who were unable to attend the workshop.

We provide here a summary of the outcomes of the academic-industrial-public sector consultation collated by the authors in conjunction with Simply Change Ltd. The authors are grateful that the Committee of the Aerosol Society facilitated an open consultation on this preliminary report across its wider membership. All contributions have been incorporated into this, final version of the report updated in Summer 2018. Opinion and feedback are still welcomed from all members, and indeed from any non-member individuals or organizations who have a research interest in aerosol science by emailing admin@aerosol-soc.org.uk. We conclude by making an authoritative set of recommendations for the future development of aerosol research in the United Kingdom.

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1. Aerosol Science: A Globally Important Research Discipline

An aerosol consists of solid particles or liquid droplets dispersed in a gas phase, with particles/droplets spanning from clusters of a few molecules, with nanometre size, up to the size of rain droplets, which are millimetre size. Not only are they prevalent in the atmosphere, but they find widespread use in industrial processes such as spray drying, a technique commonly employed in materials synthesis and product manufacture.

Aerosol science is the term used to describe our understanding of the collective underlying principles governing the properties and transformation of aerosol particles and droplets in a broad range of contexts, extending from drug delivery to the lungs to disease transmission, combustion and energy generation, materials processing, environmental science, and the delivery of agricultural and consumer products. As examples, understanding the size distributions, chemical compositions and phases of aerosol particles and how these properties are transformed over time is core to understanding the role of aerosols in all these applications and contexts.

The exceptionally small size of aerosol particles and the facile transport of material in the gas phase leads to particles and droplets with extremely dynamic properties. As a result, aerosol science provides a sensitive ability to engineer properties into novel condensed phase materials. However, the dynamic nature of aerosol properties renders prediction of macroscale aerosol behaviour difficult; for example, when aerosols impact human-occupied ecosystems, such as dispersal of noxious pollutants. Aerosols can also have a profound impact on human behaviour. For example, aerosol clouds affect visibility, an issue of paramount importance for safe operation of air, road, rail and water transport. The constitution of the air which we breathe is of primary importance to life on Earth, and thus to the areas of health and the environment. Air containing dangerous aerosols spreads rapidly, is difficult to avoid breathing in, and its deposition on the ground can leave pollution in its wake.

The potential health and environmental effects arising from the behaviour of the aerosol phase create profoundly damaging economic and societal impacts. Examples where aerosol science research is a vital component of understanding, addressing and mitigating major societal issues and developing legislation, policies and products with real life political and economic impacts include:

1. The transmission of major epidemics including influenza or other airborne infectious human disease occurs by bioaerosol.
2. The broader impacts of bioaerosol on animal and vegetative health are recognised. The 2001 outbreak of foot and mouth disease in Britain was started by airborne aerosol emissions from diseased pigs reaching sheep downwind.
3. Airborne pollution, mainly in aerosol form, from vehicles and other human activities has an impact on rates of human morbidity and mortality. The global burden of lung disease is increasing due to occupational, environmental and recreational exposure to inhalable aerosol particles.[1]
4. The potential release of anthrax spores by terrorists or bacteriological warfare must be countered and detection methods developed. The detection and control of lethal bioaerosols is a major research cost for the UK's public health and security agencies.
5. The eruption of the Eyjafjallajökull volcano in 2010 and the dispersal of volcanic ash is estimated to have grounded >100,000 flights and have led to global economic losses of $4.7Bn.[2]
6. Aerosols in the atmosphere affect the transmission of radiation, both from the sun (heating the Earth) and out into space (cooling the Earth). The radiative balance of the atmosphere and patterns of precipitation are profoundly affected by the properties and concentration of tropospheric and stratospheric aerosols, which mediate such processes as cloud formation. The science in this area is still incomplete and gives the largest uncertainty in calculating changes of the Earth's temperature from the Greenhouse Effect.
7. The potential benefits and risks of using aerosols to mitigate the impacts of climate change through geo-engineering are widely debated. In addition, control over precipitation patterns by cloud seeding has been widely investigated over many decades.

[1] PE Schwarze et al. (2006) *Human Exp Toxicol*, 25: 559-579;

[2] Oxford Economics (2010). The Economic Impacts of Air Travel Restrictions Due to Volcanic Ash. A report prepared for Airbus

Aerosol science research is of immense global importance to advance understanding, and manage the environmental impacts, of pollution and climate change. However, the impact of aerosols (and aerosol research) on the global economy is also significant. For example, legal restrictions on vehicular transport preventing emissions (such as London's congestion charging model, or odd-and-even number plate bans in cities such as Madrid or Rome); or the impact of decreased productivity and increased joblessness from pollution-derived lung disease, costing the European economy $1.58trn.[3] Although often viewed through a lens of negative economic impact, the global aerosol market makes a significant contribution: its value will grow to $84 billion/year by 2024 across the personal care, household, automotive, food, paints and medical sectors.[4] Sprays are used for delivering fuels, consumer products and agrochemicals, and spray drying is a common route to fabricating structured particles. Aerosol science is a crucial discipline for global economic growth both in terms of the production and market introduction of new high-value advanced materials such as carbon nanotubes. [5] Materials from aerosol processing are increasing in value and are common for producing nano-carbon black (£10.2 billion) and titanium dioxide (£3.3 billion).[6] The respiratory drug market, which relies on generation of aerosols for inhalation by patients, has a global size of $32bn and has been forecast to grow at 14.5%. [7]

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[3] WHO Regional Office for Europe, OECD (2015) Economic cost of the health impact of air pollution in Europe.
[4] Aerosol Market Estimates & Trend Analysis By Application, Grand View Research, Report 978-1-68038-288-4 (2016).
[5] http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/M015211/1
[6] Nano Titanium Dioxide Market by Application… 2014 - 2022, Allied Market Research, Report MA 161703 (2016).
[7] Pritchard JN. Industry guidance for the selection of a delivery system for the development of novel respiratory products. Expert Opin Drug Deliv 2015; 12:1755-65.

2. Aerosol Science: The United Kingdom Context

Aerosols are often viewed negatively in the United Kingdom context based on the historical reputation as the “dirty man of Europe” and London’s pea-soup smogs. Indeed, poor air quality is estimated to cost the UK £20 billion/year and lead to 30,000-40,000 premature deaths.[8] Environmental aerosols impact rates of morbidity and mortality and provide an important, yet poorly understood, vector in the transmission of disease (e.g. for influenza).[9] The ability to track disease transmission of bioaerosol influenza reaches public cognizance every winter with the NHS’s near-annual ‘winter crisis’. As the links between the rising incidence of lung disease and combustion emissions and environmental pollution emerge, chronic lung disease poses the most consistent negative economic impact of aerosols in the UK. The NHS spends ~£5 billion/year treating lung diseases with inhalation therapies, with more than 12 million people diagnosed with a lung condition such as asthma.[10] However, aerosol science also makes a significant positive contribution to the UK economy. Whether through materials manufacture (e.g. Johnson Matthey), the development of agricultural pesticides (e.g. Syngenta) or application of household products (e.g. AkzoNobel), aerosol (and aerosol-containing) products make a significant contribution to the UK’s export market. As an example of the UK’s centre of excellence for global product development, seven of the world’s most important pharmaceutical companies engaged in aerosol science (3M, Astra Zeneca, Chiesi, GlaxoSmithKline, Mylan, Philips Healthcare and Vectura) have significant research activity in this country.

Studies of the effects of the behaviour and properties of aerosols impact on a variety of UK Government Ministries and Departments, Scottish Government Directorates, sectors of devolved Welsh Government Cabinet responsibility, and non-governmental agencies (Table 2.1). Aerosol science also impacts substantially on every local authority across the United Kingdom through their Public Health, Health and Wellbeing; Environmental Health, and Planning activities.

[8] Every breath we take: the lifelong impact of air pollution. Royal College of Physicians, London (2016).
[9] Routes of Transmission of the Influenza Virus: Scientific Evidence Base Review, Department of Health (2011).
[10] Estimating the economic burden of respiratory illness in the UK, British Lung Foundation (2017).

Table 2.1: Branches of UK National and Devolved Government, and Non-Executive Agencies in which Aerosol Science is Applied for Decision-making

Jurisdiction	Government Departments	Public Sector Agencies with governmental remit
UK (incl. England)	• Health and Social Care • Environment, Food and Rural Affairs • Home Office • Defence • Housing, Communities and Local Government • Business, Energy and Industrial Strategy	• UK Space Agency • Met Office • Committee on Climate Change • Council for Science and Technology • Government Office for Science • Forestry commission • Animal and Plant Health Agency • Agricultural and Horticultural Development Board • Environment Agency • Natural England • Advisory Committee on Releases to the Environment • Science Advisory Council • Maritime and Coastguard Agency • Northern Lighthouse Board • Trinity House • Civil Aviation Authority • Highways England • Medicines and Healthcare Products Regulatory Agency • Public Health England • Health Research Authority • Defence Science and Technology Laboratory • Defence Nuclear Safety Committee • Nuclear Research Advisory Council
Scotland	• Health and Sport • Environment, Climate Change and Land Reform • Energy and Climate Change • Environment and Forestry	• Scottish Environment Protection Agency • Transport Scotland • Health Protection Scotland
Wales	• Economy and Transport • Energy, Planning and Rural Affairs	• Natural Resources Wales • Public Health Wales

3. Aerosol Science Research and Innovation in the United Kingdom

The UK has a strong tradition in aerosol science, dating back to the pioneering work of, for example, Stokes, Rayleigh and Aitken undertaking research in the 19th Century, which is now known to encompass aerosol behaviour. In the mid-20th century several UK-based institutions began programmes of fundamental aerosol science research, including Porton Down, AERE Harwell, the Health and Safety Laboratories, the Institute of Occupational Medicine and Rothamsted. The transdisciplinary science led to the formation in Germany and Austria of the Gesellschaft fuer Aerosolforschung (GAeF) in 1972, which provided a focus for the development of aerosol research in Europe. However, by 1975, Prof. CN Davies (a global founding father of aerosol science, then based at the University of Essex) in a Report to the Science Funding Council found 'that aerosol science was a subject of growing importance and one which had been neglected in the UK'. Reflecting the growth of academic research and its industrial exploitation, the UK and Republic of Ireland Aerosol Society was formed in 1986. UK aerosol scientists were instrumental as founding members of the European Aerosol Assembly (an organization of 9 national European learned societies, http://www.gaef.de/eaa/), and the International Aerosol Research Assembly (http://www.iara.org/). In recent years, the European Aerosol Assembly has grouped the activity spheres of aerosol science into five major themes across 11 subject groups (Table 3.1).

Table 3.1 Research Themes and Discipline Subject Groups for Aerosol Science as Categorized by the European Aerosol Assembly

Research Themes	Research Subject groups
• Basic Aerosol Processes • Measurement Techniques • Atmospheric Aerosols • Aerosols and Health • Aerosol Technology	• Aerosol-based Nanotechnology • Aerosol Chemistry • Aerosol Modelling • Atmospheric Aerosol • Electrical Effects • Fundamentals • Combustion Aerosols • Instrumentation • Inhalation, Exposure &Health • PMx (Particle measurement) • Indoor & Working Place Aerosols

Since its foundation in 1986, the UK and Republic of Ireland Aerosol Society (Feb 2018) has now grown to over 526 members, including 10 corporate members and 232 student members. The Society organizes Europe's largest annual conference in aerosol science, Drug Delivery to the Lungs. DDL is now in its 29th year and continues to grow year-on-year. For example, in December 2017, there were 748 delegates including 388 from the UK and Ireland, further demonstrating the strength of UK's aerosol science research and development in the pharmaceutical and healthcare sectors. In addition, the Aerosol Society has hosted the European Aerosol Conference (EAC) in 1992 (Oxford), 2000 (Dublin), 2011 (Manchester) and the International Aerosol Conference (Edinburgh, 1998). In 2017, the Aerosol Society successfully bid for EAC 2021 and will welcome over 800 researchers to Birmingham.

Academic research into aerosols takes places in many discipline contexts in the United Kingdom. Aerosol researchers are typically concurrent members of professional or learned societies including: Royal Society of Chemistry, Royal Society of Biology, Academy of Pharmaceutical Sciences/Royal Pharmaceutical Society, Institute of Physics, Royal Society, Royal Geographical Society, Royal Meteorological Society, Institute of Environmental Science, the Medical Colleges, and Institutes of Engineering (e.g. IChemE, IEEE). The UK and Ireland Aerosol Society is the only learned society devoted solely to advancing research and education of the fundamental and applied science of aerosols. Indeed, the Aerosol Society has frequently partnered with the above organizations for conferences on topics which are at the periphery of other societies' competencies. It is only in the last 50 years or so, that a core 'aerosol science' curriculum of cross-cutting knowledge, skills and attributes has emerged, that overlap with, and provide an intersection between many traditional subject disciplines. Thus, the modern aerosol scientist is equally likely to be undertaking research in the following academic faculties:

- Agricultural sciences
- Analytical sciences
- Atmospheric sciences
- Biological sciences
- Built environment & planning
- Chemical sciences
- Computer science & informatics
- Earth sciences
- Ecological science
- Electronics
- Engineering sciences
- Environmental sciences
- Geography
- Imaging sciences
- Material sciences
- Mathematical sciences
- Medicine & medical sciences
- Optical sciences
- Pharmacy & Pharmacology
- Physics & physical sciences
- Physiological sciences
- Public health
- Toxicological sciences
- Veterinary sciences

Research programmes investigating specific applications of core aerosol science are therefore funded by the Biotechnology and Biological Sciences Research Council, Engineering and Physical Sciences Research Council, Medical Research Council, Natural Environment Research Council, National Institute for Health Research, and Innovate UK. Historically much of the UK's research in aerosol science has been undertaken with and funded by state agencies (e.g. AERE Harwell; Health Protection Agency; MoD Porton Down; or the various agencies for environmental control). With their closure or reorganization into executive agencies, in recent years the UK's aerosol science research has been funded predominantly by research councils to study the combustion emissions, pollution and atmospheric aerosols, climate sciences and the health impacts of aerosol pollution. For example, BBSRC currently funds programmes into biological routes to synthesize metal nanoparticles,[11] and also into the biological effects of particulate matter from shipping.[12] NERC funds 130 researchers nationwide who constitute the National Centre for Atmospheric Science which is headquartered at the University of Leeds.[13] The MRC-PHE Centre for Environment and Health[14] was formed in June 2009 and provides international leadership for investigating the health impacts of environmental aerosols. The latter are just two examples of RCUK-funded programmes in which a core understanding of aerosol properties or measurement are employed in different disciplines of application.

Aerosol science has an important role to play in the research, development and innovation of the eight great technologies.[15] Aerosol routes to: construct tissue scaffolds for regenerative medicine; undertake advanced material synthesis; or developing precision agri-horticultural solutions, show that aerosol science has a powerful role to play in addressing the UK's Industrial Strategy Challenges. Companies involved in developing new and exporting technology-rich products include those involved in analytical instrumentation development, the automotive and engineering industry, fast moving consumer goods such as devices for cleaning and filtration, computing hardware and software development or pharmaceutical, and healthcare technologies. Given the importance of aerosol science for advanced materials and product manufacturing, it is unsurprising that programmes involving aerosol science are funded by the EPSRC (often in collaboration with IUK and the Industrial Strategy Challenge Fund). Examples include ANAM[16] under the 2014 Manufacturing Advanced Functional Materials call; INFORM 2020 – Molecules to Manufacture;[17] and Evaporative Drying of Droplets and the Formation of Micro-structured and Functional Particles and Films[18], under the 2015 Future Formulation of Complex Products call. In conclusion, aerosol science research continues to rank highly in national importance for the UK, with an increasing investigation into the chemistry, physics and engineering aspects of aerosol science to support novel product innovation.

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[11] https://www.bbsrc.ac.uk/research/grants-search/AwardDetails/?FundingReference=BB%2fN002520%2f1
[12] https://www.bbsrc.ac.uk/research/grants-search/AwardDetails/?FundingReference=BB%2fP011365%2f1
[13] https://www.ncas.ac.uk/en/people
[14] http://www.environment-health.ac.uk/
[15] https://www.gov.uk/government/publications/eight-great-technologies-infographics
[16] http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/M015211/1
[17] http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/N025075/1
[18] http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/N025245/1

4. The Existing Training Paradigm for United Kingdom Aerosol Scientists

Aerosol science is core to a broad range of disciplines extending from drug delivery to the lungs to disease transmission, combustion and energy generation, materials processing, environmental science, and the delivery of agricultural and consumer products (as identified in Sections 2 and 3). Despite this, there is no formal programme of education in the UK. The study of, and application of aerosol science, is undertaken in graduate-level employment following completion of a degree in many of the traditional undergraduate and postgraduate education disciplines, including: biological science; chemical science; engineering; mathematics; medicine; pharmacy; and physical science.

The European Aerosol Assembly groups the scientific activities that employ aerosol science into five key themes:

- Basic aerosol processes
- Aerosol technology
- Measurement technologies of aerosols
- Atmospheric aerosols
- Aerosols and health

Education and training in the core concepts and techniques essential for the exploitation and interpretation of aerosol science in these themes are fragmentary, occurring within the context of individual application areas (e.g. drug delivery, environmental science, materials). Such a discipline-specific and insular approach creates artificial barriers between disciplines. Invariably this leads to the graduation of scientists who only have a knowledge and understanding of the specific, core phenomena of aerosol science that are most closely aligned with applications in their direct field. For example, a chemistry graduate may have an understanding of chemical reactivity and processes within liquid droplets, but no understanding of the optical properties required to undertake spectroscopy and measure reactions in aerosols. In a further example, a biological scientist with an advanced knowledge of cell signalling in response to cell-nanoparticle contact, will graduate with no understanding of the physical chemistry underpinning the agglomeration of those nanoparticles into non-reactive microagglomerates in biological fluids.

Aerosol science is a sphere of scientific activity occupying the ground between traditional disciplines. It is likely that aerosol science will remain a transdisciplinary scientific pursuit for the foreseeable future and it is unexpected that an undergraduate curriculum in aerosol science will emerge. Scientists engaged in aerosol science typically operate in occupations that apply the knowledge, skills and attributes developed in their undergraduate curriculum to scenarios involving disperse systems. Thus, it is appropriate to examine the level of education that may be required to operate in the careers and activities discussed in Sections 2 and 3 (Table 4.1).

Table 4.1 South East England Consortium for Credit Accumulation & Transfer (SEEC)[19] Descriptors for Higher Educational Outcomes Bachelor (Level 6), Masters (Level 7), and Doctoral (Level 8)

SEEC level*[19]	Degree	Summary credit level descriptor
6	BSc	Critically review, consolidate and extend a systematic and coherent body of knowledge, utilizing specialised skills across an area of study; critically evaluate concepts and evidence from a range of sources; transfer and apply diagnostic and creative skills and exercise significant judgement in a range of situations; and accept accountability for determining and achieving personal and/or group outcomes.
7	MSc	Display mastery of a complex and specialised area of knowledge and skills, employing advanced skills to conduct research, or advanced technical or professional activity, accepting accountability for related decision making, including the use of supervision.
8	PhD & Professional Doctorate	Make a significant and original contribution to a specialised field of inquiry, demonstrating a command of methodological issues and engaging in critical dialogue with peers and accepting full accountability for outcomes.

*SEEC is a consortium of universities and HE providers formed in 1985, working together to advance the use and practice of academic credit, widening access to learning.

From a review of the knowledge, skills, and attributes of practitioners engaged in aerosol science, it is evident that they operate in a context more closely aligned with Levels 7 and 8 in the SEEC descriptors. For example, specialised skills are actually required from across a range of different disciplines (multidisciplinary areas) of study. Those working in areas as diverse as policy development, environmental risk assessment, medical and pathological diagnosis or atmospheric and climate science all operate using Level 6 skills associated with his/her initial scientific discipline. However, all occupational examples listed above, require deployment of skills and attributes in “a complex and specialised area of knowledge” and are required to

[19] SEEC Credit Levels for Higher Education – 2016 Edition, https://www.seec.org.uk/resources/

conduct research (whether data generation or gathering data generated by other sources) to engage in “advanced technical or professional activity”. Level 8 outcomes also assimilate those attributes which are demonstrated by an individual with a Level 7 qualification. It is clear that those undertaking doctoral-level research (in higher education or in industrial and professional contexts) will make a significant intellectual and discipline leap between their Level 6 qualification (e.g. BSc Chemistry) and their research practice in aerosol science. It is notable that a search using the work ‘aerosol’ through the website www.findamasters.com retrieved only two MSc degrees from over 27,017 degrees listed worldwide. In fact, the typical Masters level qualifications on entry into research in aerosol science include MSc qualifications (e.g. Chemistry, Applied Biology, Physics, Analytical Science, Engineering Science), and MEng, MPhys and MPharm integrated degrees.

In terms of training doctoral-level practitioners of aerosol science and aerosol research, there is currently no single doctoral training programme addressing aerosol science as a transdisciplinary, coherent postgraduate programme. On the contrary, discipline-specific, fragmented doctoral-level training is currently funded by MRC, NERC, BBSRC and the EPSRC under their doctoral training partnerships, doctoral training accounts, or some centres for doctoral training. Generally, these are as isolated student projects, with examples presented in Figure 4.1.

The above review demonstrates that even at the postgraduate level, the training and education of those working in aerosol science remains fragmented into traditional disciplines. Such programmes are undoubtedly beneficial in terms of researcher training and the research undertaken. However, they fail to provide a coordinated, focussed approach to equipping a cohort of scientists with a coherent knowledge base to study the important cross-disciplinary aspects of aerosol science. Instead, the UK skills base is dependent on ad hoc training events including the annual short course in the Fundamentals of Aerosol Science provided by the Aerosol Society. [20] Similarly, the University of Manchester runs a short course into the practical aspects of making aerosol measurements, crucial for environmental and engineering scientists.[21]

[20] https://aerosol-soc.com/events/fundamentals-aerosol-science-2/
[21] https://www.ncas.ac.uk/en/2156

The MRC-Public Health England funded Centre for Environment and Health: Provides researcher training for those engaged in assessing the impact of aerosols and pollution on health (including fundamental biological sciences as well as epidemiology and modelling).

MRC: Does not currently fund any Doctoral Training Partnerships focused specifically on aerosols in healthcare, although research may be in specific disciplines as isolated projects in biomedical engineering, or physiology.

NERC: Currently funds doctoral training throughout the National Centre for Atmospheric Science network, as well as several of its core Doctoral Training Partnerships (e.g. GW4+, the London NERC Doctoral Training Partnership [Environmental Pollution workstream], E3 Doctoral Training Partnership [Atmosphere & Climate workstream], or Cambridge Earth System Science NERC DTP). Although containing elements of aerosol research and training, again these are fragmented and distributed nationwide

BBSRC: Has funded 12 Doctoral Training Partnerships with cohort intakes between 2015-19 across its core themes of Agriculture and Food Security; Bioscience for Health; Industrial Biotechnology and Bioenergy; World-class underpinning bioscience; and Exploiting New Ways of Working. Many of these programmes involve research involving aerosols (e.g. crop disease transmission, virology of veterinary disease; cellular response to particulates).

BBSRC Doctoral Training Accounts: Individual universities allocate studentships through local centres of excellence. Examples of studentships and training grants listed in the BBSRC's awarded grants reveal a range of programmes (e.g. BB/P504610/1; BB/K012762/1; BB/L502492/1; of BB/R505936/1) that study aerosol particles or their interactions with biological systems.

EPSRC engages in the most extensive programme of thematically-focussed doctoral training programmes through their Centre for Doctoral Training funding approach. Since 2013, EPSRC has funded 115 focused centres on a variety of diverse topics. Several of the funded centres have included research programmes which include elements that could be classified as aerosol research. For example in: EPSRC CDT in Advanced Therapeutics & Nanomedicines; EPSRC and MRC Centre for Doctoral Training in Optical Medical Imaging - Training the next generation of scientific entrepreneurs in healthcare technologies; EPSRC CDT in Complex Particulate Products and Processes; EPSRC CDT in Condensed Matter Physics; EPSRC CDT in Fluid Dynamics; EPSRC CDT in Fluid Dynamics Across Scales; EPSRC CDT in Formulation Engineering; EPSRC CDT in Graphene Technology; EPSRC CDT in Medical Imaging; EPSRC CDT in Micro- and NanoMaterials and Technologies. The EPSRC also operates institutional doctoral training partnerships that support researcher training in centres of excellence in the chemical, engineering, mathematical and physical sciences.

Figure 4.1 Examples of researcher training and development provision delivered across the UK's research council funding schemes

Stakeholder Engagement Workshops

5. Stakeholder Engagement Workshop to Define Research and Training Priorities in Aerosol Science

Aerosol science has emerged in the 21st Century as a research area which is economically important, has profound implications for the health and wellbeing of global populations, and the study of which is required to address some of the largest politico-ethical issues of our time; namely the ecological and environmental effects of anthropogenic pollution, and the management of climate change. For this reason, in Summer 2017, several members of the Aerosol Society initiated a project to convene a workshop of the United Kingdom's leading industries and public-sector organizations involved in aerosol research. The objectives of the workshop were to: examine how they ensure appropriate researcher training of their workforce; assess how they interact with existing researcher training programmes; and examine whether the graduate and postgraduate talent pool in the UK is appropriately equipped to fulfil the needs of the leading UK and global employers.

5.1 Process and Assembled Contributors

Participants were invited to attend the workshop if they:

- Represent organizations that had attended or contributed to Aerosol Society Focus Meetings or Conferences (e.g. DDL Conference).
- Correspond to public-sector bodies with responsibility for research into aspects of aerosol science (e.g. Public Health England, Pirbright Institute).
- Contribute to research programmes that have been funded by UK Research Councils (including in several cases organization with experience of contributing to EPSRC, BBSRC, NERC and/or MRC doctoral training centres/partnerships).

The Stakeholder Engagement Workshop took place on **08 January 2018**, at the **University of Hertfordshire** in Hatfield, Hertfordshire. The attendees present are listed in Appendix 1.

5.2 Programme and Objectives

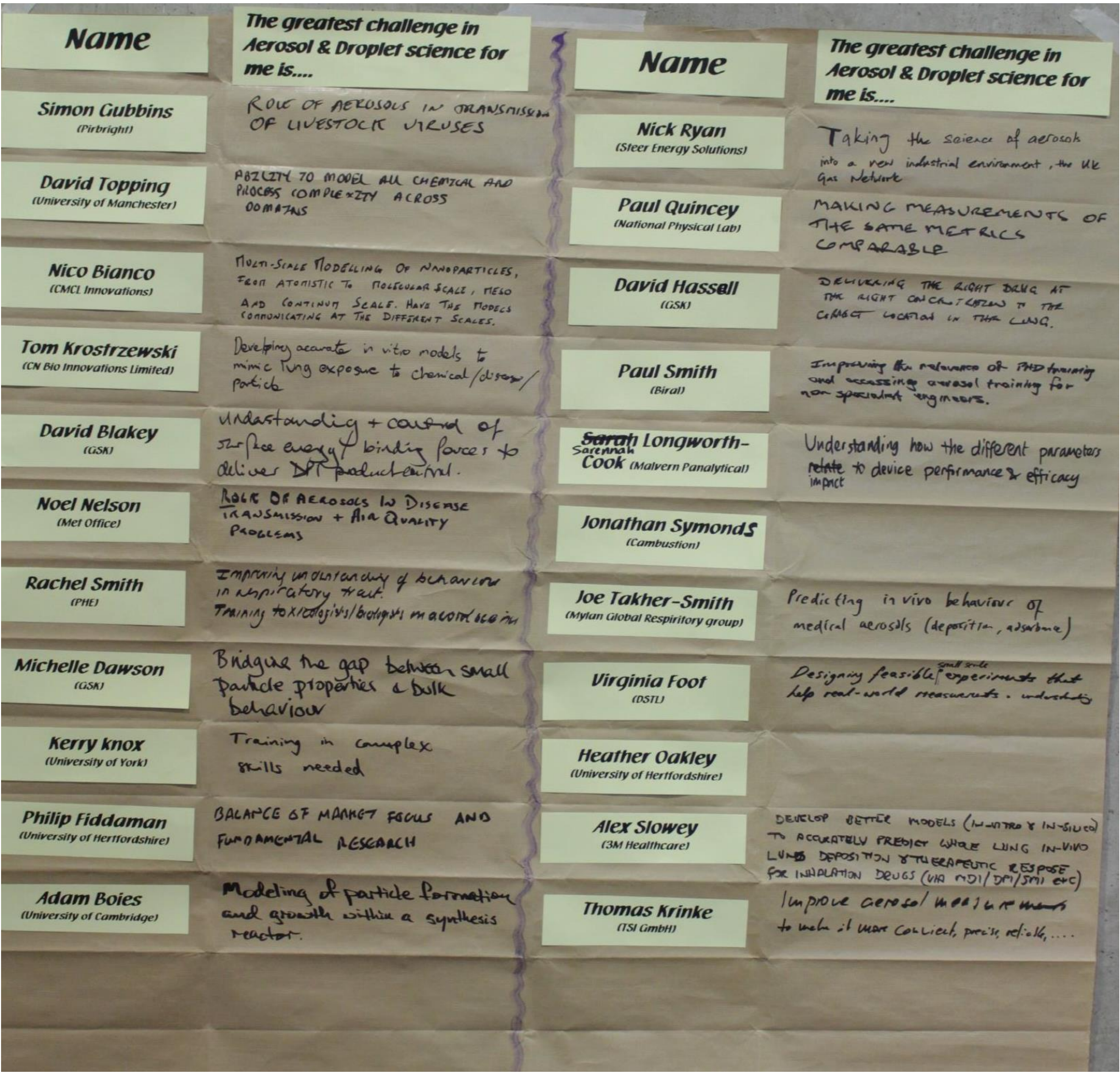
The programme for the day included the following activities:

- Introduction and overview of research funding and doctoral training models that would support aerosol science in the United Kingdom;
- Group working to identify industrial training and research requirements;
- Group working to prioritise training requirements;
- Group working to map out a potential PhD studentship training journey;
- Plenary discussion to identify models to address the Government's Industrial Strategy for technology and workforce development.

The objectives of the engagement day were defined as follows.

- To draw out critical research objectives for each specific industry related to the field;
- To explore the training needs for both the current and the future employees in their sector;
- To identify the structures in which the training and education can be delivered;
- To share ideas for ongoing industrial engagement with researcher training;
- To agree on key words that describe core concepts required in the training of aerosol science researchers.

Setting out the Stakeholder Challenges in Aerosol Science



5.3 Statements of Personal Challenges in Aerosol and Droplet Science

Individual attendees were asked to suggest their key personal challenges and topics of importance that could be addressed within the context of doctoral training programmes. The statements identified included the following:

- Understanding the role of aerosols in transmission of livestock viruses
- Ability to model all chemical and process complexity across aerosol domains
- Multi-scale modelling of nanoparticles from atomistic to molecular scale, meso and continuum scale; to have the models communicating at the different scales
- Developing accurate in vitro models to mimic lung exposure to chemicals/diseases/particles
- Understanding and control of surface energy/binding forces to delivery dry powder inhaler products
- Role of aerosol in disease transmission and air quality problems.
- Improving understanding of behaviour in respiratory tract; training to toxicologists and biologists in aerosol science
- Bridging the gap between small particle properties and bulk behaviour
- Training in complex skills is needed
- Balance of market focus and fundamental research
- Modelling of particle formation and growth within a synthesis reactor
- Taking the science of aerosols into a new industrial environment, the UK Gas Network
- Making measurements of the same metrics comparable
- Delivering the right drug at the right concentration in the correct location in the lung
- Improving the relevance of PhD training and accessing aerosol training for non-specialist engineers
- Understanding how the different parameters impact on device performance and efficiency
- Predicting in vivo behaviour of medical aerosols (deposition, absorption)
- Designing feasible small-scale experiments that help real-world measurement and understanding
- Develop better models (in vitro and in vivo) to accurately predict whole lung in vivo lung deposition and therapeutic response for inhalation drugs
- Improve aerosol measurement to make it more convenient, precise, reliable
- Predict performance, manufacturability, and stability of inhaled medicines with high fidelity

- Achieving optimal device performance and in time to meet customer expectations; managing suppliers material changes in order to minimize the impact to our customers and our business
- Developing a bioaerosol instrument that meets the needs of the aerosol community with respect to sensitivity and specificity
- Gain understanding and capture ideas
- Predicting performance after stability storage
- Turning lab into real-world performance
- Accurate categorisation of particulate matter in real time
- Linking data on droplet/aerosol size to formulation parameters
- Accurately characterising sub-micron aerosols for mass spec ion source
- Translating in vitro data into in vivo exposure
- Understanding a multi-disciplinary approach utilising aerosol science to understand biological processes
- Aerosol sample conditioning and transport
- Understanding science of aerosols to be able to develop commercial technologies, health treatments and manufacturing processes
- Appropriate error analysis prior to modelling – error propagation
- Modelling light matter interactions in a practical way
- Understanding particle-particle; particle-fluid and particle-interface interactions under dynamic charge conditions
- To understand droplet creation, break up and evaporation and confirmation of theoretical predictions
- How formulations designed to be used as aerosols are formulation-dependent or effected.
- The art of the possible
- Sensing and characterization of aerosols in the environment
- Developing skilled, practical staff with a side view of applied aerosol science and security

5.4 Research and Training Priorities

Attendees worked in groups to identify core challenges and topics which scientists working in their organizations undertake. Each group then grouped the identified topics into core training elements. The member of the group then selected the three most important elements that would need to be addressed to ensure that a new entrant to their workforce did not need any specialist on-the-job context training in aerosol science. The information gathered from each group is presented in Appendix 2 including the importance ranking given to the individual training topics. The training and research priorities were then thematically analysed to identify the cross-cutting training topics to identify knowledge, skills and competencies for each group.

Aerosol foundations
- Particle droplet interactions
- Prediction of aerosol dispersions
- Statistics of aerosol characterisation
- What is the science of the nanoscale
- Electrical properties and charging of aerosols
- Surface interactions

Respiratory behaviour
- Modelling lung deposition
- Impact of excipients on aerosol size
- Behaviour of aerosols in the lungs

Modelling & Mathematical techniques
- Modelling lung deposition
- Computational fluid dynamics
- Prediction skills
- Modelling aerosol formation & droplet drying
- Modelling evaporation

Measurement science
- How to develop aerosol characterisation methods
- Rapidly determine size distributions in real-time
- Detection of viruses in aerosols

Bioaerosol
- Detection of viruses
- In what part of the aerosol phase is the virus found

Practical & Transferrable Skills
- Problem-solving
- Developing instrumentation
- Statistics of distributions

Figure 5.1 Key training and research themes identified by Group 1

Practical & Transferrable Skills
- Engineering skills – design & manufacture for experiments
- Appraise and assess different technologies to accelerate R&D
- Willingness to challenge convention
- Problem-solving & analytical skills
- Being able to overlap between sub-disciplines
- Hands-on opportunities to perform aerosol science
- Ongoing training for industrialists

Policy and Regulatory Issues
- Environmental impacts
- Regulatory framework for medicinal aerosols & exposure

Respiratory behaviour
- How to optimize aerosol yield in the lung
- Detailed modelling of health impact

Modelling & Mathematical techniques
- Quantification of aerosol metrics
- Standardization of models
- Design of experiments statistics
- Prediction performance and manufacturability of aerosol systems
- Multiscale modelling atomistic-continuum
- Data analysis/chemometrics

Measurement science
- Quantification & qualification of measurements
- Digital engineering skills for sensor development
- Standardization of techniques
- Instrument development
- Industrialisation of common techniques

Aerosol foundations
- Understanding the fundamental science behind measurements
- Lack of knowledge of aerosol foundations in undergraduates
- Universal modelling of aerosol behaviour

Figure 5.2 Key training and research themes identified by Group 2


What are the priorities for Research & Training in Aerosol & Droplet Science?

Practical & Transferrable Skills
- Decrease waste & costs of goods through aerosol generation
- Bridging understanding form basic science across different industrial sectors
- Move to application-focused activity instead of response to regulatory standards
- Ability to tolerate ambiguity in data & use incomplete datasets
- Project management
- Commercial scale-up of technology

Environmental impacts
- Understanding environmental fate of aerosol
- Solutions to reduce ambient pollution
- Impact of airborne particles on climate change

Respiratory behaviour
- Health impacts of aerosol particles in real life
- Global epidemiology and health impacts
- Drug delivery to the lungs
- Analytics for whole lung deposition
- Drug-drug interactions & sprays
- Building better biological models

Modelling & Prediction
- Use of physical science to mimic biological effects
- Data creation & analytics
- Translate in vitro measurements to human responses
- Predictive approaches to minimize analytical burden

Measurement science
- Understanding existing technologies to foster new ideas
- Creating new low-cost sensors
- Be able to communicate instrument needs to suppliers
- Measurement of charge under dynamic conditions
- Real-time particle characterisation
- Aerosol collection

Aerosol foundations
- Understanding realistic application of characterization techniques
- Bridge gap between particles and molecules
- Chemical composition of aerosols
- Effect of environmental conditions on aerosol growth/charge
- Effect of particle composition on charge
- Light scattering sciences
- Engineering particle structure
- Aerosol transport phenomena
- Novel controlled droplet production

Figure 5.3 Key training and research themes identified by Group 3

Practical & Transferrable Skills
- Accept incomplete data
- Be able to apply specific aerosol knowledge to all sources of particulates
- Researchers who can think outside their own area of experience
- Hands-on experience
- Ability to adapt and compromise
- Practical skills in engineering
- Real-world awareness and application in 'dirty' environments
- Ability to achieve short-term results
- Good understanding of exploitation needs to apply sciences
- Collaborative projects required

Respiratory behaviour
- Understanding drug delivery to the lungs
- What is the influence of fine particle mass
- Mechanisms of disease transmission during inhalation
- Detailed understanding of aerosol in disease transmission
- Airborne bacterial/virus viability and infectivity

Aerosol foundations
- Particle-particle interaction science (e.g. drug-drug)
- Light scattering & absorption processes
- Controlling particle structure

Measurement science
- Teaching of analytical techniques
- Meaningful testing approaches
- Build instrumentations and test them, not all theory!
- Dynamic characterisation techniques
- Low cost instruments /sensors for retrieving virus aerosol
- Full characterisation of aerosol suspected of causing health impacts

Figure 5.4 Key training and research themes identified by Group 4

6. Defining a PhD Researcher Training Journey

Attendees worked in groups to identify approaches in which the multi-disciplinary skills, knowledge and attributes identified in Section 5 required of an aerosol science researcher could be developed through a structured PhD programme. Attendees self-selected one of five groups in which they could work, based on a range of PhD research topics that were pre-selected to provide coverage of several European Aerosol Assembly Subject Groups (Table 2, above). The broad subject areas were:

- Basic Aerosol Processes (Groups 1 & 4)
- Aerosols and Health (Groups 1, 4 & 5)
- Atmospheric Aerosols (Groups 2 & 3)
- Aerosol Technology (Group 2)
- Measurement Techniques (Groups 3 & 5)

The objectives of the workshop task were completed as follows:

- For the relevant subject expert practitioner(s) in the group to select a broad research question to be investigated in the PhD programme;
- For the relevant subject expert practitioner(s) to outline the range of technical skills, knowledge and anticipated investigations that would be required to address the broad research question (named 'Intra-Theme Skills');
- For non-subject expert practitioners(s) to propose technical knowledge, skills and competencies which the student could develop from a placement undertaken in their sector (or formal training relevant to their subject) which would enhance the PhD student's ability to address his/her research question ('Inter-Theme Skills');
- For the group to examine the best training route for development of technical knowledge, skills and competencies (i.e. through a formal taught programme; 'on-the-job' practical and vocational learning during placements or project work);
- For the group to examine the role of industrial or public sector organizations in researcher training and development in aerosol science.


TITLE
Atmospheric Aerosols
Yr 1,2,3,4 Coursework
Yr 1 Academic Placement
Yr 1 Industrial Placement
Yr 2-4 PhD Project
WORKSHOP SKILLS?
SHADOW? YR2?
MEASUREMENT OF MIXTURE OF VOLATILE ATMOSPHERIC PARTICLES
Intra Theme Skills
Inter Theme Skills
Broader Skills

Exemplar PhD Researcher Development Programmes

In total five research programmes were investigated across four workshop groups and these are presented in their unprocessed format in Appendix 3. Two of the researcher development programmes that were developed by the workshop groups are presented in Figures 6.1 and 6.2 below, in order to illustrate the typical training and learner journeys developed by the groups. The outcomes of the workshop exercise were summarized as follows:

- Stakeholders from academic, industrial and public sector research organizations identified a wide range of core knowledge and skills required to undertake any doctoral-level research programme in aerosol science;
- Many of the specific knowledge requirements to undertake research programmes in aerosol science overlapped between specific research themes and programme titles;
- A range of skills and competency outcomes were identified across all stakeholder groups. Some groups emphasized the importance of transferrable skills and professional competencies, compared to other groups that emphasized technical skills and competencies to undertake the research programmes;
- All groups were highly engaged and identified the opportunity and importance of cross-cutting inter-disciplinary knowledge development through formal taught programmes to equip researchers to work across disciplines;
- An ‘extra-disciplinary’ research placement within an academic institution was identified as a key way to equip researchers with collaborative and cross-disciplinary practical skills and competencies;
- The academic placement was viewed as an opportunity to develop hands-on experience (e.g. practical skills or modelling competencies) and apply knowledge outside the direct field of research to enable scientists to bridge the gap between disciplines as research practitioners;
- The industrial placement was viewed as a key opportunity to develop ‘real-world’ research experience, and to apply their knowledge and/or research outcomes in a commercial or technology development setting;
- Several industrial stakeholders saw the industrial placement as an opportunity to focus on professional development, however it was agreed a placement later in the programme would enable technical skills application and research collaboration to flourish;
- The stakeholders were supportive of using an industrial placement to develop transferrable skills of project management, regulatory issues, commercialization and policy development;
- All stakeholders were supportive and saw the need for greater connection between academic (and industrial) groups to undertake collaborative, inter-disciplinary research and development programmes.

Research Theme:	Basic Aerosol Processes
Research Programme Title:	Maximization of aerosol unipolar charging

Training delivery method	Formal taught programme	Academic research placement	Industrial placement	PhD research project
Programme-specific training topics: “Intra-theme skills”	• Droplet generation • Charging/electrostatics • Break-up/evaporation • Fluid dynamics • Size distribution • Surface interactions	• Measuring techniques • Mass/charge ratio	• Ink jet industrial processes	• Droplet charging • Spray painting • Maximum ionization for ion sources • Reduction of Pollutants
Cross-disciplinary training topics: “Inter-theme skills”	• Gauss’ equation • Maxwell’s equations • Statistical analysis • Data processing • Lung modelling	• Measurement techniques • Droplet size distribution • Microscopy • Laser Doppler anemometry • Laser induced fluorescence • Lung modelling	• Aerosol technologies	
Transferrable and professional training topics: “Broader skills”	• Project & time management • Maths and computer methods • CFD packages • Problem-solving • Presentation	• Presentation skills • Project & time management	• Presentation skills • Project & time management • Marketing and financial management • Product specifications	• Presentation skills • Project & time management

Figure 6.1 Researcher Development Programme for a PhD Project in Basic Aerosol Processes

Research Theme:	Aerosols and Health			
Research Programme Title:	**Disease transmission and treatment through targeted lung delivery**			
Training delivery method	**Formal taught programme**	**Academic research placement**	**Industrial placement**	**PhD research project**
Programme-specific training topics: "Intra-theme skills"	• Sterilization • Cell Biology & Virology • Ethics & clinical trial • Regulatory requirements • Dosimetry • ADME/transport/clearance • Advanced health impact • Deposition modelling	• Clinical placement • Target engagement • Disease transmission • Measuring PM • Source characterisation • Deposition systems • Epidemiology	• Spray drying • Particle engineering • Measurement technologies • Aerodynamic characterisation Inhalation toxicity • Regulatory context	• Lung imaging • Microbiology • Identification of where the pathogens are • Advanced cell biology • Choice of cell types
Cross-disciplinary training topics: "Inter-theme skills"	• Immunology • Detection/microscopy • CFD/Lung deposition • Dissolution kinetics • Thermodynamics • Phys/Chem characterisation • Aerosol lung interactions • Disease states	• Aerosol dispersion • Biosafety • Epidemiology • Microbiology • Atmospheric and environmental aerosols • Aerosolisation & devices • Lung physiology	• Aerosol technology • Aerosol delivery systems • In vivo/in vitro testing systems • Understanding limitations of test systems • Chemical analysis	• Environmental modelling • Epidemiology
Transferrable and professional training topics: "Broader skills"	• Toxicology • Good lab practices • Ethics and clinical • Regulatory • Policy/Governance			

Figure 6.2 Researcher Development Programme for a PhD Project in Aerosols and Health

7. Models for Industrial and Public-Sector Stakeholder Engagement in Researcher Development

The fundamental consensus from the Industrial Stakeholder Workshop was that the training needs identified are currently achieved only through on-the-job training of postgraduates who enter occupation within the organizations present.

Approaches for companies to engage with universities on projects and training

- Annual review of each PhD as part of a summer school with invited guests
- Ensuring fundamental science is addressed through formal taught programmes
- Contribute to PhD and Post-Doc events for students and supervisors
- PhD cohort to present to industry
- Provides a vehicle for company CPD
- Provide Access for training to companies' current employees
- Clarity over the purpose of industrial placement so that company can prepare correctly

Benefits of short-term student placements in the company

- Will develop good future employees, ready to hit the road running
- Offers independent peer review of on-going work, which is cost-effective especially for regulation
- Can inform product road map and current working practices in the company
- Access to expertise that isn't the company's core business
- Access to equipment that isn't the company's core business
- Creates an agile workforce for the future
- Creation of a T-shaped PhD graduate entering the workforce

Barriers to short-term student placements in the company

- Will need a vision for ownership of data e.g. will the student need to feed all the data from the company placement back into the project?
- Provisions to delay sharing of data if patent is in the process
- Sharing of information beyond an individual company and project collaborator relationship is potential
- Nationality and security risks for government work
- Barriers to non-UK students exist in the current models

- May be barriers for non-UK industries to contribute and this is a global industry
- Brexit creates a barrier due to the international aspect of the companies and potential placement sites
- IP is a barrier and an opportunity, so need to work out open innovation/pre-competitive model
- Companies ability to invest in economically volatile times

Structures to be developed to feed collaborations into doctoral training

- Contracts for internal development programmes
- Potential for shorter research projects: “Package in blocks for benefits in blocks”
- PhDs to be advertised up front, agreed with partner in advance
- Need to agree an overarching governance framework, to assess whether a project is on-track, and ensure that risks are managed
- Funding and budget structures must be identified and agreed
- Relationship to be established to support skills development
- A link to the Aerosol Society is important, to provide longevity of initiative and outcomes beyond 8 years of operation
- Need to develop IP structure based on: assignment to specific sponsors, join industry/university ownership or shared amongst all partners.

8. Industrial and End-User Engagement Feedback

8.1 Immediate Informal Feedback

As participants in the workshop were provided the opportunity to feedback as a group, all of whom expressed an interest in future involvement in the doctoral training of aerosol scientists in some format, based on Figure 8.2, below. This was based on the work that participants to define the structure of a multi-disciplinary PhD researcher development programme in Section 6. There was clear immediate consensus (Figure 8.1) that the structure was a valid way forward which secured industrial and public-sector approval as a model for doctoral training in the UK.

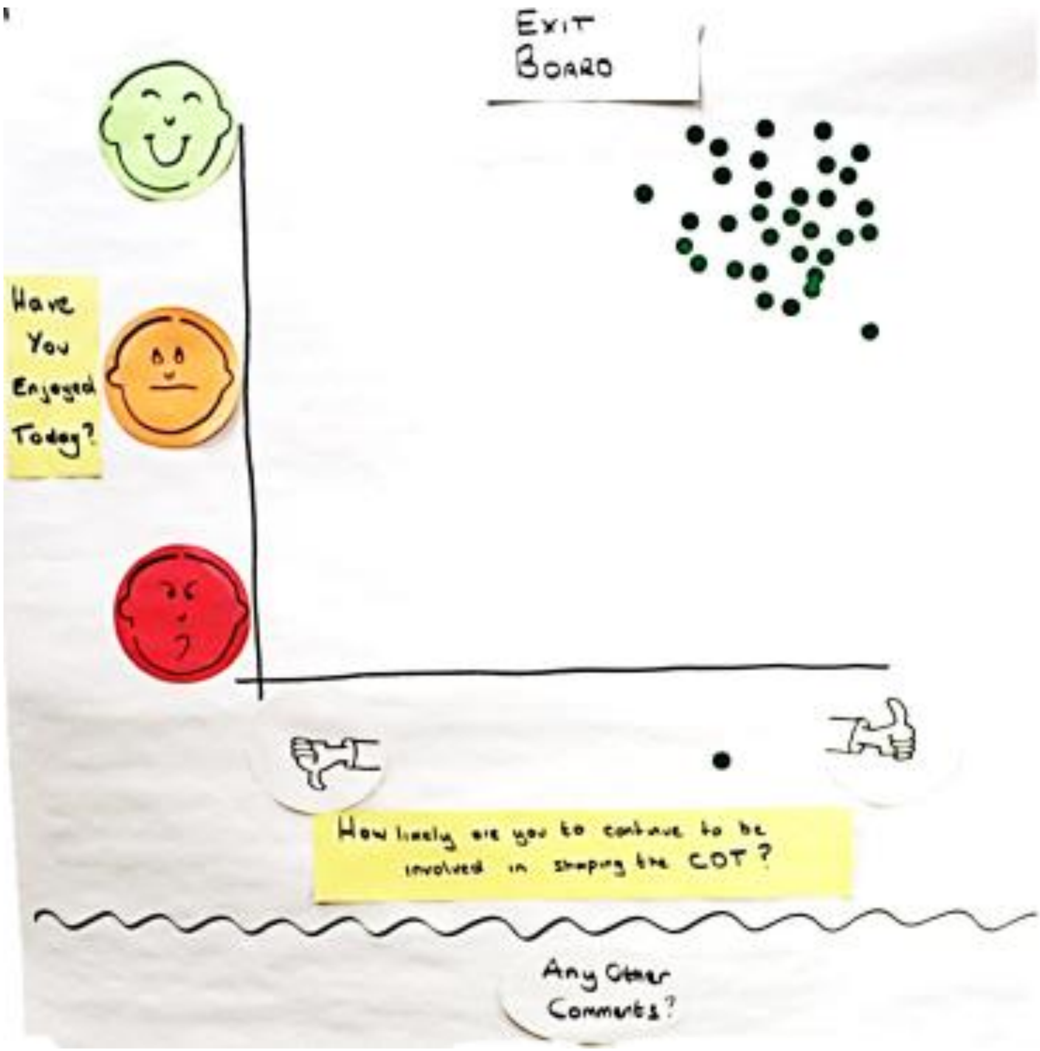


Figure 8.1 Feedback from participants in the workshop of their overwhelming desire to participate in a doctoral training centre in aerosol science.

8.2 Survey Objectives and Content

Following the Industrial Workshop all responses from the participants in the workshop were published as an interim review on the website of the Aerosol Society:

https://aerosol-soc.com/assets/uploads/2018/02/ESPRC-Industrial-Engagement-Workshop-Jan-2018-Write-Up.pdf

A draft proposal for a structure for doctoral training programme involving inter-disciplinary researcher was constructed drawing on the common structures from the individual PhD Learner Journeys (Section 6). The common structure is presented in Figure 8.2 below, which incorporates the proposal for industrial/end-user involvement in PhD mentoring and formal training which emerged from the Workshop.

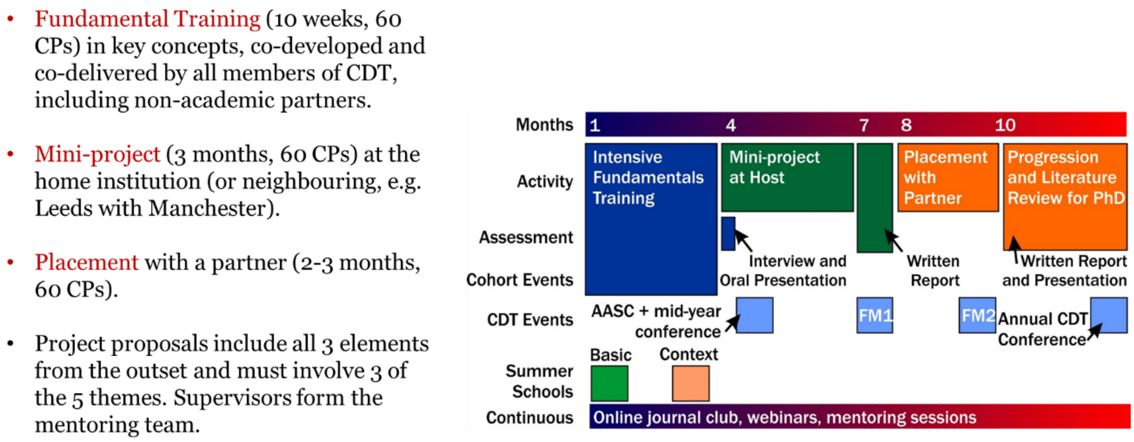


Figure 8.2 Structure for formal education and training programme to prepare scientists for interdisciplinary doctoral level research careers.

Additionally, the formal training and development topics (Figure 8.3) were presented for stakeholders to review during an online consultative survey which was run throughout Feb-March 2018. This consultation provided participants with an additional opportunity to provide feedback and propose iterations on the approaches which had been developed in the workshop.

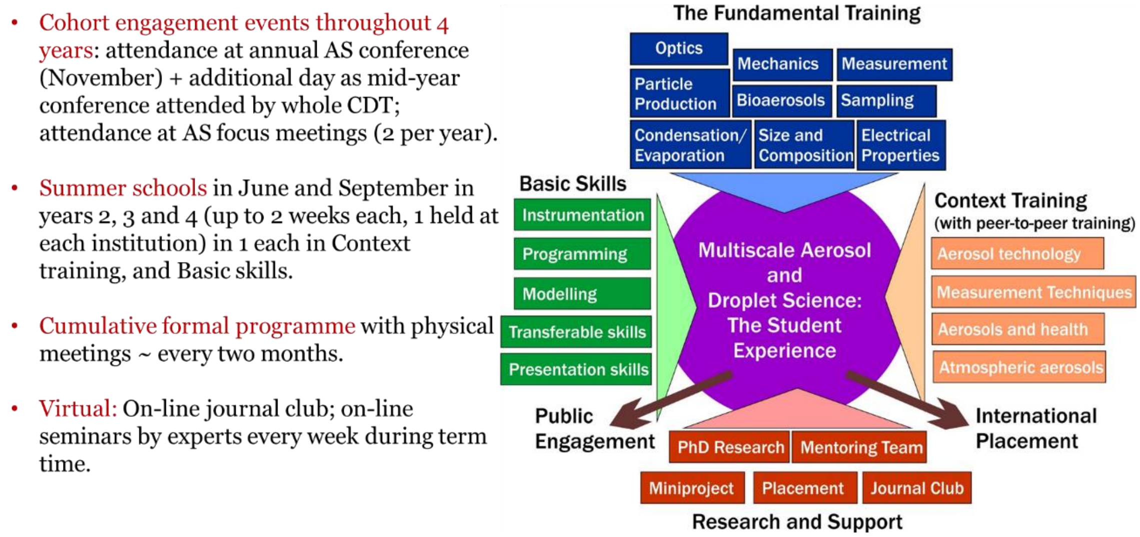


Figure 8.3 Key training and researcher development programme components for delivery throughout the 4-year doctoral training programme for aerosol scientists

8.3 Survey Summary Results

Of the responses to the survey 92% of respondents identified that their organization experienced a difficulty in recruiting scientists with the appropriate knowledge, skills and expertise to work in aerosol science research. The number of individuals in the companies requiring a formal knowledge of aerosol training varied from 3 individuals to as many as 75 individuals depending on the organization. It was of note that in those companies with a smaller aerosol science workforce, the proportion of employees who had any training (informal or formal) in aerosol sciences ranged from 0 % (in one company with three employees working with aerosols) to as high as 50 % of employees (one company with four employees working with aerosols). However, in total, the self-selected sample of 15 companies had a requirement for over 200 aerosol researchers at any given time, of whom on average 12 % had received any formal training that enabled them to undertake their research work. 67 % of online survey participants stated that they would be interested in hosting doctoral students for industrial training placement. 70 % of respondents expressed an interest in contributing to the training programme itself (e.g. developing training materials), and 69 % of respondents indicated they would engage in PhD research partnerships in an integrated, multi-disciplinary researcher development programme.

Qualitative Feedback on the Skills Gaps Faced by Organisations that Engage in Aerosol Science Research

- Aerosol Science tends to fall between the gaps in the UK, so from our point of view, formal training in this area would be useful
- We currently lack the tools to explore in detail the role played by aerosols in disease transmission (e.g. the particle size distribution of aerosols, which size particle the pathogen is found, survival of pathogen in each size particle). The CDT would help us to begin to develop suitable tools to begin to address these questions.
- Aerosol science is a huge research area. The capability of the students to apply knowledge of aerosol science across multidisciplinary areas covering physics, chemistry and biology would be invaluable.
- There is a growing need for our services in the aerosol area, but we have trouble expanding the group with people who have the relevant skills.
- There is insufficient understanding of aerosol science going into the design of products to treat respiratory diseases.
- For our area of research, respiratory medicines, the background of a typical employee (e.g. pharmacist, chemist, engineeer) does not include any formal training in aerosol science. This places a significant internal training burden and learning curve for all new employees.
- When we advertise aerosol science posts we are lucky if we get a single applicant with appropriate skills. Some potential candidates with some background in this area have a very narrow focus. The CDT would produce a greater number of qualified potential applicants with a suitable wide background training in many aspects of aerosol and droplet science. The courses developed would also be very useful for our staff who are not specialists but need targeted training in specific areas.
- An understanding and appreciation of the physical processes behind aerosol science. There is currently a lack of fundamental understanding amongst graduates.
- Ability to bridge the gap between academia and industry, especially for an SME
- A key activity of the Environment Agency is managing air pollution, and primary and secondary atmospheric aerosols form a key component of this. We need technical specialists who understand the fundamental properties of aerosols in order to inform our positions on control measures, likely impacts and how best to monitor such pollutants
- Multiscale modelling of aerosols - atomistic to continuum
- There is a lack of expertise in Bioaerosol Science in the non-defence centre in the UK
- Transfer of knowledge and skills from more technologically advanced sectors (automotive, aerospace) to agriculture

Qualitative Feedback on Training and Development Topics to Supplement those Highlighted in Figures 8.2 and 8.3.

- No, the design of the doctoral training approach seems eminently sensible
- Ability of the aerosol scientists to engineer solutions
- An emphasis on measurement techniques and their uncertainties.
- Secondments of at least 6 months duration into industry laboratories
- The themes and topics covered during the industrial engagement day captured everything well.
- Our focus is public health research so the development of a training module in this area so that budding aerosol scientists can understand how they can contribute in this exciting area would be useful. In general it would help to include some outreach activities to try and raise the profile of the science and its importance in many areas - trying to make aerosol science more generally 'sexy'.
- A basic understanding of aerosol sampling techniques.
- How to take concept from the lab to the market i.e. full knowledge of the NPD/NPI process.
- Incorporating a strong fluid dynamics component would be of great relevance in meeting our objectives around source-pathway-receptor modelling and monitoring design.
- Projects focusing on interoperable modelling of multi-phase particulate processes, based on a standard ontology shared between academia and industry.
- Focus on the interface between biological science and aerosol physics. Do not get hung up on modelling. Develop new air sampling techniques that can be interfaced with emerging techniques in biological science
- Understanding of environmental fate of spray droplets. Cross industry learning and knowledge transfer.

Qualitative Feedback on the Need for Multi-disciplinary Doctoral-level Researchers Capable of Working Across and Between Multiple Traditional Disciplines.

- Aerosol/droplet science is inherently multidisciplinary. It is important that students get exposed to the different facets of the field and the CDT will facilitate this.
- value of multidisciplinary scientists
- A doctorate containing a variety of elements is most likely to produce knowledgeable and adaptable recruits.
- Industrial involvement is key to success
- Modern complex projects always require collaborative and multidisciplinary approaches. A lot of good ideas already exist, they just need to be applied to a new area.
- We need to create a wider group of individuals with expertise and skills in aerosol and droplet science to help industry to develop products, wealth and jobs and the public sector to address a wide range of issues including climate change and health. The CDT will not only produce a much needed cohort of specialists with a wide background multidisciplinary training, which will allow flexible career development, but will also develop training which can be used by a wide range of individuals in the wider research area. Working with the Aerosol Society in these developments is an important way to ensure the legacy continues way beyond the CDT.
- An understanding and appreciation of the physical processes behind aerosol science. There is currently a lack of fundamental understanding amongst graduates.
- Solid attempt to create a well-rounded programme
- Air pollution is an inherently multidisciplinary issue, needing chemistry, physics, computational and information science knowledge as well as some appreciation of real-world applications such as protection of human and environmental health
- It makes the dialogue between industry and academia a reality through collaborative doctoral training.
- It is valuable to allow aerosol science to be interfaced into applied activites
- Multidisciplinary is the biggest value point for Syngenta, as it will facilitate transfer of knowledge from other sectors.

9. Conclusions

Research, development and innovation in aerosol science already make a valuable contribution to the United Kingdom research and high-technology economy. There is substantial opportunity and potential for technologies applying aerosol science to continue contribution to economic impact with substantial growth in technology markets including healthcare product development, novel and advanced materials, and instrumentation and sensing technologies. In addition, aerosol science is essential to address many of the issues developing around environmental impacts and climate change mitigation.

Within the United Kingdom, and to an extent on the global stage, there is little focus to the development of researchers in aerosol sciences. A wide range of industrial and public sector research organizations have highlighted the impact that current researcher training paradigms are having on their productivity and skill base. A consensus has been reached that there is a need for an academic-led researcher development programme to equip the United Kingdom's knowledge economy with scientists capable of undertaking doctoral level research programmes, both within the technology innovation sector (industries) and to secure the United Kingdom's future academic research portfolio that is essential to sustain the research and innovation pipeline.

In order to secure the future pipeline of aerosol research and development, this report has identified the urgent need to develop a cohort of research practitioners in aerosol science following a new researcher training model to include:

- A formal expert fundamental aerosol science knowledge curriculum based on the physical and engineering scientists that has been identified through a broad range of industrial and academic practitioners (Table 9.2) ;
- Inter-disciplinary knowledge, skills and competencies to facilitate the highly collaborative and cross-cutting nature of aerosol research programmes, to be delivered throughout a student's entire research programme;
- A strong programme of transferrable skills to be delivered through academic and industrial placements, with an impactful mentoring programme for researchers to develop their ability to hop between disciplines and economic sectors at all stages of the research and innovation pipeline;
- The opportunity to upskill existing workforces who have developed on-the-job knowledge with no formal education programmes. This will also achieve the development of a strong UK-wide community of connected aerosol scientists working in all sectors of research and development.

Table 9.1 Core Curriculum of Knowledge, Skills and Competencies Required of Aerosol Scientists that Equip Researchers to Deliver Doctoral-level Aerosol Research Programmes

Cross-theme Fundamental Research and Training Topics	Transferable skills	Context training
• Aerosol Motion • Aerosol Production • Aerosol Adhesion & Coagulation • Optical Properties • Electrical Properties • Aerosol Reactions • Nucleation & Particle Formation • Condensation/Evaporation • Sampling & Filtration • Particle Size Measurements & Statistics • Chemical Composition • Respiratory Deposition • Aerosol Biological Reactions • Aerosol Instruments • Thermodynamics • Bioaerosols & Microbiology • Bioaerosols & Virology	• Impact and translation of research • Responsible research and innovation • Programming, data analysis and statistics • Equality diversity and inclusion • Public engagement and communication skills • Mentoring and supervision skills • Scientific writing and interpretation • Scientific presentation • Policy and regulatory processes • Aerosol process modelling	• Aerosol technology • Measurement techniques • Aerosols and health • Atmospheric aerosols • Basic aerosol processes

Appendix 1

Attendee Organisations

3M Healthcare

Alphasense

AstraZeneca

Bespak

Biral

Cambustion

CMCL Innovations

CNBio

Defence Science Technology Laboratories (DSTL)

Droplet Measurement Technologies

Dyson

Environment Agency

GlaxoSmithKline

Malvern Panalytical

Met Office

Mylan

National Physical Laboratory

Navitec

Philips Respironics

Pirbright Institute

Public Health England

Steer Energy

Syngenta

Trolex

TSI Inc.

Waters

Appendix 2

Training Requirements Identified in Group Work Indicating cumulative score from each group member awarding a point to each of their three top-ranking topics

Ranking score	Theme	Challenge Topics
Group 1		
6	Basic understanding and foundations	• Particle droplet interactions & physics • Statistics and maths of aerosol characterisation • Problem-solving skills • What is the nano-scale? • How to develop aerosol characterisation methods, with hands on experience of instrument development • Rapidly determine size distribution in situ, real-time with good spatial distribution • Predicting dispersal of aerosols at different scales
5	Aerosol-Lung delivery	• Modelling for drug delivery to the lungs • Behaviour of aerosols in the lungs • How excipients affect droplet size of inhaled medicines • Lung deposition modelling & CFD.
1	Drying and evaporation	• Dry particle engineering • Modelling for drying e.g. spray drying • Understanding aerosols from agri-sprays • Model droplet formation from liquid streams • Model evaporation in complex gas flows
2	Bioaerosols	• Which ‘bit’ of the aerosols are viruses in? • Detection of viruses in aerosols

1	Particle-surface interactions	• Interaction of droplets with surfaces • Surface sciences
0	Charging	• Efficient charging of droplets at high flow rates (~2 mL/min) • True effect of charge.

Ranking score	Theme	Challenge Topics
Group 2		
6	Technology development	• Current state of technology & performance in products and markets • Instrument development • Engineering skills – design & making for experiments • Understanding the challenge of the switch from lab to real-world measurement • Bo be able to appraise the benefits and disadvantages of different delivery technologies and accelerate R&D • Quantification of metrics • Standardisation • Replacing outdated techniques/ technologies • Design of experiments
5	First Principles	• Application of fundamental science • Industrialisation of common 'research' techniques • Understanding of fundamental science behind techniques • Understanding fundamental aerosol science theory • Lack of knowledge about aerosol science in undergraduates
4	Modelling and data analysis	• Understanding how to optimize drug delivery (yield in the lung). • Predicting performance, manufacturability & stability of inhaled aerosol medicines • Universal/comprehensive modelling • Multiscale modelling – atomistic to continuum

		• Detailed modelling of mass and number of particles for health impacts • Quantification and qualification of measurements. • Digital engineering for soft-sensor development • Ontology of modelling • Standardization of models • Data analysis technologies: advanced chemometrics, and statistical process control
3	Ways of working	• Willingness to challenge convention • Analytical skills (investigative thinking) and problem solving • Combination of expertise e.g. aerosol science and microbiology • More overlap between sub-disciplines • Ongoing training for industrial staff and integration with universities • Practical 'hands-on' opportunities across multi-disciplines (physics, chemistry, biology, maths) • Public outreach
1	Environmental constraint	• Regulatory framework for inhaled aerosol medicines • Environmental impact of aerosol
0	Usability	• To understand and be able to propose optimization for the patient experience and hence improve compliance

Ranking score	Theme	Challenge Topics
Group 3		
7	Novel measurement technology	• Understanding of existing measurement technologies to foster new ideas • Creation of accurate, reliable, low-cost sensing platforms • Novel technologies for aerosol sensing • Research professionals communicating their instrument needs and required capabilities to instrument manufacturers • Measurement of charge on particles under dynamic conditions
7	Fundamental science	• Understanding realistic application of characterisation techniques • Students aware of various measurement techniques and what is commercially available • Bridge the gap between particles and the molecules • Chemical composition of single particles • Real-time particle categorisation • Effect of environmental conditions on particle growth/charge • Effect of particle morphology/make-up on charge build-up in heterogeneous mixtures
5	Cross-industry translation	• Novel aerosolization mechanisms • Decrease waste and cost of goods through more efficient aerosol generation • Bridging understanding form different industrial sectors to generate knowledge

		• Move from responding to regulatory requirements to responding to application needs • Physical understanding crosses industries, ned to take knowledge into new sectors • Develop consistent/overarching aerosol science field that cuts across different sectors • Appreciation of how research can translate across applications
5	Environmental/health impacts	• Solutions/technologies to reduce ambient pollution (different sectors) • Understanding the environmental fate of aerosols • Health impacts of airborne particulate matter in everyday life • Global health effect of aerosols, what do we know and what we don't know yet • Impact of airborne particles on climate change
4	Aerosolization	• Understanding the role of formulation and application in atomisation • Novel techniques for controlled droplet production • Commercial scale-up of nano/aerosol processes for industry • Predictive technologies to enhance understanding and decrease analytical burden • Consistent processability to counter challenges of micromeritics • Link outcomes of atomisation processes to formulation properties
3	Transport and deposition	• Methods for efficient capture of aerosols

		• Consistent and controlled delivery to the lung • Better and more controlled targeted underpinned by understanding • Indoor & outdoor aerosol transport including deposition, reaerosolisation, modelling
2	Predictive technology	• Understanding of how physical science can be used to mimic biology • Translating in vitro measures into human response • Ability to understand how mathematical models can aid development of better biological models • Building accurate models to mimic human organisms
0	Industry training and skills	• Produce scientist that can contribute to growth of the industry in the UK • Project management
0	Data management	• Data analytics • Data creation

Ranking score	Theme	Challenge Topics
Group 4		
9	Processes	• Understand device vs. formulation • Understand where the future landscape is for propellants • Understand drug delivery to the lungs in all its forms • Developing better analytics to understand whole-lung deposition (in vitro/in vivo/in silico). • Understanding drug-drug interactions in suspensions • What influence fine particle mass • Light scattering and absorption in particles • Measuring particle morphology/shape • Sprays • Controlling particle functionality/structure • Collection
9	Real world	• Practical skills – how to make and engineering ‘stuff’ • Awareness of real world context of aerosols in environments • Real world application in dirty environments, not lab-based • Ability to tolerate ambiguity/incomplete data
8	Training	• Accept incomplete data • Not just focused on aerosol aspect • Should be ‘aerosol aware’ and apply knowledge to all sources of particulates • Researchers who can think outside of their area of experience • Development of practical, hands-on experience

		• Abilities to adapt and compromise • Preparing for diverse professional destinations (across cohort and for each person) • Ability to reflect on professional practice and development
6	Collaboration and communication	• Developing individuals with a good understanding of the industrial ned and application of aerosol and droplet science • Using aerosol expertise to solve industrial problems • Ability for short term results in aerosol science problems • Cross-sector understanding e.g. how can understand pollutant aerosols lead to new therapeutic areas • Wanting more open innovation vs. restrictive IP situations • Security • Optimisation of existing knowledge • Continuity of projects, not a series of one-off studies • Projects that involve working with others • High-risk new topics • Applications to other areas including collection, preconcentration and capture
2	Instrumentation	• Teaching in analytical techniques • Meaningful testing • Consistent measurements • Build and make something to be tested, not all theory • Dynamic characterisation techniques • Low cost instruments for measuring and retrieving virus

		aerosols which are both sensitive and robust
0	Health	• Mechanism of disease transmission during inhalation and exhalation process • Detailed understanding of aerosols in disease transmission • Full characterisation of aerosols suspected of causing health impacts • Airborne bacteria/viruses viability and infectivity

Appendix 3

PhD Researcher Learning and Training Journeys Developed in Workshop Groups

Subject	Basic Aerosol Processes			
Research programme	Maximization of Aerosol Unipolar Charging			
	Formal taught programme	Academic placement	Industrial placement	Research Project
Intra-theme skills	• Droplet generation • Charging/electrostatics • Break-up/evaporation • Fluid dynamics • Size distribution • Surface interactions	• Measuring techniques • Mass/charge ratio	• Ink jet industrial processes	• Droplet charging • Spray painting • Maximum ionisation for ion source • Reduction of pollutants
Inter-theme skills	• Gauss' equation • Maxwell's equations • Statistical analysis • Data processing • Lung modelling	• Measurement techniques • Droplet size distribution • Microscopy • Laser Doppler anemometry • Laser induced fluorescence • Lung modelling	• Aerosol technologies	
Broader skills	• Project/time management • Maths/computer methods • CFD packages • Problem-solving • Presentation skills	• Presentation skills • Project & time management	• Presentation skills • Project & time management • Marketing and financial management • Product specifications	• Presentation skills • Project & time management

Subject	Aerosols and Health			
Research programme	Disease transmission and treatment through lung targeting & In vitro-in vivo correlation of lung deposition and toxicological effects			
	Formal taught programme	Academic placement	Industrial placement	Research Project
Intra-theme skills	• Sterilization • Biology • Virology • Ethics & clinical trial • Regulatory requirements • Dosimetry • Cell biology • ADME/transport/ dissolution • Advanced health impact • Computational modelling of deposition	• Clinical placement • Target engagement • Disease transmission • Measuring PM • Source characterisation • Deposition systems (aerosols to cells) • Epidemiology	• Spray drying • Particle engineering • Measurement technologies • Aerodynamic characterisation (size/shape etc.) • Inhalation toxicity • Regulatory context	• Lung imaging • Microbiology • Identification of where the pathogens are • Advanced cell biology • Choice of cell types
Inter-theme skills	• Immunology • Detection • CFD/Lung deposition • Particle size distributions • Microscopy	• Aerosol dispersion • Biosafety • Epidemiology • Microbiology	• Aerosol technology • Aerosol delivery systems • In vivo and in vitro testing systems	• Environmental modelling • Epidemiology

	• Dissolution kinetics • Thermodynamics • Phys/Chem characterisation • Aerosol lung interactions • Clearance mechansims • Disease states • Health impacts	• Atmospheric and environmental aerosols • Aerosolisation and devices • Lung physiology	• Understanding limitations of test systems • Chemical analysis	
Broader skills	• Toxicology • Good lab practices • Ethics and clinical • Regulatory • Policy/Governance	•	•	•

Subject	Atmospheric Aerosols			
Research programme	Penetration of atmospheric aerosols into indoor environments or Measurement of mixtures of volatile atmospheric particles			
	Formal taught programme	Academic placement	Industrial placement	Research Project
Intra-theme skills	• Fundamentals of aerosol science (Yr 1) • Lab workshops/skills • Statistics • Metrology • Air quality regulation • Sources of atmospheric aerosol/gases • Phases of matter • Aerosol transport	• Aerosol chemistry • Transport processes • Exposure models	• More relevant in later years • 6 months duration best • Research in the real world • Sampling and analysis • More of a shadowing placement?	• Atmospheric chemistry • Cloud physics • Kinetics • Nanoparticle formation/ nucleation • Aerosol aging
Inter-theme skills	• Sampling and measurement • Non-specialist topics • Physics for biologists • Deposition and resuspension • Mathematical modelling • Surface science	• Exposure sciences • Environmental chemistry • Metrology • Reaction kinetics • Lung physiology • Experimental planning	• Company induction in Year 1 • Research in the real world • Test rig design • Experimental planning	• Measurements • Sampling and characterisation

	• Light scattering • Health effects • Lung physiology • Measuring instruments			
Broader skills	• Business skills • Statistics • IT communication • Engineering design • Design of experiments • Project management • Problem solving • IP • Ethics	• Engineering design • Design of experiments • Problem solving • Networking	• Lab documentation • Health and safety • Intellectual property • Business skills Engineering design • Design of experiments • Problem solving • Networking	• Annual research presentations • Summer schools Engineering design • Design of experiments • Problem solving • Conference • Networking • Time management

Subject	Measurement techniques			
Research programme	Component-specific aerosol characterisation for differentiation of biological aerosols & Measurement of aerosols in lung models			
	Formal taught programme	Academic placement	Industrial placement	Research Project
Intra-theme skills	• Metrology • Standardization • Light scattering • Electronics/engineering • Optical properties • Spectroscopy • Aerosol generation • Applied metrology • Practical multi-instrument awareness	• Orthogonal technique comparison • Instrument practice • Analysis of relevant systems (e.g. lung tissue)	• Application training • Practical techniques • Engineering and instrument design	• Spectroscopy • Imaging techniques • Prototype & sensing development • IP management
Inter-theme skills	• Legislative understanding • Sample generation • PSD stats • Error analysis • Fundamentals • Sampling and particle transport • Gen. chemistry/physics	• Differences between dispersed and non-dispersed aerosols • Chemistry/Physics/ biology	• Assay protocol design • Basics of product assessment/requirement capture • Biopharmaceutics/PK • Toxicology • Rigorous testing method	• Exposure systems • IP generation • Exposure modelling

	• Basic health impacts of aerosols • Verification and validation of techniques • How to choose right experimental technique • Atmospheric aerosols			
Broader skills	• Business skills • IT communication • Engineering design • Design of experiments • Project management • Problem solving • Collaborative skills • Report writing • Data management/ analysis • Presentation skills • Programming • Team working • Literature searching • Collaborative skills	• Independent problem solving • Design of experimental approaches e.g. sample exposure	• Customer visits • Lab documentation skills • Health and safety • Intellectual property • Business skills • Engineering design • Design of experiments • Problem solving • Working in regulation • Inter-disciplinary teamwork • Marketing/commercial • Presentation • Data management	• Report writing and literature searching • Project management • Independent problem solving • IP management

Subject	Basic Aerosol Processes overlap with Aerosol Technology			
Research programme	"Aerosol droplet drying" & "New aerosol generator for number/mass standard generation"			
	Formal taught programme	Academic placement	Industrial placement	Research Project
Intra-theme skills	• Fluid dynamics • Error propagation • Surface-interactions	• Fluid dynamics	• CFD methods • Limitations of current state of the art • Spray drying • Specific technique training	• Wet/dry aerosol evolution cm-m-km scales
Inter-theme skills	• Sampling and measurement • Meteorological effects • Material science • Aerosolisation/devices • Degradation mechanisms and interactions (Open Air factors) • Ambient environmental background noise	• Thermodynamics • Mass & heat transfer • Risk assessment • Pulmonary deposition mechanisms • Aerosol physics and electrostatics • Analytical techniques • Feasibility studies	• Knowledge transfer • Measurement techniques	• Method development • Aerosols and health
Broader skills	• Literature searching • Technical writing • Verbal communication • Statistics/experimental design	• Interpersonal skills • Time management • Matrix/team work • IP issues/patents	• Marketing & commerce • Safety/CoSHH • IT skills	• Multi/inter disciplinary problem solving • Enterprise thinking & engagement •

	• Data analysis and understanding	• Project management	• Basic maths/numeracy • Lateral thinking &Influencing	