National Measurement System

National Measurement System Programme

for

Innovation Research and Development

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National Measurement System Programme for

Innovation R&D Metrology

Programme Document 2014 (For public release)

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NMS PROGRAMME FOR INNOVATION RESEARCH AND DEVELOPMENT CURRENT PROJECTS

CONTENTS

NPL Projects - 2011

Project No.	IRD/2011/2	Price to NMO	£72,000
Project Title	Marine Wave Power Demonstrators: TSB 'OWEL' and DECC 'Deep Ocean II' co-funded projects	Co-funding target	£70,071 secured (TSB and DECC).
Lead Scientist	Tian Hong Loh (previously Matthew Harper/Mike Collett)	Stage Start Date	Jan 2011
Scientist Team	Chong Li, Andrew Smith	Stage End Date	Nov 2015
		Est Final Stage End Date	2020
Sector	Energy	Activity	Security of Supply

Overall Project Summary:
The main innovative component of the TSB work is the design of the Offshore Wave Energy Ltd (OWEL) wave energy converter. A full-scale device comprises a number of long, adjacent ducts, open to the waves at one end and narrowing towards a submerged exit at the other end. Waves roll into the inlets of the ducts, trapping a volume of air against the walls and ceiling of each duct and compressing it as they move along the duct. The compressed air is forced into a reservoir and used to drive simple turbomachinery and generators. Through this project, OWEL will achieve validated performance of the device to make it a certifiable product.
The overall objective for the DECC Deep Green Ocean II work is to verify the commercial viability of an existing 1:4 scale power underwater 'kite' power plant plant through, reaching the performance targets on which the cost of energy calculation is based and to test the survivability of the machine during peak flows and during slack water.
NPL Contribution Summary: Both systems involve a number of complex control operations, which must be fed by accurate and well-characterised sensors. NPL will specify sensing systems to provide appropriate data and measurement for the control system. This research project will provide valuable performance information for future designs and deployments.

The Need: Cost-effective, reliable and efficient renewable energy generation systems are vital for the ongoing sustainability of the UK and worldwide infrastructure. Current wave-power generation systems employ complex mechanical methods making deployment and maintenance prohibitively expensive. The OWEL system involoves a number of complex control operations, which must be fed by accurate and well-characterised sensors.

The Solution: With the majority of generation components above water level OWEL overcomes complexity and cost problems. NPL's involvement will employ expansion of existing sensor and control system understanding, deployment of sensors and uncertainty evaluation to aid and drive forward the development of efficient and effective operation of the OWEL system. For the Deep Green work, the work is similar in scope but also involves measurements to evaluate the performance of the underwater kite.

Overall Project Description:

The OWEL technical approach is divided into two distinct phases interlinked with a breakpoint. Phase 1 will:
- Develop preliminary design options for a 500kW unit for marine deployment.
- Model options using an established computational fluid dynamics (CFD) model.
- Undertake the preliminary design of the structure and ancillary systems.
- Consider the environmental and consenting aspects to be included in Phase 2.
- Verify survivability and loadings analyses through numerical modelling.
- Analyse the fatigue loading of the structure and mooring lines.
- Present full project costing including Capex, rental fees, services and decommissioning.

After Phase 1 there will be an opportunity to evaluate progress before entering Phase 2 below, which will:
- Finalise the preliminary design ready for manufacture.
- Produce the detailed design.
- Procure, manufacture and assemble the components for the 500kW device.
- Undertake quality control measures, trial fit sub-assemblies in dry and wet tests.
- Deploy and test the 500kW device at Wave Hub, for 12 months.
- Analyse results, validate the CFD model.
- Develop and model the commercial scale unit, estimated at 2-3MW.
- Refine and update the Techno-Economic model for the commercial scale device (EMEC Performance Standards: the Carbon Trust / DNV guidelines will be used).

NPL Contribution: Specification of appropriate instrumentation and sensors for the device to monitor performance over time and capture relevant data. Structural Health Monitoring (SHM) is the use of metrology techniques and sensors to provide a continuous assessment of the state of engineering structures. NPL will apply its knowledge in this area to conduct an extensive desk based review of traditional and novel sensors for monitoring this type of structure. Longevity and appropriateness of sensors will be commented upon and recommendations made as to the most suitable instrumentation/sensor set up to maximise effective data capture. NPL will advise on how best to combine sensor data to understand the lifetime of specified sensors and the overall structural integrity of the device. Short term data capture will be used to support, inform and validate the development of control algorithms for the device. Longer term interpretation of data will be important to gain an understanding of structural integrity of the device. NPL will also investigate methods to process and interpret the types of data to be captured in an effective way. This will involve sensor and data fusion. NPL will apply data fusion methods to networks of sensors and modelling expertise to advise on correcting sensor outputs for sensor bandwidth limitations.

Overall Impact: The driver behind the development of wave energy is sustainability. Wave generators cause no pollution and offset CO2 emissions with minimal visual impact and little disturbance to the environment. A single platform, rated at 2-3MW will typically produce 1,000 MWh per year (based on 40% CofP, 40% CF & 95% availability). This equates to a CO2 offset of 5,433 tonnes, and an energy payback of 3 months (using the Carbon Trust method). OWEL and partners will contribute to establishing the UK as a world-leader in marine renewable energy, and thus help regenerate the UK's marine construction and contracting industry, especially in the SW region. The development of the wave energy industry will also reduce the UK's dependence on imported power sources, improve continuity of supply and reduce the adverse impact of conventional fossil fuel power production.

NPL work Impact: NPL will develop and incorporate metrology approaches into the important area of monitoring and control for this specialised and critical application. The need for robust measurement science within distributed measurement systems will be highlighted and showcased via this high-profile project. NPL itself will benefit from the increased exposure to this important emerging sector as well as the opportunity to employ NPL expertise and capability for real-world and critical systems. Success will be measured by the growth of this area for NPL, and publication of case-study results at conferences and in journals.

Support for Programme Challenge, Roadmaps, Government Strategies

Sustainable energy sources feature prominently in the TSB Environment & Sustainability strategy 2009-2012; Energy from the Ocean features in the FP7 Energy theme; this area aligns strongly with the NPL priority area of sustainability as evidenced by the establishment of the centre for carbon metrology; the area is also highlighted in the government DEFRA national strategy "A Sustainable, Innovative and Productive Economy". As well as an important sector, the technology and capabilities also feature strongly in many strategies: Networks and System Integration is a prominent theme within the NMO EMT Programme roadmaps; The TSB ICT strategy highlights the increasing volumes of data and information, as well as the need for environmental sustainability. The TSB also highlight the significant benefits of innovation through the proliferation of sensors and embedded systems within their EPES strategy.

Synergies with other projects / programmes

This work builds upon the expertise gained through working on projects including Innovation R&D Structural Health Monitoring Demonstrator; MET Wireless and Distributed Sensing. Going forward, this aligns closely with the EMT Programme technical theme of Networks and System Integration; The Centre for Carbon Metrology; The Materials Programme activities in Structural Health Monitoring. As well as NMO Programmes, there are also currently multiple relevant ongoing proposals including: FP7 ICT call for smart energy efficient buildings; TSB Innovation call – intelligent dynamic networking; 3rd party SHM bid with KACST. The capabilities gained by NPL will be applicable to many emerging distributed sensing and autonomous systems, placing NPL well for future calls. The increased presence in the area of sustainability will also support the Centre for Carbon Metrology and activities in this vital sector.

Risks

Overall these are ambitious projects with many potential risks resulting from the harsh marine environment. OWEL have significant experience in this sector and are aware of all the related risks and mitigations. For the NPL contribution, this is a new application area and there is a strong research element meaning exact requirements will be challenging to define earlier in the project. This will be mitigated by working closely with Plymouth University and using their experience with control systems.

Knowledge Transfer and Exploitation

The projects are collaborations with several highly influential organisations with opportunities for additional work and joint activities: e.g. NAREC, IT Power, DNV. Overall, licences to build the technology could be sold to project developers around the world. Alongside the licences, OWEL and its partners will offer a technical design and engineering service to ensure that the project will be safely and efficiently delivered. The results and findings will also be promoted through KTN (and successors), e.g. Sensors and Instrumentation, Environmental and conference presentations. The project relates to the NPL Centre for Carbon Measurement. Full exploitation will come after deployment of the first OWEL demonstrator.

Co-funding and Collaborators

TSB. £37,571 co-funding won. Collaborators are OWEL, ITPower, A&P, Mojo, Ramboll, Narec, University of Plymouth and DNV.
DECC £32,500 (65% grant) co-funding won. Collaborators are Minesto and ITPower.

Deliverables

1	**Start: 01/01/11**	**End: 30/11/15**	
Deliverable title: Co-funding for NPL contribution to TSB 'OWEL' project.			
2	**Start: 01/03/14**	**End: 28/02/15**	
Deliverable title: Co-funding for NPL contribution to DECC Deep Green Ocean II project.			

Project No.	IRD\2011\4b - 1	Price to NMO	£255k
Project Title	Multiprobe Metrology (IRD\2011\4b)– Part 1 [Nanomotion]	Co-funding	£287k
Lead Scientist	Markys Cain	Stage Start Date	Nov 2011
Scientist Team	Paul Weaver, Melvin Vospon, Tim Burnett	Stage End Date	June 2015
		Est Final Stage End Date	2017
Sector	Advanced Manufacturing	Activity	Methodology for New Capabilities
Project Champion			

Summary:
New multiferroic magnetoelectrics, high permittivity integrated dielectrics, ferroelectrics & nano-structured electromagnetic materials require new approaches to the measurement of their properties. Many of these materials are being targeted by industry as future alternatives to silicon-based technologies. The speed of modern electronic devices dictates that these materials be characterised at high frequencies, into the microwave region. Traceable high frequency metrology will accelerate commercialisation from within the UK & Europe of new markets for a wide range of new products & technologies. In this project we are developing new capabilities for the traceable characterisation of multifunctional materials up to microwave frequencies including novel microwave co-planar waveguide (CPW) & near-field scanning microwave microscopy (NSMM), scanning probe microscopy (SPM), dielectric & magnetic & coupled magnetoelectric metrology.
Note: This is Part 1 of a 3-part project. The text below describes the whole project but has the second two deliverables of the work since it is contractually required to have a separate project that provides the co-funding for the linked EU F7 Nanomotion project.

The Need:
Solid state coupling between magnetic & electric properties is a key enabler for the development of a range of novel devices based on the inter-conversion of magnetic & electric energy. Applications include sensors, tuneable filters, & transducers. Magnetoelectric & ferroelectric materials are important candidates for next generation data storage with requirements for high density & low power consumption. The manipulation of magnetic properties by electric fields (& vice versa) at small scale will be an important tool for electrical control of spin in emerging spintronics technology. Improving our understanding of these materials has become an important challenge of contemporary condensed matter physics [Vopsaroiu/Cain et al (2007, 2008)]. Traceable measurement of high frequency dielectric & magnetic quantities in industrially relevant materials is currently confined to low permittivity materials under very specific conditions & is not well developed in industry. It supports the more complex magnetoelectric metrology. As electronic devices become smaller, traceable high frequency dielectric measurements are required at the micro & nano scale. Measurement of magnetoelectric coupling requires independent variation of magnetic & electric fields & this has not been done at high frequencies (most reported measurements of multiferroic properties rely on indirect methods). There are very few reports of measurements of coupled magnetic/electric phenomena, particularly in the challenging area of coupling at high frequency [Vopsaroiu/Cain etal 2010, Hall 2005, Gregory/Clarke 2011]. The need for this work has been recognised by the very high ranking of the EMRP project (IND02).

The Solution
- Develop SPM based techniques for measurement of multiferroic coupling & dielectric response at the micro- & nano-scale.

Modelling is vital for all these activities & will be supported through our alliance with the Thomas Young Centre.

Project Description (including summary of technical work)
- Working with our European partners in this EU funded project – Nanomotion – we will develop a Scanning Probe Microscopy method for characterising the magnetoelectric coupling in micro and nanocomposite multiferroics.
- Model the effects of domains on measurement: inhomogeneity of the electric & magnetic fields for traceable permittivity measurements, interaction between E & H domains to create a new type of phase mapping of domain stability for magnetoelectric, new fundamental descriptions of domain structures in multiferroics (with the Thomas Young Centre).

Impact & Benefits: Benefits in the electronics industries will include faster clock rates & smaller device footprints, leading to higher reliability & lower price per device. The development of metrologies for high frequency applications of multiferroics & other novel materials will reduce barriers to trade & enable faster industrial uptake in many areas such as smart antennas, ultra-sensitive magnetic field detection, high efficiency electronic filters & phase shifters & more. In 2009 the world market for magnetic sensors had reached a value of $1.43 bn. With an expected annual growth rate of 9.6% the world market will approach $2.7 by 2016. Non destructive inductive metrology to determine the dynamic properties of patterned multiferroic multilayered structures is needed to determine key parameters for spin torque (ST) based magnetic sensors, memory & magnetic logic. UK based industry are developing high-speed magnetic memory, storage, logic & sensors, for example TRW will use a magnetic logic sensor to count steering column revolutions for drive by wire cars. The domain wall speed is crucial & damping plays a critical role.			
Support for Programme Challenge, Roadmaps, Government Strategies: This activity supports the strategies of the following governmental bodies: NMS: www.nmo.bis.gov.uk/fileuploads/NMS/NMS_Consultation_Doc_Support_Docs_May_09/NMS_STRATEGY_-_MASTER_gtp_2.pdf NPL: http://www.npl.co.uk/about/npls-role/national-measurement-institute/ EU FP7 NMP Knowledge-based smart materials. TSB: nanotechnology & electronics strategies. ITRS/VAMAS traceable characterisation & control of ordering in nanoferroelectrics. Metrology for Advanced Materials, nanostructures & quantum metrology – NPL (2008). Research Roadmapping on Materials (2010), CIPM Working Group on Materials Framework 7 NMP & ICT calls, Science Special Section Looking beyond Silicon (2010), research Roadmap of European Piezo Institute.			
Synergies with other projects / programmes: This project covers Phase 3 (years 6-9) of the 9-year NMS Multiprobing Programme which will allow its full vision & benefits come to fruition. The EU EMRP project IND02 and EU F7 V-SMMART projects also support this proposal. The EU F7 project Nanomotion is the research and training project that this NMS Part C project cofunds. The realisation of a combined (multiprobe) measurement technique at the nanoscale & at high frequencies (GHz) is expected in a future stage.			
Risks: The development of traceable magnetoelectric coupling using atomic force micrscopy is inherently risky technically owing to the complex interactions and interference of magnetic and electrical fields within a small volume of space. Preliminary work in Multiprobe Part 2 (completed 2011) has shown the way for this measurement and we will follow these routes in this project. The Nanomotion project is a Training project for a PhD student residing at NPL and as such the confunding required for this project supports NPL activity.			
Knowledge Transfer & Exploitation: The EU Nanomotion project will set up a European advisory board and training support structure to ensure that the research is targeted to academic and industrial needs. EMRP projects MetMags and IND02, EU V-SMMART and the Piezo institute training targeted at industrial users, NPL IAGs, IOP & the UK Magnetics Society events & knowledge transfer networks provide routes to dissemination. Knowledge transfer to industry via implementation of new relevant measurement methods, good practice guidance, work-shop & club activities, through informative web-sites, through joint research in case-studies & through publications in scientific journals & the trade press, & close collaboration with Industry			
Co-funding & Collaborators: Part B (Nanomotion) of this Project is co-funded by EU F7: Nanomotion:287 kEuros.			
Deliverables			
1	**Start: 01/11/2011**	**End: 30/06/2015**	
Fulfilling NPL's commitments to the nanomotion FP7 Project**: "**Magnetics and muliferroics at the nanoscale"			

Project No.	IRD\2011\4b - 2	Price to NMO	£280k
Project Title	Multiprobe Metrology (IRD\2011\4b) – Part 2 Co-funding for VSMMART	Co-funding	£230k
Lead Scientist	Bob Clarke, Markys Cain	Stage Start Date	Feb 12
Scientist Team	Kevin Lees, Paul Weaver, Mike Hall, Melvin Vopson, Tim Burnett, Andy Gregory, John Blackburn	Stage End Date	Jan 15
		Est Final Stage End Date	2017
Sector	Advanced Manufacturing	Activity	Methodology for New Capabilities
Project Champion			

Summary:
New multiferroic magnetoelectrics, high permittivity integrated dielectrics, ferroelectrics & nano-structured electromagnetic materials require new approaches to the measurement of their properties. Many of these materials are being targeted by industry as future alternatives to silicon-based technologies. The speed of modern electronic devices dictates that these materials be characterised at high frequencies, into the microwave region. Traceable high frequency metrology will accelerate commercialisation from within the UK & Europe of new markets for a wide range of new products & technologies. In this project (Part B of a four part Multiprobe project) we are developing new capabilities for the traceable characterisation of multifunctional materials up to microwave frequencies including novel microwave co-planar waveguide (CPW) & near-field scanning microwave microscopy (NSMM), scanning probe microscopy (SPM), dielectric & magnetic & coupled magnetoelectric metrology. The project is co-funded by the EU F7 project V-SMMART Nano (Volumetric Scanning Microwave Microscopy: an Analytical and Research Tool for Nanotechnology). This is Part 2 of a 3-part project. Parts B (co-funded by EU Nanomotion) and C (NMS) are described in separate NMS proposals.

The Need:
Solid state coupling between magnetic & electric properties is a key enabler for the development of a range of novel devices based on the inter-conversion of magnetic & electric energy. Applications include sensors, tuneable filters, & transducers. Magnetoelectric & ferroelectric materials are important candidates for next generation data storage with requirements for high density & low power consumption. The manipulation of magnetic properties by electric fields (& vice versa) at small scale will be an important tool for electrical control of spin in emerging spintronics technology. Improving our understanding of these materials has become an important challenge of contemporary condensed matter physics [Vopsaroiu/Cain et al (2007, 2008)]. Traceable measurement of high frequency dielectric & magnetic quantities in industrially relevant materials is currently confined to low permittivity materials under very specific conditions & is not well developed in industry. It supports the more complex magnetoelectric metrology. As electronic devices become smaller, traceable high frequency dielectric measurements are required at the micro & nano scale. Measurement of magnetoelectric coupling requires independent variation of magnetic & electric fields & this has not been done at high frequencies (most reported measurements of multiferroic properties rely on indirect methods). There are very few reports of measurements of coupled magnetic/electric phenomena, particularly in the challenging area of coupling at high frequency [Vopsaroiu/Cain et al 2010, Hall 2005, Gregory/Clarke 2011]. The very high ranking of the EMRP project (IND02) has recognised the need for this work.

The Solution
- Push forward our expertise in microwave dielectric scanning to 3D imaging capabilities, in collaboration with our partners in V-SMMART (FP7).
- Develop traceable metrology of high frequency multifunctional coupling & apply to industrially relevant materials.
- Develop techniques for measurement of coupling & dielectric response at the micro- & nano-scale.
- Modelling is vital for all these activities & will be supported through our alliance with the Thomas Young Centre.

Project Description (including summary of technical work)
1. Support the development of a volumetric microwave microscope for subsurface measurement of ferroelectrics in V-SMMART
2. Using the 3D SMM to gain further insight into materials properties and development of the techniques via:-
    a. Development of a new measurement method, Scanning Electron Acoustic Microscopy (SEAM) taking NPL's Laser Intensity Modulation Method (LIMM) methods for V-SMMART down to the nanoscale using electron beams rather than lasers to excite acoustic waves.
    b. Advancing state of the art in ferroelectric characterisation tools based on Electron Back-Scattered Diffraction (EBSD) and Piezoresponse Force Microscopy (PFM).
    c. The new test methodologies will be used to characterise state of the art materials with test data used to validate current understanding through materials model development with partners at Thomas Young

Centre. 3. Fulfil NPL's metrological commitments to V-SMMART, e.g. provision of traceability.
Impact & Benefits: Benefits in the electronics industries will include faster clock rates & smaller device footprints, leading to higher reliability & lower price per device. The development of metrologies for high frequency applications of multiferroics & other novel materials will reduce barriers to trade & enable faster industrial uptake in many areas such as smart antennas, ultra-sensitive magnetic field detection, high efficiency electronic filters & phase shifters & more. In 2009, the world market for magnetic sensors had reached a value of $1.43 bn. With an expected annual growth rate of 9.6%, the world market will approach $2.7 by 2016. Non destructive inductive metrology to determine the dynamic properties of patterned multiferroic multilayered structures is needed to determine key parameters for spin torque (ST) based magnetic sensors, memory & magnetic logic. UK based industry are developing high-speed magnetic memory, storage, logic & sensors, for example TRW will use a magnetic logic sensor to count steering column revolutions for drive by wire cars. The domain wall speed is crucial & damping plays a critical role. The EMRP project MetMags will position the NPL as a leader in state of the art dynamic magnetic measurements for growth markets. UK businesses that will directly benefit from this project includes: Sclumberger (IOW), BAESystems, & Power Wave for the dielectric imaging metrologies.
Support for Programme Challenge, Roadmaps, Government Strategies: This activity supports the strategies of the following governmental bodies: NMS: www.nmo.bis.gov.uk/fileuploads/NMS/NMS_Consultation_Doc_Support_Docs_May_09/NMS_STRATEGY_-_MASTER_gtp_2.pdf NPL: http://www.npl.co.uk/about/npls-role/national-measurement-institute/ EU FP7 NMP Knowledge-based smart materials. TSB: nanotechnology & electronics strategies. ITRS/VAMAS traceable characterisation & control of ordering in nanoferroelectrics. Metrology for Advanced Materials, nanostructures & quantum metrology – NPL (2008). Research Roadmapping on Materials (2010), CIPM Working Group on Materials Framework 7 NMP & ICT calls (we have bid into NMP), Science Special Section Looking beyond Silicon (2010), research Roadmap of European Piezo Institute
Synergies with other projects / programmes: This project covers aspects of the 9-year NMS Multiprobing Programme, which will allow its full vision, & benefits come to fruition. The EU EMRP project IND02 supports this proposal. The realisation of a combined (multiprobe) measurement technique at the nanoscale & at high frequencies (GHz) is expected in a future stage.
Risks: Microfabricated CPWs provide the increased frequency, magnetic field & sensitivity. Problems in manufacture would limit specification. MetMags partners mitigates. Deployment & treaceability of novel TEM for the NSMM are challenging . Our long experience in traceability of microwave measurements & expertise in our EMRP collaborators mitigate this risk. Use of standing wave methods to separate electric & magnetic field effects at high frequency is untried & technically challenging. Our combined expertise in microwave, magnetic & magnetoelectric measurements mitigates this risk. The extreme sensitivity required to isolate & independently sense magnetic & electric excitation at the nanoscale is difficult new metrology.
Knowledge Transfer & Exploitation: EMRP project MetMags , Piezo institute training targeted at industrial users, NPL IAGs, IOP, the EMMA Club (extended to Europe via IND02-EMINDA) & the UK Magnetics Society events & knowledge transfer networks provide routes to dissemination. Knowledge transfer to industry via implementation of new relevant measurement methods, good practice guidance, work-shop & club activities, through informative web-sites, through joint research in case-studies & through publications in scientific journals & the trade press, & close collaboration with Industry
Co-funding & Collaborators: Part A of this Project is co-funded by EMRP IND02: Electromagnetic Characterization of Materials for Industrial Applications up to Microwave Frequencies. This part (A) is co-funded by EU F7 V-SMMART having major industrial lead partner, Agilent.
Deliverables

1	**Start: 01/02/12**	**End: 31/01/15**	

Co-funding for the V-SMMART FP7 Project.

- The development of metrology standards for the VSMM
- Calibration kits

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NPL Projects – 2012

Project No.	IRD\2012\3	Price to NMO	£1m
Project Title	Nanoferroelectrics II	Co-funding target	£950k
Lead Scientist	Markys Cain	Stage Start Date	Apr 12
Scientist Team	Tim Burnett, Kevin Lees, Bob Clarke, Melvin Vopson, Mark Stewart, John Blackburn, Anna Kimmel, Paul Weaver, Jeremy Allam (Surrey, NPL), Mira Naftaly (TQEM), Norbert Klein (Imperial), Peter Sushko (UCL).	Stage End Date	Dec 15
		Est Final Stage End Date	Mar 18
Sector	Energy, Advanced Manufacturing, ICT	Activity	Challenge-driven R&D
Project Champion	Andy Marvin		

Summary

Nano-structured ferroelectric materials are at the frontier of current materials research with a broad & cross-sectoral range of potential new applications. NPL are at the forefront in the development of the metrological tools required to support innovation & emerging industries in this area. This proposed work would progress the current Nanoferroelectrics [NFE] I project in a logical but ambitious direction to meet future industrial need, set out on our Functional Materials roadmap. In our previous work, we have developed three new tools [1-5] and two new models [6,7] that extends current state of the art describing **static** domain structures in nanoferroelectrics,. This new project extends this metrology programme to development of new methods for *3-D* mapping of polarisation and measurement of domain dynamics for ultrafast switching characterisation of nanoferroelectrics and supports the next stage of the PFM standardisation work with modelling integral to the entire approach.

[1] Vopsaroiu et al., IEEE Trans UFFC, 58 2011 [2] Bouchenoire et al. 10th Int. Conf. Radiation Instrumentation, AIP 1234, 867 2010 [3] Burnett et al. JAP 108 042001 2010 [4] Lowe et al. J.Phys. Conf. Ser. 126 (2008) 012011 [5] Stewart et al. J. Am. Ceram. Soc., 91 2176, 2008 [6] Vopsaroiu et al. PRB 82, 024109 (2010) [7] Kimmel et al. PRL (submitted 2012).

The Need

Products & applications - such as fast 'terabit-per-square-inch' memory, automotive sensors and fuel injection systems for energy saving applications, energy efficient ultrasound and higher sensitivity sonar required for defence and medical markets, next generation high throughput manufacturing processes such as industrial inkjet printers (billboards to plastic electronics) - may be macroscale devices but their performance is governed by their nanoscale electrical and structural configuration.

NFE I developed new metrology for traceability in PFM, dynamics of ferroelectric switching and modelling of defect interaction with domains in nanostructured systems. Recent research activity exploiting nanoferroelectrics in thermal imaging systems (Irysis Ltd) has identified the long-term need to move away from bulk micromachining to thin film or self-supporting structures. The increased miniaturisation in SAW, F-BAR and other filters and non-linear dielectric components in the highly active telecoms sector (AVX, Syfer) presents major materials challenges pertinent to this proposal. Significant challenges remain, particularly in the development of techniques for understanding domain structures in 3 dimensions and at short timescales. For modelling of dynamic properties this typically involves empirical atomistic or coarser grained models. Our work in NFE I [7] has shown that it is essential to account for electronic structure and defects which can only be obtained from first principles calculations. Active research groups in this field are dominated by the large ferroelectrics groups of Penn State University (Randall), Leeds University (Bell), EPFL (Damjanovic), ETHZ (Fiebig), and NPL. A key challenge is to develop new techniques that apply these methods to dynamic systems of practical interest in both time and length scales.

The Solution: Links between the ultra-fast response & domain nucleation & growth is a central theme of our proposal which will combine 3D microscopy with PFM measurements, measurement of dynamic response to fast switching pulses, and modelling:

1. Develop new 3D nanoscale resolution functional imaging. Presently, it is difficult to interpret PFM quantitatively because this requires knowledge of the subsurface domain structure. We propose a method for 3D evaluation of domain structures in nanoferroelectrics. This will require improved traceability, particularly with regards to PFM.
2. Develop new facilities for the measurement of time dependent switching dynamics of nanoferroelectric domain processes over a wide range of timescales below 1ns and approaching 1ps (i.e. GHz to THz frequency range). We will develop optical probes to examine the dynamic response of nanoferroelectrics. This is the only way of achieving sub-ns responsivity for these materials.
3. Develop new materials models that accurately predict the ultrafast properties of ferroelectric materials that are directly linked to the materials' industrially relevant performance.

Project Description (including summary of technical work)

1. New techniques to capture the 3-D character of nanoferroelectrics will be developed by combining our world leading capability for the measurement of polarisation (LIMM), crystallographic texture analysis of EBSD and spatial representation of PFM. Improved traceability in the PFM measurement will be achieved via international collaboration under our flagship VAMAS project initiated in NFE I. 3D image slices fabricated via NPL Materials' FIB will enable 3D reconstruction of ferroelectric domains.
2. We will develop new facilities for measurement of domain response & polarisation reversal in ferroelectrics by measuring the optical (refractive index) response to high-amplitude ns to ps duration electrical pulses. The challenge here is one of providing a link between measured changes in refractive index of the ferroelectric to the materials' polarisation changes with field. A secondary challenge is experimentally combining high speed pulses with high electric field. We will conduct low-amplitude THz frequency-domain studies to allow us to measure the effects of non-linearities in the high field response. This will build on the

electrical systems developed in NFE I in collaboration with our strategic partners at the ATI, Surrey.
3. We will develop a new approach to the modelling of ferroelectric dynamics by combining the electronic structure modelling of defect enhancement of ferroelectric switching with molecular dynamics. This powerful tool, to be developed with our collaborators at TYC, will allow us to measure the influence of defect states on the results of fast switching measurements.

Impact and Benefits

Innovation: The new insight into the dynamic operation of nanoferroelectrics will stimulate innovations in ultra-fast applications for sensors, actuators, and electronic components. For example, an ability to measure and model the dynamics of NFE would help companies like Irysis develop the next generation of thermal imaging cameras based on nanoscale thin film structures, with high def and fast TV rate response needed by their industrial sectors. Ultra-fast processes in ferroelectrics are also of direct technological interest for non-linear optics, photonics, and optical data storage.
Economic: The global market $226B of which UK share is 2.7% or $6B for the electronics semiconductor industry [NESTA, Oct 2010 – Chips with everything]. The UK hosts over 500 semiconductor based companies employing about 8000 engineering staff, forming the basis of the wider UK electronics industry worth £23B employing 250,000 people. This project supports the industry with materials & devices opportunities accelerated through development & deployment of new metrologies aimed at characterising the ultimate switching speed of electronic materials, such as nanoferroelectrics. Industrial uptake of these new technologies (est. 4-10% total) will create jobs & revenue in key UK growth technology sectors.
Quality of Life: Faster and smaller mobile devices, higher bandwidth telecoms, more responsive imaging systems.
Science and Status. A breakthrough in the understanding of the polar response of the solid state by pushing the limits of the rate at which polarisation can be reversed in matter, would be publishable in nature, science and high impact factor journals.

Support for Programme Challenge, Roadmaps, Government Strategies: This project forms a part of the Functional Materials roadmap: 3D functional property mapping and dynamic properties of nanoferroelectrics. The project supports the IRD Programme Challenge – *Multifunctional Materials*, and the NPL and NMS strategy (2011), specifically supporting *Analytical methods and measurements that span atoms, molecules, and mesoscopic lengthscales, through to the continuum (e.g. methods applied at the nanoscale and to bio-systems)*, ITRS Roadmap and INTEL roadmap (4 state memory, universal memory).

Synergies with other projects / programmes: The project will be informed through partnership with the Materials programme (Multiferroic MEMS 2012 – here we will develop integrated MEMS multiferroic test structures and SEM based tools for evaluating coupling at the microscale) and with the Pathfinder programme (quantum current standards & THz spectroscopy). The project will benefit from cofunding from EU F7 proposals SELECT, ITN Next Gen, dynachip and will both support and benefit from current IRD Multiprobe III project. Crystallographic texture, via EBSD, measurement best practice will be delivered through the NMS Materials programme and complex dielectric spectroscopy of ferroelectric materials will be delivered via the Pathfinder and Physical programmes (THz spectroscopy).

Risks: Technical risks include accurate registration of the scanning region in combined measurements in Task 1, will be mitigated through insitu capability developed in this project. In task 2, unambiguously linking the optical response to the polarisation changes is a significant risk which is mitigated by focused effort in our modelling task 3. This is a large multi-partner project. Risk is minimised by making sure we have relevant experts on board and sufficient resource (PhD studentship at Surrey, and UCL).

Knowledge Transfer and Exploitation: Our KT objectives include dissemination of new knowledge to the scientific community (peer reviewed papers) and to our industrial base (IAG and the KTN outreach). Specifically, our new 3D imaging capability will be exploited by our industrial base through new collaborative projects and commercial sale of our new PFM artefact [Collaboration agreement with Bruker exists under NFE I]. In task 2, the new physics will be shared with the community through high impact journal publication and exploited through new industry led research collaborations. The modelling activity supports both objectives above and dissemination follows the same paths. The new data for molecular dynamics in this class these materials will be made available electronically to support desktop design of materials and devices. General awareness through technology press releases and release of project progress on our websites completes our plan. We will carry out these activities using our extensive KT network of which we either chair, or lead or actively participate in: IOM3 Smart Materials and Systems Committee, European Piezo Institute, IOP Dielectrics Group, EMMA-Club, & VAMAS TWA24.

Co-funding and Collaborators: Our major collaborators will be Surrey University ATI, Queens University Belfast and Tyndall Institute. Key industrial partners include Syfer, Irysis, QinetiQ, AEC (Rolls Royce). At NPL we will collaborate with Norbert Klein (Imperial), Matt Harper & Mira Naftaly (TQEM). VAMAS standardisation activity has world-leading international collaborators.

Deliverables

1	**Start: 01/04/12**	**End: 30/06/15**	

Deliverable title: New facility - 3D mapping of domains in nanoferroelectrics: An Industrial case study to demonstrate our 3D tools. [NPL, VAMAS]

2	**Start: 01/08/12**	**End: 31/12/15**	

Deliverable title: New facility: sub-ps pulsed electrical and optical measurement of fast dynamic switching in ferroelectrics. [NPL, Surrey]

3	**Start: 01/12/12**	**End:31/12/15**	

Deliverable title: Models of ultrafast dynamics to simulate the switching characteristics measured in Task 2. [NPL, TYC]

Project No.	IRD\2012\4	Price to NMO	Original budget was £1543k, £690k removed to create IRD\2012\4\EMRP co-funding project
Project Title	Fundamental scaling effects in piezoelectrics – "nanostrain"	Co-funding target Extra funding sought	achieved £500k EMRP co-funding
Lead Scientist	Markys Cain / Carlo Vecchini	Stage Start Date	April 2012
Scientist Team	C. Vecchini, J.Wooldridge, P.Weaver, M.Stewart, L.Hao, N.McCartney, J.Blackburn	Stage End Date	March 2015
		Est Final Stage End Date	March 2018
Sector	Advanced Manufacturing	Activity	Strategic Capability
Project Champion	Yong Yan		

Summary: Control of material properties at the nanoscale through application of strain by piezoelectric materials opens up a wide range of innovative new applications e.g. tuneable electronics, sensors and next generation (beyond Moore's Law) transistors. We have assembled an international team spanning the European Synchrotron Radiation Facility (ESRF), IBM (York Town Heights), and NPL to develop new metrology to exploit nanoscale piezoelectric functionality. It presents a major strategic opportunity to work closely with IBM, one of the leading industrial research organisations in the world, who have invited us to collaborate in a large project (open research with fully published outputs) to develop the science of piezoelectric materials in electromechanical transistors. This project will build on key strengths across NPL in functional materials, MEMS (micro-electro-mechanical system) and NEMS (nano-electro-mechanical system) metrology, and nanoscale SPM (scanning probe microscopy) to develop innovative new techniques for the *measurement of piezoelectrically coupled strain at the nanoscale*.

The Need : Nanotechnology presents a major opportunity for growth in UK industry in collaboration with international partners [1]. It is one of the key areas identified by the NMS [2] where the UK is a world leader and advances in metrology can support that strong position. Emerging industrial applications include configurable chemical and optical sensors and electromechanical logic. Nanoscale strain measurement has been described as one of the holy grails of nanocharacterisation [3]. It is challenging because strains of interest (10^{-4} to 10^{-6}) are at or beyond the limit of techniques such as x-ray diffraction (XRD - approximately 10^{-4}). Transmission electron microscopy (TEM) can measure strain at the nanoscale [4] but is destructive so is not suitable for measurements on functional devices. Recent research at NPL [5] and NIST [3] established high resolution electron back-scatter diffraction (EBSD) and confocal Raman microscopy (CRM) as techniques for strain measurement in the micro- to nano- scale. NIST are not able to perform in-situ combined measurements, nor the strain induced by piezoelectric coupling. Thus industrial need for accurate strain measurement at the nanoscale evades the best laboratories worldwide.

[1]Nanotechnology: a UK Industry View 2010, www.materialsktn.net [2] The Strategy for the National Measurement System: 2011-2015 [3] Vaudin, M. D et al. APL, 93, 193116 [4] Hytch M., Nature 453 1086 [5] "Correlation of electron backscatter diffraction and piezoresponse force microscopy…" Burnett, Weaver, Blackburn, Stewart, Cain, JAP108, 042001, 2010

The Solution:

To meet this need requires non-destructive strain measurement in the region 10^{-4} to 10^{-6} in nanoscale devices. We propose an ambitious multinational research endeavour with substantial in-kind support which more than matches the funding from the NMO. We will apply new technologies together with the innovative combination of existing and emerging techniques. The metrological relationships between these techniques and the definition of strain at the nanoscale require modelling of the fundamentals of piezoelectric strain at the nanoscale and strain transfer in nanostructures. NPL has a track record in nanoscale strain measurement by EBSD, coupled (not in-situ) EBSD / PFM in functional materials [5], piezo-MEMS [6] and NEMS metrology [7], digital image correlation and modelling. NPL has a strategic partnership with the UK beamline 'XMaS' at ESRF and has implemented a unique measurement system for piezo materials into their beamline. This research and multinational support makes NPL uniquely suited to carry out this work, and provides NPL and the UK with a timely opportunity to develop a lead in this area for the benefit of UK industry.

[6] "MEMS metrology for microscale piezoelectric measurement" Wooldridge et al (submitted) [7]Hao, Gallop, Cox "Excitation, detection, and passive cooling of a micromechanical cantilever using near-field of a microwave resonator" APL 2009, 95, 113501

Project Description (including summary of technical work)

1. Piezo-MEMS tools (developed in NMS Materials 2009/2012) will be scaled to down and fitted to NPL's FIB to provide integrated electro-mechanical / EBSD measurements of nano-strain in piezoelectrics.
2. Develop piezo-NEMS for strain measurement using near-field microwave resonator. [Materials, TQEM, NPL FIB]

Our companion EMRP project IND54 – Nanostrain – and its associated NMS cofounding project will work on delivering capability for combined x-ray diffraction, digital image correlation and modelling nanostrain in piezo materials.

Impact and Benefits

- Innovation: The DARPA funded work (open publishable) supporting IBM's investigation of nanostrain piezoelectricity for electromechanical logic provides NPL and the UK an opportunity to contribute to a major technological innovation to develop the next generation transistor logic providing benefits to the UK supply chain and R&D base. Capability for nanoscale strain metrology will support a wide range of UK industry and innovation.
- Economic benefit supporting UK growth in nano-functional materials and new technologies based on them ensuring strong UK participation in the $2.6 trillion market for goods incorporating nanotechnology. Collaboration with IBM in a dedicated case study will provide routes to international markets for UK technology.
- Quality of life: Better security and resource efficiency through new sensing and electronic technologies.
- Science and status: Direct industrial relevance through IBM collaboration, UK access to new user facility at ESRF.

Support for Programme Challenge, Roadmaps, Government Strategies: This project directly supports the IRD programme challenge by addressing key innovation-led technology areas as identified in NMS strategy and other UK documents (see Need section). The project is highly interdisciplinary with input from across NPL (materials, quantum), building on capability from Materials, Physical and Pathfinder programmes to develop a new direction where NPL can take an international lead. This project develops our strategy (Functional Materials roadmap) for metrology to support new innovation and emerging industrial technologies within the UK.

Synergies with other projects / programmes: This project builds on previous NMS projects: "nanoferroelectrics" by developing the metrology in a new direction of electro-mechanical coupling in functional materials; "MEMS metrology" – applying techniques developed in this project in innovative combination with EBSD; FM04 harsh environments –apply macroscale metrology of strain coupling to the nanoscale; Pathfinder 'NEMS for multi-property measurement' taken to new areas using piezoelectrically coupled devices.

Risks: Delays in nanofabrication. Mitigated by supply by IBM from their dedicated research fabrication facilities. Programme timing across organisations can lead to delays e.g. recruitment of post-docs. This is factored in to the project plan assuming a delayed start for external collaborators.

Knowledge Transfer and Exploitation In this project our overarching KT and dissemination will be carried out through the EMRP IND54 Nanostrain project. We will carry out these activities using our extensive KT network of which we either chair, or lead or actively participate in: IOM3 Smart Materials and Systems Committee, European Piezo Institute, IOP Dielectrics Group, EMMA-Club, & VAMAS TWA24.

Co-funding and Planned Collaborators: This project forms part of a wider international open research programme led by IBM which already attracts major in-kind funding to directly support the objectives of this NMS project (IBM $250k, EPSRC ESRF XMaS €400k) plus the wider IBM project (DARPA $9m). Collaboration across to the NMS co-funded EMRP IND54 Nanostrain project will develop this work at a European level.

Deliverables

1	**Start: 01/07/2013**	**End: 31/03/2013**	
Deliverable title: In-situ Piezo-MEMS tools built into NPL's FIB facility for quantitative strain mapping at the nanoscale.			
2	**Start: 01/07/2012**	**End: 31/03/2015**	
Deliverable title: Piezo-NEMS near-field microwave resonator for strain measurement in nanoscale devices demonstrated.			
3	**Start: Apr 12**	**End: 31/8/2013**	
Deliverable title: Piezoelectric measurement system deployed into Synchrotron beam line for microscale strain measurement.			
4	**Start: Apr 12**	**End: 31/8/2013**	
Deliverable title: In-plane strain at atomic scales: Nanoscale digital image correlation using scanning probe microscopy.			
5	**Start: Apr 12**	**End: 31/8/2013**	
Deliverable title: Models and datasets of nanoscale strain coupling: atomistic approaches based on defect mediated structural dynamics (NPL,TYC, IBM)			

Project No.	IRD\2012\4\EMRP	Price to NMO	£690k transferred from IRD\2012\4 funds
Project Title	Fundamental scaling effects in piezoelectrics – "nanostrain": Cofunding project	Co-funding target	£500k from EMRP
Lead Scientist	Markys Cain / Carlo Vecchini	Stage Start Date	Jul 2013
Scientist Team	C. Vecchini, J.Wooldridge, P.Weaver, M.Stewart, L.Hao, N.McCartney, J.Blackburn	Stage End Date	Jun 2016
		Est Final Stage End Date	March 2018
Sector	Advanced Manufacturing	Activity	Strategic Capability
Project Champion	Yong Yan		

Summary: Control of material properties at the nanoscale through application of strain by piezoelectric materials opens up a wide range of innovative new applications e.g. tuneable electronics, sensors and next generation (beyond Moore's Law) transistors. We have assembled an international team spanning the European Synchrotron Radiation Facility (ESRF), IBM (York Town Heights), and NPL to develop new metrology to exploit nanoscale piezoelectric functionality. It presents a major strategic opportunity to work closely with IBM, one of the leading industrial research organisations in the world, who have invited us to collaborate in a large project (open research with fully published outputs) to develop the science of piezoelectric materials in electromechanical transistors. This project will build on key strengths across NPL in functional materials, MEMS (micro-electro-mechanical system) and NEMS (nano-electro-mechanical system) metrology, and nanoscale SPM (scanning probe microscopy) to develop innovative new techniques for the *measurement of piezoelectrically coupled strain at the nanoscale*.

The Need : Nanotechnology presents a major opportunity for growth in UK industry in collaboration with international partners [1]. It is one of the key areas identified by the NMS [2] where the UK is a world leader and advances in metrology can support that strong position. Emerging industrial applications include configurable chemical and optical sensors and electromechanical logic. Nanoscale strain measurement has been described as one of the holy grails of nanocharacterisation [3]. It is challenging because strains of interest (10^{-4} to 10^{-6}) are at or beyond the limit of techniques such as x-ray diffraction (XRD - approximately 10^{-4}). Transmission electron microscopy (TEM) can measure strain at the nanoscale [4] but is destructive so is not suitable for measurements on functional devices. Recent research at NPL [5] and NIST [3] established high resolution electron back-scatter diffraction (EBSD) and confocal Raman microscopy (CRM) as techniques for strain measurement in the micro- to nano- scale. NIST are not able to perform in-situ combined measurements, nor the strain induced by piezoelectric coupling. Thus industrial need for accurate strain measurement at the nanoscale evades the best laboratories worldwide.

[1]Nanotechnology: a UK Industry View 2010, www.materialsktn.net [2] The Strategy for the National Measurement System: 2011-2015 [3] Vaudin, M. D et al. APL, 93, 193116 [4] Hytch M., Nature 453 1086 [5] "Correlation of electron backscatter diffraction and piezoresponse force microscopy…" Burnett, Weaver, Blackburn, Stewart, Cain, JAP108, 042001, 2010

The Solution:

To meet this need requires non-destructive strain measurement in the region 10^{-4} to 10^{-6} in nanoscale devices. We propose an ambitious multinational research endeavour with substantial in-kind support which more than matches the funding from the NMO. We will apply new technologies together with the innovative combination of existing and emerging techniques. The metrological relationships between these techniques and the definition of strain at the nanoscale require modelling of the fundamentals of piezoelectric strain at the nanoscale and strain transfer in nanostructures. NPL has a track record in nanoscale strain measurement by EBSD, coupled (not in-situ) EBSD / PFM in functional materials [5], piezo-MEMS [6] and NEMS metrology [7], digital image correlation and modelling. NPL has a strategic partnership with the UK beamline 'XMaS' at ESRF and has implemented a unique measurement system for piezo materials into their beamline . This research and multinational support makes NPL uniquely suited to carry out this work, and provides NPL and the UK with a timely opportunity to develop a lead in this area for the benefit of UK industry.

[6] "MEMS metrology for microscale piezoelectric measurement" Wooldridge et al (submitted) [7]Hao, Gallop, Cox "Excitation, detection, and passive cooling of a micromechanical cantilever using near-field of a microwave resonator" APL 2009, 95, 113501

Project Description (including summary of technical work)

This NMS project represents the cofunding for the EMRP IND54 Nanostrain project (start date 1/7/13)

WP1: Combined X-ray Diffraction and Interferometry Measurements of Dynamic Strain in Nanoscale Materials
WP2: FTIR and SNOM Measurements of Strain in Nanoscale Materials
WP3: Electron Microscopy Based Methods for Strain Analysis in Nanoscale Materials
WP4: Modelling and Visualisation of Strain in Nanoscale Materials
WP5: Creating Impact
WP6: Management and Coordination

Impact and Benefits

- Innovation: The DARPA funded work (open publishable) supporting IBM's investigation of nanostrain piezoelectricity for electromechanical logic provides NPL and the UK an opportunity to contribute to a major technological innovation to develop the next generation transistor logic providing benefits to the UK supply chain and

R&D base. Capability for nanoscale strain metrology will support a wide range of UK industry and innovation.

- Economic benefit supporting UK growth in nano-functional materials and new technologies based on them ensuring strong UK participation in the $2.6 trillion market for goods incorporating nanotechnology. Collaboration with IBM in a dedicated case study will provide routes to international markets for UK technology.
- Quality of life: Better security and resource efficiency through new sensing and electronic technologies.
- Science and status: Direct industrial relevance through IBM collaboration, UK access to new user facility at ESRF.

Support for Programme Challenge, Roadmaps, Government Strategies: This project directly supports the IRD programme challenge by addressing key innovation-led technology areas as identified in NMS strategy and other UK documents (see Need section). The project is highly interdisciplinary with input from across NPL (materials, quantum), building on capability from Materials, Physical and Pathfinder programmes to develop a new direction where NPL can take an international lead. This project develops our strategy (Functional Materials roadmap) for metrology to support new innovation and emerging industrial technologies within the UK.

Synergies with other projects / programmes: This project builds on previous NMS projects: “nanoferroelectrics” by developing the metrology in a new direction of electro-mechanical coupling in functional materials; “MEMS metrology” – applying techniques developed in this project in innovative combination with EBSD; FM04 harsh environments –apply macroscale metrology of strain coupling to the nanoscale; Pathfinder 'NEMS for multi-property measurement' taken to new areas using piezoelectrically coupled devices.

Risks: Delays in nanofabrication. Mitigated by supply by IBM from their dedicated research fabrication facilities. Programme timing across organisations can lead to delays e.g. recruitment of post-docs. This is factored in to the project plan assuming a delayed start for external collaborators.

Knowledge Transfer and Exploitation: In this project our overarching KT and dissemination will be carried out through the EMRP IND54 Nanostrain project. We will carry out these activities using our extensive KT network of which we either chair, or lead or actively participate in: IOM3 Smart Materials and Systems Committee, European Piezo Institute, IOP Dielectrics Group, EMMA-Club, & VAMAS TWA24.

Co-funding and Planned Collaborators: This project forms part of a wider international open research programme led by IBM which already attracts major in-kind funding to directly support the objectives of this NMS project (IBM $250k, EPSRC ESRF XMaS €400k) plus the wider IBM project (DARPA $9m). Co-funding is provided by the EMRP 2012 IND54 Nanostrain project to develop this work at a European level.

Deliverables

1	**Start: 1/7/2013**	**End: 30/6/2016**	
Deliverable title: EMRP1: Combined X-ray Diffraction and Interferometry Measurements of Dynamic Strain in Nanoscale Materials			
2	**Start: 1/7/2013**	**End: 30/6/2016**	
Deliverable title: EMRP2: FTIR and SNOM Measurements of Strain in Nanoscale Materials			
3	**Start: 1/7/2013**	**End: 30/6/2016**	
Deliverable title: EMRP3: Electron Microscopy Based Methods for Strain Analysis in Nanoscale Materials			
4	**Start: 1/7/2013**	**End: 30/6/2016**	
Deliverable title: EMRP4: Modelling and Visualisation of Strain in Nanoscale Materials			
5	**Start: 1/7/2013**	**End: 30/6/2016**	
Deliverable title: EMRP5: Creating Impact			
6	**Start: 1/7/2013**	**End: 30/6/2016**	
Deliverable title: EMRP6: Management and Coordination			

Project No.	IRD\2012\5	Price to NMO	£497k
Project Title	Chemical Imaging using Bifunctional Electrochemical Scanning Probes	Co-funding target	
Lead Scientist	Andy Wain	Stage Start Date	Apr 12
Scientist Team	Alan Turnbull, Andrew Pollard, William Kylberg	Stage End Date	Dec 14
		Est Final Stage End Date	Mar 18
Sector	Advanced Manufacturing, Health	Activity	Strategic Capability
Project Champion	Pankaj Vadgama		

Summary

The aim of this project is to advance the state-of-the-art in high-resolution chemical imaging via the development of novel bifunctional electrochemical probes.

The Need

Controlling the chemically reactive nature of functional materials is a ubiquitous challenge that requires a detailed knowledge of interfacial phenomena over various length scales. The intelligent design of novel materials with tailored chemical properties impacts areas of critical importance across a spectrum of requirements, ranging from the chemically reactive (e.g. heterogeneous catalysts for chemical energy conversion), through to the chemically inert (e.g. corrosion-resistant alloys for oil and gas pipelines). Electrochemically active interfaces are of notable interest and the related challenges in materials and surface science have an extensive impact across UK industry. For example, the discovery and development of cheaper, more sustainable electrocatalysts for fuel cells is one of the bottlenecks to their widespread use.

The behaviour of solid-liquid interfaces is governed by a complex interplay of dynamic processes such as mass transport, charge transfer and reactive chemistry that can only be truly understood through real-time interrogation at a localised level. Whilst tools for the physical and chemical characterisation of surfaces are prevalent (e.g. AFM, EDX analysis), they lack the ability to measure in-situ surface reactivity (speciation, mechanisms and kinetics). Electrochemical scanning probe microscopies offer a solution to this challenge through chemical mapping of reacting surfaces. Currently such techniques suffer from one of two limitations: (i) the lack of topographical feedback to maintain controlled tip-surface separation and (ii) an inherent inability to study the behaviour of reagents that cannot be generated electrochemically. These limitations restrict both the spatial resolution of the technique and the diversity of reactive systems that can be investigated.

The Solution

Building on current NPL capabilities in electrochemical scanning probe microscopy and pooling expertise from both the Materials and Analytical Sciences Divisions, we propose to extend the state-of-the-art by developing a novel high-resolution electrochemical imaging system that addresses the limitations highlighted above. Bifunctional capillary probes with sub-micron sized apertures will be fabricated that utilise ion-conductance as a means of topographical positioning control, whilst enabling intricate local reactivity measurements simultaneously through a secondary channel, which may operate in one of three ways:

- **Redox Electrochemistry**; the second channel will consist of a simple microelectrode and be used to interrogate surface reactivity through amperometric (current) measurement.
- **pH-Measurement**; the second channel consists of a functionalised microelectrode (e.g. iridium oxide deposited on platinum) that enables determination of local pH through potentiometric (potential) measurement.
- **Reagent delivery**; the second capillary barrel contains a "dosing reagent" dissolved within a water immiscible solvent and locally partitions into the solution. Current is then collected at the substrate when the probe passes over active regions.

Preliminary work has been undertaken in the first of these modes, but the application of this dual measurement approach has not been explored in any depth. The advancements offered will significantly broaden the scope of reactive chemistry that can be imaged using electrochemical microscopy, leading to a breadth of applications in fields of commercial importance.

Project Description (including summary of technical work)

The project will focus initially on the development of the novel probes and instrumentation described above and validation of the new methodologies using standard substrates. The utility of the proposed techniques towards the meticulous extraction of surface kinetics through measurement of diffusive concentration profiles will be tested with reference to a model system with known electrode and chemical dynamics, of which there are many examples.

Our aim is to then demonstrate the new measurement capability by application to industrial problems in which identifying surface reactivity on a local scale is a key issue. These may include, for example:

- **Electrocatalysis**; Measurement of electrokinetics at the single catalyst particle level and determination of active sites that control the behaviour of supporting carbon nanomaterials have remained long-standing challenges in the fuel cell industry. The improved working distance control of the proposed bifunctional probes will help resolve issues of spatial resolution and help make such measurement a reality. Furthermore, the reagent delivery mode will allow the study of less conventional electrocatalytic reactions, such as the oxidation of methanol, a reaction of significance to direct methanol fuel cells.

- **Charge Transport in Solar Energy Devices**; Structure-activity relationships are of critical significance in the development of new photocatalytic materials, particularly in the growing field of photoelectrochemical water splitting. The proposed multifunctional probes lend themselves to the simultaneous mapping of surface topography and photocatalytic activity.
- **Advanced Corrosion Monitoring**; Two problems relevant to the oil and gas industry will potentially be explored. The first relates to the visualisation of localised corrosion processes of materials as a function of applied stress to understand better how damage develops in service. The second challenge concerns the efficiency of corrosion inhibitors, wherein we will use the developed methodology to determine the uniformity of inhibitor molecule coverage in situations where non-uniform corrosion has already occurred.

Impact and Benefits

The scientific ramifications of this work are broad and the knowledge and insights generated will enable improved characterisation of surface reactivity in functional materials, indirectly leading to:

- More efficient, cheaper, sustainable electrocatalysts for fuel cell applications
- Higher performance materials for solar energy conversion
- Improved materials selection and inhibitor formulations

Direct Benefits to NPL include:

- Enhanced NPL capability in electrochemical microscopy, establishing world-leading status
- Potential for industrial partnerships through provision of niche measurement service to UK industry

Support for Programme Challenge, Roadmaps, Government Strategies

Strong alignment with NMS strategy in key national challenges, including:

- **Growth** - Advanced instrumentation (characterisation tools, methodologies, scanning probe techniques)
- **Energy** - Measurement and characterisation methods supporting fuel cells and photovoltaics
- **Sustainability** - Transition to a new generation of functional materials with improved efficiency

Synergies with other projects / programmes

The work builds upon the foundation laid through previous projects in the Materials and ChemBio programmes. The advanced local electrochemical measurements promised will support current projects in fuel cells (Materials, TSB, FP7), catalysis (IRD), photovoltaics (Materials, IRD, EMRP) and in the corrosion theme.

Risks

Proof-of-concept has been established in each of the *single* channel modes so risk should be limited to the addition of the topographical channel and the ability to independently measure topography and activity without interference. This should be mitigated through expertise in electronics and ion conductance microscopy both in and outside of NPL. Furthermore, the use of ion current measurement in AC and DC modes will be investigated as a means to circumvent any such signal convolution.

Knowledge Transfer and Exploitation

Our primary objective is to develop a unique capability, so the output focus will be on high impact publication and dissemination to the scientific community via international presentations. The aim is to not only evaluate the versatility of the developed tools but also to explore extended applications beyond those highlighted, leading to potential avenues of new science. Knowledge transfer to/from UK industry will be achieved through current industrial advisory groups, notably in the fuel cell and corrosion themes. These will also provide a springboard for potential future industrial exploitation, e.g. through TSB or direct funding.

Co-funding and Collaborators

Project collaborators will provide support via technical input and/or provision of the required materials:

- **Johnson-Matthey** – world leaders in fuel cell catalyst development
- **BP** – interest/expertise in corrosion inhibition and in-situ stress imaging
- **EMPA** – experience in photoelectrode materials
- **Bath University** – interest in materials for solar energy conversion
- **Cardiff University** – expertise in catalysis
- **Imperial College London** – world experts in ion conductance microscopy

Deliverables

1	**Start: 01/04/12**	**End: 30/04/13**	
Deliverable title: Evaluation of bifunctional probe fabrication and implementation approaches (NPL report)			
2	**Start: 01/04/13**	**End: 30/12 /14**	
Deliverable title: Novel high resolution imaging system enabling local surface reactivity measurements through dual channel measurement (peer reviewed publication)			
3	**Start: 01/01/13**	**End: 30/12/14**	
Deliverable title: Demonstration of bifunctional probes to local reactivity measurements for energy applications (peer reviewed publication and conference presentation)			

Project No.	IRD\2012\8	Price to NMO	£621k
Project Title	Controlled biomolecular immobilisation for differential diagnostics	Co-funding target	£500k
Lead Scientist	Max Ryadnov	Stage Start Date	Apr 12
Scientist Team	Baptiste Lamarre, Santanu Ray, Alex Shard	Stage End Date	Mar 15
		Est Final Stage End Date	
Sector	Health	Activity	Challenge driven R&D
Project Champion	Pankaj Vadgama		

Summary: The project aims to provide a precision rationale for relating biological functionality with physicochemical parameters pertaining to biomolecular immobilisation for differential molecular diagnostics. Main objectives are (i) to establish a comprehensive measurement methodology which will enable quantitative assessment and prediction of biological responses as a function of immobilisation, and (ii) to provide reference points enabling directed or controlled biomolecular immobilisation.

The Need: The ability to detect one specific biomarker in the pool of related antigens is critical for the unambiguous diagnosis of a given disorder or its state. The detection is not limited to active pathogenic forms. Latent infections in tuberculosis alone account for a third of the world's population. This emphasises the need for differential diagnosis – an approach allowing systemic identification of an entity amongst multiple alternatives. The approach applies to all diseases. However, equally generic are challenges that prevent it from routine use and hinder the development of IVD and POC devices. Reliability and quantitative reproducibility remain to be clear issues. Most tests are optimised as surface-based, which ensures straightforward readout and conversion of affinity constants into measurement values. One generic problem is the loss of activity of immobilised biomolecules due to their uncontrolled and multifocal attachments. This is characteristic for all surface-based assays that continue to suffer from batch-to-batch variations proving costly for clinic. The issue escalates further to a "misdiagnosis" problem derived from "unacceptable levels of wrong results" (Reuters, 07/2011), which prompted WHO to dub current bio-fluid tests as "sub-standard". WHO urges to introduce stricter regulations and quality control for all tests, which will have a considerable impact on IVD. In this light, the project advances key objectives in EC directives and EMEA regulatory documents (e.g. 2001/83/EC, 2008/29/EC, EMEA/CHMP/GTWP/125459/2006) and for IVD standardisation; BS EN ISO 17511:2003 and BS EN ISO 15193:2009 in vitro diagnostic medical devices: "…measurement of quantities in biological samples with metrological traceability…" and "…measurement of quantities in samples of biological origin…".

The Solution: A saving solution is provided in controlled biomolecular immobilisation. The choice is driven by demands for more affordable, rapid and transportable assays with a particular emphasis on those devices that can be readily assembled and used in different settings. However, further progress is impossible without establishing empirical and quantitative relationships between standard physical parameters (degree of coverage, thickness, biomolecular structure) and biological performance (functional loading, bioaffinity). Our recent study within the TSB's "fighting infection through detection" programme can serve as an example. The study has demonstrated that the detection of interferon gamma, a measure of tuberculosis progression, can be monitored and drastically enhanced using surfaces with orientedly immobilised antibodies. This offers a fundamentally new approach allowing for quantitative biomarker capture in complex biological matrices (cell culture, serum). However, it has also become apparent that several factors need to be addressed before an optimised orientation can be considered. These include control over single layer deposition, environmental responsiveness of functional surfaces and non-specific protein adsorption. Given the complexety and extent of the required measurements a direct support at the NMI level is indispensible.

Project Description (including summary of technical work): The project sets to deliver comprehensive parameterisation of biomolecular immobilisation, which will be done in three phases; in the first, an experimental self-assembled monolayer platform (ELISpot format) will be generated for protein immobilisation for quantitative biomarker detection by surface analysis techniques (e.g. SPR, QCMD, ellipsometry, XPS) and the obtained data will be fed into the second phase focused on (i) establishing the benchmark relationships and (ii) applying these for controlled (rectified) immobilisation; the third phase will concern the validation of the relationships using biological matrices (serum). By the end of the third phase we will formulate an integral capability for the correlation of physical data with biological responses, will generate performance prediction maps and will arrange at least one on-site traceability study on specific targets in clinical or/and industrial settings. Biomarker targets will be chosen in relation to infectious and cancer and/or genetic diseases.

Impact and Benefits: the scale of the raised issues is largely attributed to the virtual absence of publically accepted reference points for the development of new diagnostic platforms. This results from the lack of measurement-based protocols that small enterprises cannot afford and big companies are too rigid to initiate, implement and maintain. Metrologically sound reference methods and protocols are necessary and can only be provided by an NMI. This project will impact on the molecular diagnostics market through the translation of prototype assays underpinning more efficient time-to-positivity tests with higher sensitivity and specificity leading thus to reduction in cost per analysis. This will see the establishment of a new measurement and reference laboratory service. Healthcare and increased quality of life are the areas where this project will impact most. One example is the rise of antimicrobial resistance derived from hospital-acquired infections which has already produced "superbugs" (MRSA). This challenge remains far fundamental and widespread for individual companies to take on. Indeed, 40-50% NHS patients acquire MRSA on their final admission (National confidential study of deaths following MRSA infection, UK's National Statistics and Department of Health). Conservative estimates show >5,000 death cases each year in England alone, with the cost to the NHS exceeding £1 billion per year (National Statistics, HPA and Parliament reports). An immediate problem is the precise (differential) diagnosis of MR(esistant)SA versus unharmful MS(ensitive)SA. Failure to address this will continue incur hidden and additional costs. This is where this project will have a sustained impact, be it improved quality control or enabled new diagnostic capabilities. The project will contribute to regulatory frameworks for IVD medical devices, which will promote broader

involvement in UK's NMI/DIs in the formulation of efficient high-throughput and POC devices. The global POC market may be worth over £15 billion by 2015 with the CAGR of >10%, but markets for differential diagnostics remain untapped by test and device developers. This is where radical advancement is needed and where this project will impact within 5 years.
Support for Programme Challenge, Roadmaps, Government Strategies: The project conforms directly to UK government strategies and programme roadmaps with key objectives pertaining to: (i) NMS strategy under the health challenges aiming to: "…enable…diagnostic…technologies to be brought to the market, support optimisation of these technologies in clinical practice…" and "… develop measurement protocols and standards to enable infectious disease detection technologies ..."; (ii) RCUK strategy vision and interdisciplinary research initiatives under the "lifelong and health wellbeing" programme and other cross-council programmes through established IRCs and a new RCUK initiative "…targeting themes of healthy ageing and factors over the whole life course that may be major determinants of health and wellbeing in later life"; (iii) TSB mainstream focus areas (detection of infectious agents and emerging technologies) and their implementation under the new TSB's "concept to commercialisation"; (iv) the project aligns with the key EMRP objectives (EMRP Outline 2008) related to Grand Challenges in Health: "…from qualitative towards quantitative diagnostics…, multimodal measurement procedures"; "…traceable measurements methods for analyte/matrix-combinations with increasing complexity…".
Synergies with other projects / programmes: The project builds upon the completed TSB study which aimed at providing an ELISpot model assay for the diagnosis of tuberculosis. The project is harmonised with the objectives of BA19 in developing nanoprobe platforms for infectious disease biomarkers and in building a new capability for nanoparticle-assisted detection of low abundance biomarkers; BA22 in the development of linear dichroism spectroscopy as a new measurement tool to support drug discovery and development in relation to biomolecular folding and recognition. It aligns with IRD16 in developing functional bio-inorganic interfaces supported by the outputs of NB1 focused on measuring biomolecules at interfaces and with recently funded EMRP h06 project "metrology for the characterisation of biomolecular interfaces for diagnostic devices".
Risks: Medium risks may include (i) "compromised production of biomolecular immobilisation" or (ii) "undetectable levels of immobilised proteins in biological matrices". (i) The surfaces can be manufactured in-house and obtained from collaborators (Orla PT, Newcastle and Eindhoven). The technology is robust and carries no risk for supply; (ii) the completed TSB-funded study has shown that SPR can detect sub-nanomolar concentrations of target antigens in serum and cell culture media.
Knowledge Transfer and Exploitation: The results, reference protocols and methods, will be converted into measurement services to support UK industries. The outputs will be ensured to remain available to the community in accordance with the BIS/TSB's exchange of best practice policies. Active engagement with relevant KTNs such as Sensors/Instrumentation, Bioscience/Nanotechnology, and Biotech/Healthcare Special Interest Groups at NPL will broaden our access to industry. Wherever appropriate the results will be disseminated in scientific and trade journals and forums and reported to standardisation bodies (BSI, BIPM).
Co-funding and Collaborators: A collaborative R&D TSB proposal has passed the first stage.

Deliverables			
1	**Start: 01/04/12**	**End: 30/03/13**	
Deliverable title: experimental surface platform with immobilised proteins for at least one biomarker type (e.g. IFN-γ)			
2	**Start: 01/07/12**	**End: 30/03/13**	
Deliverable title: biomarker detection quantified by surface analysis techniques (SPR, QCMD, ellipsometry, XPS); optimisation of bioconjugation methods (protein-surfaces, protein-nanoparticles) *(paper)*			
3	**Start: 01/05/13**	**End: 30/04/14**	
Deliverable title: obtained data systematised for benchmark relationships between immobilisation and biofunctionality; one-two peer-reviewed publications and one industrial lecture/workshop			
4	**Start: 01/05/13**	**End: 30/04/14**	
Deliverable title: application of obtained relationships for controlled (rectified) immobilisation with quantification *(paper)*			
3	**Start: 01/05/14**	**End: 31/03/15**	
Deliverable title: relationships validation using biological matrices, performance prediction maps, planning follow-up studies One peer-reviewed publication, one publication in trade magazine and one industrial lecture/workshop			

Project No.	IRD\2012\9	Price to NMO	£659k
Project Title	Metrology for Structured Surfaces	Co-funding target	£745k
Lead Scientist	Richard Leach/Mark Gee	Stage Start Date	Jun 12
Scientist Team	John Nunn, Claudiu Giusca, Chris Jones	Stage End Date	March 2015
Sector	High Value Manufacturing Energy Efficiency	Activity	Strategic Capability
Project Champion	Ben Beake		

Summary This project will facilitate the introduction of structured surfaces in a range of industrial products by enhancing the understanding of the relationship between structure and functional performance. The technical work will be concerned with the development of novel characterisation techniques to enable the fast, validated and traceable evaluation of the 3D topography of patterned surfaces, the measurement of the functional performance of patterned surfaces, and the modelling of the performance of patterned surfaces.

The Need Structuring of surfaces at the nano and micro scale holds the promise of step change improvements in the functional performance of the surfaces of engineering components. Many sectors of industry will benefit from this technology through better control of properties such as, friction, optics, electrical function and fluid flow. Thus this technology will contribute to the drive to transform, e.g., the efficiency of automobile transport identified by the King Report and the International Energy Agency Advanced Materials for Transport Group. The take up of this technology is hampered by the lack of appropriate metrological techniques to assess these surfaces, to characterise their performance, and to model their behaviour. Current metrology methods use sensors that cover a very small area and hence are too slow in industrial applications. Some preliminary products have already been produced using this technology, e.g. piston rings patterned by laser processing, but this work has been carried out by a laborious, time consuming empirical process because of the lack of the necessary knowledge of the relationship between measurements of the surface and their functional performance. Government funding is required for this challenging metrological work as key investment in metrology through this project will have a major effect in transforming the performance of products across wide sectors to industry.

The Solution A step change improvement in characterisation techniques will enable timely introduction of this new technology. As the new functionality depends on the topographic patterning of large (up to metres) of surfaces with nanometre precision, fast, accurate characterisation of large areas of the surface needs to be made, and novel analysis methods will be developed that can address this challenge providing the key information on surface structure that is required. These measurements will be made using new optical (e.g. dispersive coherence scanning interferometry) techniques developed in project EF/2011/06, 2011-2014 (NPL has existing and developing world-leadership in areal surface topography measurement). So that the key parameters that control performance can be identified, the surface structure determined through these measurements needs to be correlated with their functional performance. In this project the focus of the work will be concerned with tribological performance as NPL already has expertise in this area. Modelling will be required to ensure that the necessary understanding of how functional performance can be related to the surface structure is developed in a coherent way so that prediction of performance can be made for a range of patterned surfaces. This challenging interdisciplinary work will draw on both the expertise of the EM Division on topographical characterisation, and the Materials Division on the functional performance of materials. The key deliverables of the project will be:

- Methods developed for fast large scale characterisation of the structure of surfaces with nanometre accuracy.
- Scientific papers on the functional performance of these structured surfaces.
- Modelling methods for the prediction of performance from key surface characterisation parameters.
- Good practice guidance on the measurement to function relationships that can be applied in industry.

Project Description The work will comprise:

- The development of novel characterisation techniques (using existing measurement methods) to enable the fast, validated and traceable evaluation of the 3D topography of patterned surfaces.
- The development of sampling methodologies and data processing to derive 3D surface parameters relevant to applications.
- Measurement of the frictional performance of key pattered surfaces chosen to represent the major types of patterning, correlating the performance to key parameters.
- The development of techniques to evaluate the durability of patterned surfaces under mechanical contact.
- Modelling of the frictional performance of patterned surfaces to develop a fundamental understanding of the relationship between structure and functional performance.

Impact and Benefits This project will deliver the underpinning metrology necessary for manufacturing with deterministic control of surface topography that can improve , e.g. friction, wear, aerodynamics, fuel efficiency, biocompatibility and spectral response. Specifically it will:

- Lead to new science on the characterisation of surfaces and understanding of how the topography of surfaces can give better functional performance.
- Develop NPL’s capability in application of metrology to the knowledge-based design of surfaces.
- Enable the effective and efficient design of functional surfaces for applications across manufacturing industry.
- Give a competitive advantage to UK industry, both through better products and through more efficient manufacturing.
- Give surfaces with lower friction leading to considerable increases in fuel efficiency (10 %) and reduced environmental impact.
- Lead to surfaces able to give better control of fluid flow in applications such as medical diagnostic devices.

- Give the ability to engineer new functions into a product such as self-cleaning glass or colouring without paint.

The project has real technological and scientific relevance and, therefore, a large potential to create a positive impact on people's lives through improvements in fields as diverse as medicine, consumer electronics and the energy conservation.

Support for Programme Challenge, Roadmaps, Government Strategies This project addresses several challenges in the strategies of the NMO and the government (TSB High Value Manufacturing, Advanced Materials, Healthcare, Nanoscience, Sustainable Energy) by enabling the development of innovative and energy efficient products, increases in the fuel efficiency of transport systems and reductions of impact on the environment, increases in the efficiency of manufacturing and reducing the waste of materials, and better healthcare products such as diagnostic devices. The project fits with the roadmaps for the M4, Engineering and Flow and EMRP Programmes addressing the requirement for high resolution measurement of structured surfaces.

Synergies with other projects / programmes This project will draw on the capability developed in previous projects in the Materials Programme such as FM01 where preliminary work was carried out on the functional evaluation of patterned surfaces, in the IRD Programme where Project T11 developed techniques to monitor the degradation of surfaces from wear, and in the Engineering and Flow Programme where Project EF/2011/06 is currently developing fast methods for the measurement of the topography of surfaces. Good links with industry will be established so that the methodology that is developed can be taken up by industry. Dissemination will continue after the end of the project to ensure that the maximum impact can be achieved.

Risks The main risk of the project is to develop new characterisation methods to address the major challenge of measuring large areas quickly with micro- to nanometre resolution. This will be mitigated by looking at several different approaches and settling on one method for further development when the feasibility has been confirmed. Another risk is concerned with the development of a universal approach to the modelling of the relationship between the topography of a patterned surface and its function. This will be ameliorated by the careful choice of representative surfaces and by partnering with an academic with appropriate modelling skills.

Knowledge Transfer and Exploitation A coherent plan for knowledge transfer will be implemented that will include the production of good practice and its dissemination by direct contact with industry and publication as an NPL Good Practice Guide. Scientific publications will be made, as appropriate, in peer reviewed journals to disseminate the project results to the scientific and technical communities. Two areas where exploitation is foreseen are the development of new characterisation methods for the assessment of patterned surfaces where the option of licensing the new technology will be explored. Similarly there are likely to be exploitation opportunities with the modelling aspects of the project. Results will be presented at a themed meeting of the Measurement Network. An industrial stakeholder group will also be formed to ensure that industry has the opportunity to inform the project concerning industrial priorities, and to receive key output from the project.

Co-funding and Collaborators This project is of considerable interest to many sectors of industry so direct support of the project will be sought from key industrial stakeholders in the early stages of the project. The value of this direct support is likely to be £40k. One proposal has also been submitted to FP7 on the rapid characterisation of the topography of structured surfaces which fits many of the objectives of this project. The value of this co-funding is £250k. A proposal will also be submitted to the 2012 EMRP Industry call on Patterned Surfaces. The value of this co-funding will be £300k

Collaboration will be through the universities of Southampton (nCATS), Imperial, Huddersfield (EPSRC Advanced Metrology Centre), and Cranfield (EPSRC Ultra-Precision Centre). This will include PhDs, masters students and leverage for EPRSC funding. The collaboration with nCATS at Southampton will be carried out through the support of an EPSRC Postdoc worth £90k that has been agreed under the £2.5M funding that nCATS was recently awarded on Green Tribology, and a short KTS with Southampton and TWI worth £65k. Industrial partners will include Ford, Neuteq, Cranfield Precision, Rolls Royce, Airbus, John Crane and TWI.

Deliverables

1	**Start: 01/06/12**	**End: 30/03/15**	
Deliverable title: Characterisation of structured surface - 2 scientific papers			
2	**Start: 01/10/12**	**End: 30/03/15**	
Deliverable title: Measurement of the functional performance of patterned surfaces - 2 scientific papers			
3	**Start: 01/09/12**	**End: 30/03/15**	
Deliverable title: Modelling and prediction of functional performance of patterned surfaces - 2 scientific papers			
4	**Start: 01/05/12**	**End: 30/03/15**	
Deliverable title: Dissemination, management and exploitation - NPL Good practice guide, meetings of stakeholder group			

Project No.	IRD\2012\10	Price to NMO	£472k
Project Title	Next Generation Optical Remote Sensing Technologies	Co-funding target	£250k
Lead Scientist	Rod Robinson	Stage Start Date	Sept 12
Scientist Team	Fabrizio Innocenti, Tom Gardiner, Andrew Conner, Andrew Finlayson, Marc Coleman	Stage End Date	Mar 15
		Est Final Stage End Date	Mar 20
Sector	Environmental Sustainability	Activity	Challenge-driven R&D
Project Champion	Rodney Townsend		

Summary

Develop novel UK capabilities to provide optical remote sensing (ORS) technologies able to address requirements to quantify and report greenhouse gas (GHG) emissions. Provide research and innovation to enable the UK to maintain its world leading position.

The Need

There is a pressing need to achieve a step change in the UK's capability to measure and quantify GHG emissions, including CO_2 and methane from fugitive (leaks) and area sources. This is driven by requirements to meet climate change reduction targets and to understand current emissions. Significant measurement challenges exist, including requirements to quantify emissions of new species, quantify emission sources that are extremely difficult to measure, and to support the development of new emission factors and emission models. EU Directives on environmental pollution (IPPC, IED, EPRTR) require reporting of the total emissions, including fugitive emissions from sites such as petrochemical plants and landfills. The EU-ETS includes carbon capture and storage (CCS) technologies and these also require detection and quantification of leaks. EU IPPC Bureau's Best Available Technique Reference documents (BREFs) identify ORS techniques, including Differential Absorption Lidar (DIAL) and open-path techniques as potentially able to fulfil these monitoring requirements. In the US NIST have identified "a need to improve and evaluate ground-based, […] remote sensing for distributed sources" and the need to characterise the uncertainties in CO_2 flux measurements in a May 2011 report from their Steering Committee on GHG emissions quantification and verification strategies. Current state of the art in emission flux measurement is the DIAL technology developed at NPL, this is recognised as world leading, for example by the US EPA's 2008 2nd International Workshop on Remote Sensing Of Emissions. There are only two operating mobile emission monitoring UV/IR DIAL systems in the world, both developed at NPL. NPL is working with stakeholders such as the oil industry body Concawe, who recognise NPL expertise as world leading. DIAL is able to monitor emission fluxes of single species at a time, with uncertainties of 20%-40% and typical detection limits of ~ 50 ppb for methane. However, the uptake of ORS techniques is currently limited by the complexity of the equipment and cost to deploy.
The techniques require highly trained and experienced operators, and a significant degree of expert user configuration is needed. More automated operation will enable wider uptake of ORS. Research into new ORS technologies, such as multispectral imaging is needed to realise their potential to provide multicomponent measurements. There a requirement to link short-term highly detailed studies of emissions (typical of current ORS) with longer-term monitoring to support reporting of annual emissions and to allow improved control of GHG emissions to deliver greener processes (part of Government's Carbon Strategy 4.1).

The Solution

NPL's track record in developing and validating ORS technologies will enable the NMS to address the market failure caused by the complex technology and high costs which have inhibited wider exploitation of the ORS technologies. This will provide UK leadership in relevant ORS capabilities by:

- Enabling real-time, online emissions flux determination in the field
- Reducing complex post-processing and data visualisation processes to improve market exploitation
- Meeting future requirements for quantifying power generation, industrial and distributed sources of emissions, including quantification of GHG emissions from agriculture
- Linking quantified emissions measurements over a short timescale, to longer term fixed systems providing time series of emission measurement data.

Project Description (including summary of technical work) The areas of innovation will include:

- **Improved flexibility of ORS systems**. Review of future ORS technology options. Modelling of system and atmosphere, identification of optimum GHG wavelengths to detect plumes against background levels. Reduce complexity of ORS systems to enable more rapid deployment through collaborative research with laser suppliers to develop more configurable and modular laser sources, reducing the time required to configure ORS technologies for different measurement tasks and reducing cost of deployment.
- **Improved detection sensitivities.** Current systems have fixed configuration. Development of adaptive systems (optical and electronic) to optimise detection sensitivities at different ranges and conditions. Achieve improved detection sensitivities for key GHGs at longer ranges (e.g. <30ppb detection at 500m for methane).
- **Real-time flux determination.** Improve one of the key sources of uncertainty in the current determination of emission fluxes by optimising algorithms and meteorological measurement configuration. Research and modelling of meteorological impact of wind variability and frequency structure and optimisation of measurement methodology to address this. Develop enhanced real-time processing to assimilate wind data and concentration data and produce real-time flux determination with < 15% uncertainty for typical measurement levels; current uncertainties can be >30%.
- **Integration of short term flux measurement with long term continuous monitoring**
  Integration of different ORS technologies such as multispectral techniques and DIAL to extend short-term measurements to long term time series. Identify required parameters for long term monitoring and assess potential technologies to select most appropriate (e.g. Tuneable Diode Laser spectroscopy, Open-Path-FTIR). Develop uncertainty model and methodology

to combine short term DIAL measurements with long term Path Integral Concentration (PIC) measurements. Field validation study and assess performance in determining long-term emission rates.

Impact and Benefits

Environmental benefits and quality of life benefits will be met by addressing needs expressed in the Government's Carbon Plan, i.e. improving knowledge of emissions (e.g. 6.4 addressing landfill methane emissions, 7.11 addressing agriculture) and therefore improving the ability to model UK emissions. There are significant economic benefits to industry due to the ability to identify the locations of emission sources using ORS techniques, and to improve the UK's reporting of emissions by enabling emission factors to be improved and reducing exposure to risks through over or under reporting, and potentially enable inclusion of more sources in market mechanisms and mitigation measures. Reducing the complexity of the DIAL technique and improving its regulatory efficacy by linking to longer term measurements will enable wider exploitation and will encourage stakeholders to develop commercial capabilities based on the research outputs and support UK technology companies in exploiting the emerging clean technology market. The project will position the NMS and the UK at the forefront of research activities in the GHG emissions field and provide capabilities enabling the UK to participate in international GHG research programmes (e.g. EMRP, FP7).

Support for Programme Challenge, Roadmaps, Government Strategies

This project aligns completely with the NMS Strategy Document 2011-2015 Priority science area of Quantitative environmental monitoring (including remote sensing) and under the Overarching Challenge that, "…advanced instrumentation are examples of areas where the UK is a world leader and where advances in measurement science can support that strong position". This project aligns with the IRD Roadmap for Environmental Sustainability addressing the item pollution monitoring and control.

Synergies with other projects / programmes This work builds on NPL's unique set of remote sensing capabilities and environmental monitoring research carried out under the NMS ChemBio (project RS1), IRD Programme and NPL SR Programme/EPSRC PDRA scheme. Links with work underway in the NMS Physical Programme for traceable measurements for Earth Observation instrumentation and improved laser sources.

Risks The main technical risk is the challenge in developing real-time flux determination. Work will be informed by existing DIAL projects, which are providing datasets on wind fields and modelling which will define achievable capabilities.

Knowledge Transfer and Exploitation

NPL has strong links with key stakeholders in the area of ground based ORS, for example, with petrochemical industry through research projects with Concawe. Methods developed for DEFRA and the EA will facilitate landfill and other area source emissions monitoring policy going forward. There is currently a proposal at CEN to standardise DIAL, an activity that NPL will lead. Method development and standardisation enables uptake of innovation by allowing use of techniques by regulators and research communities. IP exploitation, including licensing, includes existing contacts with instrument manufacturers and will utilise the Sensors KTN. Scientific exploitation will include the ability to utilise the capabilities developed in research such as Defra emissions factor projects, future EMRP environment calls and in FP7 and subsequent calls.

Co-funding and Collaborators Stakeholders already engaged include the oil industry environmental group CONCAWE, UK Government through Defra and its regulatory body the Environment Agency and the waste industry including companies such as Veolia. Through developing and disseminating expertise this programme will also exploit the UK's existing leading international position, enabling the global exploitation of the IP generated with collaborators such as the US EPA.

Deliverables

1	**Start: 01/09/12**	**End: 31/07/14**	

Deliverable title: Improved flexibility of ORS systems

Review of ORS techniques. Modular system developed and demonstrated. Publication on capabilities in peer reviewed journal

2	**Start: 01/10/ 12**	**End: 30/09/14**	

Deliverable title: Improved detection sensitivities

Demonstrations of improved detection sensitivities at different detection ranges (< 30ppb at 500m range). Improved processing algorithms. Validation of improved techniques. Peer reviewed paper(e.g. Journal Environmental Monitoring)

3	**Start: 01/09/12**	**End: 31/07/14**	

Deliverable title: Real-time flux determination

Validate improved approach in field experiment (15% uncertainty). Report on capability in peer reviewed publication.

4	**Start: 01/04/13**	**End: 30/03/15**	

Deliverable title: Integration of short term flux measurement with long term continuous monitoring

Field demonstration of methodology for long term (>1 month) monitoring. Peer reviewed paper (e.g. Journal of Air and Waste Management).

Project No.	IRD\2012\11	Price to NMO	£644K
Project Title	Novel photovoltaic characterisation techniques	Co-funding target	£500K
Lead Scientist	Simon Hall	Stage Start Date	Apr 12
Scientist Team	Simon Hall, Fernando Castro, Craig Murphy, Paul Miller, Mike Shaw, Kevin O'Holleran	Stage End Date	Mch 15
		Est Final Stage End Date	
Sector	Energy	Activity	Challenge-driven R&D
Project Champion	Dr Jan C. Petersen		

Summary

A viable UK photovoltaic (PV) market is reliant on traceable efficiency measurement. Competitive, cost-effective manufacturing requires advanced quality control. This project will address these urgent industrial needs and position NPL at the forefront of photovoltaic characterisation. A novel, advanced technique will be developed in close collaboration with Cambridge University that will allow, for the first time, fast, spatially-resolved measurement of intensity, linearity, angular and polarisation characteristics of thin film photovoltaics. NPL will setup a traceable efficiency measurement facility to provide validation of the new method and to enhance the link between the SI and world radiometric reference standards, which typically are used separately. The novel measurement capability has the potential to aid mass production of PV by reducing waste and improving performance by incorporating traceable, high speed and large area measurement into the production process. It combines high quality new science with significant potential for future third party revenue.

The Need

Solar Photovoltaics are a multibillion worldwide market and a key element of the UK Government energy strategy (100% UK market increase in 2010). NREL (USA) provides the current defacto industry standard PV efficiency measurements and is only currently available to USA companies due to high demand. Only three other labs worldwide can provide traceable tests to IEC standards. None in the UK, despite high demand. High speed, large area photovoltaic efficiency measurement is required to reliably characterise large scale production and reduce costs by improvement of quality and wastage reduction. Existing usage of Raman, X-ray and current mapping do not fulfil these criteria due to limitations such as high cost and slow measurement time.

UK has a strong research effort in organic solar cells (OPVs) with many SMEs in the forefront of innovation. There is a lack of cohesive R&D effort to provide a measurement infrastructure to improve competitiveness and innovation in the international marketplace. OPVs degrade due to lack of appropriate encapsulation, therefore avoidance of transport to measurement facility overseas is highly desirable. A major barrier to market for solar cells is the energy cost/efficiency ratio. A cost per watt reduction of a factor of five is required to make PV competive without subsidy. Therefore a measurement solution for quality control of large area PV production isimperative . Fast measurements that can be incorporated in-line are stronglypreferred for roll-to-roll organic PV technology, which could provide the cost savings required for PV ubiquitous use. [1] EU Directive 'Promotion of the Use of Energy from Renewable Sources states: 20 % of Europe's total energy consumption from renewable energy by 2020'.

The Solution

- A step change in characterisation capability compared to bulk measurements combined with a more efficient and consistent way to relate the world of radiometric reference to the SI.
- We propose to utilize a new Cavendish Laboratory theory to develop a novel device that will allow fast and cost-effective spatially resolved characterisation of solar cells. A comprehensive analysis method will be developed in collaboration with Cambridge University.
- This laser based system will provide spatial intensity and linearity, angular, polarisation characterisation as well as fast spatial mapping of efficiency vs. wavelength. Spectral measurement will be traceable to SI. Spatially resolved measurements allows new posssibilities for process and quality control as well as valuable R&D insight.
- The potential for inline measurement for UK manufacturing processes will be investigated
- NPL is the perfect organisation to provide these measurements: existing expertise in organic photovoltaics R&D and materials characterisation and strong optical measurement capability (SI traceability / adaptive optics expertise).

Project Description (including summary of technical work)

NPL will convert the theoretical concept of energy absorbtion interferometry, (EAI) developed by the Cavendish Laboratory, and demonstrated in the sub-mm range, into a visible and near infra red instrument using a spatial light modulator to provide a variable phase difference spatially between two coincident beams on a photosensitive absorber. A multidisciplinary team will produce an intial prototype utilizing the EAI technique and characterise it using existing techniques e.g. Raman. EAI determines the state of coherence of the electromagnetic field to which any energy-absorbing structure is sensitive. Once the state is known, the amplitude, phase, polarization pattern and responsivities of the individual modes that make up the overall power reception pattern, among other properties, can be determined. In turn, these modes reveal detailed information about the dynamical behaviour of the energy loss mechanisms. To summarise, we'll build an initial system that allows varying patterns of laser light to be projected onto a photovoltaic (PV) cell. A variably phase delayed beam split off from the original beam will be overlaid over the initial beam to allow the spatial absorption characteristics of the PV cell to be rapidly measured. We will compare this with conventional NPL spatial responsivity. EAI will be invaluable in setting up a validated, traceable photovoltaic device efficiency measurement capability. Specifically, the angular, spatial and linearity characteristics of the solar cell can be derived. We'll also investigate the possibility of deriving properties through depth resolved measeurement . The traceability targets of the work will link PV cells calibrated using the international radiometric reference to the SI using solar simulators and other existing coherent and incoherent light sources.

Impact and Benefits

- The results of this project will enable faster development for UK industry positioning the country to reach a much larger share of a worldwide PV market. Novel technique has IP potential that could assist in industrial uptake.
- Provide link between radiometric standards and the SI for the first time and strengthen strategic link with the Cavendish Laboratory. In the longer term, the technique could be incorporated into the production process, reducing PV development and production costs. This would lead to widespread renewable energy use and opening an even larger market for PVs (currently only 3% of EU electricity is generated by PVs).
- Significant potential for third party revenue through measurement services and device development.
- Position NPL at the forefront of PV characterisation and open new posibilities of future measurement development. For example towards solar concentrator PV characterisation.
- Quality of Life benefits from renewable energy use and microgeneration for the UK population

Support for Programme Challenge, Roadmaps, Government Strategies

- Maps onto the “Spatial mapping- efficiency” and “Organic device efficiency v wavelength,T, angular” milestones in the organic electronics roadmap-2 Micro-scale/device properties & modelling roadmap.
- This project links to the NMS priority areas of low carbon technologies and sustainability it also would form an important part of the proposed NPL centre for carbon measurement.
- DECC’s July 2011 “UK Renewable Energy Roadmap” relies on the uptake of photovoltaics to achieve the 80% emissions reduction by 2050. UK Government strategy Renewable Obligation, Climate Change Bill, Microgeneration Strategy, UK Energy Marketing Strategy

Synergies with other projects / programmes

Draws on expertise from a number of disciplines across NPL. The proposal forms part of an effort to develop a wide and deep capability to characterise novel photovoltaic devices and thus support the drive to improve renewable energy production and the establishment of a viable UK industry in this area. EMRP IND07 Thin Films, TSB SCALLOPS, NMS Materials Programme “Advanced Metrology for Novel Photovoltaics Technologies”.

Risks The risk of this work strand is medium, because this new technique has not been demonstrated in the optical domain but the potential if EAI is demonstrated, both scientifically and industrially is very significant. In particular, challenges exist to validate the phase change applied by the spatial light modulator onto the variable probe beam and in ensuring that registration of the two beams is sufficient to generate the predicted solar cell response change. These challenges are mitigated by the significant expertise gained by NPL through previous adaptive optics projects and with the ongoing spatial light modulator research in collaboration with Durham university through STFC funding. The development of the EAI technique is facilitated by the link with Cambridge University research.

Knowledge Transfer and Exploitation

8 planned Publications in major journals (e.g. Optics Letters; Optical Express etc) Collaboration with existing national networks such as the EGS KTN and the ESP KTN will allow co-sponsored meetings and use of connect platform to disseminate project results. The EMRP “Thin Films “ project and the European Energy Research Alliance network will be used to inform European stakeholders. Plan to hold a workshop on organic PV using the existing OE-A network. Case study of experimental PV with UK SME. Generated IP will be evaluated for possible protection via patents. Joint applications in process to external funding bodies to exploit the EAI technique through increased scope and applicability of the capability for critical PV measurements.

Co-funding and Collaborators

EC FP7 (TSB) OLAE+ 1.8 million Euro bid (500K Euro for NPL lead partner) Agreed with NMO, Cambridge KTP £150K, STFC IPS £450 K, STFC CASE £180K. Cambridge Uni (Prof Withington) 10% FTE through STFC

Deliverables

1	**Start: 01/04/12**	**End: 30/11/13**	
Deliverable title: First Prototype device: To develop a groundbreaking PV measurement capability: *Energy Absorption Interferometry (EAI)* in close collaboration with theoreticians at The Cavendish Laboratory.			
2	**Start: 01/04/12**	**End: 31/01/ 14**	
Deliverable title: PV traceability chain: To setup validated, traceable photovoltaic device efficiency measurement service to support the novel measurement capibility and UK supply chain.			
3	**Start: 01/11/13**	**End: 31/03/15**	
Deliverable title: Comparitive measurements and traceability chain : Measure samples measured by other techniques such as Raman and x-ray and compare results. Optimise measurement system and produce second prototype.			
4	**Start: 01/10/12**	**End:30/04/13**	
Deliverable title: Validation of digital SLM using samples provided by materials EMRP project.			

Project No.	IRD\2012\12	Price to NMO	£531k
Project Title	Verification of Carbon Savings for Smart Infrastructure	Co-funding target	~£150k potential
Lead Scientist	Paul Wright, Hilary Elliott	Stage Start Date	Apr 12
Scientist Team	Alistair Forbes, Peter Harris, Michael Collett	Stage End Date	March 15
		Est Final Stage End Date	Oct 15
Sector	Environmental Sustainability	Activity	Challenge-driven R&D
Project Champion	Martin Charter		

Summary: The Dept. for Business Innovation and Skills [BIS] states that the UK environmental and low carbon market is valued at £112 billion with an expectation that it will grow 25% by 2015. Of that, the Low Carbon Technology market is expected to be worth ~£2 billion by 2030. It is critical that we ensure investments in low carbon innovation are made with confidence in the knowledge that the resultant technologies will deliver the reduction in Carbon Emissions required for the UK to meet its legal commitments set out in the Climate Change Act [2008]. This project aims to develop an independent and adaptable methodology for the verification of Carbon Savings, underpinned by the development of a new standard, to provide confidence to investors, thereby maximising economic benefit and societal and environmental impact.

The Need: UK Government is currently investing into the vision of a low carbon economy, driven at achieving the UK legal commitment set out in the 2008 Climate Change Act. Examples of funding include Low Carbon Network Fund [OfGem] >£500M; DECCs Low Carbon Innovation Fund [£160M] and the Green Deal. In fact, ~50% of the commitments made in the Carbon Plan e.g. Reforming the Grid [DECC, HMT] etc., need to be supported by an independent tool to provide confidence that the investment will result in the level of "Carbon Savings" required to ensure value for money from an environmental perspective. As such, more and more investors require prediction and demonstration of "carbon savings" associated with proposed bids, but with little thought for the consistency or methodology by which those carbon savings are calculated. This makes comparison (and large-scale roll out) of outputs high-risk and in some cases impossible. It is the responsibility of those investing to ensure they do so in areas which offer the highest potential return in the reduction of carbon emissions. NPL is ideally placed to provide the metrological framework to independently quantify Carbon Savings with a focus on analysis of uncertainty, something that current commercial tools cannot offer. Indeed OfGem have recently stated that whilst critical, "without detailed guidance, quantification of carbon benefits is subjective and of limited use in evaluating relative benefits" and that what is required is "a suitable process that calculates benefits that are comparable across multiple and differing projects". This work will offer a standard methodology in the form of a PAS document to sit alongside ISO14040 [Life Cycle Assessment] and PAS2050 [Carbon Footprinting] demonstrated through a Smart Infrastructure trial.

The Solution: The outcome of the project will be a metrological tool built on validated algorithms, models and a methodology for uncertainty analysis only offered by an NMI. The tool will deliver a rigorous assessment of the effectiveness of low carbon intervention and underpin the assessment of proposals and activities associated with low carbon trials. The tool will specifically focus carbon savings in Smart Infrastructure with input parameters including economic, statistical and behavioural analysis linked with sensor data, in order to determine the net carbon reduction of a low carbon trial compared to a conventional system of similar characteristics. The shape and delivery of the tool will be influenced by delivery partners including National Grid and Distributed Network Operators. It is anticipated that the tool will be developed into an independent standard methodology (PAS document) for the Verification of Carbon Savings. Once developed, the tool will be easily adapted to deliver a demonstration of effectiveness in other low carbon trials e.g. Building Performance and Clean Transport.

Project Description (including summary of technical work):
The tool to be developed is a mathematical model consisting of multiple, continuously changing inputs and outputs such as sensor measurements, demographics, energy use, carbon cost of energy, tariff inducements, building energy, local generation sources, supply chain and spot carbon costs. The modelling approach will incorporate an ***Uncertainty***, ***Sensitivity***, ***Constraint*** and ***Behaviour*** analysis. The ***Uncertainty*** analysis will involve an estimation of carbon impact associated with different generators (coal, oil, gas, wind, PV etc) with associated uncertainty. Given generation costs, it is then possible to determine an optimal mix of power generation to meet a demand profile (Load) and the resulting carbon impact for such an optimal solution can again be estimated with associated uncertainty. The ***Sensitivity*** analysis will determine which input uncertainties provide the most contribution to the overall uncertainty associated with carbon impact and to determine what measurement information would be most beneficial in reducing uncertainties. The ***Constraint*** analysis will determine which factors are barriers to reducing the carbon impact. The ***Behaviour*** analysis will determine what changes in generation and consumer behaviour would reduce the carbon impact while still achieving the same level of activity. These variables will be assimilated into the model (dependent on the trial under test) in order to calculate the carbon cost. To assess the net carbon saving a second model of a "control" will be used to estimate the carbon cost in the conventional case. The approach must be rigorous and conducted within metrological principles and an uncertainty framework. Implementation will require data interfacing, handling and reporting tools to be developed. The project will engage with a demonstrator Smart Grid trial for electricity distribution from the outset which will not only provide evidence of the effectiveness of the tool but also begin to embed design best practice thereby minimising the carbon impact. Relevant skills exist within NPL to provide technical input and guidance on uncertainty evaluation and modelling of sensitivity, constraints and behaviours however, it is envisaged that a full-time Industrial Statistician (post-doc) will be appointed to work fulltime on the delivery of the final methodology.

Impact and Benefits: (i) **Independent and traceable determination of carbon savings** of Smart Infrastructure trials with plans to translate capability to other areas including Building Performance and Clean Transport (**ii**) **Successful low carbon systems** trialled under schemes e.g. Low Carbon Network Fund, will, if successful be scaled-up to a national level representing a multi-billion investment in a critical national infrastructure. Success criteria for these trials include net carbon saving. This project will provide a **rigorous framework within which that assessment can be made thereby ensuring future large scale systems are selected on the basis of demonstrable environmental and societal benefit and value for money** (**iii**) **Significant positive economic impact in mitigating investment risk in Low Carbon Technologies** e.g. **DESIGN PHASE**: to determine whether a proposed activity can deliver the carbon savings required and / or compare and select proposed interventions at the design phase in an informed and confident way. Such early stage analysis reduces investment risk by enabling changes to the project design ahead of implementation. **POST DEVELOPMENT**: to assess the success of an investment made e.g. through the Green Deal and thereby decide whether additional interventions are required to meet the specification needed (**iv**) **Delivery of impact at all levels of the supply chain** from Consumer (Green Deal) through technology / trial developers (LCNF) through to Government Investment (DECC / BIS) (**v**) **Valuable support for the UK and Europe's aspirations to meet climate change targets** (**vi**) **NPL positioned as the partner of choice** based on unique independent world leading uncertainty framework for Carbon Savings assessment.

Support for Programme Challenge, Roadmaps, Government Strategies: The tool underpins the National Measurement System strategy to establish a Centre for Carbon Measurement and provides underpinning support for (**i**) work considered under the proposed Centre for Carbon Measurement work-programme Low Carbon Technologies theme (**ii**) Governments commitments to reduce UK emissions [Climate Change Act 2008] (**iii**) Government Departments commitments set out in the Carbon Plan and associated policies (**iv**) UKs position in aligning itself with European initiatives e.g. European Technologies Verification scheme for the Performance Assessment of Environmental Technologies

Synergies with other projects / programmes: This project adds value to (though is not dependent on) other live and proposed work including (**i**) EMRP Smart Grids project (and other projects under the Sustainable Energy and Environment Calls within EMRP) (**ii**) Commercial Audits for commercial Carbon Savings Methodologies (**iii**) Assessment of Green Sustainable Airports to include Carbon Footprinting (**iv**) IRD Wireless Sensor Networks project (**v**) IRD project in Life Cycle Analysis (**vi**) Proposed NPL Strategic Research project in Distributed Sensor Networks.

Risks: The demonstration of the effectiveness of this tool relies on existing partnerships with Distributed Network Operators [DNO] in the delivery of qualified low carbon trials e.g. Smart grid trial (OfGEM). In terms of access to facilities and data, it also relies on the cooperation of the National Grid to provide carbon intensity of generation data for the Smart Infrastructure demonstration and the access to building design and performance parameters in the case of housing stock retrofit activities. Both challenges can be overcome through existing partnerships and future bidding opportunities as outlined in this proposal.

Knowledge Transfer and Exploitation: The expectation is that this methodology could be used in the development of a standard for the Verification of Carbon Savings which does not currently exist. Discussions with The British Standards Institute have highlighted that under ISO14040 [Lifecycle Assessment standard] a PAS, Publically Available Specification, for the independent verification of *Carbon Savings* is "not only feasible but absolutely required". This is in addition to PAS 2050 which focuses predominantly on *Carbon Footprinting*. It is our aim that the capability will become "the standard" used to assess the effectiveness of all future low carbon trials in the UK. Presentations and publications particularly aimed at regulators and the national and international electricity and construction communities will be critical in engaging stakeholders and ensuring take-up. Once complete, the tool will be adapted and applied to other low carbon schemes e.g. Building Performance and Clean Transport funded by the inclusion of NPL led work packages in non-NMS projects and as contract R&D, consultancy or service by NPL.

Co-funding and Collaborators: (**i**) **Smart Infrastructure**: Working within a DNO and or National Grid led project under the OfGem Low Carbon Network Fund and Network Innovation Competition programmes respectively, there is an opportunity for us to demonstrate the effectiveness of the tool within a Smart Infrastructure environment. Involvement will entail access to the information including designs of the energy network, Smart Meter and other sensor data and generation carbon intensity data. This is a considerable amount of data and it represents a considerable commitment in staff time from the DNO and National Grid. Total cash cofounding is expected at **~£150k** associated with the LCNF and NIC calls in 2012-2013 (ii) An opportunity which is currently being explored is through OfGem and / or the Energy Networks Association both of whom have shown considerable interest in the accurate assessment of carbon savings in their investments. All cases are expected to provide in kind support to the development of the NPL Carbon Savings tool. Academic, Private and Public Sector will influence the delivery of this project.

Deliverables

1	**Start: 01/04/12**	**End: 30/03/15**	
Title: A carbon savings tool, consisting of algorithms, models and methodologies and incorporating statistical, economic, uncertainty and behavioural analysis interfaced with measurements.			
2	**Start: 01/04/13**	**End: 28/02/15**	
Title: *Demonstrator:* In collaboration with a Distribution Network Operator led Smart Grid trial and National Grid, application of Carbon Savings tool (D1) in determining the net carbon savings achieved in the trial compared to a conventional grid.			
4	**Start: 01/10/13**	**End: 30/06/15**	
Title: Engage Industry & Deliver Impact			

Project No.	**IRD\2012\13**	Price to NMO	£2,627.5k[from original project; £138k removed to co-fund TSB PGT, £379k removed to co-fund EMRP GraphOhm]
Project Title	Real-time methods for the measurement of key properties of Graphene at the device scale	**Co-funding won**	£100k from TSB PGT, £260k from EMRP GraphOhm
Lead Scientist	J T Janssen	**Stage Start Date**	1/4/2012
Scientist Team	Olga Kazakova, J T Janssen, Ian Gilmore, Deblulal Roy, Chris Hunt, Tim Burnett, Alexander Tzalenchuk, Markys Cain, Andy Pollard	**Stage End Date**	30/10/2015
		Est Final Stage End Date	
Sector	Growth (Champion Yong Yan)	**Activity**	Strategic Capability

Summary: *"Understanding the factors that influence the electrical transport in graphene and it's uniformity at wafer scale under environmental exposure are highly desirable"* .Christos Dimitrakopolous IBM, T.J. Watson research Centre. Recent work at IBM has already demonstrated the feasibility of the first high-frequency graphene electronics circuits, for radio-frequency applications (Lin, Science 332, 1294 (2011); Wu, Nature 472, 74 (2011)).

It is essential to cross the laboratory to production line gap; *"Going from laboratory demonstration to real-life application can be a difficult process and this is where many new technologies have failed in the past. Metrology plays an essential role in this process by providing reliable and reproducible measurement technology which gives confidence in the results of research"*. Kostya Novosolev, joint Nobel prize winner for his work on graphene.

Graphene, a single layer of carbon atoms in a hexagonal lattice, has displayed exceptional new physical effects and scientific interest has soared rapidly (70,000 citation of 3000 papers produced in 2010). New applications such as all-carbon electronics, high-frequency transistors, chemical and biological sensors, ultracapacitors, solar cells, etc., require industrially produced graphene which cannot be realised without measurement methods applicable to fabrication lines. The lack of this metrology is therefore a roadblock to progress. The properties of graphene are determined by the morphology and chemistry of the "graphene" as it can be doped or contaminated and it is supported by a substrate. Therefore, techniques need to be developed which can measure essential properties on a local scale and, most importantly, correlate these measurements with performance. _In use these device will have to be "packaged" to protect the Graphene from atmospheric exposure and the effectiveness and compatibility of this packaging needs to be assessed. The project proposed here develops methods for rapid and reliable measurement of electronic, chemical and structural parameters of epitaxial graphene grown on SiC and CVD grown graphene essential to take it from the laboratory to the production line and the quality of any packaging layers.

The Need. New measurement methods will be required in every fabrication line using graphene to enable development at the same pace as academic progress so that industrial companies can turn inventions into products. The potential of graphene (see table in impact and benefits) cannot be exploited without methods that are valid over the large-scale, for example, fast, contactless electrical measurement methods for testing of epitaxial graphene devices. Currently used methods are time-consuming, complicated and expensive and the obtained information is still generalized over the whole device and not correlated with the exact composition and morphology of graphene.

Metrological challenges, such as determination of the graphitization level and layer thickness, quantitative measurement of dopant concentration with sensitivities of better than 10^{10} atoms per cm^2 , need to be coupled with measurement of corresponding changes in electrical and electronic properties to understand the effect of surface functionalisation and contamination on the graphene properties. According to the ITRS roadmap graphene production will move from research to pre-production in the next few years.

Industrially relevant large-area graphene can be produced using two different routes, sublimation of SiC or CVD growth on metal (MBE growth is also possible but still in its infancy). The electrical properties of monolayer graphene are very different from bi-layer or tri-layer graphene and homogenous covering is required for most applications (this is not necessarily the case for applications which rely on the unique structural properties of graphene like high-strength composite materials). In the case of epitaxial graphene grown on SiC and depending on the growth conditions, the percentage coverage of the wafer with mono-, or bi-layer graphene will vary and appears to correlate with the number of step edges present in the SiC crystal. Identification of step edges is easy with AFM based techniques but identification of the number of graphene layers is much more difficult (Burnett, Nano Letters 11, 2324 (2011)) and needs to be combined with other more advanced functional scanning techniques or Raman analyses. The doping of graphene on SiC is determined by charge transfer from the SiC crystal and an interface layer between the substrate and graphene.

The properties of this interface layer and how they control the electron density are unknown. Similar issues exist for CVD growth of graphene on metals. A fingerprint of the domain structure of the metal substrate remains in the graphene layer after growth and lift-off, the different thermal expansion coefficients of metal and graphene cause ripples to be formed. The density of such domains and ripples will dramatically affect the electrical mobility.

The Solution - *To provide validated real-time measurement methods applicable to graphene in fabrication settings.*
In principle all key measurements are possible in the laboratory using dedicated equipment and specifically designed and fabricated samples (Tzalenchuk, Nature Nanotechnology 5, 186 (2010)). Whilst this may be useful in research settings, it does not meet the needs of industry. The challenge is to combine/integrate a number of techniques which can give a meaningful result on the factory floor and apply them to a single sample. The properties of graphene are determined by the structure on the nano-scale but the aim of the industry is to produce graphene by the square metre. Hence high-speed, contactless measurements are required which can be validated against established metrological standards. The methods can be used to investigate “packaged” graphene in combination with novel methods that overcome the challenge of performance assessment of ultra thin packaging material.

Contactless methods - Electron-beam microscopy (i.e. PEEM, LEEM) and functionalised electrical scanning probe microscopy (i.e. SKPM and EFM) have been recently successfully used to identify the number of layers in epitaxial graphene, but they need further development, validation and correlation with large-scale transport properties.
We propose a method that combines electrical measurements with Raman microscopy and spectroscopy techniques. This contactless technique can then be simplified to provide a mapping method for epitaxial and exfoliated graphene. Functional electrical microscopy (EFM, SKPM, SCM) will be applied to measure key data such as the graphitization level, thickness, distribution of the electrical potential and charge, electrical state of dopants and impurities, work function, and capacitance with a very high special resolution (<20 nm). Rapid, large scale laser/ electron beam intensity modulation method (LIMM) and Near field Microwave Microscopy (NFMM) and will be evaluated as candidates for development for high frequency electronic/dielectric and thermal properties of graphene.

tion methods -Secondary ion mass spectrometry (SIMS) and x-ray photoelectron spectroscopy (XPS), are not currently suitable for Graphene. SIMS is the tool for quantitative measurement of the dopant profile over the first 10 nm of an ultra-shallow implant. XPS is the key tool for non-destructive depth profiles of complex layer structures for high-k dielectrics for smaller device architectures and quanitifaction of surface functionalisation. Graphene presents a new challenge in surface sensitivity with a requirement of a depth resolution of around one atomic layer above and below the graphene and substrate interface which requires new capability development (e.g. ion beam development and new g-ogram method for data interpretation). Micro-Raman spectroscopy is a key metrological tool for graphene to quickly and reliably determine the number of graphene layers and quality of the graphene. Tip-enhanced Raman spectroscopy is a new variant of this technique with potential for non-destructive imaging of the surface chemistry with spatial resolutions of better than 20 nm. TERS could be developed for nanoscale imaging of surface dopants, functional groups and nanoscale contaminations and to study the effect and measurement of graphene layer edge-effects. Helium and neon ion microscopes have recently been shown to be extremely useful for graphene nanofabrication and imaging with sub-nm resolution. The potential of these instruments for quantitative surface elemental analysis through backscattering spectrometry has not yet been developed.

t Description (including summary of technical work):
This project delivers a step change in the state of the art from a series of methods only suitable for measurement over a small area to an integrated system scanning over a device

1) ***Aim*:** Measurement of key electrical parameters and characteristics of epitaxial graphene. ***Realization***: EFM, SKPM, SCM, NFMM and LIMM measurements will be performed in ambient conditions on epitaxial graphene grown by solid-state graphitization of SiC on both C- and Si-sides. Various types of conducting probes and samples with different numbers of layers will be studied. A comparative research on exfoliated graphene on SiO_2 and on CVD grown graphene on suitable substrates will be performed. Interaction and charge exchange between graphene and the substrate, as well as between individual layers will be studied
2) ***Aim:*** Development of EFM/SCM spectroscopic measurement techniques. ***Realization***: Optimal conditions for spectroscopy will be developed to enable use over a wide area. The role of capacitance and Coulomb interactions will be understood. Quantum capacitance studies of epitaxial graphene will be performed
3) ***Aim:*** To trial and develop large-scale methods. ***Realization:*** Large-scale (scanning) methods from Aim 1 will be trailed and the best candidates developed to measure carrier-density and mobility. These measurements will be correlated with local methods.
4) ***Aim:*** Metrological methods for the identification of various graphene layers. ***Realization***: Identification will be achieved using microscopy and spectroscopy techniques. Correlation of sample morphology (including various complex growth modes) with electrical mapping will be accomplished. Angle resolved XPS can be used to give quantitative measurement of the thickness of a uniform graphene layer with sub-nm precision.
5) ***Aim:*** Measurement tools to investigate the role of transfer doping in the electrical/ electronic properties of graphene. ***Realization***: Electrical microscopy and spectroscopy will be developed and performed on n- (i.e. NH_3, alkali atoms) and p-doped (i.e. N_2O, H_2O, O_2, organic molecules) graphene. Process of decoupling of graphene from a SiC substrate due to hydrogen intercalation will be studied for extrinsic (from dopants) and intrinsic (from substrate) doping.

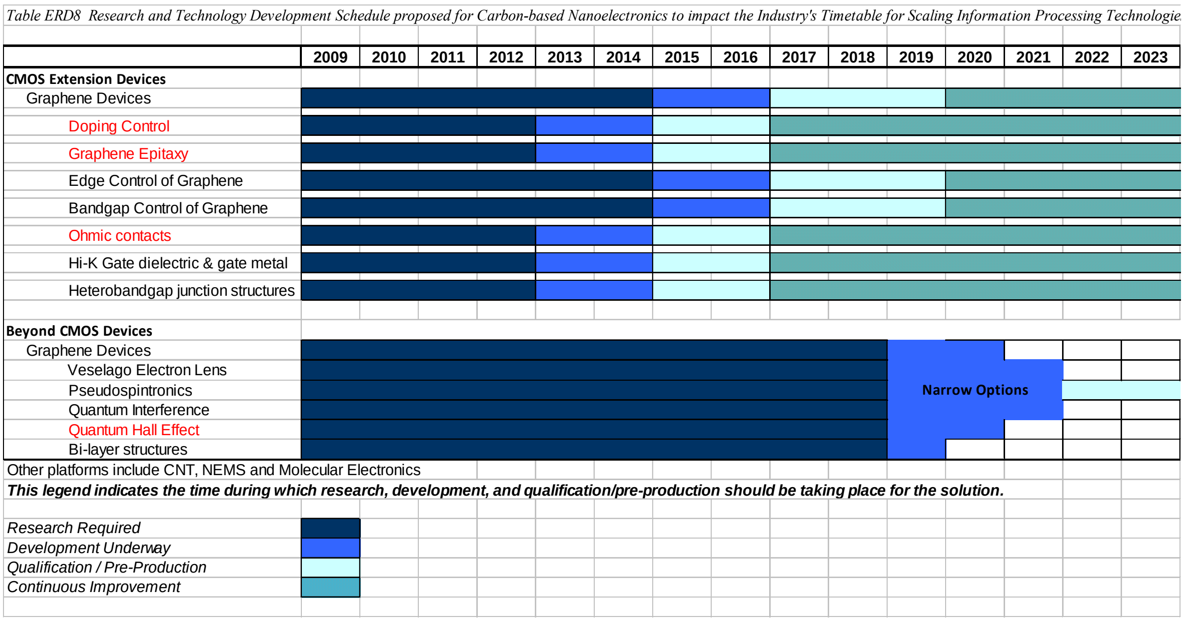
6) ***Aim:*** Tools to quantify dopant concentration, defect state and identification of contaminants for correlation with electrical performance. ***Realization (aims 5 and 6)***: Electrical microscopy and spectroscopy will be developed and performed on n- (i.e. NH_3, alkali atoms) and p-doped (i.e. N_2O, H_2O, O_2, organic molecules) graphene. Process of decoupling of graphene from a SiC substrate due to hydrogen intercalation will be studied for extrinsic (from dopants) and intrinsic (from substrate) doping. Fitness for purpose assessments will be made over large areas.

7) ***Aim:*** Establish methods, using metrological techniques, for the assessment of the robustness of "packaged" Graphene in devices operating under real conditions and their compatibility with Graphene. ***Realization***: The performance of exceptionally thin packaging materials will be assessed using sub-micro scale interdigitated combs on a silicon substrate. Compatibility will be assessed by packaging the graphene then using the other tools developed in the project to determine whether the graphene has been affected by the packaging.

Impact and Benefits The electronics sector will be first to exploit the extraordinary properties of graphene in new applications and extending existing technologies which are reaching the end of what is technically possible such as ultra-fast transistor and interconnects for the ICT industry (see ITRS roadmap below. Potential applications of graphene include, ultra-small transistors, super-dense data storage, wearable electronics, ultra-capacitors to store and transmit electrical power and highly efficient solar cells. The ability to dope Graphene will lead to the development of chemical sensor systems. The global market for graphene-based products will be worth an estimated $67 million in 2015 increasing to $675.1 million in 2020 at compound annual growth rate of 58.7%.

Segment	Growth rate %	**Value in 2015**	**Value in 2020**
Capacitors	67.2%	$26	$340
structured materials	39.1%	$17.5	$91
displays	-	-	$43.8
photovoltaics	36.1%	$7.5	$35.0
thermal management	8.4%	$15	$22.5

ITRS Roadmap Shows the technical development needs for which metrology has to be delivered in parallel



Support for Programme Challenge, Roadmaps, Government Strategies

The project enables the UK government and European growth agenda for the exploitation of the markets for graphene-based products by supporting the £50m UK national research initiative for graphene announced by the chancellor *"We will fund a national research programme that will develop production methods that take this Nobel-Prize winning discovery from the British laboratory to the British factory floor"* and the £1billion FP7 Flagship project (http://www.graphene-flagship.eu/GF/index.php) proposed to kick-start a graphene based industry in Europe. NPL aims to be the metrology partner in both of these opportunities by delivering the tools outlined in the ITRS roadmap; "non-destructive in-situ measurement methods to improve the balance between measurement speed, accuracy, and precision"

Synergies with other projects / programmes: The project develops surface analysis capabilities (SIMS, TERS, XPS) from the Chembio programme and electrical methods (EFM, SCM, SKPM, LIMM, NFMM) being developed in the pathfinder and materials programmes.

Risks: The collaborators will provide graphene but the quality may not be exactly as expected.

Knowledge Transfer and Exploitation. Knowledge transfer to stakeholders will be through a new NPL "Graphene Futures Campaign" with a dedicated web space, special interest group, and bi annual meetings. Exploitation of the outcomes will be through a variety of routes and not solely focussed on graphene:

- offering a service to assess very thin packaging materials for the electronics, photonics, sensors and food sectors
- using NPLs combined capabilities for research focussed consultancies on new materials for the sensor and electronic industries (e.g. the new gas exposure capability from Chembio Programme)
- establishing NPL as the prime partner providing metrology for the national research initiative (NRI) and flagship project on graphene seeking joint and additional investment to deliver metrology related technical capabilities
- integrated solutions to metrology challenges for industry through relationships with UK instrumentation suppliers

Our track record shows that we will be able to publish collaboratively in high impact journals.

(1) **Nature Nanotechnology 5, 186-189 (2010).** *Towards a quantum resistance standard based on epitaxial graphene.* A. Tzalenchuk, S. Lara-Avila, A. Kalaboukhov, S. Paolillo, M. Syväjärvi, R. Yakimova, O. Kazakova, T. J. B. M. Janssen, V. Fal'ko et al

(2) **Applied Physics Letters 97, 112109 (2010).** *Charge transfer between epitaxial graphene and silicon carbide***.** S. Kopylov, A. Tzalenchuk, S. Kubatkin and V. Falko.

(3) **Advanced Materials, 23, 878–882 (2011).** *Nonvolatile Photo-Chemical Gating of an Epitaxial Graphene - Polymer Heterostructure* **;**S. Lara-Avila, K. Moth-Poulsen, R. Yakimova, T. Bjørnholm, V. Falko, A. Tzalenchuk, and S. Kubatkin.

(4) **Physical Review B 83, 233402 (2011).** *Anomalously strong pinning of the filling factor ν = 2 in epitaxial graphene***;** T. J. B. M. Janssen, A. Tzalenchuk, R. Yakimova, S. Kubatkin, S. Lara-Avila, S. Kopylov, and V. I. Fal'ko.

(5) **Nano Letters, 11, 2324–2328 (2011)** *Mapping of local electrical properties in epitaxial graphene using Electrostatic Force Microscopy;* T. Burnett, R. Yakimova, O. Kazakova.

(6) **Solid State Communications 151, 1094 (2011).** *Engineering and metrology of epitaxial graphene,* A. Tzalenchuk, S. Lara-Avilla, K. Cedergren, M. Syvajarvi, R. Yakimova, O. Kazakova, T.J.B.M. Janssen, K. Moth-Poulson, T. Bjornholm, et al.

Co-funding and Collaborators: Linkoping and Chalmers Universities, Sweden, Lancaster University, Exeter University (graphene centre), EMRP Graphene project 2012 Industry call, Flagship Graphene (proposed). IMEC, the largest European semiconductor research institute and Samsung.

<table>
<tr><td>1</td><td>Start: 01/4/2012</td><td>End: 30/9/2012</td><td></td></tr>
<tr><td colspan="4">Deliverable title: State of the art assessment , initial experiments and review of measurement tools for graphene
Evidence: Report and project plan, disseminated to webspace and graphene campaign launch meeting.</td></tr>
<tr><td>2</td><td>Start: 01/08/2012</td><td>End: 31/10/2014</td><td></td></tr>
<tr><td colspan="4">Deliverable title: Development of wide area measurement tools for the electrical characteristics of Graphene
Evidence: 2 publications in peer-reviewed journals per year.</td></tr>
<tr><td>3</td><td>Start: 01/08/2012</td><td>End: 31/10/2014</td><td></td></tr>
<tr><td colspan="4">Deliverable title: Development of wide area measurement tools for the structural characteristics of graphene
Evidence: 2 publications in peer-reviewed journals per year.</td></tr>
<tr><td>4</td><td>Start: 01/08/2012</td><td>End: 31/10/2014</td><td></td></tr>
<tr><td colspan="4">Deliverable title: Validated Measurement tools for the chemical analysis of graphene extended to wide areas
Evidence: 2 publications in peer-reviewed journals per year. [TSB PGT co-funding removed]</td></tr>
<tr><td>5</td><td>Start: 01/6/2012</td><td>End: 31/07/2014</td><td></td></tr>
<tr><td colspan="4">Deliverable title: Tools for the assessment of performance and compatibility of "graphene packaging materials"
Evidence: 2 publications in peer-reviewed journals.</td></tr>
<tr><td>6</td><td>Start: 01/08/2012</td><td>End: 31/08/2015</td><td></td></tr>
<tr><td colspan="4">Deliverable title: Wide area measurement tools to correlate the electrical, structural and chemical characteristics Evidence: 1 publication in peer-reviewed journals per year.[EMRP GraphOhm co-funding removed]</td></tr>
<tr><td>7</td><td>Start: 01/09/2012</td><td>End: 30/10/2015</td><td></td></tr>
<tr><td colspan="4">Deliverable title: Dissemination and knowledge transfer
Evidence: 3 project workshops linked to graphene campaign, demonstration of techniques and engagement with industry, academia and instrumentation sector.</td></tr>
</table>

Project No.	IRD\2012\13\EMRP	Price to NMO	£379,496 [removed from IRD/2012/13]
Project Title	Co funding for EMRP Project Graphohm	Co-funding won	£260,058 from EMRP GraphOhm
Lead Scientist	Alexander Tzalenchuk,	Start Date	1/6/2013
Scientist Team	Ruth Pearce, Olga Kazakova, Jt Janssen,	End Date	30/05/16
Sector	Measurement infrastructure	Activity	Strategic Capability

Summary

This project supports NPLs role in the EMRP Graphohm project which aims to exploit the unique properties of Graphene to deliver improved precision in resistance measurement to the SI system, and traceability directly to end users by exploring the science and technology required to produce a bench top device. The consortium of NMI, University and industry partners will interact with stakeholders from the calibration industry to ensure impact is created by early adoption of enhanced calibration capabilities that could revolutionise the dissemination of the SI.

The Need

Quantum resistance metrology uses the quantum Hall Effect (QHE) to reproduce the unit of electrical resistance with unprecedented precision and in combination with the unit of electrical voltage, based on the Josephson Effect, the full range of electrical quantities can be spanned by NMIs. After the forthcoming redefinition of the international system of units, SI, also the kilogram will rely on the QHE for its reproduction.

The technical complexity of the systems currently used to realise quantum standards precludes their widespread use except in specialised facilities that NMIs operate and this therefore necessitates a hierarchy of secondary standards to disseminate the electrical quantities to the end-users. A simpler to use primary standard of electrical resistance, shortening present-day calibration chains, is made possible by the unique properties of Graphene and the key goal of this JRP is to develop these Graphene based systems. .

The Solution

Graphene exhibits the QHE at lower magnetic fields and higher temperatures than any other material, systems therefore become possible that use closed cycle cryo-coolers or non-pumped liquid helium dewars. Combined with compact superconducting magnets such systems fulfil the main requirements of simplicity and transportability – eventually becoming a 'bench-top QHE'.

Three main problems need to be solved to enable working devices to be produced: 1) the establishment of fabrication routes for graphene films of sufficient quality to produce reliable and long-living devices rather than research materials, 2) the development of new instrumentation to make full use of the offered advantages of Graphene and 3) characterisation of the performance of graphene in terms of the exact field and temperature margins to give high precision operation.

This activity is co-funded from IRD/2012/13 deliverable 6 "Wide area measurement tools to correlate the electrical, structural and chemical characteristics" (TQEM)

Project Description (including summary of technical work)

This project enables NPL to collaborate in the following packages of the EMRP project focussed on DC electrical measurements;

- Advancing the device fabrication methods to fulfil requirements of metrology in terms of homogeneity, contact resistance, variety of sizes, controlled disorder, edge structure, etc. Metrological grade graphene material and devices will become available to NMIs.
- Developing the synthetic procedures for precise, quantitative, non-destructive characterisation of graphene and graphene devices combining structural, chemical and physical methods.
- Performing precision QHE measurements on graphene to test the limits of achievable uncertainty under relaxed experimental requirements of temperature and magnetic field.(NPL lead)
- Developing customized instrumentation which allows graphene to be used as an intrinsically referenced resistance standard, including peripheral, but vital instrumentation for scaling of the singular QHE value of 12.9 kΩ.

Impact and Benefits

The ideal of quantum (intrinsic) standards is to create a system that is more distributed, with the primary reference available wherever it is needed, reducing the costs and inconveniences of traditional calibration chains thus reducing the cost and inconvenience of traditional calibration chains and driving innovation in how and when calibrations can be carried out.

Impact and Benefits

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Support for Programme Challenge, Roadmaps, Government Strategies

The project supports the aim of the NMS Strategy that the "definition and realisation of the base and derived units are actively researched with more precise methods being introduced as they become available" and participation in the EMRP to "facilitate closer integration of the nationally-funded metrology research programmes".

The specific need for this project is outlined in an number of EURAMET and BIPM documents, particularly the CCEM strategic planning document "'*Big' Problems in Electromagnetics*" and the EURAMET roadmap "*Innovative calibration means in electricity/magnetism*". It also supports NPL's metrology 2020 initiative by delivering the quantum SI directly to end users.

Synergies with other projects / programmes

The project uses the basic knowledge of Graphene developed in the FP7 Project *ConceptGraphene* by developing specific know how that enables working metrological devices to be made. MIKES, who are partners in Graphohm are also partners in the EMRP Project *MacPoll* that uses Graphene's sensitivity to adsorbates for the creation of sensors. MIKES will transfer the knowledge gained in that project so it can be used in reverse to de-sensitize Graphene in end user environments.

Risks

The project is dependent on the supply of Graphene on known high quality over a suitable area. To mitigate this risk multiple suppliers of graphene.

Knowledge Transfer and Exploitation

The impact of the JRP will be realised via the following activities taking advantage of the greater funding for this activity available in the EMRP project:

- Knowledge transfer through the stakeholder committee, best practice guides, papers, presentations and the project web-site
- Training and dissemination of JRP knowledge via national liaisons with universities, companies, and other stakeholders, and via best practice guides
- Exploitation of JRP results for improved graphene production, preparation, characterisation techniques and measurement infrastructure established via the stakeholder committee and other graphene research and application networks

Co-funding and Collaborators

The project is cofunded by the EMRP programme in collaboration with the partners outlined below;

	Organisation	Country
PTB	Physikalisch-Technische Bundesanstalt	Germany
CMI	Cesky Metrologicky Institut Brno	Czech Republic
EJPD	Eidgenoessisches Justiz- und Polizeidepartement	Switzerland
LNE	Laboratoire national de métrologie et d'essais	France
MIKES	Mittatekniikan Keskus	Finland
SMU	Slovenský Metrologický Ústav	Slovakia
SP	SP Sveriges Tekniska Forskningsinstitut AB	Sweden
KRISS	Korea Research Institute of Standards and Science	Republic of Korea

Deliverables

1	**Start: 01/06/13**	**End: 30/05/16**	

Deliverable title: Developing synthetic procedures for precise, quantitative, non-destructive characterisation of graphene

Evidence: Peer reviewed paper on the correlation between morphology and electrical transport in graphene.

Project No.	IRD\2012\13\TSB	Price to NMO	£138,369 [removed from IRD/2012/13]
Project Title	Co-funding for TSB Graphene Printed electrodes for large-area, low-cost, flexible electronics technology (PrintGraphene Technology (PGT))	**Co-funding won**	£100,055 from TSB grant
Lead Scientist	Andrew Pollard	**Stage Start Date**	1st Nov 2013
Scientist Team	Bonnie Tyler, Debdulal Roy, Alex Shard, Ian Gilmore	**Stage End Date**	31st Oct 2015
		Est Final Stage End Date	
Sector	Advanced manufacturing and services	**Activity**	Strategic Capability

Summary

The project will develop the metrology tools for chemical, optical and structural characterisation of high value, low-cost, conductive graphene inks and the large-area, transparent, flexible, conductive electrodes subsequently printed using these graphene inks. This TSB project is in partnership with DZP Technologies (a UK SME) and will ultimately lead to the production of graphene electrode prototypes. A clear route has been identified to the commercialisation of these conductive electrodes made from these graphene inks that will have applications in areas such as high technology displays, lighting and photo-voltaics. UK SMEs, Cambridge Display Technology (CDT) and Plastic Logic, support this project and regard the proposed industry-focussed research as vital to the commercialisation of graphene for UK industry in display and lighting technology.

The Need

A stable, transparent, low-cost, flexible, and conductive material that can be mass produced is required to replace ITO in displays, lighting and photo-voltaic applications, and consumer and energy products that are widely used in today's society and technology. ITO is expensive due to the energy costs of processing and the availability of indium, a rare metal, in the future could be limited. New materials are needed to secure sustainable production of these products in the future, which are less reliant on scarce resources such as indium. Additionally, alternatives to ITO are also being sought for flexible electronics, an exciting new area that has had intense interest recently ("Flexible phones 'out by 2013'" BBC News, 30 Nov 2012), as it is widely acknowledged in the industry that ITO is unsuitable for flexible electronics. ITO is also not suitable for roll-to-roll processing which is the desired manufacturing method for the plastic electronics industry.

The Solution

The project proposes the design, development and ability to manufacture new multifunctional, high value, low cost, conductive graphene inks and related printing methods. The potential of graphene for this application has been proven but there are no commercial products developed yet. NPL's role will be to continue the development of metrological methods and tools we are using for graphene layers and devices produced from different growth methods and to characterise the chemical properties of them. This will include the use of ellipsometry, Raman spectroscopy and TERS, SPM, XPS and SIMS. **This activity is co-funded from IRD/2012/13 deliverable 4 "Validated measurement tools for the chemical analysis of graphene extended to wide areas"**

Project Description (including summary of technical work)

The main technical objective of the work is to develop and demonstrate a process for producing transparent flexible graphene electrodes that meet specific performance targets. These targets were set as a result of our discussions with potential users of the new technology. All work in the project will make use of solution processing methods which have important advantages compared to alternative CVD methods. The structural and chemical characterisation of the liquid-phase exfoliated graphene flakes and printed electrodes throughout the ink and printing development process will be crucial to producing an acceptable performance electrode prototype when characterising the films optically and electrically. Techniques such as AFM, SEM, Raman spectroscopy and TERS will first be used to understand the lateral size and thickness of the produced flakes, before these techniques and XPS, UPS, SIMS and ellipsometry are used to also quantify and map the chemical contaminants present in the printed films, the work function of the surface and the optical properties.

Impact and Benefits

- NPL will further its expertise in the advanced 2-D materials metrology area and broaden characterisation capabilities for conductive inks and flexible, conductive electrodes. This will suppprt 3rd party non grant opportunities increase our profile as the world-leading National Measurement Institute (NMI) for graphene and 2-D materials characterisation.
-
- UK industry will develop the expertise in producing cheap graphene electronics, a platform technology predicted to revolutionise multiple applications, leading to UK market and job creation with the aim of developing products in the UK instead of Korea or other overseas countries, which has been highlighted by both George Osborne and David Willetts ('Graphene: Patent surge reveals global race' BBC News, 15 Jan 2013) as extremely important.
- Flexible electronics, the target market for this project, has the potential to introduce new products in critical areas such as assisted living and healthcare (wearable biosensors and medical devices), energy (efficient lighting and photo-voltaics), consumer safety (smart packaging, food tracking) and low carbon vehicles (reduced weight electronics).
- The environmental benefits of introducing graphene are widely recognised as carbon is an extremely cheap and abundant material and much more sustainable than elements such as indium. Additionally, water-based methods will be used to produce the graphene films, avoiding toxic and hazardous solvents and liquid-phase exfoliation will be cheaper and less energy-intensive.

Support for Programme Challenge, Roadmaps, Government Strategies

This project links with NPL's Graphene strategy for developing graphene and 2-D material characterisation capability and supports a UK SME in the fledgling graphene industry, which is an NPL and UK Government aim.

Synergies with other projects / programmes

This project will enable future 3rd party work with UK, EU and international companies requiring reliable characterisation of graphene and 2-D materials, inks and printed films. This work will progress into other projects characterising 2-D materials included in devices such as flexible electronics and photovoltaics.

Risks A number of risks are inherent within the project and will be mitigated if they occur:

- Graphene being unstable/ difficult to print – DZP have extensive experience in specialist ink formulation and chemical formulation. Experience gained in small scale TSB feasibility project has shown that ink formulations are achievable
- Characterisation tools cannot be successfully applied to graphene - Previous experiments at NPL have already shown the ability to characterise other types of graphene layers and devices with the outlined surface analysis techniques
- Scale up of electrode production - Large-scale printing using conductive inks has already been shown to be viable and liquid-phase exfoliation has been shown to produce large amounts of graphene whilst maintaining low-cost
- Obtained electrodes not transparent and/or not conductive – it will still be possible to use graphene in other less demanding applications; valuable know-how that can be applied in other uses of graphene
-

Knowledge Transfer and Exploitation

- Exploitation is likely via IP and licensing, which will be granted to third parties in order to develop products, through licensing, or licensing combined with joint development agreements. The project team has already identified several UK SMEs as end-users, Cambridge Display Technology (CDT) and Plastic Logic who are actively developing printed electronics products, sepcifically in lighting and displays, and Akzonobel, who require large-scale coating of materials with graphene, for uses in anti-corrosion thus creating an immediate route to market.
- NPL will exploit the valid surface analysis metrological tools and methods developed in this project to characterise new advanced 2-D materials in general. The work will position the UK at the frontier of measurement techniques required for the forthcoming graphene-based technological advances. Results will be disseminated via peer reviewed journals (open source where possible), trade journals and both oral and poster presentations at major workshops and conferences. This will mean the project results will be disseminated to both UK industry and academics.

Co-funding and Collaborators

50% co-funding (£100k) by TSB already won. DZP Technologies are a UK SME leading the TSB project and will develop the graphene inks and printing methods. CDT, Plastic Logic and Akzonobel are UK SMEs who would like to test the end-prototypes.

Deliverables

1	**Start: 01/11/13**	**End: 30/09/15**	

Deliverable title: Develop valid metrological methods to characterise structural and chemical properties of graphene layers deposited directly from dispersions, as well as inks printed on different substrates. Characterise the electrical, optical and mechanical properties of the graphene films printed using graphene inks developed, supporting the optimisation of the inks and printing processes

2	**Start: 01/11/13**	**End: 31/10/15**	

Deliverable title: Monitor progress of the project to ensure successful completion, disseminate project outputs, develop exploitation plan and take actions for its implementation following project completion. Provide input to DZP Technologies to provide any guidance they will need in developing inks and printing processes.

Project No.	IRD\2012\20	Price to NMO	£312.5K
Project Title	Transparent Electrodes for Large Area, Large Scale Production of Organic Optoelectronic Devices	Co-funding target	£320K
Lead Scientist	Fernando Castro (MAT)	Stage Start Date	Sept 12
Scientist Team	James Blakesley (MAT), William Kylberg (MAT), Martin Rides (MAT), Tony Maxwell (MAT)	Stage End Date	Oct 15
		Est Final Stage End Date	Oct 15
Sector	Energy/ High Value Manufacturing	Activity	Methodology for New Capabilities
Project Champion			

Summary

This project is part of a €9.8M FP7 activity recently awarded that will demonstrate the production of large area organic electronics using high throughput manufacturing technologies based on roll-to-roll wet deposition processes. In particular, by developing large area transparent conducting barrier foils which will be used for the production of flexible organic light-emitting devices (OLED), light-emitting electrochemical devices (LEC) and flexible organic photovoltaics (OPV). Scale-up of device area to high throughput production without degradation of performance or yield is a key objective of the project. Innovative testing, reliability validation and disposal issues are an integral part of the project.

The Need

Despite strong competition from Asian companies, Europe is at the forefront of industrial development in the field of large area optoelectronics. Key to this field is the possibility of fabricating functional devices from solution by processes similar to those employed in the printing industry. Processes based on high throughput production methods such as roll-to-roll (R2R) fabrication are particularly price competitive but add a significant constraint on the materials used: substrates and functional coatings must be flexible in order to be compatible with R2R. In order to achieve large scale dissemination (> $1GW_p$ /year) and produce a real ecological impact, high throughput, low-cost processes have to be further developed. The quality and availability of flexible transparent electrodes is essential for industrial implementation. Besides lighting and energy conversion perspectives various applications in the field of plastic electronics, such as touch screens, LCD displays, signage devices are also interested in novel flexible electrode strategies to reduce cost. Major challenges remain in terms of mechanical stability of flexible components and devices, degradation under accelerated testing and repeated bending.

The Solution

- Novel protocols for electrical characterisation upon mechanical bending of flexible substrates.
- Testing of degradation mode using controlled atmospheric environements and in-situ characterisation.
- Custom-made mechanical testing

Project Description (including summary of technical work)

NPL leads workpackage 1: “Constraints, Standards, Validation”. NPL’s work include:

- Assessment of existing and foreseen standards related to processes and methods used in the project.
- Development of a testing facility for in-situ electrical resistance test of flexible electrodes during repeated bending cycles.
- Investigation of degradation modes using custom made testing chamber that allows environmental control and in-situ testing
- Mechanical testing of devices and components, using known methods and further developing new ones, such as thermal scanning microscopy.

Impact and Benefits

- Increases visibility of NPL capability in organic electronics through collaboration with several new partners, including a major worldwide company (OSRAM).
- Builds new capability at NPL on testing of flexible electrodes and flexible devices.
- Builds NPL know-how on legal and technical constraints for roll-to-roll production of plastic electronic devices. This can open opportunities for consultancy work.
- Builds close link with UK SME (Eight19).

Support for Programme Challenge, Roadmaps, Government Strategies			
● Maps onto the "Stability" organic electronics roadmap. ● This project links to the NMS strategy/priority areas of low carbon technologies, sustainability, global competitiveness, and advanced manufacturing. ● UK Technology Strategy Board Electronics Photonics Electrical Systems technology pillar (2008). UK Dept for Business Innovation and Skills, Plastic Electronics: A UK Strategy for Success (2009). DECC's July 2011 "UK Renewable Energy Roadmap" relies on the uptake of photovoltaics to achieve the 80% emissions reduction by 2050. UK Government strategy Renewable Obligation, Climate Change Bill, Microgeneration Strategy, UK Energy Marketing Strategy			
Synergies with other projects / programmes Builds upon IRD Degradation project and extends capability used for TSB SCALLOPS and EMRP Thin Films projects. The proposal follows the ten year road map for the organic electronics area to place NPL a world leading NMI in this area.			
Risks The very thin layers used as active layers may pose a limit to what type of mechanical testing that can be used. This is particualry challenging on flexible and soft substrates. Mitigation: possible issues have been discussed and will be clarified at the beginning of the project. Contigency: Requirements for new/modified mechanical testing will be developed/adapted during the project.			
Knowledge Transfer and Exploitation The European Energy Research Alliance network will be a viable mechanism to inform our UK and European partners. The work is antecipated to lead to a high impact paper. future joint projects and third party work.			
Co-funding and Collaborators This project is to co-fund project FP7 TREASORES.			
Deliverables			
1	**Start: 01/09/12**	**End: 31/10/15**	
Deliverable title: Co-fund to FP7 TREASORES			

Project No.	IRD\2012\21	Price to NMO	£204.5k
Project Title	Co-funding for H2FC EU Infrastructure Project	Co-funding target	
Lead Scientist	Gareth Hinds	Stage Start Date	Jul 12
Scientist Team	Gareth Hinds, Andrew Brown, Edward Brightman, Arul Murugan	Stage End Date	Oct 15
		Est Final Stage End Date	2015
Sector	Energy	Activity	Development of Existing Capabilities

Summary

This project provides co-funding for NPL's participation in the H2FC EU Infrastructure project, which brings together for the first time leading European research institutions of the hydrogen community together with those of the fuel cell community, covering the entire life-cycle of hydrogen/fuel cells, i.e. hydrogen production, storage, distribution and final use in fuel cells. The main objective of H2FC is to generate a structured and integrated alliance based on complementary, state of the art, rare or unique infrastructures to serve the needs of the scientific community and facilitate future research. Three main activities are covered by the project: 1) Networking 2) Transnational access and 3) Joint research activities. NPL is taking part in each of these activities in two distinct research areas - polymer electrolyte fuel cell metrology and hydrogen purity measurements.

The Need

Hydrogen fuel cells are promising candidates as more efficient and environmentally-friendly alternatives (or hybrid partners) for conventional energy conversion technologies such as the internal combustion engine, batteries and gas turbines. Drivers for commercialisation include higher energy efficiency, security of supply, lower carbon emissions and reduced pollution (both chemical and noise). Widespread uptake has so far been hindered by the high cost of materials and manufacturing and the limited durability of fuel cells under realistic operating conditions. A number of key degradation modes have been identified by industry, including start-up/shut-down, freeze/thaw, fuel starvation and corrosion of metallic bipolar plates. In many cases there is a lack of fundamental understanding of these degradation mechanisms, exacerbated by a lack of in situ measurement capability within the fuel cell. In terms of ex-situ materials qualification, the current accepted method for assessing the corrosion resistance of bipolar plates (testing in strong acid) is not representative of service conditions and may be misleading.

In addition, the performance of polymer electrolyte membrane (PEM) fuel cells is hugely dependent on the presence of hydrogen fuel impurities at ppm and sub-ppm levels; for example, sulphur compounds cause irreversible damage to fuel cell performance, and carbon monoxide and ammonia lead to reversible damage in performance. Knowledge of the impurities in hydrogen is also crucial for validating claims of the hydrogen storage capability of novel materials. The threshold levels proposed in draft international standards for some contaminant species are highly challenging: up to 1,000 times lower than in other bulk gas products. Moreover, the ability to measure fuel quality covers a fundamental role in performing R&D activities in the area of hydrogen fuel quality definition with respect to cost effective hydrogen production, storage, distribution and use in fuel cells, and in developing low cost, durable and impurity-tolerant anodes for fuel cells. Hydrogen producers, stack developers, system integrators and end-users urgently require accurate and traceable measurements of hydrogen purity.

The Solution

In order to improve durability of PEM fuel cells, more fundamental insight is required into the critical degradation mechanisms. This will be achieved through the application of novel in situ measurement techniques to real world fuel cell problems. Durability of two main components of the fuel cell will be considered: the membrane electrode assembly (MEA) and the bipolar plate, reflecting the respective interests of both MEA and fuel cell manufacturers. A novel reference electrode design will be applied to the study of carbon support corrosion during PEM fuel cell start-up/shut down. A more representative test method for assessment of corrosion resistance of metallic bipolar plates will also be developed, supported by in situ measurement of water chemistry under operating conditions.

In order to meet the pressing needs of industry for accurate and reliable methods of hydrogen fuel quality, robust and traceable methods will be developed for the analysis of key contaminant species (*i.e.* those which have the most deleterious effect on fuel cell efficiency).

Project Description (including summary of technical work)

1. Fuel cell metrology

The reverse current decay mechanism during start-up/shut-down has been identified by industry as a particular concern for fuel cell durability. Many aspects of this process are poorly characterised and not well understood. In this project, a novel approach to the use of reference electrodes in PEM fuel cells will be developed to investigate the variation of potential across both anode and cathode to shed light on the degradation mechanism. The results will be used to suggest potential mitigation strategies. A more representative test method for the corrosion resistance of bipolar plates will be developed. This will be supported by in situ measurement of water chemistry in the vicinity of the bipolar plate under various operating conditions. The effects of mechanical compression and galvanic coupling will also be addressed using a specially designed model cell. The output of this work will be in the form of a draft international standard, which will be submitted through IEC TC 105 – Fuel Cell Technologies.

2. Hydrogen purity measurement

The project will first review the existing best practices and state-of-the-art for hydrogen purity analysis, including those methods published in national and international standard, test protocols, and the peer-review literature. Novel techniques for the analysis of trace contaminants in hydrogen and hydrogen-based gas mixtures for use in fuel cells will then be developed. A series of challenging analytes will be selected and traceable analytical methods (e.g. gas chromatography, mass spectrometry, FTIR) will be developed to meet the limit-of-detection equipment specified by industry and ISO. The focus will be on techniques that allow simultaneous measurement of multiple species underpinned by the development and validation of a series of gaseous traceable reference materials. The key criteria will include the compatibility with fuel cell requirements in terms of detection limit, stability, accuracy, measurement range, resolution, response time, selectivity, complexity, cost and availability. Particular attention will be paid to the accurate and representative sampling of hydrogen, as this is crucial to ensure that any measurements, but particularly those of ultra-trace concentration of reactive and unstable species, are fully robust. Consideration will also be given to the development of an impurity enrichment device based upon selective permeation membrane technology. The development and use of such a device will 'concentrate' the levels of impurities within a sample of hydrogen, meaning that analysis may be carried out to a much higher level of confidence.

Impact and Benefits

- Acceleration of the demonstration phase of PEM fuel cell technology and fostering of greater public acceptance.
- Access to broader hydrogen and fuel cell research infrastructure for UK SMEs.
- Impact directly on UK industry by providing major UK gas suppliers and SMEs with a measurement facility to ensure their hydrogen meets the stringent international specifications.
- Help facilitate the roll-out of a hydrogen refuelling infrastructure across the UK. This, coupled with the use of hydrogen from renewable resources, will help the Government attain their CO_2 emissions targets.
- Impact directly to the activities of ISO TC 197 in developing specifications for hydrogen fuel quality, and ISO TC 158 in developing international standards for methods for hydrogen purity analysis.
- NPL strengthens its global reputation in hydrogen and fuel cell metrology, facilitating participation in a number of complementary collaborative research projects that will add significant value to the NMS-funded work.

Support for Programme Challenge, Roadmaps, Government Strategies

- Addresses a key part of the IRD Programme Challenge in Energy Generation & Transmission.
- Supports the ChemBio Programme gas analysis theme roadmap target of 'supporting a hydrogen economy'.
- Well aligned with NPL/NMO Energy Strategy.
- Aligned with wider UK government and EU strategy on low carbon technologies.
- Technology Strategy Board focus areas of: Transport, Environmental Sustainability, and Energy Generation and Supply.

Synergies with other projects / programmes

- Fuel cells: IRD Fuel Cell Durability (2011-2013), TSB project on fuel cell durability (2009-2013). Fuel cell consortium led by NPL has been established to bid into the EMRP Energy Call in 2013.
- Hydrogen: ChemBio H1 (Traceable measurements of hydrogen quality and storage capacity), European New Energy World JTI 'HyQ' - Hydrogen fuel quality requirements for transportation and other energy applications.

Risks

This project, while challenging, is well aligned with NMS work in both the IRD and ChemBio Programmes. The risk is low given the progress to date under the NMS Programmes and the expertise of the NPL scientists involved.

Knowledge Transfer and Exploitation

- Via EU H2FC project meetings, workshops and the project website.
- Through the existing NPL Fuel Cells Industrial Advisory Group, EU industry partners and other external collaborators.
- International conference presentations (Gordon Conference, Fuel Cell Seminar, Grove conference, etc.).
- Peer-reviewed publications (Int. J. Hydrogen Energy, J. Power Sources, etc.).
- International standards bodies: IEC TC 105 (Fuel Cell Technologies), ISO TC197/WG12 (Hydrogen fuel – product specification) and ISO TC158 (Gas analysis).

Co-funding and Collaborators

- The partners for this EU project comprise the major fuel cell and hydrogen research organisations in Europe, including CEA, SINTEF, BAM, FZ Julich, JRC Petten, IFE, EMPA and the Paul Scherer Institute.
- IAG: Johnson Matthey, Intelligent Energy, Acal Energy, AFC Energy, C Tech Innovation, UCL, Imperial College, U. Surrey.
- Industrial partners will supply materials, components, test cells and drawings, access to test facilities, practical support and advice, test data for validation of models and critical assessment of techniques developed in the project.

Deliverables

1	**Start: 01/07/12**	**End: 30/10/15**	
Co-funding for H2FC EU Infrastructure project			

Project No.	NMS/IRD2012/22	Price to NMO	£411,680
Project Title	Cofunding for EMRP Project – i17 Metrology for airborne molecular contamination in manufacturing environments	Co-funding won	£293,764 from EMRP i17
Lead Scientist	Geoff Barwood	Stage Start Date	01/06/2013
Scientist Team	Geoff Barwood, Chris Edwards, Helen Margolis, Patrick Gill, Paul Brewer, Marta Doval Minarro & Yarshini Kumar	Stage End Date	31/05/2016
		Est Final Stage End Date	
Sector	Advanced manufacturing	Activity	Methodology for new capabilities

Summary

There is a demand from high value industry sectors for continuous measurement and control of airborne molecular contamination (AMC) for the optimization of microfabrication processes to improve yields and maximise the performance of devices. However, accurate and robust measurement techniques that can provide data fast enough to control these processes are lacking. It is the aim of the EMRP project to bring together the expertise of European NMIs, instrument makers and industrial users to scope and deliver these measurement techniques and through their future standardisation meet the industry need. An additional benefit will be the support that this provides related to legislation for occupational health and safety.

NPLs role in the project is threefold: 1) the development of suitable gases for calibration purposes and their qualification procedures, 2) the assessment of suitable spectroscopy techniques and 3) the development of the NICE-OHMs system using special expertise in high finesse cavities and frequency locked laser systems.

The Need

Technological progress in high tech industries is limited by the ability to manage contamination from the chemicals used in the manufacturing process. These molecules are reactive and adsorb easily to surfaces, difficult to measure and disruptive to the microfabrication process. Currently available instrumentation is not fit-for-purpose due to high costs, large size, and slow measurement time compared to required response time. Recent progress in quantitative molecular spectroscopy has brought the detection limits of typical contaminants to a level that can meet the industrial need for AMC measurements. In particular, laser-based techniques have reached such technical maturity that their use in industrial environment has become possible. However, these new techniques can only be applied in industrial production in conjunction with validated methods for sampling, measurement, and the generation of calibration gases

The Solution

The consortium will explore the practical potential of state-of-the art optical spectroscopic techniques for traceable AMC monitoring in clean room environments by:

- Assessing the usability techniques for online detection
- Developing an advanced spectroscopic system (NICE-OHMS) for improved sensitivity (NPL main focus)
- Improving the applicability of Gas Chromatography to AMC monitoring
- Developing dynamic generation methods for trace level airborne molecular contaminants.
- Developing suitable sampling techniques for practical AMC monitoring

Project Description (including summary of technical work)

NICE OHMs

The main objectives for NPL are to develop:

- A scannable high-finesse optical cavity for the chosen molecule and the associated vacuum system.
- An electronics system for locking the laser to the cavity and the PDH RF sideband to an adjacent cavity resonance.
- Data processing and control systems for observation of the signal, cavity tuning and temperature control
- And to measure and report on the quality of the NICE-OHMS signal

Reference standards

The project will develop a capability for generating reference standards for several key AMCs in manufacturing environments (e.g. NH_3, HCl and HCHO) at trace amount fractions. The system will provide traceability for measurements of these compounds. Key technology issues to address will be the identification of a feasible dynamic method which enables a variable reference standard of the compound of interest at ppb – ppt amount fractions (the majority of methods target higher amount fractions), a stable source of the target compound and any reaction from the target compound to be controlled and minimised. [This is a co-funding deliverable from CB/2013/GA13].

Impact and Benefits

The European semiconductor industry was ranked as the most R&D intensive sector by the European Commission in 2011 [9]. This sector supports around 110,000 jobs directly and up to 500,000 jobs indirectly in Europe, operating in a worldwide market valued at over € 215 billion in 2011 [10] (Data from the European Semiconductor Industry Association (ESIA)). In such high value business, where product yield directly affects the profitability of the industry, even a small change in the yield can lead to savings/profits of hundreds of millions of euros.

This project will lead to fewer product failures and less downtime of facilities and will therefore increase the competitiveness of the European Industry. Benefits are not limited to the semiconductor industry; other industries that will benefit include aerospace, pharmaceuticals, medical devices, food, and healthcare.

The techniques and devices developed could be directly applied to e.g. breath analysis used in medical analysis and indoor/outdoor air quality monitoring.

Support for Programme Challenge, Roadmaps, Government Strategies

This project supports the NMS strategy objective to grow the high value manufacturing sector Nanotechnologies, plastic electronics, new production technologies (such as laser based machining), and advanced instrumentation. It focusses on the need identified in the International Technology Roadmap for Semiconductors (ITRS[1]),'…. *for better AMC monitoring instrumentation in the clean room to measure AMC at the part per trillion level (by volume) in real time.*'

Synergies with other projects / programmes

This project aligns with other T&F projects in developing optical frequency standards based on iodine and acetylene (an existing EMRP project). It also aligns closely with a recently-won ESA project to develop a CO_2 stabilised laser for environmental monitoring. The work on the development of reference standards in this project align closely with GA13 "Primary standards for process gases and micro-manufacturing applications" in the Chem-Bio Programme.

Risks

The principle scientific risk to the project is that there is an unforeseen reaction between the gas under test and the cavity mirror coatings that degrade the finesse and transmission over time. Within WP1, we will need to steer the choice of gas towards suggestions such as ammonia rather than an aggressive acidic gas such as HF. The main risk associated with WP3 on reference standards is whether application of the new measurement techniques will be successful. This risk has been reduced by preliminary calculations. Access to methods and protocols used in industry will be required for the development capabilities.

Knowledge Transfer and Exploitation

The dissemination of project results will be done by the following mechanisms:

- Project newsletter and website: Each participant will contribute to the biannual newsletters and publish it on the JRP-website
- Guidelines: At least three guidelines related to online AMC monitoring techniques, dynamic generation of reference gases and practical applicability of NICE-OHMS.
- Workshop. A final workshop with training on developments in AMC monitoring.
- Publications. At least 6 publications in peer-reviewed journals (e.g. Applied Physics B, Optics Express, Review of Scientific Instruments) and industrial application journals (e.g. Solid State Technology, Clean Room Technology).
- Conferences .A dialogue with industry will take place at existing conferences that appeal to both science and industry (e.g. "CleanRooms CCT - Clean Rooms and Contamination Control Technology", "nano tech", "Symposia of the International Confederation of Contamination Control Societies").
- Standards. To ensure that the developments made by the project make the most impact into industry, project members will interact strongly with the ISO/TC158 (working group 5: dynamic methods) and the VDI/VDE-GMA committee Optical Analysis Technology in Industry and Environment (OPTAM). Results and methods will also be reported to the CCQM Gas Analysis Working Group and the Gas subcommittee of the TCMC of EURAMET.

Co-funding and Collaborators

The project is a technical collaboration between the funded partners: MIKES, CMI,INRIM,NPL,PTB,VCL, HCP Photonics Corporation and the unfunded collaborators VDI, Adixien,Murata, Fraunhofer IAF, Vaisala, and Modulight.

Deliverables

1	**Start: 01/06/13**	**End: 30/04/16**	

Deliverable title: Development of NICE-OHMS system for detection of the chosen molecule, including report on how the off-line method could be applicable to AMC monitoring and extended to more complex molecules**.**

2	**Start: 01/06/13**	**End: 30/06/16**	

Deliverable title: A fully validated facility consisting of dynamic reference standards(e.g. ammonia and acid gases) and high precision analytical techniques to underpin measurements of key airborne molecular contaminants in manufacturing environments at trace amount fractions (**ASD component**)

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NPL Projects – 2013

Project No.	IRD\2013\02	**Price to NMO**	£503k
Project Title	MEG with an atomic magnetometer	**Co-funding target**	£300k
Lead Scientist	Witold Chalupczak	**Stage Start Date**	01.10.2013
Scientist Team	Witold Chalupczak, Patrick Josephs-Franks	**Stage End Date**	30.09.2016
		Est Final Stage End Date	
Sector	Health-Diagnostics	**Activity**	Methodology for new capabilities
Project Champion	Barbara Domayne-Hayman		

Summary: Biomagnetic signals cover the frequency range from near zero to radio frequencies (rf) in the case of magnetic resonance signal induced in high bias fields. In terms of the measurable signals generated by living human tissues, they range from about 1 fT (brain) to 100 pT $Hz^{-1/2}$ (heart). There are several biomagnetic measurements and imaging techniques: Magnetic Resonance Imaging (MRI), Magnetoencephalography (MEG), Magnetocardiography (MCG), liver susceptometry, near-dc magnetometry, neurography, magnetogastrography. Currently, MEG is perceived as the dominant area of biomagnetism. MEG is a technique that detects the extremely weak magnetic fields produced by neural currents. Method is already widely accepted in advanced neurological and psychological research as well as in clinical practice, where is used mostly for preoperative functional mapping and localisation, especially of epileptic foci. Commercial MEG systems are based on superconducting quantum interference device detectors (SQUID). Operation of SQUIDs sensors requires cryogenics (liquid helium temperature). Atomic magnetometers enable measurements of the magnetic field with fT $Hz^{-1/2}$ sensitivity over a wide frequency range without cryogenics. The immediate aim of this project is to develop and test a MEG system with room-temperature atomic magnetometers as the sensor. The overall aim is to develop a novel, commercially attractive, system for measuring biomagnetic signals in a number of key, clinically important, applications.

The Need: MEG is a technique that detects magnetic fields (1-200 fT) produced by neural currents using highly sensitive magnetometers arrayed around the scalp. There are over 120 commercial systems operating around world. The high cost of equipment acquisition (~$3M) and ongoing maintenance (~$0.2M/year) of the commercial, cryogenic, SQUID based system is a likely contributor to the limited availability of instruments. Problems with Helium supply have further hampered the global uptake of this technology. There was general agreement at a recent conference on Biomagnetism in Paris that because of the high maintenance cost of the SQUID based systems there was an urgent need for the creation of low cost alternatives. Moreover, it was recognised that magnetometers could be used to exploit recent advances in low-field NMR and MRI for molecular imaging based on nuclear spin hyperpolarisation.

The Solution: In recent years, alkali-metal-vapour atomic magnetometers have emerged as a promising non-cryogenic, low-cost alternative to SQUIDs in biomagnetic applications. Atomic magnetometers have demonstrated ability to detect MEG signals from human subjects. However, standard atomic magnetometers are based on potassium or rubidium vapour at an elevated temperature (180ºC). In the course of a previous IRD project we have developed a new configuration of atomic magnetometer that is able to achieve $fT/Hz^{-1/2}$ sensitivity in near-room temperature (Appl. Phys. Lett. 100,242401, 2012). This magnetometer is based on an indirect optical pumping technique developed at NPL (Phys. Rev. A 85, 043402, 2012). Sensitivity of the detector is only limited by photonic shot noise, quantum atomic projection noise and probe beam back action. Although the demonstration of the system was performed in the rf domain we have recently proved similar sensitivity over wide range of operating frequencies including dc domain. It is this flexibility that would allow the NPL magnetometer to be developed into a useful commercial device that could be exploited in clinical applications.

Project Description: We plan to develop and test a sensing/ imaging system for MEG application based on the NPL indirectly pumped atomic magnetometer. The first part of the work will include optimisation of the operating conditions (lasers power, laser detunings, atomic vapour density, etc.) that will meet the requirements of the validation specification. We would also need to explore a few geometries of the measurement system to allow particular implementations to be investigated. This will be followed (some work will be done in parallel) by design and development of a portable system that will be able to operate with limited magnetic and vibrational screening. The system we have tested so far contains five layers of magnetic shielding and significant vibrational isolation (optical table). It currently provides great flexibility in tuning of the measurements parameters but for a specific application these can be restricted with some implementation advantages. The design will include critical analysis of the magnetometer components (in particular the laser system) in order to introduce as many simplifications as possible. Validation will be performed at York Neuroimaging Centre (licenced for clinical diagnostics) and will include a comparison with a commercial SQUID based device. It needs to be pointed out that while the project is focused on one particular application (MEG) the first two phases of the work contribute to development of the general magnetic sensing platform that could be implemented in different measurements (e.g. low field NMR, detection of functionalised paramagnetic particles, spin based molecular imaging developed in York).

Impact and Benefits : Over 300,000 individuals in the UK have epilepsy and only one third are managed using conventional anti-epileptics; Neurodegenerative disorders are now amongst the commonest problems in the elderly and differential diagnosis in the early stages is particular difficult. Both of these problems affect the dynamics of the brain. Techniques to investigate brain dynamics are currently expensive and limited to large Centres. Over 40million MRI scans are carried out per year globally and 40% of these require the injection of a contrast agent to improve the diagnostic quality of the scan. There is an internationally recognised need for a different approach to molecular imaging based on sensitive devices that offer the capability to provide specific diagnostic information. Recognition of this by the Wellcome Trust led to the provision of Strategic Award level funding to the University of York to develop a new route to examining brain processes and chemistry. The global impacts could be large and were recognised by an editorial in Nature Chemistry calling these latter developments as potentially revolutionary in their scope and application to medicine. Early intervention in neurodegenerative disorders could have major benefits for patients as well as society at large. The commercial benefits are also potentially very large. A recent market evaluation shows that imaging agents are worth some $6billion per annum and the associated hardware purchase was estimated to be $4billion per year. A new magnetometer would be very disruptive as it would provide an alternative to having to use invasive contrast enhancing agents and

expensive cryogen based magnets, moreover it would allow simultaneous investigation of the MEG signal. Development of the room temperature atomic magnetometer lead to series of publications (4 papers in Phys. Rev. A, 1 in Appl. Phys. Lett., two drafts in preparation phase) and we envisage that the next phase will also generate significant scientific output.			
Support for Programme Challenge, Roadmaps, Government Strategies: The work in this project aligns well with the 'Health' Challenge in BIS's NMS strategy. The medical and health sector requires techniques that exploit new physics-based diagnostic methods where computer enhanced variants of existing methods cannot be improved further. TQEM's exploitation strategy is to develop sensor systems and instrumentation based on its track record in innovation of high precision devices for metrology purposes. The work proposed here helps to deliver the NMS healthcare challenge to Enable new drugs and therapies, and prognostic, diagnostic and assistive technologies to be brought to the market quicker and at lower cost.			
Synergies with other projects / programmes The proposed developments addresses two of the research challenges announced by the Wellcome Trust as being some of the most pressing and fundamental problems that confronts human and animal health. It is also ideally placed to respond to the MRC's strategy of 'picking research that delivers', bringing health impacts of fundamental research to people and to address global health issues. The project is also aligned with the priorities of the Technology Strategy Board in the areas of Bioscience, electronics & sensors, healthcare and in resource efficiency. Last this project has a very close link to the work carried out in York (http://www.york.ac.uk/chym/) where they have created an electronics system to take data from large arrays of sensors for use in low field biomagnetism measurements and in imaging.			
Risks: Sensitivity and bandwidth of the magnetometer are the key performance parameters of the sensor. While we have demonstrated that the sensitivity of the system is comparable to other detectors our systems operate with relatively narrow bandwidth. The bandwidth in principle could be adjusted to fit particular applications by operating magnetometer either in specific configuration (Quantum Non-demolition measurements) or at higher temperature (up to 40ºC). Engineering challenge is set by aim to build imaging system operating with array of the sensors. So far we have experience working with single or two sensors and more complex configuration will have to be developed.			
Knowledge Transfer and Exploitation: We envisage that the project will lead to development of new types of magnetic field sensor and sensing techniques based on atomic magnetometer. We plan to report stages of the development in peer-reviewed papers and relevant conferences. On the other hand, validation of the sensing system paves the way to wider dissemination. We plan to exploit existing links between York Neuroimaging Centre and SMIEs. York Neuroimaging Centre has licences for clinical work, which would enable shortening the way towards commercialisation (beyond proof of principle measurement).			
Co-funding and Collaborators: It is planned that the development of the atomic magnetometer will be conducted at NPL while validation, adjustment and further testing will be done at York Neuroimaging Centre. Centre has magnetically shielded room and operational MEG system using a multi-channel SQUID system. The system was originally developed by a commercial company, but electronics part has been upgraded, by York, so that the front end link to the squid readout electronics can be replaced by other interfaces (e.g. atomic magnetometers). Access to operational hardware and software signal processing interface will significantly reduce time required for development sensor system and subsequently cost of the work package. Collaboration with Neuroimaging Centre sets NPL in a very good position to apply for external funding (Wellcome Trust, EPSRC, MRC).			
Deliverables			
1	**Start:** 01/09/2013	**End:** 30/09/2014	
Deliverable title: Optimisation of the atomic magnetometer in partially screened environment. The work package will include measurement and optimisation of the magnetometer sensitivity and bandwidth with limited shielding (reduced number of the magnetic shields, active compensation of the ambient magnetic field), as well as testing of the different measurement geometries. The latter will include recently proposed geometry that allows so-called Quantum Non-demolition Measurements, which enables suppression of probe beam back action (reduction of the noise) and increase of the measurement bandwidth. We will to engage the manufacturers of the commercial MEG system (e.g. Elekta) at that stage of the project.			
2	**Start:** 01/09/2013	**End:** 30/09/2015	
Deliverable title: Development of the portable sensor. Current status of the measurement system provides with possibility of exploration of the wide phase space of experimental parameters such as atomic density, laser beams powers, detuning, and polarization. The second phase of the project will include critical analysis of system components that should enable simplification of the measurement instrumentation as well as design, development, testing of the compact magnetic sensor (detection head fibre connected to the lasers).			
3	**Start:** 01/09/2014	**End:** 30/09/2016	
Deliverable title: Validation of the detection system by comparison with commercial magnetoencephalography system. Parallel measurements of magnetic field generated by brain with SQUIDs and atomic magnetometer sensor are planned. Evaluation will include measurements of the spatial resolution of the atomic magnetometer based sensor.			

Project No.	IRD/2013/03*	Price to NMO	£ 500k
Project Title	Methodology for characterizing radiobiological impact of Au nanoparticles for diagnostic and therapeutic applications	Co-funding target	
Lead Scientist	Giuseppe Schettino / Alex Knight	Stage Start Date	1 April 2014
Scientist Team	Caterina Minelli, Hugo Palmans, Peter Sharpe, Sebastian Galer, Olga Kazakova, David Shipley	Stage End Date	31 March 2017
		Est Final Stage End Date	
Sector	Health	Activity	Methodology for new capabilities
Project Champion	Stuart Green (AIR WG)		

Summary: Gold nanoparticles (GNPs) are currently being developed for a wide range of medical applications including their use as dose enhancer in radiotherapy and contrast agents in diagnostic imaging. Clinical exploitation of GNPs is however hampered by poor and limited understanding of the mechanisms underpinning observed radiobiological effects and possible increase in health risks due to exposure to ionizing radiation of tissues doped with high Z material. This proposal concerns the development of a comprehensive methodology specifically focused to characterize the radiobiological properties of GNPs involving the assessment, quantification and quality control of key parameters. The proposal has been shaped in collaboration with academic research groups with significant expertise in medical exploitation of nanoparticles, as well as industrial partners to ensure achievement of deliverables and maximum impact.

The Need: Research into manufacturing and usage of GNPs for biomedical applications is extremely active with great potential for industrial opportunities and to impact quality of life. Possible applications include RadioTherapy (RT) dose enhancement and contrast agents for medical diagnostic imaging due to gold biocompatibility, relatively straight-forward chemistry of functionalization, and high atomic number compared to soft tissues. Despite some promising *in-vivo* studies, clinical exploitation of this technique is stalled by uncertainties and lack of models on the reported enhancement of ionizing radiation effects in presence of high Z nanoparticles. Radiotherapy is the most widely used and successful cancer treatment strategy. Currently limitations relay on the max dose which is possible to deliver to the tumour volume without causing harmful side effects due to dose absorbed by healthy tissues. Understanding the dose and effect enhancement factor produced by nanoparticles in cancer cells is critical to improve and optimize radiotherapy planning. Moreover, all diagnostic and therapeutic techniques employing ionizing radiation have associated long term health risks which are offset by the patient benefits. Use of high Z nanoparticles will inevitably alter the pattern of radiation dose absorbed with consequent modification of risks which, although are not expected to outgrow the benefits, need to be fully assessed. Driven by the unique chemical and physical properties of nano-scale materials, radio-enhancement and/or radio-sensitizing effects have been reported with contradictory data highlighting the inefficiency of macroscopic models based on mass attenuation coefficients and the critical impact of a wide range of interconnected parameters such as nanoparticle size, charge and coating, cellular uptake, and quality of the incident radiation. These can affect both radio-toxicity and cellular uptake with direct consequences for cell inactivation, tissue imaging and health consequences. It is therefore unanimously agreed that large scale systematic investigations to quantify the radiation-biological impact of GNP are required for their optimization and standardization as medical devices. Such investigations will have to be supported by a suitable metrology with rigorous and traceable standards to define and quantify key parameters as requested by regulatory procedures.

The Solution: To develop a comprehensive methodology for assessment, quantification and quality control of key parameters regulating dosimetry and radio-biological effects of GNPs for evaluation of potentials and limitations of specific NP products for their clinical exploitation. This will include elements of microscopy (for GNP uptake and intracellular localization), nanotechnology (physical characterization of GNPs and analysis of the synthesis processes), dosimetry (micro- and macroscopic dose enhancement and ionization distribution following radiation exposure), radiation chemistry (production of reactive radical species and alteration to the scavenging environment) and radiobiology (acute and long term cellular effects) combined by modelling and data analysis. Mathematical modelling of radiation transport will be a significant aspect, particularly the local changes in energy deposition around the nano-particle surfaces. Detailed analysis of the behaviour and effects of GNPs will provide a full description on the interaction of GNPs and IR with biological matter so driving forward their *in-vivo* applications. The project will deliver standards, traceable and comparable measurement methods and provision of regulatory recommendations for fast, reliable and effective screening of functionalized GNP for use as contrast agents and in RT. This will support mechanistic investigations and allow estimation of potentials and limitations of the clinical use of GNP as well as allowing optimization of manufacturing and functionalization. The project is directed to GNPs as Au is the primary choice for both *in-vivo* imaging and radiotherapy studies but the methodology will be easily applicable with minimum modifications to any NP product to be used in combination with ionizing radiation.

Project Description: Parameters of specific interest for the dosimetry and radio-biological effects enhanced by GNP will be defined through literature reviews and targeted *in-vitro* experiments. To include selection of reference nanomaterial and appropriate cell based models, and development of reference markers and bio-phantoms to quantify dose enhancement (extra amount of energy absorbed due to GNP presence), radiobiological effectiveness (increase quality of damage induced due to variation in local dose distribution) and radiation induced oxidative stress (change in the yield and spectrum of radical produced). The assay cascade will also include optimization of established techniques to develop methodology and critical infrastructure for rapid multi-parameter screening of functionalised NPs of clinical interest. This will involve GNP characterization protocols, traceable measurement methods and Monte Carlo modelling. Models (using micro- and macro-dosimetry approaches) will be developed to link physical-chemical parameters to radiobiological enhancement and identify optimum GNP therapeutic and diagnostic strategies including recommendations on the radiation beam, cell specificity, and NP concentration. Physics and chemical characterization will be mainly performed using expertise and facilities available at NPL (Biotech and Surface Analysis); modelling, simulations and dosimetry will be done by the NPL dosimetry experts; radiobiology work will be carried out both at NPL (Biotech and Dosimetry group facilities/expertise) and in collaboration with radiobiology groups at QUB, UoS and UCL.

Impact and Benefits: This work will enhance NPL's scientific profile in nanomaterial, radiation-biology/dosimetry, advanced RT and diagnostic fields strengthening existing collaborations (e.g. Queens University Belfast (QUB), the University of Surrey (UoS) and University College London (UCL) have active research projects centred on medical application of GNPs and their functionalization) and nurturing new ones (e.g. Research Complex at Harwell (RCaH) currently optimizing a plasmon resonance approach to detect GNP in live cells and the established Nanoparticle Characterization Laboratory (NCL) in the US focused on toxicology and pharmaceutical efficacy of NPs). Outputs will provide a powerful tool for the wider nanotechnology community incentivizing industry (reducing their R&D costs and risks) and driving forward the clinical use of GNP with great potential benefits for health care and patients. Methodology, expertise and technology developed will provide NPL a new area of activity with capability for validation protocols and measurement certificates for companies to use in MHRA (Medical and Healthcare Regulation Agency) and EMEA (European Medicines Agency) application required for marketing authorization and medical use.

Support for Programme Challenge, Roadmaps, Government Strategies: This work is in line with NPL's long-term strategic aims supporting research, development and application of advanced modalities for RT and "Health and Care". It will address key strategic areas of Horizon 2020 (Nanotechnologies, Biotechnologies and Health) with a truly multidisciplinary approach and the EPSRC implementation of nanotechnology strategies ("Nanotechnology Grand Challenge: Healthcare"). Developed metrology for medical use of GNPs aligns with NPL Science Strategy in particular the implementation of objectives 2, 4 and 6 and priority area of measurements and modelling applied at the nano-scale. The approach and techniques developed will have a strong affinity and provide significant support for the sustainability of planned activities of Dosimetry, Biotechnology and Surface and Nanoanalysis groups at NPL.

Synergies with other projects / programmes: Synergy with AIR Dosimetry long-term strategy for the definition of biological weighted quantities for RT. Added value for high Z nanoparticles for MRI imaging (i.e. gadolinium-based NPs from Nano-H, partner in ARGENT project) as new MRI-Linac RT facilities (Elekta-Philips) are being developed. This will link Dr. O. Kazakova EU program (characterization and development of magnetic nanoparticles for MRI imaging) and existing collaboration between Elekta and AIR as dosimetry and radiobiological characterization in strong magnetic fields is a key step on the Dosimetry road map.

Risks: This is a new area for NPL and therefore of relatively high risk in terms of methodology and capabilities. However, this is mitigated considerably by existing experience in the radiobiology and biological imaging aspects of the project and by the considerable modelling and computational expertise at NPL, as well as the collaboration with external partners with previous expertise (NCL has characterized over 250 NP products).

Knowledge Transfer and Exploitation: Characterization service for industry, subcontracting in research proposals, product development; publications, reports, meeting presentations. Major worldwide companies producing nanoparticle for medical applications are supportive and interested in submitting products for full radio-biological characterization once methodology has been developed and traceable standard certificates can be issued. Validation protocols and certificates will be drafted in association with MHRA (which is fully supportive of the initiative) to ensure compliance with current regulatory framework. Work planned is also expected to provide support for MHRA in the foreseen nanotechnology-specific guidance. Academic and industry groups working on the development of nanoparticles for MRI and pharmaceutical purposes and as sensors in biological environments have also expressed interest in the methodology as their products could be used in combination with IR. Radiobiological characterization will well complement the assay cascade developed at NCL which have expressed strong interest in a formal collaboration to expand their characterization range. Certification in the area of dosimetry/radiobiology is not in competition with USA. As the methodology develops, we will link with relevant EU industrial and academic partners for exploitation, collaboration and to bid for further specific research grants. Taking advantage of the multidisciplinary network and expertise put together by the program, specific tested and certified nanoparticles will be taken forward for full product development in collaboration with industrial manufacturers, small SMEs and relevant health care providers (i.e. Varian – BioSynergy program on development and introduction to market of diagnostic agents that enhance cancer diagnosis/ treatment).

Co-funding and Collaborators: MRC grant application under development to realize GNP products for detection and RT treatment of specific cancers with QUB and UCL. Proposals for Horizon 2020 framework to be submitted in response to relevant calls (strategic areas: Nanotechnologies, Biotechnologies and Health). EPSRC sponsored project on development of personalised cancer therapies (£1.5M total) will be linked to this project. EU ITN (Initial Training Network) collaboration (ARGENT) starting Sept'14 (8 academic and 3 industry partners across Europe), contribution to NPL program to include manpower; share of expertise and in kind contributions (nanoparticles, irradiation facilities). Access to irradiation facilities to be provided also by UCL, QUB and Clatterbridge Cancer Centre. Use of microscopy facilities at RCaH, conditional to proposal approval, to include sponsorship for travel, accommodation, subsistence and consumables. 50% PhD student co-sponsoring from UCL & QUB worth £30000/year. Full support from NCL to assure compatibility and complementarity of existing FDA approved methodology and assay cascade. Established contacts with MHRA to ensure validation protocols are in accordance with regulatory framework.

Deliverables

1	**Start: 01/04/14**	**End: 30/09/15**	

Deliverable title: Definition of parameters of interest for the radio-biological effects induced by GNP through literature reviews and targeted experiments

2	**Start: 01/07/14**	**End: 31/03/17**	

Deliverable title: Development of a methodology and critical infrastructure for rapid multi-parameter screening of specifically functionalised nanoparticles of clinical interest

3	**Start: 01/01/15**	**End: 31/03/17**	

Deliverable title: Radiobiology and physiologically-based models to identify optimum GNP clinical strategies

Project No.	IRD\2013\06	Price to NMO	£500k
Project Title	Measurement of GHGs in the presence of varying background gas concentrations	Co-funding target	£250k
Lead Scientist	Rod Robinson	Stage Start Date	April 2014
Scientist Team	Fabrizio Innocenti, Peter Harris, Alistair Forbes, Valerie Livina , Marc Coleman, Andrew Finlayson	Stage End Date	March 2017
		Est Final Stage End Date	
Sector	Sustainability	Activity	Methodology for new capabilities
Project Champion	Rodney Townsend		

Summary
The goal of the project is to develop novel UK capabilities to improve quantification of greenhouse gas (GHG) emission fluxes using optical remote sensing (ORS) technologies to address the role of GHGs in the evolution of the Earth's climate. We aim to provide research and innovation to enhance the UK's world leading technological position by means of innovative tools, and support other measurement fields with similar data interpretation challenges.

The Need. Accurate quantification of GHG emissions is critical to understanding and mitigating climate change.
- A key challenge is measurement of emissions from area/distributed sources (e.g. landfill, process plant, fracking)
Evidence: Volume of research and measurement work in which NPL is engaged in this field.
These measurement techniques are in the process of being accepted as Best Available Techniques (BAT) by the European Commission, for quantifying fugitive emissions – making this an extremely timely research need.
- Significant scientific technical challenge in the determination of GHG emissions is the ability to measure these gases in the presence of varying atmospheric background concentrations.
Evidence: This team's experience from current/previous NMS programmes which have developed improved flux determination approaches including improved use of meteorological data. Remaining issue is extracting emission data from varying background levels. The discrimination of spatially and temporarily varying emissions from a varying background is a complex analytical challenge in measurement science. Variations in other atmospheric parameters such as pressure and temperature also affect the background levels. The current approaches make very broad assumptions about the background levels, and this is currently the key limiting uncertainty source in quantifying GHG emissions with the required detection sensitivities.

The Solution.
This project will be leveraging the expertise and outputs from current IRD projects which have developed improved GHG flux determination methods (e.g. through improved measurement and use of wind data), and combine this with NPL's strengths in developing mathematical algorithms and innovative methods for discriminating and extracting concentration information from background levels in dynamically changing 2D observational data. The mathematical tools are being developed at NPL for monitoring temporal changes in 1D (time series) and 2D variables and for identification of various trends and patterns intrinsic to the system dynamics in order to study statistical properties of various data components, with their further attribution to natural and anthropogenic sources. Through the NMS these core tools will be possible to apply more widely to support a range of measurement problems in other climate subsystems and in wider metrological areas (e.g. environmental noise mapping)
The approach will be extensible to a wide range of measurement problems in Earth observations, such as ocean acoustic data, which are being studied by the NPL Acoustics Group. The quantification of emissions from shale gas extraction (fracking) will be used as a test case to demonstrate the application of the methodologies to real world problems – there is added value to using this test case as there is a key and timely societal and economic need to assess emissions from unconventional gas extraction.

Project Description (including summary of technical work)
The areas of innovation driven by the collaborative research between mathematics and environmental groups will include:
1) **Mathematical tools for background removal**. Mathematical tools (delivered and applied as a software package) to enable the assessment of background and source variation, to optimise the discrimination of emission plumes from background in 2-d data sets, to enable the optimised removal of time varying background gas levels and to determine uncertainty inputs for emission estimates using these mathematical techniques. We also plan to investigate whether the measured data undergoes temporal changes in structural components and to time their occurrence using dynamical statistical tools. The novelty of the proposed methodology is in applying recently new methodology pioneered in the UK by Livina et al in 2007 and generalising it for studying various components of data (trends and fluctuation) The methodology is based on the theory of dynamical system and studies evolution of the system potential from a recorded trajectory using a number of advanced techniques, such as Unscented Kalman Filter, wavelet denoising, Detrended Fluctuation Analysis with temporal indicators, potential contour plots and potential forecasting based on approximation and extrapolation of the probability density using Chebyshev polynomials.
2) **2-d Data smoothing**. Computational tools to provide optimised smoothing and kriging of spatially inhomogeneously sampled data sets of the type usually generated by the GHG measurements, with background removal, also applicable to 2-d data sets in other measurement fields in Earth observations, and potentially in wider metrological fields.
3) **Background characterisation**. Measurement methods to provide additional data to improve background discrimination, such as isotopic ratio measurements and the measurement of correlated atmospheric parameters.
4) **Implementation and validation**. Protocols/standards to implement these methods and field validation at shale gas test sites.
This work will be delivered jointly by AS/Environmental Measurements Group and MAT/Mathematics and Modelling Group.
Acoustics group will provide input data for application of these techniques in the acoustics area.

Impact and Benefits The outputs of the project will:

- Directly result in the improved determination of GHG emissions, with improved detection sensitivities and lower uncertainties. Support UK government in meeting GHG reporting commitments.
Support industries such as agriculture, waste management, petrochemical and energy supply by providing better understanding of their GHG emissions and an increased ability to control these emissions.
- Provide timely, key data quantifying methane emissions from shale gas extraction, to inform the decision making process on the viability of this unconventional fuel source within the UK.
- Result in further economic, societal and scientific impacts through the exploitation of the knowledge and data generated by the immediate improvement in UK GHG measurement capability.
- Directly benefit other measurement areas where similar discrimination of a spatially resolved region of enhanced levels above a background level is required (e.g. acoustics). The development of such a transferrable, core, toolset, aligns with the aims of IRD.

Support for Programme Challenge, Roadmaps, Government Strategies

This project aligns completely with the EMG Environmental Technologies theme road map, delivering key enabling science to address improved emission flux determination, measurement capabilities for CDM in support of international treaty obligations, and delivers key technologies and deliverables identified in the roadmap such as uncertainties in remote sensing.
The project aligns with the MM Roadmap to undertake mathematical modelling in support of societal challenges, such as those related to the environment and climate, and to develop and apply mathematical tools to problems where the conventional model-fitting paradigm is less easy to apply, with a challenge of abundant observational data. The project addresses the programme challenges in the BIS NMS strategy 2011-2015 under sustainability (S 3.1.3) and explicitly addresses the specific statement that the NMO will through the NMS 'Provide **standards and techniques for measurement of emissions of greenhouse gases'** and will support the work of the Centre for Carbon Measurement by providing accurate data to improve emissions factors and feed into emissions trading and reporting.

Synergies with other projects / programmes This work builds on NPL's unique set of remote sensing capabilities and environmental monitoring research carried out by EMG under the NMS ChemBio and IRD programmes. It will provide innovative cross disciplinary research using the expertise in the mathematical group, linking to the recently approved NMO project on time series analysis of geophysical data. It links with an EMRP Environment call SRT on future emissions measurements which includes fugitive (area source) emissions. It aligns with the work programme and strategy of the centre for carbon measurement.

Risks The main technical risk is the challenge in developing robust, generally applicable algorithms. Work will be informed by co-funding DIAL projects, which will provide datasets to support the algorithm development.

Knowledge Transfer and Exploitation NPL has strong links with key stakeholders in GHG emission measurement, for example, with petrochemical industry through research projects with CONCAWE. Methods developed for DEFRA and the EA will facilitate landfill and other area source emissions monitoring policy going forward. The inclusion of these measurements in BAT will require industry to use them in the future, providing a key route to exploitation. CEN TC 264 WG38 chaired by NPL, is developing a standard on fugitive emissions which will be a key dissemination output. Method development and standardisation enables uptake of innovation by allowing use of techniques by regulators and researchers. Fracking is a controversial technology, and regulatory monitoring requirements are likely, which will provide further impact in the future. Scientific exploitation will include the ability to utilise the cabilities developed in research such as Defra emissions factor projects and EMRP environment calls. The core IP generated will be the mathematical tools, with application in other metrology fields enabling wider exploitation.

Co-funding and Collaborators Stakeholders already engaged include CONCAWE, UK Government through Defra and its regulatory body the Environment Agency and the fracking industry (iGas, Cuadrilla) and researchers (BGS). Through developing and disseminating expertise this programme will also cement the UK's existing leading international position, enabling the global exploitation of the IP generated with collaborators such as the US EPA. The project will have potential co-funding from EMRP 2013 Environment research topic on 'Metrology to underpin future regulation of industrial emissions'.

Deliverables

1	**Start: 01/04/14**	**End: 31/03/16**	
Deliverable title: Mathematical tools for background characterisation and removal from spatial data and assessment of the uncertainty on emission rates from applying these methods			
2	**Start: 01/10/14**	**End: 31/03/17**	
Deliverable title: Optimised smoothing and kriging of 2-dimensional concentration data			
3	**Start: 01/01/15**	**End: 31/12/16**	
Deliverable title: Development of capabilities to measure correlated atmospheric parameters to improve background removal			
4	**Start: 01/10/15**	**End: 31/03/17**	
Deliverable title: Demonstration and refinement of techniques using field campaign at a shale gas site			

Project No.	IRD/2013/09 – modified to create IRD/2013/ESA	**Price to NMO**	£967k
Project Title	Sensor networks: data to knowledge	**Co-funding target**	£700 k [won £78,700 from esa]
Lead Scientist	Alistair Forbes (MAT)	**Stage Start Date**	1st October 2013
Scientist Team	Richard Barham (AIR), Elena Barton (MAT), Richard Brown (AS), Maurice Cox (MAT), Michael Hall (MAT), Peter Harris (MAT), Richard Jackett (AIR), Nick Martin (AS), Stephen Robinson (AIR), Toby Sainsbury (AS), Pete Theobald (AIR), Steven Turner (MAT)	**Stage End Date**	30th September 2016
		Est Final Stage End Date	
Sector	Sustainability: sensors	**Activity**	Methodology for New Capabilities
Project Champion	John Collins		

Summary This project will develop the mathematical and statistical modelling, algorithms and software to analyse data gathered using sensor networks. The project will extend concepts such as uncertainty, traceability and calibration to sensor networks so that sensor networks can be regarded as distributed *metrology* systems. The project will enable metrology to address issues associated with challenges outside the laboratory, particular relating to environment, energy and sustainability, and smart asset management. The mathematical and statistical tools will be developed and validated in three applications in the environmental domain in support of EU directives that mandate monitoring. Other application domains relating to smart infrastructure monitoring, process control, building performance evaluation, etc., will be developed as co-funding opportunities are realised.

The Need Multi-modal sensor network technology has an enabling role in societal challenges associated with environment, climate, energy and sustainability, smart asset management, etc. The development in recent years of low-cost sensors has resulted in these devices being used extensively for monitoring applications, both for environment and industrial applications. The challenge is to use the increase in *data* to deliver a corresponding increase in *knowledge* to improve science and decision-making. A key issue to be able to perform the in-situ calibration of the network as a whole rather than relying on costly laboratory calibration of individual sensors that does not take into account their actual operating conditions.

The Solution Data assimilation and statistical learning tools will be applied to address the data-to-knowledge challenge associated with multi-modal sensor networks and maximise knowledge gain. The aim is to use the rich supply of data to build models of the responses of the underlying systems. Once the models are established and validated, the network can be kept in calibration using much less resources. The tools will be co-developed with applications involving existing and proposed sensor networks addressing air quality, urban and marine monitoring requirements. Other application areas will be developed through aligned projects.

Project Description

WP1 Mathematics and statistical modelling

- Network models: network topology, location of sensors, data communication, sensor deployment and characterisation, sensitivity analysis (which sensors are giving the most useful information) and uncertainty analysis (what is the aggregate uncertainty associated with a network), resilience to rogue sensors (can we detect when a sensor is giving invalid data).
- Network design and optimisation: optimising network topology (where to place sensors), type of sensor (best mix of sensors), calibration strategies (e.g., how often to perform field calibrations using accurate roving sensors).
- Data assimilation and statistical learning applied to sensor network data: which variables are most strongly correlated (taking into account variable time lags), subset selection (which variables are most useful in prediction the behaviour of the complete system), hierarchical statistical models and Bayesian inference (that can be used to determine the accuracy of sensors in-situ), change point analysis (detecting when the system changes behaviour).

WP2 Case studies

- Ambient air networks application. Development of spatio-temporal correlation models, Gaussian processes, positive matrix factorisation methods, efficient validation and interrogation of large data sets produced by air quality networks, optimal design and cross-calibration of sensor networks, more accurate and robust source apportionment and trend analysis tools.
- Urban environment application. Acoustic and air quality network data combined with meteorological and traffic management data to provide high-value diagnostic information. The acoustic and chemical signatures associated with vehicles, aircraft, etc., will be correlated to provide a much richer source attribution.
- Marine environment application. New marine acoustic monitoring networks will be designed to determine trends in ship noise (in response to EU directives), integrating existing networks of smart buoys that monitor other ocean parameters and Automated Information Systems that provide commercial ship locations.
- Watching briefs on other applications: transport and energy distribution infrastructure, process control, condition monitoring, building performance evaluation, health and well-being

Impact and Benefits

- The project will enable the UK to meet EU directives cost effectively. The UK annual spend on sensors for air quality alone is £15 M. Better use of air quality sensor network data could save up to £3 M p.a. The European market of environmental sensing is estimated at €170 M p.a., while the 2014 EU Horizon budget for Societal Challenges, including climate, health, energy and sustainability, is €3.3 B. Much of that expenditure will involve sensor networks. Better design of networks will reduce the resources required by 10 % to 50 % (typical improvements using design optimisation), leading to significant savings, by collecting the right data and being able to understand what it means. The EU budget for climate change, 2014-2020, is €960 B. Sensor networks, with validated and dependable performance, will be key to ensuring decisions relating to climate change are made wisely. This project will feed into CEN and ISO standards for environmental monitoring.
- Knowledge from sensor networks will reduce the cost of legislative compliance (the UK spends £8 B annually on environmental protection) and facilitate more effective regulator input to protect public health and improve quality of life. (In

the UK, an estimated 29,000 premature deaths p.a. are caused by air pollution).

- The project will help define the role of metrology in the "big data challenge", particularly on how knowledge for end-users can be extracted from sensor network data and enable metrology to play its role in addressing societal challenges.

Support for Programme Challenge, Roadmaps, Government Strategies

- The project provides the enabling metrology component to meet "the big data challenge", announced by David Willetts, January 2013, and supports the NMS digital challenge on smart infrastructures.
- Sensor networks (data acquisition, data to knowledge) will be a key enabling technology in two of the four Metrology 2020 themes, *Smart and interconnected world* and *Embedded and ubiquitous measurement*, and four of the Metrology 2020 application areas, *Monitoring the state of the planet*, *Energy efficiency and diversity of supply*, *A healthy population* and *Managing key resources and infrastructure*.
- The project also directly supports BIS/EPSRC initiatives in *Future Cities*, *Big Data* and *Data to Knowledge*.

Synergies with other projects/programmes

- The NERC funded SNAQ (sensor networks for air quality) project provides a small-scale demonstration of the tools to be developed. The project feeds directly into the work of the European grouping of air quality reference laboratories (AQUILA) and its outputs will be used to design the next generation of European air quality monitoring procedures.
- The project will provide the technical capability to align with EMRP environment and energy projects involving sensor networks and an ESA co-funded project on sensor networks and smart infrastructure.
- The acoustics component has a direct synergy with Defra project ME5210 on monitoring ambient noise in UK waters.

Risks i) New algorithms do not add significant value to the data sets generated. Mitigation: design the data-to-knowledge algorithms in line with the inferences/decisions to be made (regulation control) so that the knowledge generated is targeted at bringing immediate benefit. Ii) Some underlying systems are too complex to develop validated data assimilation tools. Mitigation: re-prioritise applications on the basis of likely success; use EPSRC to encourage more research.

Knowledge Transfer and Exploitation

- Stakeholder workshops will be held throughout the project to capture user requirements and build exploitation routes.
- Scientific outputs will be disseminated by high impact publications in the peer-reviewed literature, presentations at international conferences, and the provision of algorithms and software tools.
- Case studies in WP2 will be published and their outputs will directly improve the UK's monitoring capabilities.
- Input into relevant national and European standardization committees, e.g., CEN TC264, ISO TC146, ISO TC43 will ensure the UK leads in terms of meeting the requirements of legislation and formulating future requirements.
- Any knowledge gained relevant to ambient air monitoring will inform the running of the UK's air quality networks to benefit scientific outcomes and provide cost savings.
- As the project has significant carbon impact, the Centre for Carbon Measurement will promote the project outputs.

Co-funding and Collaborators The air quality component of the project will have cash co-funding of £250k from the networks which NPL operate on behalf of Defra. In kind funding of £100k will be provided from The Centre for Ecology and Hydrology through the provision of sensors, and from industrial manufacturers (Gradko Environmental and PASSAM) through the provision of sensor equipment. The ESA project on sensor networks and smart infrastructure will contribute £100k cash co-funding. EMRP Environment and Energy proposed projects could contribute further cash co-funding of £750k. Collaborators and stakeholders include Defra, Marine Scotland, CTBTO (provision of network data, implementation of methodologies), CEN and the EC (development of cost effective reference methods), the Transport Research Laboratory, Bureau Veritas, Arup, City of Westminster, Glasgow City Council, and partners in the NERC SNAQ consortium (Cambridge, Imperial).

Deliverables

1	**Start: 01/10/13**	**End: 30/09/15**	
Deliverable title: Core mathematical and statistical capability: network models, with supporting algorithms and software			
2	**Start: 01/10/13**	**End: 30/09/15**	
Deliverable title: Sensor network design and optimisation: algorithms and software			
3	**Start: 01/10/13**	**End: 30/09/16**	
Deliverable title: Data assimilation and statistical learning for sensor network data: algorithms and software.			
4	**Start: 01/10/13**	**End: 30/09/16**	
Deliverable title: Case studies, air quality, urban and marine environments. Analysis of large air quality datasets. Demonstration of data assimilation applied to multi-modal networks in urban environment. Design of marine acoustic monitoring network.			
5	**Start: 01/10/13**	**End: 30/09/16**	
Deliverable title: Project management, project dissemination and impact, and stakeholder workshops			

Project No.	IRD/2013/09/ESA – linked to IRD/2013/09	**Price to NMO**	£90,000 [removed from IRD/2013/09]
Project Title	Co-funding for ESA Feasibility Study to develop a Transport Infrastructure Integrity Management (TIM) Service	**Co-funding won**	€92,678 from ESA grant
Lead Scientist	Elena Barton	**Stage Start Date**	01.01.2014
Scientist Team		**Stage End Date**	31.01.2015
		Est Final Stage End Date	
Sector	Sustainability: sensors	**Activity**	Methodology for New Capabilities

Summary

Increasingly stringent safety criteria are required to asses and manage a wide variety of assets that operate under extreme operational conditions or hazardous environments. A distributed infrastructure system such as transport, energy and water supply present unique challenges due to the large scale and difficulty of access. Local monitoring gives a limited advantage to the global network. Satellite technologies could provide a much needed improvement. This ESA project is in partnership with two UK SMEs,Moniteye Ltd and Nottingham Scientific Ltd (NSL), together with the Satellite Applications Catapult. The main outcome of the feasibility study will be an outline design for a full-scale demonstrator on a high profile transport infrastructure asset as a flagship example for the Transport Infrastructure Integrity Manager (TIM) service and supported by a developed supply chain.

The Need

Knowing and managing the integrity and health of large scale transport infrastructure assets such as roads, bridges, retaining walls, tunnels and embankments is a very important objective for transportation maintenance teams. Economic factors and need of public safety are imperative elements to adopt cost-effective and innovative solutions. To address the scale of distributed infrastructure and difficulties of access warrant the inclusion of satellite/remote sensor technologies. The main challenge for novel services based on data using sensor networks is to transform sensing data into reliable information products, satisfying traceability requirements. A well-founded metrological framework is needed to provide the same confidence as derived from a single calibrated sensor measurement.

The Solution

This project will explore the feasibility of using novel methods of data evaluation for transport infrastructure that are essential to ensure reliability of measured data and provide specified levels of confidence for information extracted from this data. It will help to bring together a range of application domains by providing a common technological platform on which to build future multi-disciplinary solutions to scientific and societal challenges.

This activity is co-funded from IRD/2013/09 deliverable 3 "Data assimilation and statistical learning for sensor network data".

The TIM Service is planned to be a new generation of asset monitoring services that can be deployed across multinational organisations that incorporate best available data sources and provide robust and credible information. An integrated high value solution can only be realised if the service makes use of location and mapping capabilities of space assets and ground in-depth point sensor networks.

This activity is co-funded from IRD/2012/13 deliverable 2 "Sensor network design and optimisation:"

Project Description (including summary of technical work)

The main technical objective of the work is address the lack of fundamental science that underpins quality assessment of information obtained using distributed sensor networks. The main challenge is to transform sensing data into reliable information products, satisfying traceability requirements. More work is required so that inferences based on the enhanced information available from a distributed sensing network can be made in a well-founded metrological framework and with the same confidence as those derived from a single calibrated sensor measurement. Specifically for the Transport Infrastructure Integrity Manager (TIM) Service we will start start with area listed below:

- NPL in collaboration with the project Advisory Committee members and possibly the Satellite Applications Catapult will evaluate the feasibility for data integration using existing data in London from satellite and ground measurements. The investigation will be focused on determining the extent to which the precise position of a known object in the real world correlates to the position on radar or other remote images. A suitable reference frame for London area will be examined. It will help to provide reassurance for back / forward compatibility of the service.
- Improvement in information quality by optimising the locations of ground sensors will be explored using simulations. Types of simulations will be chosen during this project and will depend on data availability.
- Remote Data Centre enabled sensor feedback functions will be explored. These functions will allow the sensor data to be pre-processed and optimised before transmission.

Impact and Benefits

- NPL will further its expertise in advanced metrology and develop new capabilities for evaluation of uncertanty for distributed sesnor networks.
- Moniteye will evaluate cost– benefit for some promising technologies and develop a business model for a new type of monitoring service. This service will focus on transport infrastructure but can be extended to other indusrties such as water and energy supplies.
- The feasibility study will lead to a €3million demontrator project based on a strategic UK transport network site.

- Connect Plus is an active partner in this project and provides full maintanece and upgrade of the M25. The initial focus of this feasibility study is on London and the M25. However, Connect Plus is a consortium. The four companies that form this consortium - Skanska, Balfour Beatty, Atkins, and Egis - are major players in the EU. Connect Plus therefore has a direct route to a very large share of the European market. It will help UK SMEs to reach new markets.

Support for Programme Challenge, Roadmaps, Government Strategies

- Mathematics and modelling group strategy
- EU Metrology 2020 program
- Big Data
- Managing key resources and infrastructure

Synergies with other projects / programmes

- NEW04, NEW06, and an EMRP project proposal on environmental sensor networks (2013 energy call JRP g16)

Risks A number of risks are inherent within the project and will be mitigated if they occur:

- Various numerical techniques will be investigated to provide solutions to significant scientific challenges but there is no guarantee that the best fitted methods will be identified within the timescale of the project. Collaboration with academia will help to shortlist the methods for consideration.
- This area requires consensus between the full supply chain such as academics, technologies providers and manufacturers, maintenance companies and asset holders together with regulatory bodies. NPL is well positioned to bring together and develop existing collaborations further.
- Cost-benefit of this type of service is yet to be determined. The latest technologies and most advanced data analysis techniques may still be expensive. By providing business analysis conducted by a commercial company the future developments will be more focused.

Knowledge Transfer and Exploitation

- Exploitation is likely via IP and licensing, which will be granted to third parties in order to develop products, through licensing, or licensing combined with joint development agreements.
- NPL will contribute to the development of a new framework to estimate the uncertainty associated with data and data analysis. It will be part of a new metrology for distributed sensor networks and will provide nput into relevant national and European standardization committees, to ensure the UK leads in terms of meeting the requirements of legislation and formulating future requirements.
- New calibration and traceability procedures for large scale sensor networks will require consensus. The project will undoubtedly broaden the outreach and will reduce the cost of legislative compliance for regulated industries such as the transport network. It will help to increase in uptake of sensor technologies.

Co-funding and Collaborators

50% co-funding (€92,678) by ESA has already been won. Moniteye, a UK SME , will provide local sensor networks for this feasibility study. It will provide the business plan for the future demonstrator project as it is envisaged to be a new Integrated transport service provider. NSL will provide GNSS equipment and expertise. The Space Applications Catapult will provide expertise in communication and earth observation technologies and also use of its data centre in Hallow to collect and process aggregated data (GNSS, EO integrated with Moniteye measurement data.)

Deliverables

1	**Start: 01/11/13**	**End: 31/1/15**	

Deliverable title: Introduction of traceability concept for distributed sensor networks deployed in outdoor environment.

Deliverables

2	**Start: 01/11/13**	**End: 31/1/15**	

Deliverable title: Demo of an optimised simulated sensor network to improve the information quality.

Project No.	IRD\2013\11	Price to NMO	£862k
Project Title	In situ diagnostics and advanced modelling for PEM fuel cells	Co-funding target	£500k
Lead Scientist	Gareth Hinds	Stage Start Date	01 Oct 2013
Scientist Team	Edward Brightman, Alan Turnbull, Neil McCartney, John Blackburn, Stephen Giblin, Stephanie Bell, Michael de Podesta, Jenny Wilkinson	Stage End Date	30 Sept 2016
		Est Final Stage End Date	2020
Sector	Energy	Activity	Development of Existing Capabilities
Project Champion	Graham Cooley		

Summary

This follow-on project represents a key stage in the NPL fuel cell metrology roadmap and will build on the world-leading in situ measurement and modelling capability established at NPL since 2005 under the IRD Programme. Highlights to date include a world first measurement of relative humidity in the gas channels of an operating PEM fuel cell, a novel reference electrode that allows for the first time in situ mapping of electrode potential across the active area of the cell, an innovative technique for measurement of active catalyst area in fuel cell stacks and a 2D model of fuel cell performance in an accessible software package (Comsol). This work has led to the publication of more than 20 papers in highly respected peer-reviewed journals and several invited talks at international conferences. The critical next step will be to extend the NPL fuel cell model to 3D in order to provide a powerful new design tool for industry, with the flexibility to be applied to a range of hardware geometries. The 3D model will be validated using the cutting edge in situ measurement techniques developed in this and previous projects. Assessment of impedance spectroscopy as a diagnostic tool has been identified by industry as a significant requirement and this will form a key part of the experimental development work in this project. The overall impact of the project will be to facilitate design optimisation through more effective in situ measurement and modelling tools, improving fuel cell performance/durability and accelerating commercialisation of this environmentally-friendly technology. A parallel objective will be to assess the feasibility of in situ measurement techniques for related electrochemical energy storage technologies such as batteries and electrolysers.

The Need

Fuel cells are promising candidates as more efficient and environmentally-friendly alternatives (or hybrid partners) for conventional energy conversion technologies such as the internal combustion engine, batteries and gas turbines. Drivers for commercialisation include higher energy efficiency, security of supply, lower carbon emissions and reduced pollution. Widespread uptake has been hindered by the high cost of materials and manufacturing, limited durability of fuel cells under realistic operating conditions and the lack of a refuelling infrastructure. Improvements to fuel cell durability are constrained by a lack of fundamental understanding of degradation mechanisms, exacerbated by limited in situ measurement capability within the fuel cell and the absence of accessible fundamental models of fuel cell performance. Carbon neutral use of hydrogen as a fuel implies generation from renewable sources and efficient storage, which will require parallel advances in electrolyser and battery technologies. The UK has a relatively strong presence in the global fuel cell/hydrogen industry, with a number of innovative SMEs emerging, but the technology requires government support in order to become economically competitive.

The Solution

Extension of the NPL fuel cell model from 2D to 3D, validated by the advanced in situ measurement techniques, is key to the successful impact of the project and will provide a powerful new tool for use by industry in the optimisation of fuel cell performance and durability. The focus will be on understanding and mitigating key degradation modes such as start-up/shut-down and cell reversal. Complementary to this work, the use of electrochemical impedance spectroscopy as a diagnostic tool will be investigated using NPL's unique reference electrode array, developed in the previous project. Finally, the applicability of in situ measurement techniques to other related technologies, such as batteries and electrolysers, will be explored.

Project Description (including summary of technical work)

1. 3D fuel cell model: The NPL 2D representative volume element model will be extended to 3D using a coupled channel model to account for variations in input parameters across the active area of the cell. The model will be tested in two separate software platforms and validated using in situ measurement techniques developed in this and previous projects and via literature data. The output of this work will be an accessible 3D model with the flexibility to accommodate different hardware geometries.

2. Impedance spectroscopy as a diagnostic tool: The use of impedance spectroscopy in fuel cell characterisation has been limited conventionally to measurement of membrane resistance. Here the broader applicability of impedance spectroscopy as a diagnostic tool will be assessed at both single cell and stack level. The technique will be combined with NPL's unique reference electrode array to characterise the spatial distribution of the impedance response across the active area. The objective of the work will be to identify useful applications of impedance spectroscopy in characterisation of fuel cell performance and durability.

3. Development of in situ measurement techniques for related technologies: Performance and durability improvements in electrolyser and battery technologies are key to the development of a hydrogen economy. Innovative in situ measurement techniques based on thermal imaging, reference electrodes and impedance spectroscopy will be developed for prototype systems. The aim will be to inform design optimisation through the generation of previously unobtainable in situ data.

Impact and Benefits

The improvements to PEM fuel cell performance and durability facilitated by this project will:

- accelerate the demonstration phase of the technology and foster greater public acceptance
- give UK industrial partners a global competitive advantage via early access to the outputs during the course of the project

In the broader context commercialisation of electrochemical energy storage technology will:

- make a significant contribution to meeting the UK's greenhouse gas emission targets
- create employment opportunities in an entirely new sector
- lead to improved urban air quality and reduced noise pollution

- reduce UK dependence on imported oil and gas

This project will ensure that NPL continues to strengthen its world-leading reputation in PEM fuel cell metrology, facilitating further participation in complementary collaborative research projects and contract research that will add significant value to the NMS-funded work. Increasing involvement in European projects will add further synergy to the work.

Support for Programme Challenge, Roadmaps, Government Strategies

- Addresses a key part of the IRD Programme Challenge in Energy Generation & Transmission.
- Integral part of the NPL Fuel Cells roadmap and critical to future growth in this area.
- Key science area identified in NPL/NMO Strategy: low carbon and sustainable technologies in energy generation and usage.
- Well aligned with wider UK government and EU strategy on low carbon technologies.

Synergies with other projects / programmes

This project is well aligned with both existing (EU/TSB) and proposed (EMRP) fuel cell projects in which NPL is a partner, where the main focus is on improving fuel cell durability. The project is highly multidisciplinary in nature, with cross-Divisional participation from the Electrochemistry, Materials Modelling, Electrical, Temperature and Humidity groups. Within NPL the project has synergies with projects on hydrogen purity (ChemBio Programme) and catalyst metrology (IRD Programme). Broadening of the remit of the work to explore related electrochemical technologies (primarily batteries and electrolysers) is strongly supported by the Industrial Advisory Group and in line with strategic trends at both UK and EU level. This is also reflected in the broader remit of proposed NPL bids to the EMRP Energy Call in the areas of grid storage and electric vehicles.

Risks

The primary technical risk is that the computation time required for the 3D fuel cell model may be prohibitively long. This will be mitigated by parallel development of the model under two different software platforms, Comsol and Zinc. On the experimental side, the risk with any in situ measurement is that it may perturb the system. Rigorous checks will be performed to ensure that any such perturbation is minimised. The track record of the scientific team indicates that the overall level of technical risk is low.

Knowledge Transfer and Exploitation

- Key to maximising the impact of the project will be uptake of the NPL 3D model by industrial partners and stakeholders from the wider fuel cell industry via licensing agreement with Comsol and/or distribution by NPL using the Zinc software platform.
- Consolidation of NPL's world-leading position in the field will facilitate further participation in collaborative research projects and attract commercial third party work based on these innovations, expanding the revenue stream for NPL in this area.
- Dissemination of scientific outputs will occur via IAG meetings, international conference presentations (Gordon Conference, Fuel Cell Seminar, Grove Conference), peer-reviewed publications (J. Power Sources, Int. J. Hydrogen Energy) and participation in international standards committees (IEC TC 105 – Fuel Cell Technologies).

Co-funding and Collaborators

- IAG: Johnson Matthey, Intelligent Energy, Acal Energy, AFC Energy, C Tech Innovation, ITM Power, UCL, Imperial College.
- Industrial partners will supply materials, components, test cells and drawings, access to test facilities, practical support and advice, test data for validation of models and critical assessment of techniques developed in the project.
- EU FP7 H2FC (Fuel Cells & Hydrogen) Infrastructure project (total NPL funding £514k), 2011-2015.
- NPL is part of two separate consortia bidding to the 2013 EMRP Energy Call in the areas of grid storage and electric vehicles.
- The project will part support two PhD students at UCL as part of a strategic collaboration on in situ measurement techniques (thermal imaging and impedance spectroscopy) in electrochemical energy storage technologies.

Deliverables

1	**Start: 01/10/13**	**End: 30/09/16**	
Deliverable title: Development and validation of 3D fuel cell model in accessible software platform **Evidenced by:** 3D model in accessible software platform + scientific paper in peer-reviewed journal			
2	**Start: 01/10/13**	**End: 30/09/16**	
Deliverable title: Assessment of electrochemical impedance spectroscopy as a diagnostic tool **Evidenced by:** Two scientific papers in peer-reviewed journals			
3	**Start: 01/10/13**	**End: 30/09/16**	
Deliverable title: Development of in situ measurement techniques for related energy technologies **Evidenced by:** Two scientific papers in peer-reviewed journals			

Project No.	IRD\2013\12	**Price to NMO**	£826k
Project Title	Innovative metrology for critical defect identification in large area plastic electronics	**Co-funding target**	£500k
Lead Scientist	Fernando Castro (Phase 1), Richard Leach (Phase 2)	**Stage Start Date**	01.10.2013
Scientist Team	James Blakesley (MAT), Christopher Jones (EM), George Dibb (MAT), Stephen Giblin (TQEM)	**Stage End Date**	30.09.2016
		Est Final Stage End Date	
Sector	Global competitiveness	**Activity**	Methodology for new capabilities
Project Champion	Tim Ryan		

Summary The key challenges for plastic electronics are durability and scaling up of production with minimal performance loss. Small defects that change the functional properties of devices are critical to both issues. Current metrology is not able to uniquely identify which defects are critical and thus should be monitored during production to improve product quality, reduce costs and increase competitiveness. This project will develop: 1) an innovative capability to directly correlate defect type with performance loss in plastic electronic devices; 2) fast, large-area measurement methods for in-line monitoring of topographical defects, in collaboration with two Centres for Innovative Manufacturing. By focusing on monitoring only the critical defects, the requirements for large amounts of data analysis will be reduced, facilitating the implementation of in-line roll-to-roll (R2R) production quality control.

• **The Need** One key advantage of plastic electronics is the possibility of high-value low-cost manufacturing via production of large-area devices using printing and coating methods. Despite a multi-billion pound potential market, penetration of new plastic electronic products has been hindered by two main challenges: lifetime of products; scaling up of production with minimal performance loss. One problem is at the heart of both these challenges: defects (or inhomogeneities) that arise during manufacture or under operation can lead to low product quality and to preferential paths for degradation (reducing product lifetime). Identifying which properties and defects are important for the operation and stability of devices is currently problematic due to the lack of adequate metrology and modelling tools.

• Currently, companies make use of indirect information, such as changes in optical density or the presence of hot spots in thermography images. However, the link between images and the nature of defects is not understood. A critical requirement for both direct and indirect methods is to have reference samples with defined defect types for measurement validation.

• Metrology tools that can image defects during R2R production would significantly reduce R&D and scaling up costs and improve the competitiveness of UK industry. The high speed of production and large area of products requires novel methods with high dynamic range sensing and fast data analysis of large amounts of data. Finding ways of reducing the amount of data to be analysed and identifying the required measurement accuracy vs. impact on product performance is key to substantially relax instrumentation requirements.

• The UK Government has identified organic electronics as one of its priorities[1] due to the large number of SMEs and start-ups in the country and the world-leading expertise in academia. The Secretary of State for Business, Innovation and Skills highlighted the importance of the area saying: "It is a sector in which Britain has huge potential for leadership and with it employment and economic growth."[2] This project aims to build new capability to underpin the UK competitive edge in plastic electronics.
(1) Hauser report – 2010; (2) DBIS Plastic Electronics strategy - 2009

The Solution A two phase solution is needed to address the challenge.

• *Phase 1:* A novel charge extraction based 2D mapping method coupled with innovative system modelling will be developed to enable local characterisation of performance loss, such as charge recombination, and direct correlation of local performance with known dimensional defect information, measured using advanced topography characterisation methods. For the first time, reference defect artefacts will be developed to enable validation and calibration of imaging methods used for defect detection in plastic electronics. Specifications for a fast, large-area imaging method will be produced as input for Phase 2.

• *Phase 2:* A step-changing prototype high-throughput instrument for in-line dimensional characterisation of selected defect types will be developed. Appropriate validation and calibration techniques will also be developed supported by outputs from Phase 1. Demonstration will be carried out in collaboration with an industrial partner.

Project Description *Phase 1: Identify impact of defects on functional properties* *i) Develop novel 2D high-resolution mapping method to link defect type and performance loss.* Innovative modelling will be developed to select the best measurement configuration and conditions. A charge extraction based method will be set up and characterised at NPL (in collaboration with Imperial College London and Merck Chemicals). A major challenge will be the development of the technique to allow high-resolution mapping of defect features (tens to hundreds of micrometres) for the first time. *ii)* A range of reference defect types typically encountered during production will be produced. These include, but are not limited to, physical and chemical defects (e.g. thickness variation in the electrode changes local electrical resistance), registration and patterning errors. The dimensional characteristics of defects in 3D will be calibrated using a range of advanced surface topography measuring instruments. *iii) T*he novel charge extraction mapping technique combined with feature-based characterisation will be used to determine the impact of different topography defect types on the functional properties of organic electronic devices. This will be used to specify the instrument requirements for defect detection in Phase 2 (decision point at month 18).

Phase 2: Implement large-area measurement methodology for crucial defects detection. *i)* Design novel R2R compatible measurement system and develop instrumentation at NPL. *ii)* Characterise NPL's prototype instrumentation in a real R2R steering system (fast detection, large area samples) at Cranfield University as part of the EPSRC CIM in Ultra Precision. This work will be carried out in collaboration with the EPSRC CIM in Large-Area Electronics. *iii)* Demonstration of the new instrumentation will be carried out at an industrial partner site (real R2R production). The mapping method of Phase 1 will be correlated to data from the Phase 2 instrument to validate the in-line identification process (case study with industrial partner).

Impact and Benefits

• The innovative methodology for the measurement of recombination losses and defect detection in large areas with high

resolution will have a direct impact in scaling up and quality control of processing, reducing R&D time for companies. The project will culminate a case study with an industrial partner, opening up various routes to exploitation as a component of R&D cycles. • The demonstration of in-line R2R monitoring of dimensional defects will have direct impact in the whole printed electronics industry and will further enhance NPL's standing within the industry. • Novel reference samples for defect detection will allow (for the first time) the validation of imaging methods used to characterise plastic electronics. The impact extends well beyond the validation of the charge extraction methods and would be applicable to any other imaging method. This allows determination of measurement sensitivity to defects and benchmarking of different methodologies.			
Support for Programme Challenge, Roadmaps, Government Strategies Plastic electronics has the potential to be a $300 billion global market within 15 years and has been identified by the TSB as one of five technology areas in which investment would have a significant and lasting impact on the UK economy. The UK electronics market is one of the largest of the European markets (~10 % of the UK's GDP). It is highly dispersed with SMEs playing an important role. Government strategy and roadmaps: OE-A Roadmap for Organic and Printed Electronics (4th edition, 2011), TSB Electronics Photonics Electrical Systems technology pillar (2008)-Plastic and printed electronics, DBIS Plastic Electronics strategy (2009), Hauser report (2010), PV Implementation Plan (Solar Europe Industry Initiative) highlights needs for scaling up research. Support from VAMAS TW36 (Organic Electronics).			
Synergies with other projects / programmes This proposal builds on expertise developed on photocurrent mapping, electronic characterisation of plastic electronics and optical sensor development. These work has led to > 8 invited talks and > 9 peer-reviewed papers since 2011. The synergy with the following projects has decreased the required overall budget of the IRD project significantly: EMRP Industry *Thin-films* (2011-2014), EFM project *Ultra Precision Manufacturing Metrology* (and its co-funding from FP7 project NANOMend), IRD MAT16 *Advanced Metrology for Novel Photovoltaic Technologies* (2010-2012); IRD project *Advanced Metrology for Enhanced Lifetime of Organic Diodes* and VAMAS TWA36 *Organic Electronics*.			
Risks This project combines medium to high risk work. Where risk is high we have identified a contingency solution and included a breakpoint in month 18 for a decision to be made. High-risk: Feasibility of Phase 2 relies on development of sensor technology as part of the NMS EFM project and on the specifications determined in Phase 1. The contingency will be to develop large area faster opto-electrical measurements. These are suitable for manufacturing quality control but not for R2R monitoring.			
Knowledge Transfer and Exploitation The close engagement with industrial and academic partners will facilitate knowledge transfer and uptake of technology. The developed instrumentation IP will be licensed with a commercial instrument manufacturer. The demonstration of the new capability will attract substantial grant work (our experienced scientist team has already brought over £1.7M of grant funds since 2011). We expect that the off-line charge extraction mapping could be coupled with the advanced degradation chamber developed in the IRD project *Advanced metrology for enhanced lifetime of organic diodes* to provide *in-situ* characterisation of defects in a controlled atmosphere. We also expect synergies with the adaptive optics work in IRD *Photovoltaics* that could potentially lead to fast and large area application of the novel charge extraction method. There is also potential for cross-over applications in other industrial areas (e.g. inorganic printed electronics, inorganic thin-film PVs, micro-optic arrays). The project is expected to produce a number of high-calibre journal and conference papers. The Rayleigh Awards in 2012 and 2013 (NPL's prize for best published paper) were won by scientists involved in this proposal.			
Co-funding and Collaborators EPSRC CIM Large-Area Electronics (£250k, Phase 2 design and characterisation), Knowledge transfer Scheme (KTS) grant experienced post doc researcher (£120k, Phase 1), EPSRC CIM in Ultra Precision (£50k in kind, access to R2R platform), Prof. James Durrant (Imperial College) (£50k in kind, Phase 1 setup and sample designs), Merck Chemicals (£20k in kind, Phase1 material supply, sample design). Discussions with Eight19, M-Solv and SPECIFIC are underway to decide on the more suitable partner for the case study in Phase 2.			
Deliverables			
1	**Start: 01/10/ 13**	**End: 30/09/15**	
Deliverable title: Novel 2D high resolution imaging method to link defect type and performance loss as demonstrated by peer-review publication. (MM Division)			
2	**Start: 01/10/14**	**End: 30/09/16**	
Deliverable title: Innovative prototype high-throughput instrumentation for in-line dimensional measurements of selected defect types as demonstrated by industrial case study and peer-review publication. (EM Division)			
3	**Start: 01/11/15**	**End: 30/09/16**	
Deliverable title: In-line sensing technology validated by using off-line performance mapping as demonstrated by peer-review publication. (MM Division)			

Project No.	IRD\2013\13	**Price to NMO**	£351.5K
Project Title	Metrology for printed electronics manufacturing using non-contact high speed techniques	**Co-funding target**	£120K
Lead Scientist	Chris Hunt (MAT)	**Stage Start Date**	1/10/13
Scientist Team	Martin Wickham (MAT), Claudiu Giusca (EM)	**Stage End Date**	31/03/17
		Final Stage End Date	
Sector	Growth	**Activity**	Methodology for new capabilities
Project Champion	Tim Ryan		

Summary Large area printed electronics on flexible substrates such as paper and PET has the potential to be used in a wide range of low-value items such as sensors, smart packaging, RFID and product security. The majority of this business will be fabricated on high speed, sheet fed commercial print systems with capabilities of up to 100m/min. Optical and electronic quality assessment of electronic structures at high speed is needed to ensure that the UK is ideally placed to exploit this high value market.

The Need Large area printed electronics on flexible substrates such as paper and PET has the potential to be used in a wide range of low-value items such as sensors, smart packaging, RFID and product security. It represents one of the most promising and disruptive technologies of our time. Some analysts see the market reaching over $50 billion by the end of the decade, and even over $300 billion in 15 years. It has been identified by the TSB as one of five technology areas in which investment would have a significant and lasting impact on the UK economy. The ability to embed simple electronic and sensor functionality into low-value items will result in a dramatic expansion of markets. The smart packaging global market is expected to increase to $1.7bn in the next 10 years and consumer packaged goods that have electronic functionality will reach 35 billion units in the same timeframe. The fabrication of the majority of this market will migrate from electronics OEMs to the commercial print industry where techniques such as flexography, gravure, offset lithography and inkjet printing will be utilised. Demonstrators of poster sized printed electronics are already being produced and the print industry is anxious to exploit this new technology. Outside of the potential solar panel market, there are few likely products with the volume to require roll-to-roll processing. Conventional screen printing for flexible circuit manufacture is capable of running at 10m/min at print widths up to 2m. Rotary screen printing can improve this to around 15m/min. The majority of the commercial print industry uses large sheet feed systems easily capable of 100 m/min at print widths up to 2m wide. All these techniques use sheet feed systems which have the advantage of being significantly less sensitive to tension of the substrate during processing, yet still with the advantages of large area and high speed. The commercial print industry currently assesses product on a visual quality basis (the products only function visually) so to control deposition and functionality of electronic circuits, high speed, large area metrology will be required. Small defects unapparent to the human eye will cause major issues in quality and functionality of printed electronic circuits. Market leaders, whilst extremely interested in exploiting this technology, do not want their brand tarnished by poor functionality. Implementation of this new disruptive technology will require the co-ordination of effort from a range of industries not previously associated with electronics and therefore will require significant public funding to ensure success.

NPL Capability: NPL is ideally situated to carry this work forward, building on expertise in characterising flexible printed electronics systems. Currently there are techniques for measuring electrical and dimensional properties over small areas and at low speeds, but for high speed manufacture, high dynamic range sensing is required, i.e. high resolution, large area, fast sensing.

The Solution The successful implementation of printed electronics systems requires the development of a suite of metrology methods to enable improved high speed manufacturability of smart packaging systems. Current inks are primarily two-phase systems where deposition and cure have a profound effect on their functionality. Their performance is highly dependent on the intra-action of the phases and the interaction between materials during production. The aim of the project is to develop rapid quality assessment techniques for printed electronics systems. NPL has been active in a current IRD project (Metrology for flexible plastic electronics systems) in evaluating the printed electronic media, both in terms of mechanical and electrical characterisation during curing and drying, and the prediction of lifetime performance. A contactless technique based on eddy current sensing, complimented by non-contact surface topography measurement and characterisation of typical defects, will be developed for high speed printing applications. New non-dimensional characterisation techniques for detecting and identifying defect types will be developed. Fabrication of a range of typical print defects will allow correlation of the electrical and optical techniques to determine the most viable combination to ensure maximum fault coverage and best response times.

Project Description The project will investigate suitable quality assessment techniques for high speed commercial printed electronics. Contact less eddy current sensing will be developed, there being no commercially capable system. This is challenging since we need to excite measurable losses in the system, which will require high frequency excitation, while avoiding inductance issues, some element of frequency scanning is needed to match the change in properties as the ink cures. This will require coil, drive electronics, and analytical solutions. This work builds on a platform of impedance techniques developed in the current IRD project (IRD\2011\14 Metrology for flexible plastic electronics systems). The first phase of this project will enable this technique to be refined and adapted to high speed applications. This will be complimented in the second phase by non-contact surface topography measurement and characterisation of typical defects in high speed printing. Using these capabilities new characterisation techniques for detecting and identifying defect types will be developed. In phase 3, these concepts will be tested in a case study with CPI(catapult)/In2Tec(SME collaborator) in a production scenario to determine the most viable combination to ensure maximum fault coverage and speediest response.

D1: Development of electrical measurement for high speed fabrication quality assessment: Development of eddy current techniques for high speed non-contact applications in commercial sheet feed systems. Publish peer reviewed paper.

D2: Development of surface topography measurement and characterisation techniques: Development of novel dimensional characterisation techniques of defects using existing optical 3D traceable topography measurement methods. Publish peer reviewed paper.

D3: Proof of concept tested by case study at CPI/In2Tec to detect print defect sensitivity and efficiency: Fabrication of defects on sheet fed large area printed electronics. Characterisation of defects and acceptable structures using high speed electrical and optical techniques. Correlation of the electrical and optical techniques to determine the most viable combination to ensure maximum fault coverage and best response times.

Impact and Benefits

Currently the UK is among the world's leading players in PE, and the opportunities to be a major part of a whole new manufacturing sector are both real and realisable. The UK has strengths in terms of research, development and commercial activity, and is well-placed to profit economically, in intellectual property obtained and in terms of manufacturing employment

The development of materials testing techniques to validate production quality is essential to improve market acceptance of low cost printed electronics in a wide range of applications. This project will enable NPL to build on its reputation as provider of metrology R&D for the UK by development of the necessary measurement capability for assessing the performance of the new systems (2 recent patent applications and 2 TSB collaborative projects). The developed techniques will be considered for patent or IP licensing opportunities. The capability will further enhance NPL's standing within the industry, leading to 3rd party test work in qualifying the new materials. The measurement best practice developed will be disseminated to the wider electronics community so those who wish to benefit from PE manufacture can do so. The adoption of these disruptive techniques has been recognised by the UK print industry as being critical to its future in the UK. The UK commercial print industry is currently the fifth largest in the world, with over 10,000 UK businesses, turning over £15Billion annually and employing 140,000 people, with no indication of it going off-shore. The provision of high quality printed products with significant functionality and added value is very attractive to this industry and is necessary to prevent significant loss of traditional business to overseas competitors.

Support for Programme Challenge, Roadmaps, Government Strategies

This project aligns well with the "sustainability" and "growth" challenges in the BIS's NMS strategy, and aligns with NPL's strategy on organic electronics and advanced materials. It has been identified by the TSB as one of five technology areas in which investment would have a significant and lasting impact on the UK economy. It also aligns with the Strategic Business Plan (SBP) of IEC TC 119 (Printed Electronics) and the `OE-A Roadmap for Organic and Printed Electronics´.

Synergies with other projects / programmes

The project strongly aligns with a number of projects in the Materials and Engineering Measurement Divisions. In particular "Metrology for flexible plastic electronics systems" (IRD); EFM project "Ultra Precision Manufacturing Metrology (and its co-funding from FP7 project NANOMend)" (EFM); "Metrology for structured surfaces" (IRD)

Risks

This research project will be delivered by scientists with experience in electronics printing and testing, and 3D optical inspection technologies. This will minimise the risk of technical failure. Access to methods and protocols used in industry will be required for the development of capabilities at NPL. These risks will be mitigated by close collaboration with industry.

Knowledge Transfer and Exploitation

The measurement protocols developed by NPL will be disseminated to the wider community and to companies and organisations outside of the printable electronics community, so those who wish to benefit from advanced electronics manufacture can do so. The Knowledge Transfer Networks (KTNs) will be used, as well as NPL's existing excellent dissemination routes, including NPL's Technology Clubs, and IAGs. Traditional routes will be followed including publications in refereed academic journals, conference presentations and feature articles in trade journals. Standardisation of the metrology will be initiated to facilitate a wider uptake of the technologies developed. NPL will continue to be active in IEC TC 119: Printed Electronics, ensuring the UK leads in forming future standards in this area.

Co-funding and Collaborators

CPI high value manufacturing catapult, In2Tec, Novalia, GEM, Timpsons, EPSRC CIMs in Large-Area Electronics (Cambridge), Cleaner Electronics Research Group at the School of Engineering and Design (Brunel)

Deliverables

1	**Start: 01/04/2014**	**End:30/09/2015**	
Deliverable title: Development of electrical measurement for high speed fabrication quality assessment			
2	**Start: 01/04/2014**	**End: 30/09/2016**	
Deliverable title: Development of surface topography measurement and characterisation techniques			
3	**Start: 01/04/2014**	**End: 30/09/2017**	
Deliverable title: Proof of concept tested by case study at CPI/In2Tec to detect print defect sensitivity and efficiency			

Project No.	IRD\2013\14	Price to NMO	£523k
Project Title	Metrology for advancing the performance and lifetime of organic electronic devices	Co-funding target	£175k
Lead Scientist	Paul Brewer (AS)	Stage Start Date	01/04/2014
Scientist Team	Chris Hunt (MAT), Owen Thomas (MAT), Valerio Ferracci (AS), Marta Doval Miñarro (AS), Yarshini Kumar (AS)	Stage End Date	31/03/2017
		Est Final Stage End Date	31/03/2017
Sector	Growth	Activity	Methodology for new capabilities
Project Champion	Ben Beake		

Summary

One of the biggest challenges for emerging technology based on organic electronics and graphene is assuring the lifetime of the product. These materials are highly sensitive to moisture and oxygen and metrology to underpin quantitiative degradation studies of the active components and performance measurements of encapsulating barrier materials is essential for future success of the technology. This project will provide traceability for electrical impedance sensors targeting moisture, to address these pressing requirements and sustain UK leadership in the high technology advanced manufacturing sector.

The Need

Organic electronics offer a promising solution to meet the increasing technological demands for large area, low-cost, flexible optoelectronic devices. Since their discovery, other exciting new prospects have emerged, such as graphene, which has displayed exceptional new physical effects and there are a large number of new applications where these properties may be exploited (eg. all-carbon electronics, high-frequency transistors and solar cells). A major obstacle to introducing these materials into the commercial market is their limited lifetime due to their degradation in the presence of moisture and oxygen. High performance barrier materials are used to minimise the exposure of such devices and NPL has developed a capability to underpin measurements of water vapour transmission rate (WVTR) with a limit of detection of <5 x 10^{-5} $g.m^{-2}.day^{-1}$ which is low enough to validate these developments. Despite these advances, there is a pressing need from industry for accurate and traceable electrical sensors for demonstrating adequate encapsulation of these highly sensitive materials. Moreover, these sensors are also required to study degradation mechanisms and the influence of moisture ingress on device function and performance. There is currently a lack of traceability disseminated to industry developing devices based on these materials and analytical instrumentation.

This is suitable for inclusion in the NMS portfolio as it exploits current knowledge base capability in a research and innovation environment, is challenge-led and aims to meet emerging industry and societal needs. It will support innovation and exploit synergies between the Chem-Bio and Materials Knowledge Base programmes. The 'New Industry, New Jobs' initiative published in April 2009, which set out the Government's active industrial strategy, identified plastic electronics as one of a range of new industrial technologies in manufacturing in which strong UK capabilities should be a priority for Government support. There is a UK government and growth agenda for the exploitation of the markets for graphene-based products. This is demonstrated by a £50M UK research initative announced by the chancellor "*We will fund a national research programme that will develop production methods that take this Nobel-prize winning discovery from the British laboratory to the British factory floor*".

The Solution

This proposal takes a new direction on current research on WVTR at NPL by collaborating with the Materials division to develop a novel electrical impedance sensor with optimum sensing capability for water that meets the challenging requirements for high sensitivity and selectivity. A dynamic gas calibration device will be designed, constructed and validated to calibrate the electrical sensor and in turn provide a means of disseminating traceable and accurate detection of water on the device to support degradation studies of different active components, intrinsic barrier performance measurements and water ingress mechanisms. The sensor response will detect the difference between intrinsic permeation in the film, penetration through pin holes and finite transport to the coating substrate interface. A new capability will also be developed to disseminate traceability for measurements of oxygen transmission rate at <5 x 10^{-5} $g.m^{-2}.day^{-1}$. This new approach based on state-of-the-art, real time spectroscopies to measure previously inaccessible low concentrations of oxygen will be employed and will allow the performance of the barrier layer to be monitored with high precision and time resolution. This proposal represents an extensive advance in sensor-based techniques and is essential to ensure market success of new electronic technologies.

Project Description (including summary of technical work)

This project will develop an infrastructure for disseminating reference standards of water vapour and oxygen to industry for measurements of degradation of active components in devices, measuring the change in device function with water ingress and measuring the ingress mechanism through barrier materials. This will be achieved by developing electrode materials and geometry, in conjunction with probing techniques for targeting water with an optimum sensing capability. A novel calibration device to provide traceability for the electrical impedance sensors will be designed constructed and validated. It will be used in device degradation studies and barrier performance measurements.

Impact and Benefits

In 2009, manufacturing was the third largest sector in the UK economy in terms of share of UK GDP and generated some £140bn in gross value added, representing just over 11% of the UK economy. The UK is currently among the world's leading players in advanced manufacturing (plastic electronics in particular) with a market value that is $2 billion today and is forecast to grow at an astonishing rate to as much as $330 billion in 2027. This project will have a direct and significant impact on the UK economy by removing barriers to innovation and trade within the advanced manufacturing industry. It will also have a substantial impact on the environment and quality of life by underpinning the development of high efficiency, low cost photovoltaic devices. Over the past 3 years NPL has taken great strides toward providing traceable measurements of water vapour transmission rate at the challenging limits of detection required for plastic electronics technology and is the currently leading NMI in Europe for these measurements. Research has resulted in the development of a capability to underpin measurements of WVTR with a limit of detection of <5 x 10^{-5} $g.m^{-2}.day^{-1}$.This capability and expertise will provide a platform for this project where the outputs will directly support research and development in industry. Specific examples of high-impact benefits:

- The development of a calibration device will be used to support measurements of the influence of water on new materials used in organic electronic devices and assess the suitability of encapsulating barrier layers.
- Measurements to support instrument developments aimed at assessing encapsulation performance and sensor technology.
- More stable sensor materials and hence better monitoring of water ingress into devices.
- Traceable measurements of OTR to support the development of high performance barrier layers.

Support for Programme Challenge, Roadmaps, Government Strategies

This project aligns well with the "sustainability", "growth" and "energy" challenges in the BIS's NMS strategy, aligns with NPL's strategy on organic electronics, advanced materials, energy and emission reduction. It is a fundamental part of the CBKB Gas Analysis Theme Roadmap. It is essential work to deliver NPL's Metrology 2020 vision, particularly in the areas of "energy efficiency and diversity of supply" and "the big factory". This project also addresses the 2011 International Technology Roadmap for Semiconductors, the OE-A Roadmap for Organic and Printed Electronics (4th edition, 2011) and the Royal Society of Chemistry's Grand Challenges on 'energy' as set out in their roadmap 'Chemistry for Tomorrow's World'. It also supports EU directives 2009/28/EC on promotion of energy from renewable sources and 2010/31/EU on the energy efficiency of buildings.

Synergies with other projects / programmes

The project strongly aligns with a number of projects in the Time, Quantum and Electromagnetics and Materials divisions funded by the EMRP and NMS Innovation Research and Development. In particular "Real-time methods for the measurement of key properties of graphene at the device scale" (£3.2M IRD), "Metrology for the manufacturing of thin films" (3M EUR - EMRP) and "Advanced metrology for enhanced lifetime of organic diodes" (£470k IRD). All three projects involve research targeted towards degradation studies and encapsulation of active components in devices based or graphene and plastic electronics. This proposal has good synergy and will provide access to data and facilities.

Risks

This research project will be delivered by scientists with experience in sensor technology and in the preparation and analysis of trace level gas mixtures. This will minimise the risk of technical failure. Access to methods and protocols used in industry will be required for the development of capabilities at NPL. These risks will be mitigated by close collaboration with industry.

Knowledge Transfer and Exploitation

The outputs will be disseminated by high impact publication in peer-reviewed literature, presentations at international fora and via provision of reference standards developed. These will be of particular relevance to the academic and industrial community in the plastic electronics, graphene and micro fabrication arenas. NPL will continue to be active within the Organic Electronics Association (a working group representing the whole value chain in organic and printed electronics). Input into relevant standardisation committees (IEC TC91 and ISO TC158) will enable the work to be transferred and used effectively, ensuring the UK leads in terms of meeting and forming future requirements.

Co-funding and Collaborators

This project aligns with new deliverables formulated under the EMRP JRP18i "Metrology for the manufacturing of thin films" due to commence in 2013 (£60k). Further co-funding will in-kind co-funding from industrial collaborators. Collaborators for this work will include academia (Oxford and Newcastle universities), UK industry (e.g. VG Scienta, The Centre for Process Innovation, Plasma Quest Ltd and Philips), and several NMIs (VSL, PTB and METAS).

Deliverables

1	**Start: 01/04/2014**	**End: 30/09/2014**	
Deliverable title: Review methods for generating dynamic reference standards for gas sensor calibration, with a particular focus on oxygen and water vapour.			
2	**Start: 01/10/2014**	**End: 31/03/2017**	
Deliverable title: Develop electrode materials and geometry for optimum sensing of moisture.			
3	**Start: 01/10/2014**	**End: 31/03/2017**	
Deliverable title: Design, construct and fully validate a novel dynamic calibration device to provide traceability for electrical impedance sensors for moisture used in device degradation studies and barrier performance measurements.			
4	**Start: 01/04/2014**	**End: 31/12/2015**	
Deliverable title: Design, construct and validate an automated capability based on state of the art, high precision spectroscopy for measuring oxygen transmission rate with a limit of detection of $< 5 \times 10^{-5}$ $g.m^{-2}.day^{-1}$.			

Project No.	IRD\2013\19	Price to NMO	£210 k [€230k]
Project Title	Certification of biometric systems to support innovation and interoperability (Co-funding for HECTOS)	Co-funding target	£220k [€260k]
Lead Scientist	Tony Mansfield	Stage Start Date	01.09.2014 2014
Scientist Team	Tony Mansfield +1 Recruit, support from Mathematical group	Stage End Date	31.08.2017
		Est Final Stage End Date	
Sector	Security	Activity	

Summary

This project co-funds a European FP7 project 'Harmonized Evaluation, Certification and Testing Of Security products' (HECTOS) which applies measurement capability and standardisation for innovative measurement solutions in biometric evaluation to support the European Market in security product development and systems interoperability. NPL's focus will be producing case studies and certification schemes to evaluate and incorporate for the first time novel and developing test methods into an agreed system for evaluation of biometric products. Partners in the project are developing similar methodologies for explosives detection.

The Need

Interoperability of security products and systems is essential to enable the best solution to be implemented and tailored to a particular scenario. Innovation is critical to continually improve security and is hindered by the lack of a harmonised approach in the EU and Associated Countries across application areas (e.g. critical infrastructure, crisis management). This presents a barrier to development by the European security systems industry.

Standardization is an important key in providing interoperability between different security products and different users of the technologies which are part of a larger system of systems. When solutions adhere to standards they become interoperable and confidence in the systems enable cooperation between different law enforcement agencies, first responders and others across borders.

Accreditation procedures differ among security products and for some security products the information ("standard") needed to make the conformity assessment needs to be classified to protect the security function. In such cases extra care is needed in the selection of the accreditation body and procedures. Independence of and trust in the accreditation National body is then of outmost importance.

The Solution

In order to enhance the trust of professional users and EU citizen's security products need to be evaluated by independent parties on scientifically valid basis. This relies on their being mechanisms and methodologies for accreditation of conformity assessment bodies and test laboratories (and other similar organisations) responsible for verifying conformity.

Biometric recognition is being used for personal authentication in a broad variety of security applications, such as access to secured areas, automated document checks at border control, CCTV surveillance for individuals on watch lists. Aspects of performance relevant to biometric systems include recognition error rates (i.e., false match and false non-match errors), throughput, conformance to standards, interoperability, quality of image capture, resistance to spoofing. Despite the established standards, certification schemes for biometric systems and components remain in adequate.

HECTOS will advance state of the art in certification of biometric systems and products in the following ways:

- Providing a framework for biometric product certification to help avoid a multiplicity of incompatible certification schemes.
- Extending existing certification schemes to cover a broader range of biometrics (where possible maintaining compatibility with the existing schemes.
- Addressing certification of spoof-resistance capabilities of biometric systems based on outputs of projects and initiatives on spoof detection

Project Description (including summary of technical work)

NPL involvement in HECTOS is focussed on a case study for biometrics. Evaluation & certification methods proposed will be applied to specific types of biometric products to assess all steps, the outcomes, and to validate the feasibility as outlined below:

1	Selected product types, use cases, and validation criteria for biometric case studies	Month 8
2	Working set of performance requirements and associated evaluation methodologies for the selected biometric case studies	Month 14
3	Results of Test & Evaluation for the selected biometric case studies	Month 24
4	Summary of findings from application of evaluation and certification schemes from WP3 to biometric products, for integration in WP8	Month 28

Impact and Benefits

For some application areas (e.g. aviation security) compliance with the standard will be compulsory. In these cases the standard may be referenced by the appropriate EU law in form of a directive or regulation. Through the implementation of the harmonised evaluation and certification schemes developed by the project, the results of HECTOS will contribute to increased performance and accelerated development of security products used to enhance the security of citizens in Europe, as well as increased trust in those products.

Support for Programme Challenge, Roadmaps, Government Strategies

This project directly supports the NMS strategy aim to "Provide standards and measurement methodologies to support the security of citizens, infrastructure and utilities, intelligent surveillance and border and data security, and the maintenance and development of defence capabilities". It aligns with the Government's National Cyber Security Strategy ('Protecting and Promoting the UK in a Digital World') and relevant government department strategies such as those of the UK Border Agency, FCO "Secure Integrated Networks", and Home Office digital strategy.

Synergies with other projects / programmes

Significant synergy with UK Centre for the Protection of National Infrastructure (CPNI) biometrics work. Also the CESG (Information Security Arm of GCHQ)-driven UK Biometrics Working Group

Risks

1. Selected 'Use Cases' do not represent best priorities. Mitigation: work with partners and use CPNI-gained experience to ensure sensible choice.
2. Partners do not agree recommendations or they cannot be satisfactorily implemented. Mitigation: Refine recommendations to ensure would allow certification against requirements of multiple schemes, or to align schemes of different certification authorities.

Knowledge Transfer and Exploitation

The timeline of the Security Programming Mandate (M/487) envisages Mandates to the 3 defined topics (CBRNE, border security, crisis management/civil protection) to be given in the middle of 2013 to the European Standardization Organizations. DIN as a partner will take care of a close cooperation with the executing standardization committee on European level to ensure information exchange. The HECTOS case studies and the analysis of application scenarios (biometrics and explosives) contribute to the dedicated topics of these mandates. Introducing project results to European standardization would build the basis for future certification mechanisms in the European Market. Additionally, HECTOS could help provide information and results for action 2 of the Security Industrial Policy SIP, which is dedicated to provide recommendations for EU harmonized certification approaches to be accepted in the security market (e.g. biometrics and screening of explosives within the area of airport screening).

Co-funding and Collaborators

Partners: Swedish Defence Research Agency – Sweden (LEAD PARTNER), Morpho, SAFRAN Group – France, Iconal Technology Ltd – UK, Fraunhofer ICT & IGD – Germany, The Netherlands Organization for Applied Scientific Research- The Netherlands, University of Warwick – UK, Deutsches Institut für Normung e.V. – Germany.

Deliverables

1	**Start: 1/9/14**	**End: 31/8/16**	
Deliverable title: *Evaluation of case study Biometric recognition product certification*			
2	**Start: 1/9/15**	**End: 31/8/17**	
Deliverable title: *Extrapolation of case studies to the domain of physical security products*			
	Start: 1/9/15	**End: 30/8/17**	
Deliverable title: *Elements for roadmap on European certification, accreditation and standardization for physical security products.*			

Project No.	IRD/2013/20	Price to NMO	£214,141
Project Title	CHEETAH - Cost- and material reduction for higher energy output of solar photovoltaic modules	Co-funding won	£197,894 from FP7 Cash co-funding only
Lead Scientist	Fernando Castro (MAT)	Stage Start Date	January 2014
Scientist Team	James Blakesley (MAT)	Stage End Date	December 2018
		Est Final Stage End Date	
Sector	Energy, High-Value Manufacturing, Sustainability	Activity	Methodology for New Capabilities
Project Champion			

Summary

Europe has invoked the SET-Plan to design and implement an energy technology policy for Europe to accelerate the development and deployment of cost-effective renewable energy systems, including photovoltaics. With lower cost of solar electricity, PV could significantly contribute to the achievements of the 20-20-20 objectives. In CHEETAH, all members of the Joint Program on PV of the European Energy Research Alliance (EERA-PV) will, through collaborative R&D activities, (1) focus on solving specific bottlenecks in the R&D Joint Program of EERA-PV, (2) strengthen the collaboration between PV R&D performers in Europe through sharing of knowledge, personnel and facilities, and (3) accelerate the implementation of developed technologies in the European PV industry. Specifically, CHEETAH R&D will support Pillar A (performance enhancement & energy cost reduction) of the SEII Implementation Plan, through materials optimization and performance enhancement. CHEETAH's objectives are threefold:
1) Developing new concepts and technologies for wafer-based crystalline silicon PV (modules with ultra-thin cells), thin-film PV (advanced light management) and organic PV (very low-cost barriers), resulting in (strongly) reduced cost of materials and increased module performance;
2) Fostering long-term European cooperation in the PV R&D sector, by organizing workshops, training of researchers, efficient use of infrastructures;
3) Accelerating the implementation of innovative technologies in the PV industry, by a strong involvement of EPIA and EIT-KIC InnoEnergy in the program.
It is the ambition of CHEETAH to develop technology and foster manufacturing capabilities so that Europe can regain and build up own manufacturing capacity in all parts of the value chain in due time.

The Need

Industry revenues in PV production amount to $77 billion in 2012, of which 88% can be attributed to crystalline silicon PV. Thin film PV technologies are expected to become a $20 billion market by 2022. The OPV market today is worth $4.6 million and forecast to rise to $630 million in 2022. The European PV industry is facing major competition from emerging countries. Indeed, in the last years China and Taiwan have made huge investments in the upscaling of PV manufacturing, and have succeeded in drastically reducing production costs. This has led to a shift in mass production of wafers, cells and modules to Asia, but also to the introduction of production overcapacities, which, in combination with a temporarily stagnant market, caused a global crisis in the PV industry. Only by joining forces can Europe effectively shift actual technologies to new generation of technologies that will allow it to face the fierce competition from Asia.
European-wide collaboration between (public) R&D providers and industrial actors is required to decrease the quantity and cost of materials used while increasing overall performance of the cells and modules. This is crucial to ensure EU competitive in PVs. For the case of organic PV, stability is the key bottleneck hindering the commercialisation of this disruptive energy technology. Today, the strategy for developing polymer solar cell is based on improving power conversion efficiency and subsequently improving the stability through improved encapsulation methods and encapsulation materials. However good encapsulation is too expensive. Therefore a different approach is needed, where solar cell development starts by choosing stable solar cells that are compatible with scaling up of the production process. The challenge is how to compare the stability of different OPV materials quickly and effectively.

The Solution

NPL's solution is to develop a methodology to screen materials and layer combinations for enhanced stability and built a database of materials parameters that can be used as a platform for the development of long-lived low-cost organic solar cells.

Project Description (including summary of technical work)

NPL leads Task 10.2: Methodology to screen materials and layers combinations for enhanced stability
Material screening tests and accompanying lifetime-prediction models will be developed to enable rational optimisation of individual layers and interfaces for improved stability against oxygen, water, UV and elevated temperature. The aim is to develop tests that can be used by industry to accelerate optimisation of materials and processes for better stability of the final product. The tests and models will be validated against accelerated testing and field trials of complete devices. NPL will study degradation in a range of photoactive-layer materials with a unique environmental chamber with ppm-level control over oxygen and humidity levels. Decay of electronic performance and optoelectronic properties (such as recombination rates and charge-carrier mobility) will be monitored in-situ and used to establish models of degradation. Metrics will be defined to describe the stability of

photoactive materials. Benchmarking tests will be developed to evaluate these metrics for single materials and donor-acceptor material formulations, building a library of material stability parameters.
NPL will also contribute to Task 5.3: Guidelines for standards for next generation PV technologies.
The participants will produce for month 48 of the project a comprehensive status report on standards for PV systems and priorities for development work. This will bring together the innovative expertise from the R&D organisations as well as opinions of industry. A mid-term report will be produced as a separate deliverable that will be handled only internally and will serve as a main benchmark for the final report.

Impact and Benefits

It links with strategic new EU partners (all key PV R&D players in Europe)
Builds new capability: we will develop and evaluate the feasibility of a benchmark test for material degradation screening
Generates new knowledge: we will build a library of degradation mechanisms in key state of the art materials used in organic solar cells.

Support for Programme Challenge, Roadmaps, Government Strategies

NMS Strategy: This project links to the NMS strategy/priority areas of low carbon technologies, sustainability, global competitiveness, and advanced manufacturing. Maps onto NPL's "Stability" organic electronics roadmap.
BIS/EPSRC/BBSRC/TSB: UK Technology Strategy Board Electronics Photonics Electrical Systems technology pillar (2008). UK Dept for Business Innovation and Skills, Plastic Electronics: A UK Strategy for Success (2009). DECC's July 2011 "UK Renewable Energy Roadmap" relies on the uptake of photovoltaics to achieve the 80% emissions reduction by 2050. UK Government strategy Renewable Obligation, Climate Change Bill, Microgeneration Strategy, UK Energy Marketing.
Roadmap: Solar Photovoltaics Competing in the Energy Sector: On the road to competitiveness (European Photovolatics Industry Association); OE-A Plastic Electronics Roadmap.

Synergies with other projects / programmes

Project fully aligns with NPL strategy for OPV. It builds upon expertise being developed under the project IRD degradation.

Risks

New benchmark test is not sufficient to evaluate degradation. Mitigation: Two approaches will be tested in parallel.
Difficulty to obtain state-of-the-art material. Mitigation: Partners have access to materials.

Knowledge Transfer and Exploitation

The work is anticipated to lead to a high impact paper, future joint projects and third party work.

Co-funding and Collaborators

This is a co-fund project to FP7 CHEETAH.

Deliverables

1	**Start:** 01/01/14	**End:** 31/12/17	

Deliverable title: Co-fund to FP7 CHEETAH

Project No.	IRD/2013/21	Price to NMO	£398,915
Project Title	Co-funding for EMRP g14 Towards an energy-based parameter for photovoltaic classification	Co-funding won	£289,205 from EMRP
Lead Scientist	James Blakesley (MAT)	Stage Start Date	1st May 2014
Scientist Team	Fernando Castro (MAT), George Dibb (MAT), Simon Hall (EM), Paul Miller (EM)	Stage End Date	31st April 2017
		Est Final Stage End Date	
Sector	Energy	Activity	Methodology for New Capabilities
Project Champion			

Summary

This project will cofund the NPL contribution to the €3.6M EMRP ENG55 PhotoClass project. The photovoltaic (PV) world market volume is approximately 50 billion Euros per year, and is becoming an increasingly important source of energy for many European countries. Across that market PV products are sold on the basis of a power rating (kW) measured under standardised, but unrealistic conditions. Consumers and investors, however, are interested only in the total energy (kWh/year) produced under real conditions. Furthermore, different PV technologies perform optimally under different conditions, but this is not encompassed in the power rating metric. This project aims to develop and promote energy-rating methodology for the PV industry to overcome these deficiencies. It includes the development of standards for energy-rating, as well as the development of new and improved metrology for measuring energy-rating parameters with low cost and high accuracy.

The Need

Investment in PV projects is dependent on the ability to accurately predict energy yield of an installation. When the conditions of use deviate from the standardised conditions that are used for rating PV products, the uncertainty in yield predictions increases. This is particularly the case for non-ideal climates, such as those in Northern Europe and the UK. As margins can be small, this uncertainty adds considerable financial risk to projects. Therefore, there is a need to both reduce the uncertainty in the characterisation of PV devices, and to encourage the use of energy-rating methods that characterise devices under a range of different conditions. Furthermore, as PV moves increasingly to more challenging climates and environments, the choice of technology becomes increasingly important. Some technologies will be better suited to certain climates, but this is not accounted form in the current power rating standards. Lacking the information to choose the optimum technology, developers will often opt for the conservative choice of the most tried and tested technology. This can stifle innovation.

The Solution

The use of an energy rating for PV that distinguishes between different climatic zones will help consumers and investors to ensure that the choice of technology is appropriate. This will lead to a) improved energy yields due to better choice of technology at the consumer level; and b) better targeted investment in R&D for new technology optimised for non-standard conditions. A standard for energy rating of PV is currently under development by IEC TC82. This project will a) assist the completion of this standard; b) promote the use of the standard by engaging with industry and developing guidelines for its use; c) develop metrology to reduce cost and time required to characterise devices according to the new standard; and d) develop metrology and reference devices to reduce the uncertainty in energy rating.

Project Description (including summary of technical work)

The EMRP project comprises 7 funded partners, 2 REGs and 3 unfunded partners. The project is coordinated by PTB. There are 6 work packages:

- WP1 Develop an energy-based metric for photovoltaics
- WP2 Reference devices
- WP3 Detector characterization
- WP4 Source characterization methods
- WP5 Creating Impact
- WP6 Management and Coordination

NPL (MAT) will lead WP1, which will be coordinated closely with Loughborough University and the JRC. NPL (MAT and EM) will also make major contributions to WP3, developing new methods for faster/lower cost characterisation of PV devices.

Impact and Benefits

Foreseeable impacts of the project are:

- PV is a clean and secure energy source. Increased implementation will tackle national and international climate change, pollution, and energy-security challenges.
- The project will lead to greater adoption of the use of energy rating within the industry.
- Reduced financial risk due to lower yield-prediction uncertainties will accelerate investment in PV, particularly in marginal regions.
- The adoption of energy-rating will promote the use of more diverse technology optimised for different conditions, and promote investment in R&D. The prominent role of the UK and Europe in PV R&D suggests that this will be beneficial to

European and British enterprises of various sizes.
- Improved metrology will reduce the cost to industry of implementing energy rating.

Support for Programme Challenge, Roadmaps, Government Strategies

NMS Strategy: This project links to the NMS strategy/priority area of low carbon technology.

EU 2020 and UK 2050 renewables targets: By accelerating adoption of renewable PV energy, this project assists the European and UK governments to meet their targets of 20% renewable energy production by 2020 and 80% reduction in GHG emissions by 2050.

Roadmap: Aligns to UK Microgeneration Strategy, UK Solar PV Roadmap and EU SET and SEII PV roadmaps.

Synergies with other projects / programmes

Builds upon IRD Photovolatics and IRD Defects project. Builds collaboration with partners likely to be key to future projects, e.g. Loughborough University and Supersolar Hub, BRE National Solar Centre.

Risks

Contributions to WP3 (MAT and EM) involve the development of novel technology for a step-change in PV characterisation. This is necessarily medium to high risk, and could fail to deliver significant improvements over existing methods. The project is structured to minimise negative impact on other tasks in this case. WP1 (MAT) involves more incremental development, and the main risks are from non-delivery by collaborators.

Knowledge Transfer and Exploitation

The results will be disseminated via high-impact publication and conference presentations. Our existing and future projects will also be used to inform our UK partners. We anticipate that the work will lead to future joint projects and, in the longer term, to third-party work.

Co-funding and Collaborators

This project cofunds the NPL contribution to the EMRP ENG55 PhotoClass project.

Deliverables

1	**Start: 01/05/14**	**End: 30/04/17**	

Deliverable title: MAT cofounding form EMRP PhotoClass project

- Task 1.1, 1.2: Lead delivery of energy-yield prediction software tool including yield and uncertainty map for Europe and standard climatic zones and annual yield variance
- Task 1.3: Deliver guidelines for strategies to achieve optimal balance of measurement cost versus yield-prediction uncertainty
- Task 3.4: Paper on the demonstration of a novel method for fast angular dependent photocurrent measurements, with potential to reduce costs to industry of performing such measurements

2	**Start: 01/05/14**	**End: 30/04/17**	

Deliverable title: EM cofunding for EMRP PhotoClass project

- Task 3.1: Design and implementation of a prototype multiple-wavelength compressive-sensing method for area characterisation of solar devices. The method has potential to accelerate characterisation and rating of PV device
- Task 3.1: Report describing the validation of the compressive sensing system using the NPL spatially resolved photocurrent mapping facility with an uncertainty analysis
- Task 3.1: Paper on the multiple wavelength compressive sensing system compared with the polychromatic spectral response facility with an uncertainty analysis submitted for publication in a peer reviewed journal

Project No.	IRD/2013/22	Price to NMO	£561,821
Project Title	Co-funding for EMRP g25 Traceable characterisation of thin-film materials for energy applications	Co-funding won	£403,459 from ERMP grant
Lead Scientist	Fernando Castro (MAT)	Stage Start Date	1st July 2014
Scientist Team	James Blakesley (MAT), Simon Hall (EM)	Stage End Date	30st June 2017
		Est Final Stage End Date	
Sector	Energy	Activity	Methodology for New Capabilities
Project Champion			

Summary

This project is part of a 3.7M EUR EMRP activity led by NPL that will develop complementary metrology tools for the characterisation of thin film for energy applications. The focus will be on technical challenges shared by complex thin film technologies in respect to performance, durability and cost-effective manufacturing that require innovative metrology and modelling to enhance device functionalities and improve competitiveness. As an output, NPL will deliver novel measurement prototypes and innovative measurement protocols. Efficient knowledge transfer mechanisms will be used to disseminate JRP results and ensure impact, including workshops, training and a stakeholder e-forum.

The Need

The global market for low-carbon goods and services is projected to grow from £3.5 trillion in 2008 to just under £4.5 trillion by 2015.[1] This multi-technology market growth is driven by EU targets for the use of renewable energy and energy efficient devices with significant implications in increasing the supply of advanced materials and technologies. Europe's shift to a low carbon economy requires a combination of multiple technologies, such as power electronics, solid state lighting, energy efficient windows and solar energy. Thin film materials underpin numerous energy technologies and thus play a vital role in meeting targets on emissions, electricity availability and reduced cost. Countries that develop the know-how to characterise and model such materials and technologies improve competitiveness and ensure leadership in this area. This JRP will take an innovative and ambitious approach of developing a multi-faceted metrology framework to ensure an energy efficient Europe and to extend Europe's leadership in energy technology and innovation.

The Solution

Development of complementary metrology tools for thin film characterisation, such as

- Development of models for the interpretation of advanced materials measurements and their correlation to product performance.
- Development of validated methods for multi-parameter characterisation of energy thin film materials under specific stress conditions.
- Development of large-area characterisation methods for process optimisation in thin-film energy material production, including fast contact and non-contact methods.

Project Description (including summary of technical work)

NPL leads the overall project. Technical work include:

- Developing innovative in-situ muiltiparameter characterisation methods and multiphysics modelling software
- Development of novel optical property mapping method
- Development of ultrafast photocurrent imaging method

Impact and Benefits

- Increases visibility of NPL capability in functinoal characteriastion of thin films for energy applications.
- Builds new capability at NPL on in-situ characterisation, large area characterisation and modelling.
- Enhances NPL leadership position in the area of thin films characterisation.
- Builds closer link with European NMIs and stakeholders.

Support for Programme Challenge, Roadmaps, Government Strategies

● Maps onto the "photovoltaics" roadmap.

● This project links to the NMS strategy/priority areas of low carbon technologies, sustainability, global competitiveness, and advanced manufacturing.

● POWER ELECTRONICS: A STRATEGY FOR SUCCESS, Report of the Department for Business, Innovation and Skills URN 11/1073 (October 2011); UK Technology Strategy Board Electronics Photonics Electrical Systems technology pillar (2008). UK Dept for Business Innovation and Skills, Plastic Electronics: A UK Strategy for Success (2009). DECC's July 2011 "UK Renewable Energy Roadmap" relies on the uptake of photovoltaics to achieve the 80% emissions reduction by 2050. UK Government strategy Renewable Obligation, Climate Change Bill, Microgeneration Strategy, UK Energy Marketing Strategy

● "Action Plan for Energy Efficiency: Realising the Potential" (Communication from the European Commission, COM(2006)545 final of 19.10.2006); COMMUNICATION FROM THE COMMISSION, "Europe2020, A European strategy for smart, sustainable and inclusive growth”

Synergies with other projects / programmes

Builds upon EMRP thin Films project, IRD Photovolatics and IRD Defects project.

Risks

All methods to be developed in this project are advanced novel characterisation techniques and therefore this is a medium to high risk project. The risks are associated with challenges in increasing measurement resolution, for instance, capacitance of the sample being too large or pixel crosstalk when measuring with multiple light beams. Analysing and minimising these challenges is part of the project.

Knowledge Transfer and Exploitation

NPL will contribute with organisation of workshops (including Altech) and publication of papers, reports and measurement protocols.

Co-funding and Collaborators

This is a co-fund project to EMRP ENG53 ThinErgy

Deliverables

1	**Start: 01/06/2014**	**End: 31/05/2017**	

Deliverable title: Co-fund to EMRP ENG53 ThinErgy (MAT)

- Develop a novel method for spatially resolved in-situ optoelectronic multiparameter characterisation
- Develop model for multiparameter simulation of new method above.
- Develop high resolution photocurrent imaging system
- Validated software to control full experiment including electrical data collection and analysis for fast, high-resolution, photocurrent imaging of solar cells
- Report on the validation of photocurrent imaging including datasets of reference defect samples and a comparison to laser beam induced current
- Requirements document for defect reference samples
- Samples with known defect sizes produced and characterised

2	**Start: 01/10/2014**	**End: 31/06/2017**	

Deliverable title: Co-fund to EMRP ENG53 ThinErgy (EM)

- Design of an optical spatial phase modulation system to demonstrate electro-absorption interferometry (EAI) as a method to probe thin film electro-optic materials for intensity related absorption, linearity, angular and polarisation characteristics
- Report describing the development of theory translating the microwave implementation of the Electro-absorption interferometry technique to the optical domain
- An optical spatial phase modulation system for demonstrating EAI high-speed measurement system
- Dataset of measurements of large area defect samples by phase-sensitive high-speed laser scanner

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NPL Projects – 2014

Project No.	IRD/2014/01	Price to NMO	£1,091,023
Project Title	Particle metrology for Pharmaceuticals (PharmIDaBall)	**Co-funding target**	650k (EMPIR 2014 Industry call orH2020)
Lead Scientist	Caterina Minelli	**Stage Start Date**	01/10/2014
Scientist Team	Natalie Belsey, Aneta Sikora, Steve Spencer, Andy Wain, Mike O'Connell, Gianluca Memoli, Stuart Davidson, Giuseppe Schettino, Maurice Cox, Ali Rae, Deb Roy, Alex Shard.	**Stage End Date**	30/09/2017
		Est Final Stage End Date	
Sector	Healthcare	**Activity**	Methodology for New Capabilities
Project Champion	Barbara Domayne-Hayman		

Summary: This project will address metrology challenges related to the use of particles that are widely used in the pharmaceutical industry. It will develop new measurement capability for determining size, size distribution, density and chemistry of particles. The work is vital for many applications including: catalysis-assisted synthesis of pharmaceuticals, drug encapsulation and targeted delivery. In close collaboration with instrument manufacturers and product developers, the project will respond to pressing measurement needs, with a strong focus on interfacial properties and underpinning size measurement. The methods developed will be applied to industrial samples to encourage widespread adoption and inform regulation.

The Need: The pharmaceutical and medical sectors increasingly depend upon nano-scale engineering. This reliance ranges from the catalysts used to synthesise active ingredients to the design of advanced drug delivery vehicles. The materials used in these areas range from nanometres to micrometres in particle size, from dense and hard metals to buoyant and deformable bubbles. The methods employed to measure the size and chemistry of such particles are often diverse, incomparable or simply provide the wrong answer. There is a pressing need to measure the thickness and chemistry of particle coatings because of the critical impact on particle function, behaviour and stability. Understanding and refining the performance of products requires methods to measure these relevant properties in the most cost-effective and accurate manner. In light of the need to support the development of a high-tech economy in the UK, maintain UK sectorial advantage and guide the regulation of nanomaterials, it is necessary to provide industry and academia with clear guidance, accurate methods and internationally accepted standards.

The Solution: This project will develop measurement methods for size, size distribution, density and chemistry of particles including metal, oxide, polymer, peptide and composite nanoparticles (NPs), emulsions, liposomes and bubbles. At NPL, X-ray photoelectron spectroscopy (XPS) has been innovatively used in parallel with liquid-based particle sizing techniques for the measurement of the thickness of NP coatings. Within a previous IRD project, we successfully tested this approach on model NP systems, receiving international appreciation for the ease and potential high throughput mode of application (e.g. >7 invited talks in 2013/2014, quick uptake within international community, interest in standardisation from ISO TC 201). We also demonstrated how analytical centrifugation well complements XPS and other particle sizing techniques and in depth data analysis produces quantitative detailed information on the size and density of particles and their coatings. With the support and feedback of our industrial partners, we will apply, expand and optimise these methods to commercial and customised samples, provide guidance on sample preparation and measurement protocols, and produce representative case studies. This will ensure that the methods will be tested and optimised in accord with industrial requirements and in compliance with EU regulation.

Project Description: The project will be divided into four work-packages: (1) Metrology for assessment of particle coatings: methods to accurately measure the chemistry and thickness of NPs' interface, with focus on XPS, will be developed and inform less expensive approaches, such as particle size and charge measurements, which are commonly used in the context of quality control. Rigorous uncertainty budgets will be produced through the use of size-selected and mass-filtered particle clusters with atomic-level control which will be produced at the unique capability of the Nanoscale Physics Research Laboratory (Birmingham). Novel methods for surface analysis of NPs will also be investigated, for example: *in-situ* second harmonic generation spectroscopy and *ex-situ* low energy ion scattering in collaboration with Imperial College London. (2) The measurement of size, size distribution, agglomeration and density of low-density and/or polydisperse particles and particle-like systems used in drug delivery and other therapies, with focus on the use of analytical centrifugation. The synergetic use of analytical centrifugation and liquid pyknometry will also be assessed to develop novel approaches to measure particle (drug) loading. (3) New measurement methods for measuring sub-micrometre bubble size, including tuneable resistive pulse sensing, particle tracking analysis and advanced acoustic methods. (4) Methods to characterise the reactive interfacial chemistry of NPs used as green catalytic platforms for synthesis of pharmaceuticals. This will include infrared spectroscopy for identification of molecular adsorbates at NP surfaces in liquid media, as well as electrochemical characterisation of NP faceting and *in-situ* analysis of their catalytic properties. Supported by measurements in (1), this will provide an important link between structure and activity.

Impact and Benefits: The UK pharmaceutical industry accounts for 0.6% of the UK GDP, with over 300 companies having a combined turnover of £31bn (*Strategy for UK Life Sciences*). Improved formulations and routes of administration of active ingredients not only enhances the efficacy of drugs, minimises their side effects and treats more diseases, they also extends the patentable lifetime of a drug, which is a major concerns of advanced pharmaceutical companies. Particle technology has already delivered innovation in pharmaceutical manufacturing and its full exploitation holds the potential to profoundly impact the sector. An example is Abraxane, a highly effective NP-based treatment for pancreatic cancer with sales predicted to reach ~$1bn by 2017: the NP formulation, with a particle size of 'about 130 nm', allows for sophisticated engineering of the particle's surface which enhances effective accumulation of antitumor drug in cancers. This project will provide the pharmaceutical industry with new measurement solutions of direct relevance to the performance, reproducibility and regulation of particles. This will inform optimisation of particle design for specific applications, e.g. targeted delivery, drug encapsulation and catalysis-assisted synthesis of pharmaceuticals. Characterisation of diverse industrially-relevant particle systems with cost-effective measurement methods as case-studies will facilitate their dissemination and adoption. NPL, instrument manufacturers and measurement service providers will thus be able to showcase new measurement services to the pharmaceutical industry, with Escubed alone anticipateing a future 30% growth in the NP characterisation service it offers. This project has a strong support of industrial and academic partners (17 support letters offering in-kind contribution totalling at almost £100k). Their involvement in from initial project formulation will ensure the establishment of a robust and pragmatic metrology framework that will continue supporting the pharmaceutical sector beyond the end of the project and will give businesses the required confidence to invest and grow. This project will also enable NPL to address more challenging measurement needs in the future, such as the distribution and availability of active ingredients within NPs and the efficacy of surface coatings for targeted drug delivery. Finally, as highlighted by the recent "Have your say" NPL survey, capabilities developed in this project will also impact on other industry sectors (including Life Science, Automotive and Nuclear) which face the metrology and regulatory challenges of nanomaterials. Examples include cosmetics, food, packaging, adhesive, aeration industries and microbubble manufacturers.

Support for Programme Challenge, Roadmaps, Government Strategies: This project will support the development of Advanced Materials and Nanotechnology across different fields, which is one of the Eight Great Technologies in which the UK is set to be a global leader also through "metrology and […] characterisation equipment that is required for both the development and manufacturing of advanced materials" (*Rt. Hon. Willetts, 2013*). In line with the *Strategy for UK Life Sciences*, this project will contribute to the building of a "life sciences ecosystem" through strong collaboration of a world-leading metrology institute with academic and industrial partners, thus facilitating the translation of research to commercial products and promoting an industry and R&D partnership in support to SMEs and start-ups in the sector, which have been identified among the "barriers to the full and complete exploitation of nanotechnology in the UK" (*Nanotechnology: a UK Industry View, KTN report, 2010*). This project also directly addresses two of the key priority areas for pharmaceuticals identified by the KTN report for the *Future of High value Manufacturing in the UK*, namely "Improved formulation and product platforms" and "Manufacturing challenges of novel drug delivery and smart packaging", meets the need of the EU legislation and influences the licensing of new pharmaceutical products.

Synergies with other projects / programmes: The project has strong synergies with EMRP projects BioSurf, NanoChOp and SurfChem, IRD INTERACt, IRD GNP. The project also aligns with 3D nanoSIMS and NiCE-MSI projects and matches the Acoustics' Group strategy for ultrasound imaging and drug delivery and complements current and future activities in the Electrochemistry Group on the theme of catalysis and NPL's core programme on measurement uncertainty evaluation.

Risks: 1) XPS time is very limited. Mitigation: where possible collaborate with organisations having XPS facility. 2) Commercial NPs may be too irregular in shape for accurate measurements. Mitigation: work with partners that can supply well defined spherical particles. 3) Determination of particle size and size distribution relies upon finding suitable primary methods or calibrants. Mitigation: collaborate widely with other NMIs and academics to access suitable materials.

Knowledge Transfer and Exploitation: An intense program of stakeholder engagement with involvement of end-user community through international IUVSTA workshop on NP characterisation chaired by NPL, instrument user meetings at NPL and conclusive large event. Other activities: update of NPL website, co-shared publications, news stories/case study on company and NPL websites with link to LinkedIn. Main targeted sectors are pharmaceuticals, instrument manufacturers and particle producers.

Co-funding and Collaborators: Co-funding: £650k from EMPIR or H2020, 80% chances of success; committed in kind from BASF, Syngenta, Inanovate, Liquid Research and Endomagnetics; committed service from NanoSight, Izon, Analytik, Escubed; one fully funded and one co-funded PhD student from University of Kingston and Birmingham respectively. Active collaborations with the Centre for Doctoral Training in Advanced Therapeutics and Nanomedicines of the Schools of Pharmacy at Nottingham and London. Other collaborations: University of Leeds, York, Cardiff, UCL, Vienna, ICMAB, Chalmers and Washington.

Deliverables

5	**Start: 01/10/14**	**End: 30/04/15**	
Set up measurement capabilities. Deliverable: SOP for characterising low density NPs, proof of principle for SHG of NPs, delivery of international NP workshop, project and exploitation plans. Stage gate review in January/February when EMPIR result known			
1	**Start: 01/05/15**	**End: 30/09/17**	
Metrology for assessment of particle coatings. Deliverables: Year 2: 1 peer reviewed publication and 1 user meeting. Year 3: 1 peer-reviewed publications and 1 industrially relevant case study.			
2	**Start: 01/05/15**	**End: 30/09/17**	
Metrology for low-density NPs. Deliverables: Year 1: good practice guide. Year 2: 1 user meeting. Year 3: 1 peer review publication and 1 industrially relevant case study.			
3	**Start: 01/05/15**	**End: 30/09/17**	
Metrology for measurement of bubble size. Deliverable: Year 2: 2 technique evaluation and proof of concept. Year 3: 1 peer review publication and 1 industrially relevant case study on size measurements of lipid supported bubbles.			
4	**Start: 01/05/15**	**End: 30/09/17**	
Measurement methods of NP-based catalytic platform. Deliverables: Year 2: proof of concept. Year 3: 1 peer reviewed publication and 1 industrially relevant case study.			

Project No.	IRD/2014/02	Price to NMO	£935,464
Project Title	Photoacoustic differentiation of biomaterial-cell interfaces	Co-funding target	£230k
Lead Scientist	Max Ryadnov	Stage Start Date	01/01/2015
Scientist Team	Bajram Zeqiri, Santanu Ray, Nilofar Faruqui, Srinath Rajagopal	Stage End Date	31/12/2017
		Est Final Stage End Date	
Sector	Health Diagnosis	Activity	Methodology for New Capabilities
Project Champion	John Collins		

Summary: The project will enable a 3D photoacoustic differentiation of biomaterial-cell interfaces with detailed understanding of scaffold metrics (porosity, branching, matrix orientation and strength) and their impact on instructive cell proliferation (structural models). Key objectives will be to develop (i) imaging methods independent of mechanical and elastic properties of biomaterial-cell interfaces, and (ii) parameterised structural models of these interfaces.

The Need Recently the UK government has announced eight great technologies in which Britain is to become a world leader (*David Willetts, Eight great technologies, Policy exchange 2013*). Synthetic biology, regenerative medicine and advanced materials are three of these technologies to impact on the UK life sciences sector most. Structural tissue repair can serve as a merging point for all three. This is the challenge that attracts the largest healthcare investment globally (*Wall Street Journal reports, 2012, 2013*) and is a major reason for existing and revised EC regulatory directives (*2001/104/EC; EC/1394/2007*). With profound impacts on healthcare (injury-induced cancers, chronic wounds, neurodegeneration), the challenge drives industry strategies which focus on biomaterial devices (scaffolds, implants) capable of supporting tissue repair at the biomaterial-cell interfaces. Barriers to commercialisation include batch-to-batch variations of such devices, inconsistency in their functional profiles and high costs associated with processing personalised treatments. Collectively, these prompt the need for reliable measurements to map out physical principles instructing cell organisation at biomaterial interfaces. Para-clinical tests based on clinical tissue imaging (MRI, USI) are not suitable for these length scales. Therefore, industry sets new targets for methods providing molecular cell and scaffold imaging (*e.g. NIH-led cell therapy standardisation discussions*). This is the underpinning metrology which will enable repeatable measurements and reliable structural models that is of the utmost need. Structural metrics related to instructive cell development (scaffolds) have yet to be associated with any reference methods (diagnostic imaging) or certified reference materials. A methodology combining (i) correlative biomaterial-cell measurements, (ii) parameterised scaffold profiles and (iii) real-time imaging methods independent of mechanical and elastic properties of cells and tissues are necessary to allow measurement comparability.

The Solution A saving solution to these challenges is two-fold. Firstly, by emulating the physico-chemical characteristics of the native extracellular matrix (porosity, branching, networking), (bio)polymeric scaffolds provide instructive support for future tissues, which develop from the bottom up starting with cell-scaffold interactions. Secondly, precise cell-scaffold correlations reflecting biologically relevant interactions can be provided by a rapidly emerging modality of photoacoustic (PA) imaging. PA uses highly focussed, short time duration laser pulses to selectively heat the material (cell-scaffold) whose subsequent rapid expansion generates acoustic pressure waves. Strongly focussed acoustic receivers detect these signals, pinpointing their origin, which with wide-bandwidth acoustic detectors enables Photoacoustic Microscopic (PAM) imaging reaching sub-micron resolution (doi:10.1117/1.JBO.17.2.020501). Indeed, PAM has been successfully applied to tumour angiogenesis monitoring, blood oxygenation mapping, functional brain imaging, skin melanoma detection and single-cell imaging. By exploiting endogenous optical absorbers within the cell, the technique has been applied for label-free imaging of single melanoma and red blood cells. The critical advantage of PAM over all other methods is its dependence on the *optical*, and not *physico-morphological*, properties of the tested material, which greatly boosts achievable contrast. PA can also image deeper tissues compared to that of other optical imaging modalities. These characteristics make it ideal for distinguishing and parameterising correlations in molecular cell-scaffold interactions. Given the complexity of the required measurements, direct support at the NMI level is indispensible.

Project Description: The project will be delivered in three interrelated phases, three main deliverables, culminating in application demonstration in the final (fourth) phase. (i) 1-2 phases, executed in parallel, will (i), guided by project Stakeholder Group input, optimise PA capability (resolution, laser choice) for 3D cell-scaffold imaging (morphology, interactions) for relevant time and length scales (localised cell proliferation versus cell migration); and (ii) establish a parameterised set of scaffold metrics (porosity, branching, strength) as a function of cell guidance (structural models). Different scaffold types will be used to map out principle scaffold parameters which will be cross-probed by conventional microscopy techniques with a complete range of spatial and temporal resolution (confocal fluorescence, atomic force and electron microscopies); (ii) 3 phase will formulate an experimental demonstrator platform for PA microscopy of the scaffold-cell models developed in the previous two phases in terms of PA resolution and 3D live imaging; (iii) 4, final phase will explore a platform application for a real-live problem in house or at an industry site, using a proposed reference methodology supported by quantitative measurements, and planned follow-up studies.

Impact and Benefits: The project builds on the internationally leading expertise based in the NPL: ultrasonic metrology, related to detection of high frequency acoustic fields, and bioengineering (for latest track record see JACS 10.1021/ja411325c), to establish a new cross-divisional healthcare capability. This will provide a radical step change in the real-time and 3D monitoring of biomaterial-cell interfaces (by end of project), unique in Europe. Research will focus on engaging with existing industry programmes (*SynBiCyte*, *Kirkstall, Xeno Medical, Roslin Cells, Malvern Cosmeceutics*) who will provide technical and commercial advice for the project. The technical impact of the project is two-fold; it will (1) develop metrologically sound differentiation of biomaterial-cell interfaces, which is of strong demand by industry with a favourable patent landscape, and (2) extend the lab's

medical physics position with applied molecular cell imaging impacting on measurement science and service (mid-term 3-5yr from start). The project will advance medical diagnostics as well as regenerative medicine, synthetic biology, beauty care and drug design, and a basis for a new measurement framework for clinical diagnosis (and by association, treatment) of tissue disorders, with medical and cosmetic industry stakeholder involvement. The project will generate a transferable technology that will bring benefits to the stakeholders and UK industry (project yr 3). Thus, aside from being aligned with prioritised great technologies the project will impact on the ability of UK industry to exploit an extensive body of research knowledge into commercial products (yr 5-7), given that to date the UK is failing to compete in commercialisation stages (*BIS, Government office for Science, "UK growth opportunities for the 2020s", 2010*), and advance IVD standardisation objectives (e.g. 2008/29/EC, EMEA/CHMP/GTWP/125459/2006, BS EN ISO 17511:2003/ISO 15193:2009).
Support for Programme Challenge, Roadmaps, Government Strategies: The project conforms to UK government strategies and programme roadmaps with key objectives pertaining to: (i) NMS strategy under the health challenges aiming to: "…enable…diagnostic technologies to be brought to the market, support optimisation of these technologies in clinical practice…"; (ii) RCUK strategy vision and research initiatives under the "lifelong and health wellbeing" programme and other cross-council programmes through established IRCs and a new RCUK initiative "…targeting themes of healthy ageing and factors over the whole life course that may be major determinants of health and wellbeing in later life"; (iii) TSB mainstream focus areas (regenerative medicine and synthetic biology) and their implementation under the new TSB's "concept to commercialisation". The project aligns with (iv) the key EMRP objectives (EMRP Outline 2008) as to Grand Challenges in Health: "…from qualitative towards quantitative diagnostics…, multimodal measurement procedures"; "…traceable measurement methods for analyte/matrix-combinations with increasing complexity…"; and (v) Metrology 2020 vision in all aspects under a healthy population theme: "point of care diagnosis", "synthetic and systems biology", "advanced therapies and drug delivery".
Synergies with other projects / programmes: The project shares synergies with previous and current NMS projects – ChemBio (BA22, BA38), NanoBio (NB2); EMRP (HLT10) and SR "deterministic measure of biomolecular self-assembly". Individual project phases build upon direct industry contracts (SynBiCyte, Kirkstall, Xeno Medical, Roslin Cells, MedImmune, Malvern Cosmeceutics) that address different measurement issues including biomedical scaffolds and 3D live cell imaging.
Risks: PA imaging cannot be developed (low). Mitigation: PA imaging is now routinely performed for different applications including tumour and tissue imaging, PA-based imaging systems are commercially available and we will collaborate with a top academic group who are developing and have tested original PA modalities. Biomaterial-cell interactions are difficult to detect (medium, low after mitigation). This risk is fundamental for the outlined needs. Mitigation: response metrics are at cell localisation levels, where variations are a "go/nogo" choice, allowing risk to be identified at early stages.
Knowledge Transfer and Exploitation: KT to the research community and industrial users will be achieved through peer-reviewed publications in scientific and trade journals and participation in conferences and trade fairs. The project will lead to IP in acoustic detection techniques, functional imaging methodologies and/or biomaterial differentiation. Methodologies developed will be leveraged through measurement services (subcontracting) and planned 3rd party grants (TSB, EMPIR and H2020). Our broader engagement with industry will be through our links with BioIndustry Association, the Alliance for Regenerative Medicine, Blonde McIndoe RF, UK Regenerative Medicine Platform, TSB Cell Therapy Catapult and the EPSRC network for Innovative Manufacturing and Regenerative Medicine (see also collaborators), and specialist BSI and VAMAS WG for biomaterial standardisation. A Stakeholder Group will meet annually and with a joined Workshop at project end.
Co-funding and Collaborators: Co-funding will be sought through R&D projects (industry contracts, final phases, and grants from NIHR, TSB, SBRI, EMPIR (Health, 2015) and H2020-NMP (nanomatrices and nanovectors, 2015). These ventures will be with efficient stakeholder partnerships including academics/clinicians with joint studentships from UCL, ICL, ICR and Edinburgh, industry (see above in Synergies and letters of support) as well as and large industrial translation centres (SynBiCyte).

Deliverables			
1	**Start: 01/01/15**	**End: 31/05/16**	
Deliverable title: optimise PA capability for combinatory cell-scaffold imaging for relevant time and length scales, correlate with conventional microscopy techniques (SEM, AFM, confocal); one publication			
2	**Start: 01/01/15**	**End: 31/05/16**	
Deliverable title: establish a parameterised set of scaffold metrics (porosity, branching, matrix orientation and strength) as a function of cell guidance (structural models); one publication			
3	**Start: 01/02/16**	**End: 30/04/17**	
Deliverable title: formulation of an experimental demonstrator platform for PA microscopy of the scaffold-cell models			
4	**Start: 01/04/17**	**End: 31/12/17**	
Deliverable title: platform application using one industry-provided problem, planning follow-up studies. One peer-reviewed publication, one publication in trade magazine and one industrial lecture/workshop			

Project No.	IRD/2014/03	**Price to NMO**	£ 836,989
Project Title	Additive Manufacturing: Dimensional and Integrity Assessment by XCT and Microstructural Examination	**Co-funding target**	
Lead Scientist	Peter Woolliams	**Stage Start Date**	01/10/2014
Scientist Team	Mark Gee, Claudiu Giusca, Wenjuan Sun, Jerry Lord	**Stage End Date**	30/09/2017
		Est Final Stage End Date	
Sector	Advanced Manufacturing- High Value Manufacturing (Aerospace)	**Activity**	Metrology for new capability
Project Champion	John Collins		

Summary Additive manufacturing (AM) is rapidly becoming established for producing complex production metallic parts in many industries, including Aerospace. It provides wider design freedoms, customisation, part count reduction, part weight reduction and shorter development times, providing companies a significant competitive advantage. However, process stability and part validation are key barriers to its wider uptake. X-ray computed tomography (XCT) gives a unique way of non-destructively assessing parts for integrity and mechanical tolerance, both external and internal. Improvements in XCT accuracy are required by the AM industry to improve manufacturing machines (better process stability and in-process monitoring) that do not require individual part testing enabling the production of higher quality, cheaper parts. XCT will be complemented by assessment of the microstructural and mechanical integrity of AM materials.

The Need AM offers significant technical and business advantages and is being actively investigated by a number of large multinationals in the Aerospace, Space, Defence, Oil & Gas, Medical and Automotive sectors, e.g. Rolls Royce, Airbus and GKN. It is rapidly becoming used to produce highly complex metallic production parts. For AM parts to be quality assured in high value applications, they need individual assessment– the layer by layer processes currently has high levels of process variation and layer and microstructure defects can occur. XCT is increasingly being used in the AM industry for part assessment, being uniquely able to assess internal features that are otherwise not measureable non-destructively. Initial NPL work on XCT has shown for simple parts, there can be large measurement uncertainties and significant disagreement with conventional dimensional measurements. These measurements need to be validated using destructive sectioning and traceable dimensional measurement and comparison with other NDE techniques. Another key need is to assess the effect that defects and features in the microstructure of these materials have on the mechanical performance of these materials. The UK is one of the leading nations in the development and use of AM, accurate measurement and the resulting standards are a widely-agreed need for the industry, but have not been addressed by funding to date. This proposal needs Government funding as no group is actively addressing this pressing need the AM industry faces. In order for most impact, the research needs to be carried out openly and independently. The proposal relies on NPL's leading expertise in the areas of XCT dimensional measurement and functional microstructural measurement of materials.

The Solution This project will develop novel measurement strategies and methods for data interpretation to enable XCT to accurately determine the internal geometry of AM produced parts (reducing systematic errors. e.g. from part geometry and material composition, and overall uncertainties) and to accurately assess internal surface topography (there is no current capability) and material defects. To validate the XCT analysis, novel test artefacts will be developed and traceably characterised using destructive testing and dimensional and surface topography measurement as well as stepwise metallographic sectioning combined with optical and SEM examination (for materials microstructure including EDS chemical analysis and EBSD structural analysis). Method validation with different part designs and a range of materials and AM processes will be undertaken. The 3D microstructure and material properties inside the part will be assessed using FIB-SEM including EDS and EBSD, miniaturised mechanical testing, scanning indentation assessment, nano-indentation and conventional mechanical testing. This will provide information for the development of assessment routines that can relate the materials microstructure to local and overall mechanical performance, and validate the detected defects. Research will also be carried out on the utility of other NDE techniques including acoustic microscopy, pulse thermography and ultrasonic examination (to be compared with the XCT results) to investigate the potential of these techniques to provide high performance, low cost NDE techniques for industry. The need for novel measurement methods to be developed for accurate non-destructive assessment of parts with graded and anisotropic material and mechanical properties will also be examined.

Project Description The project work will include:

- Development of novel measurement strategies and methods for data interpretation to enable XCT to accurately determine the external and internal geometry of AM produced parts with reduced uncertainties
- Methods for the accurate assessment of internal surface topography and material defects.
- The development of novel test artefacts that will be accurately characterised using conventional destructive testing, conventional CMMs and surface topography techniques.
- Detailed assessment of defects and 3D microstructure in samples using stepwise metallographic sectioning and FIB SEM combined with optical and SEM examination (for dimensional measurement, surface texture and materials microstructure including EDS chemical analysis and EBSD structural analysis).
- Assessment of mechanical properties using miniaturised mechanical testing, scanning indentation assessment and nano-indentation as well as conventional mechanical testing.
- Development of the routines for evaluating the relationship between the materials microstructure and local and overall mechanical performance.

- Evaluation of other NDE techniques including acoustic microscopy, pulse thermography, and ultrasonic examination and their comparison with the results of the XCT examination.
- Identifying novel measurement methods for accurate non-destructive assessment of parts with graded and anisotropic material and mechanical properties.

Impact and Benefits The outputs from the project will enable the AM industry (design software companies, AM machine makers and end-users) to improve their processes, so parts can be designed and made to tighter mechanical tolerances, requiring less post processing (surface and microstructural improvement), which add to the cost and environmental impact of AM production. BSI has recently launched a "Standards for AM NDE" focus group, which the outputs of the project will feed into. The methods developed will also benefit the wider users of XCT instruments, and polymer AM users. The research will position NPL to be able to develop novel metrology to address the future needs of the AM industry for characterising parts that are currently only being proposed (e.g. with multi-materials and graded functionality).

Support for Programme Challenge, Roadmaps, Government Strategies This project is aligned with the NMO IRD Strategy "Growth - Advanced Manufacturing" topic to support the Aerospace sector. AM is a key technology in the TSB "High-Value Manufacturing Strategy" focussed on exploiting the UK's ability to design and manufacture innovative products. It also addresses the aims of the "Future Factory", producing bespoke parts "right first time" through near-net shape manufacturing in the NPL2020 Vision. The TSB AM SIG report "Additive Manufacturing - Shaping our national competency", showed the need for underpinning characterisation capability to push up the TRL of metallic AM production.

Synergies with other projects / programmes The project will interact with the current FP7 AMAZE and TSB Anvil projects, part of which is to develop "test artefacts" for machine testing and quality control. The proposal is aligned with NMS EFM proposals for XCT calibration and performance verification and will be linked to the EMPIR XCT for AM proposal. The project will work closely with the National Centre for Additive Manufacturing and Near-net Shape Production at the MTC and leverage the work conducted at the EPRSC CIM in Additive Manufacturing at Nottingham. Two PhD students will deliver academic aspects of the work (one dimensional and one materials) through the CDT in AM at Nottingham.

Risks This is a technically demanding project, the risk is only medium provided the co-authors collaborate. Sample production: NPL has no AM capability, multiple organisations have agreed to supply samples, enabling process variability and different materials to be assessed. External measurements: comparison measurements from collaborators and supporters will enable the methods developed to be better tested - several organisations support the project, mitigating this risk. The previous NMS EFM project has given NPL a firm understanding of the operating principles of XCT and the various influence factors.

Knowledge Transfer and Exploitation The outputs of the project will be disseminated by peer reviewed journal and conference publications. Regular meetings will be organised between NPL, research institutes and industrial partners. There will be periodic presentations at NPL Measurement Network and KTN events. The work will be presented to ISO and ASTM to begin the process of standardisation. The methods developed will be demonstrated at the MTC and be available for exploitation by the project collaborators and XCT manufacturers to drive the benefit to other commercial users of XCT instruments. There is also the potential for software IP and measurement services income.

Co-funding and Collaborators EMPIR "XCT for AM" PRT submitted £350k co-fund. Nottingham CDT: access to AM machines, sample production and expertise (£80k) and 2 PhD students at a cost of £60k. MTC will be seeking aligned research (£100k) and STFC have pledged time on their facilities (£150k). The project will also have support from Southampton (µVIS Centre) and Nikon and Zeiss as instrument manufacturers. Renishaw (AM machine manufacturer) and Moog (Aerospace AM user) will provided AM expertise and test samples. There are strong collaborations with international research institutes such as the University of Padova, KU Leuven, DTU and PTB. A Steering Committee will be set-up comprising the supporters and other stakeholders from the industrial and academic AM user community to ensure the project has the greatest impact.

Deliverables

3	**Start: 01/10/14**	**End: 28/2/15**	
Project initiation and stage gate review. Deliverables: exploitation plan, project plan, co-ordination and confirmation of stakeholder group and initial detailed planning for project, e.g. sample specification.			
1	**Start: 01/03/15**	**End: 30/9/17**	
Develop and validate methods for evaluating the microstructurally related materials performance of AM parts. Comparison of other NDE techniques for defect detection and assessment of measurement needs for future graded and anisotropic materials. Evidenced by publications and input from steering committee and stakeholders.			
2	**Start: 01/03/15**	**End: 30/9/17**	
Develop and validate methods for obtaining improved traceable dimensional and accuracy (both externally and internally) of complex AM made metallic parts using XCT. Validation against other non-contact techniques and destructive sectioning with CMM traceability of custom test artefacts. Evidenced by publication and Stakeholder workshop demonstrating high TRL capability at the MTC to expand industrial collaborations and uptake.			

Project No.	IRD/2014/05	**Price to NMO**	£219,568
Project Title	Bubble shell metrology for diagnostic and therapeutic applications (BUBBLECOAT)	**Co-funding target**	£60k
Lead Scientist	Gianluca Memoli	**Stage Start Date**	01–Jan -15
Scientist Team	Alex Knight, Charles Clifford, Debdulal Roy, Ken Mingard, Caterina Minelli	**Stage End Date**	31-Dec-15
		Est Final Stage End Date	
Sector	Health - Drugs & therapies	**Activity**	Methodology for New Capabilities
Project Champion	Barbara Domayne-Hayman		

Summary Lipid-coated microbubbles (~2 μm diam.) have been successfully used as ultrasound contrast agents for the past 10 years, allowing earlier and cheaper detection of liver cancers and cardiac diseases. Pharmaceutical companies are looking to extend this success to other types of cancers and to transform microbubbles into vectors for drug delivery and targeted therapeutic applications. This leads to manufacturing new bubbles, engineered with functionalized shells, which will eventually have to be approved by the regulators. Since there is no agreed method to measure bubble shell characteristics, not even in static conditions, current manufacturing techniques can guarantee little repeatability on shell parameters and regulators have no easy way to assess the safety of novel bubble-based treatments. This clearly prevents both new diagnostics uses (contrast depends on how well the shell is known) and therapeutic applications. This project focuses on measuring one of the key shell parameters: the amount of lipids/drugs present on the shell (i.e. its "thickness"), both in static conditions and during oscillations. Different techniques will be tested, producing a set of guidelines for the benefit of regulatory bodies and industries alike.

The Need Classical ultrasound scanning ("unenhanced") is the first-line technique used in screening the ~90,000 patients suspected of cardiac disease or cancer in the liver/colorectal region each year (National Institute for Health and Care Excellence, 2012). Unenhanced ultrasound, however, is often not sufficient to distinguish benign lesions from malignant tumours ("inconclusive" ~40% of the times), so the person is usually referred for either MRI and/or CT, increasing the cost for the NHS and the impact on patients' quality of life (e.g. a delay on treatment). Intravenously injected in the blood as Ultrasound Contrast Agents (UCAs), lipid-coated microbubbles (~2 μm diam.) are becoming the routine solution in many UK hospitals. Like little "bells", they are excited by an external ultrasonic scanner, which then captures their resonant acoustic emission (depending on their size and on the physical characteristics of their shell) to enhance contrast. This diagnostic technique is extremely efficient in highly vascularised tissues – i.e. 95% efficiency in the liver (measured in 2008) – but requires further studies to be applied to the other killers e.g. prostate and breast cancers, (92,000 UK cases in 2011, Cancer Research UK). The widely accepted way forward is to load the bubble shell with ligands targeted to specific tumoral cells. "Targeted" microbubbles can be used also for treating arteriosclerotic plaques, as ultrasound-induced bubble oscillations may facilitate their ablation. Agreed methods for shell characterisation in static/shear-flow conditions and to assess the bubble-tissue attachment strength are crucial for this innovative use of microbubbles. The other innovative microbubble-related technology consists of loading bubble shells with medicines for ultrasound activated, localised drug delivery. Microbubbles are potentially less toxic than nanoparticles and, once activated by ultrasound, can facilitate drug delivery acting as micropumps. Input was collected from clinicians (International Contrast Ultrasound Society), established pharmaceutical companies (Bracco, GE Healthcare), research consultants (Phoenix Solutions), enterprises new to the microbubble market (Tide Microfluidics, SINTEF), academia (Leeds, Oxford): for this technique to work there is a need for reliable metrological tools to assess the quantity of payload on the shell (i.e. the shell "thickness). A set of measurement guidelines, produced by an independent institution, will help to ensure that all the bubbles "perform as expected", but will also facilitate the decision of governmental bodies (e.g. FDA, EMEA) during the licensing process of new bubbles, potentially reducing the length of clinical trials on humans and the amount of testing on animals.

The Solution This project addresses a metrological issue common to the diagnostic and therapeutic needs above: how to determine the shell "thickness" (i.e. the amount of material in the shell). BubbleCOAT will help manufacturers, investigating the feasibility of measuring shell thickness in absence of volume oscillations with a set of manufacturer-selected techniques, including solutions never used before for lipid-coated bubbles (i.e. Raman, 2nd harmonic, STORM, cryogenic FIB), as well as others recently attempted in the literature (i.e. AFM). Currently, in fact, there is no clear agreement on the uncertainty related to the different techniques or a clear understanding of their validity, even for those already used in the literature. We will use commercial and customised samples (produced e.g. by Leeds, a supporting partner in BubbleCOAT) and produce representative case-studies, collected into guidelines. BubbleCOAT will also incorporate research-stage techniques, recently demonstrated on polymeric bubbles (i.e. Mie scattering, acoustic emission), into the unique facility built at NPL for manipulating microbubbles (NPL "sono-optical tweezers"), aiming to highlight changes in thickness during controlled oscillations. Measurements in these conditions, more relevant to clinical end-users, have not been attempted so far. Measurement protocols will inform ISO TC281 ("Fine bubble technologies") through BSI mirror committee, promoting harmonised approaches to comply with EU regulation.

Project Description (including summary of technical work) This project will test the applicability of different techniques to microbubble solutions, both as purchased "off the shelf" (Sonovue, Optison) and specifically manufactured by industrial and academic stakeholders. A preliminary assessment of bubble size distribution will be obtained using microscopy and Coulter methods (IZON). Techniques will be benchmarked with polymeric bubbles (Akzo Nobel). [WP1] *Static measurements*. This WP includes techniques where NPL has already a good track record, but whose use is challenging with bubbles – i.e. stochastic optical reconstruction microscopy (STORM), Atomic Force Microscopy (AFM), Raman and Second-harmonic imaging microscopy (Analytical Sciences), FIB/SEM of frozen samples (Materials). For each of these techniques a small feasibility study will be conducted, leading to 4 case study reports, informing WP2. [WP2] *Dynamic measurements*. Two techniques will be incorporated and compared in the metrological environment offered by NPL's sono-optical tweezers, producing new metrological capabilities: Mie scattering (used with polymeric bubbles in *Soft Matter*, 2012) and changes in the acoustical emission (emerged from recent Strategic Research-funded projects, 2013). These, together with high-speed cinematography, will be crucial to monitor the shell during acoustic excitation and will lead to a journal paper. [WP3] *Coordination*. Manage the other WPs; collate into a paper the static measurements from WP1 & WP2; produce good news stories, update website, liaise with external stakeholders.

Impact and Benefits In the Strategy for UK Life Sciences, impact relates especially to improvements to healthcare and economic, commercial and production benefits (BIS, 2011). Commercial microbubbles (i.e. Sonovue, Optison, Sonazoid, Definity) are licensed pharmaceutical products: novel microbubbles, for more advanced applications, need to pass through highly expensive regulatory safety tests before reaching the market (current global value: 250M$ - CAGR 4.1%). A standardised set of microbubble characterisation methods (i.e. a "bubble Pharmacopoeia") would, *in the medium term*: (i) Benefit the established companies and the many SMEs investing in targeted or drug-loaded microbubbles (a potential 130 M$ market: Frost and Sullivan, 2013), saving "trial and error" time to establish their own portfolio of quality assurance techniques. (ii) Assist regulatory bodies (e.g. FDA) in licensing decisions, providing established tests for novel microbubble products. (iii) Contribute to a faster licensing process and consequently to a reduction of the involved animal testing. (iv) Improve quality of life, as patients would see diagnostic microbubbles become therapeutic agents sooner. Moreover, recent studies (Lassau *et al.*, 2013) have shown that if the acoustic emission (i.e. the shell) of UCA microbubbles could be characterised within 10%, it would be possible to distinguish the 60% non-respondents to anti-angiogenetic drugs simply by an ultrasound scan. This would lead – *in 10 years' time* – to stratified treatments of cancer, saving up to £6.6k per patient (ICUS, 2014), with ~£2m annual savings in the UK (annual patients from Cancer Research UK, 2011). NPL authors (Harfield *et al.*, 2013) demonstrated that a 15% accuracy in characterising the shell properties might be sufficient to use bubbles as biosensors (a 7 M$ market in the UK), for local in-vivo measurements of e.g. pressure and viscosity. Techniques developed within this project will also be useful to food/cosmetic companies, using bubbles in their products (e.g. ice-cream). The results of this project will feed into the standardisation process of ISO TC-281 ("Fine bubble technologies"), confirming NPL's leading metrological role worldwide, producing high quality science (as measuring shell properties is at the cutting edge of microbubble research) and exploiting the unique facilities built during the SR-funded project.

Support for Programme Challenge, Roadmaps, Government Strategies

This project also aligns with the microbubble strand within the NMS Medical Ultrasound Roadmap. In particular, it exploits the unique capabilities built at NPL through Strategic Research funding. This project supports the BIS Strategy for Life Sciences, as it will: (i) facilitate the development of novel (microbubble-based) localised treatments for chronic diseases; (ii) contribute to overcome regulatory barriers in the otherwise lengthy licensing process for targeted microbubbles, to be used as contrast and therapeutic agents; (iii) provide industries with a set of guidelines for quality assurance and patients with benefits on a shorter timescale; (iv) reduce the amount of animal testing, by providing standardised ways to characterise bubble shells; (v) favour the uptake of stratified medicine, through more accurate diagnoses. Finally, this project aligns with the activities of ISO TC281 "Fine bubble technologies", with four of the 18 topics in the Horizon 2020 Health Programme and with the priorities expressed in the "Priority Medicines for Europe and the World Update Report" (WHO & EU Commission, 2013).

Synergies with other projects / programmes The project links strongly with the NPL SR project "Microbubbles: sensors for the micro-world" and with the EMRP project BioSurf. Objectives match the AIR strategy for ultrasound imaging and drug delivery.

Risks Risk1: feasibility studies produce non compatible thickness values; Mitigation1: the different techniques will be compared (in pairs) on other bubble-related measurands. R2: samples are too difficult to characterise; M2: case studies will be defined in detail with partners, selecting reasonable samples. R3: uncertainties related to dynamic measurements may be too high; M3: feasibility studies will be used to benchmark dynamic measurements. R4: other groups develop a novel technique; M4: we will work with Leeds, who have published AFM measurements in 2014, and relationships with other teams have been activated.

Knowledge Transfer and Exploitation 2 journal papers, 3 good news stories on NPL website and KTN networks, discussions in ISO TC281, outreach activities, seeking enlargement of the stakeholder consortium. Presentations at annual ICUS bubble conference and Leeds Symposium. Periodic non-confidential updates on "POP!" page (hosted on NPL website) and Tumblr.

Co-funding and Collaborators Further funding will be sought from EMPIR (Health) or H2020; Co-funding: committed in kind from Uni Leeds, IZON, Phoenix Solutions. Active collaborations with Tide microfluidics, ICUS, Unilever, SINTEF, UCL, Oxford Uni, Imperial College, University of Tours. Other possible collaborators: Bracco International, GE Healthcare, Glasgow Uni.

Deliverables

1	**Start: 01/01/15**	**End: 30/09/15**	
Deliverable title: 5 feasibility studies + case studies internal reports on static thickness measurements.			
2	**Start: 01/02/15**	**End: 31/10/15**	
Deliverable title: One paper on dynamics measurements of bubble thickness submitted to a peer reviewed journal.			
3	**Start: 01/01/15**	**End: 31/12/15**	
Deliverable title: 1 peer reviewed paper collating feasibility studies, 3 good news stories, management of stakeholder group.			

Project No.	IRD/2014/07	Price to NMO	£275,029
Project Title	Addressing new challenges in automotive and aerospace particle emissions	Co-funding target	n/a
Lead Scientist	Paul Quincey	Stage Start Date	1 October 2014
Scientist Team	David Butterfield, Liz McGhee, David Butterfield, Jordan Tompkins, (AS ~80%); Theo Theocharous (EM ~10%); Peter Harris (Mat ~10%)	Stage End Date	30 September 2015
		Est Final Stage End Date	n/a
Sectors	Environmental sustainability (Pollution & waste reduction); Advanced Manufacturing & Services (High-value manufacturing)	Activity	Methodology for New Capabilities
Project Champion	Jan Petersen		

Summary

This project will develop novel measurement techniques for key aerospace and automotive particle emissions. Specifically it will underpin the use of laser induced incandescence (LII) in aerospace particle mass concentration measurements, a technique that is soon to have a key role in the industry within an Aerospace Recommended Practice (developed through the Society of Automotive Engineers committee SAE E-31), but which has never been given a sound metrological basis. It will also develop innovative methods of particle number concentration measurement for both the aerospace and automotive sectors. In both sectors measurement uncertainties are a major concern – the aerospace sector has the task of bringing uncertainties of 100s of % down to manageable levels, while the automotive sector needs to reduce uncertainties from around 20% to around 10%, to handle the difficult problem of new petrol engine emissions legislation within the Euro 6 (car) and Euro VI (heavy duty vehicle) standards. Much deeper understanding of uncertainties will be obtained, leading to significantly higher accuracies.

The Need

Both the aerospace and automotive industries face new problems in the control of particle emissions, requiring innovative solutions. The external consultation exercise highlighted specific regulatory needs from Rolls-Royce, firstly in the area of calibrating black carbon emissions from aeroengines, where they are planning to adopt the LII technique. This technique involves the rapid heating of airborne soot particles with laser pulses, combined with monitoring the incandescence signal to determine soot concentration and primary particle diameter. Early results have shown deviations from other soot-type measurement methods of up to a factor of 7. Rolls-Royce also raised the issue of evaluating and reducing uncertainties in particle number losses within the long particle sampling line (approximately 8 m) used in an aeroengine test. Jaguar Land Rover (JLR) raised more general issues in the area of emission measurements; discussions with them have focused on the practical problem of reducing uncertainties in particle number concentration measurements from petrol engines as concentrations decrease in line with new legislation, leading to decreased signal-to-noise.

The Solution

There is sufficient common ground in the required topics to define a focused one year research-based project that will address them. Analytical Science Division has considerable expertise and laboratory facilities in reference methods for black carbon, in generating combustion-type particles, and in quantifying particle mass concentrations, which can be coordinated with expertise and LII instrumentation from Rolls Royce, together with laser measurement expertise within Engineering Measurement, to address the black carbon issue with laboratory studies. Estimating and combining uncertainties from the sampling and measurement parts of particle number concentration determination are similar problems across the aeroengine, automotive and ambient air sectors, with most progress being made in ambient air. With specialist help from the Mathematics and Modelling Group, rapid progress can be made to identify the major sources of uncertainty for the industrial partners' purposes, and then to reduce them.

Project Description

The project consists of four deliverables, though in terms of technical output there are in effect only two, with the work within Engineering Measurement and Mathematics and Modelling groups separated into individual deliverables as required by the accounting system.

For the LII deliverables, there will be some extended NPL lab work, using our CAST soot generators to compare LII, aethalometry, filter mass and Elemental Carbon/Organic Carbon methods. There would be extensive prior consultation with both Rolls Royce and NRC Canada on the regulatory requirements and possible technical ways forward. We have all necessary equipment except that we would need to borrow LII instruments. Engineering Measurement would contribute to the operation and understanding of the LII systems. The goal, achievable within the timescale and resources of the project, is to develop calibration methods suitable to allow LII to be used to measure the mass concentration of particle emissions from aeroengines.

The number concentration deliverables will consist of a mixture of NPL lab work, site measurements by NPL , to evaluate realistic losses in sampling lines, for example, combined with theoretical studies. These theoretical studies, carried out largely by the Mathematics and Modelling Group, would include modelling size-dependent losses within sampling lines, for example by diffusion and thermophoretic processes, and combining all relevant uncertainty components, together with sensitivity analysis. In this case the prior discussion with be with Rolls Royce and JLR, to ensure that requirements are understood and existing data are evaluated. The work would cover vehicle engine emissions and aeroengine emissions, and would also encompass ambient air measurements, where the conditions are different, but the mechanisms governing uncertainties are the same. The endpoints will be validated uncertainty budgets for the relevant measurements, suitable for identifying areas that can be addressed to provide viable, cost-effective methods for number concentration measurements needed for both regulation and research.

Impact and Benefits

The UK aerospace industry is the second largest in the world, contributing £24 billion to the economy annually, while the UK automotive sector has an annual turnover of £11.2 billion, and is the fourth largest vehicle producer in Europe. These vital UK industries will benefit directly from valid, traceable and timely measurements of their engine emissions, which need controlling within the current and emerging international environmental legislation. Competitiveness will be improved both by better quantification of parameters during research and development, and by being able to demonstrate robust compliance with legislation. More specifically, the project will build on NPL's strong links with Rolls-Royce and develop links with JLR and extend them to other stakeholders in the automotive and aerospace industries via development of a stakeholder group towards the end of the project. The stakeholder group will also help define new metrology areas for potential government support

Support for Programme Challenge, Roadmaps, Government Strategies

The work in this project aligns well with the 'Sustainability' and 'Health' Challenges in BIS's NMS strategy, and fits into the NMS roadmap for particle metrology. NPL's Metrology 2020 Vision sets out goals, especially in the areas of 'Monitoring the State of the Planet' and 'A Healthy Population', which are consistent with the aims of this project. The proposed work is integral to the aim to reduce engine emissions within the 2013 Government strategy *Lifting Off – Implementing the Strategic Vision for UK Aerospace*, and with the requirement for internal combustion engine innovations within the 2013 Government strategy *Driving success – a strategy for growth and sustainability in the UK automotive sector.*

Synergies with other projects / programmes

The project will mainly use facilities and expertise within the Particles Theme of the ChemBio Programme, specifically P10, *Facilities for airborne particle measurements,* and soon-to-start deliverables to extend these facilities within P16 *Novel sampling and measurement techniques for emerging pollutants in air*. The work is also directly relevant to third party work for Defra, for whom we measure particle number concentrations at monitoring sites around the country, and in measurement services relating to calibration of number concentration instruments, where we have recently performed work for Perkins Engines, for example.

Risks

The main risks either concern critical failures of instruments or facilities, or technical issues that make the objectives of the project too difficult to achieve. In the first case, the facilities at NPL are regularly used and maintained, and we can have high confidence that problems can be managed, while we have contingency in the acquisition of other equipment like the LII, where for example contacts with Cardiff University can be utilized. In terms of technical issues, such as their being no viable prospect for calibrating LII, or insuperable barriers to reducing uncertainties, the information gained will still be very valuable to the industrial partners, while modified objectives can be defined.

Knowledge Transfer and Exploitation

The main outputs will be new services that can be offered to the aerospace and automotive sectors, and indirect input into relevant regulatory guidance documents produce by the UNECE Particle Measurement Programme (for automotive emissions) and SAE E-31 (aerospace). The new capabilities should lead to further research and collaborative work. Technical publications are also likely, with the agreement of the industrial partners.

Co-funding and Collaborators

Collaborators will include Rolls Royce and JLR. Both organizations sent letters strongly supporting the project and offering both consultancy and practical help with, for example, equipment. The proposal builds on existing links with Mark Johnson, Global Emissions Measurement Expert at Rolls Royce (though the letter is signed by Pete Loftus, Head of Measurement Engineering). At JLR, Phil Lawson, Emissions Test Technical Lead, has recently taken over from Mike Braisher, our previous contact there. They have both agreed to supply facilities and equipment as well as expertise. There would also be informal collaboration with Greg Smallwood at NRC Canada, who is an expert in the LII technique. Jan Petersen from the Danish National Metrology Institute, who is on the IRD Working Group and has an interest in airborne particle measurements, has agreed to act as Project Champion.

Deliverables

1	**Start: 01/10/14**	**End: 30/09/15**	

Deliverable title: Calibration methods for laser induced incandescence instruments; to include Optical contribution, specifically providing a metrological understanding of laser induced incandescence instruments, suitable to define calibration procedures and uncertainties.

Endpoints: a measurement service and publication available; contribution to final project report in Deliverable 2.

2	**Start: 01/10/14**	**End: 30/09/15**	

Deliverable title: Defined uncertainties for automotive and aerospace particle number concentration emission measurements; to include Mathematical contribution, specifically modelling size-dependent particle losses within sampling lines, and combining all relevant uncertainty components, together with sensitivity analysis.

Endpoints: report on uncertainties with recommendations for best practice; final project report, including details of potential further work defined with key stakeholders from the stakeholder group formed for the project.

Project No.	IRD/2014/08	Price to NMO	£318,380 (NPL) £91,950 (LGC)
Project Title	Disruptive mass spectrometry techniques to underpin the next generation of radiochemical measurement	Co-funding target	Cash co-funding only
Lead Scientists		Stage Start Date	01/04/15
Scientist Team		Stage End Date	31/06/16
		Est Final Stage End Date	
Sector	Energy and Environmental Sustainability	Activity	Challenge driven R&D
Project Champion	John Collins		

Summary

The project will deliver the capability for radiochemical measurement by mass spectrometry to complement contemporary radiometric techniques. This will address needs with the linked areas of nuclear decommissioning, environmental radioactivity monitoring, radioactive decay metrology and nuclear forensics. Novel methods will be developed using mass spectrometry and sample preparation facilities at NPL and LGC, to allow traceability to the Becquerel (Bq) for the measurement of difficult to measure radionuclides in complex matrices without the need for extensive sample preparation. The project has support from the nuclear industry, academia and the instrument manufacturer. The sample range is undergoing discussion with Sellafield Ltd and NNL but the preferred radionuclides are those associated with nuclear fuel use such as $^{238, 239, 240, 244}Pu$, $^{235, 236, 238}U$ and $^{236, 237}Np$ in complex matrices. Following a literature review, priority will initially be given to a technique for ^{90}Sr measurement, a priority for decommissioning, environmental monitoring, and clean-up around Fukushima.

The project will be a success if the benefits are demonstrated and the techniques are adopted by the nuclear industry and the associated supply chain. The NPL-LGC collaboration (plus unfunded partners) is a strength of the project, testing the robustness of the techniques to prove the concept to the industry and the regulators.

The Need

There is a need for accurate measurement of radionuclides at environmentally relevant concentrations and a reduction in the uncertainty of activity concentrations (in Bq) in samples relevant to the nuclear industry. This is driven in part by the stringent requirements of legislation with respect to nuclear decommissioning and the environmental monitoring of the impact of such activities. The current requirements for these measurements are such that traditional radiochemical techniques alone are unlikely to be sufficient in accuracy and rapidity, and therefore must be augmented by innovative complementary techniques. This is because either their sensitivity is not sufficient (due to the nature of the emitted radioactive particles) or the acquisition times would be too long (due to the extended radioactive decay half-life of the particular isotope). This is a pressing issue for regulators and the nuclear industry and a different approach is now needed; one which combines radiochemistry expertise with novel mass spectrometry strategies.

The Solution

Many of the current challenges in radiochemical measurement relate not only to the requirement to perform isotopically-unique radioactivity identification at very low concentrations but also to make these measurements in highly complex matrices. Sample preparation using wet chemical techniques are rarely ideal because of the need to extract the active component without loss of the target analyte. For example, Inductive-Coupled Plasma Mass Spectrometry (ICP-MS) offers the possibility to make contributing measurements, however the sample matrix has remained a problem. In most cases these complex matrices cause significant polyatomic and isobaric interferences which can undermine the mass spectrometry measurement. Amongst the Interference-reducing ICP-MS instrumentation (sector field ICP-MS and collision/reaction cell ICP-MS), triple quad ICP-MS instruments have emerged as a novel technology capable of resolving such interferences, in some cases, by using mass discrimination prior to a chemical reaction cell, followed by a further mass discrimination step. Direct and matrix-independent measurement of complex samples providing traceability to the radioactivity in Becquerel then becomes possible for relevant radionuclides in realistic matrices, at low concentrations. This project aims ultimately to develop a key capability for the measurement of important, long-lived radionuclides. Improved accuracy measurement of individual isotopes of a given radioactive element (such as Neptunium or Plutonium) directly from complex sample media will also be a unique facility, when complemented by other traditional radioactivity measurements within the AIR division at NPL, for minor-actinide radioactivity traceability.

Project Description (including summary of technical work)

Following a comprehensive literature review and consultation with stakeholders in the nuclear industry, priority radionuclides and matrices will be identified for further study. It is envisaged that a rapid method for ^{90}Sr analysis will be a priority, followed by metrologically challenging long-lived radionuclides in fission waste such as ^{79}Se, ^{93}Zr, ^{129}I and ^{135}Cs; nuclear fuel activation products including $^{236,237}Np$ and $^{239,240}Pu$; and tracer element systems such ^{236}Np and ^{244}Pu.

The measurement resources available to the project team include triple quad systems at NPL and Southampton University (SU) (as an unfunded partner), and triple quad and sector field ICP-MS at LGC. This is supported by sample preparation facilities at

NPL, LGC and SU and direct solid sampling devices such as laser ablation at LGC, supported by radiometric expertise at NPL and access to the UK's largest stock of radionuclide standards. The team will deploy these resources depending on the radionuclide & matrix, to develop the sample preparation and measurement techniques. The reasons for any discrepancies will be investigated and causes identified. Internal standards and QC standards will be developed as part of these studies; if suitable for use by others, these materials may be used as reference materials.

Following such scoping studies, method(s) will be selected for further study taking into account the constraints of running analyses in the nuclear industry. These methods will be validated and documented following ISO17025 and Eurachem guidelines, and detailed uncertainty budgets calculated. The results from the studies will be published in the scientific literature, as well as at relevant conferences, workshops and meetings.

Impact and Benefits

Direct impact will be through the successful adoption of developed methods by the nuclear decommissioning industry, its regulators and stakeholders, and related standardisation bodies such as CEN and ISO. The project will enable the UK to conform defensibly to EC directives, using novel methods with a validated capability. This will provide enhanced quality of information through a step change approach to radiochemical measurement. In particular, it could provide information on radionuclide content of waste materials leading to more cost-efficient long-term management and sentencing. Ultimately the techniques developed will reduce the cost of legislative compliance and facilitate more effective regulator input to protect public health, environmental sustainability and improve quality of life. Wider benefits will accrue from the new capability in terms of additional sectors in which the new facility could impact, such as environmental forensics and monitoring.

Support for Programme Challenge, Roadmaps, Government Strategies

The project aligns with Defra and the NDA's stated plans for 'Developing the civil nuclear supply chain' as part of the current TSB strategy for driving innovation, in particular in the stated theme areas of: i) Construction, installation and commissioning; ii) Operations and maintenance; and iii) Decommissioning and waste management, including storage. The project also meets many of the challenges outlined in the Government's Nuclear Energy Research and Development Roadmap, in particular in the baseline case scenarios where support is required for their R&D Programme themes of 'Operations and Maintenance', 'Waste Management and Decommissioning' and 'Geological Disposal'. The Nuclear Waste Research Forum has also identified relevant 'Industry challenges in waste and decommissioning' to which this project would contribute. The work also aligns with many of the Nuclear Decommissions Challenges identified by INNOVUS (an NNL, NDA and University of Manchester collaboration), which is trying to grow significantly the research, development and innovation activity in the UK nuclear industry.

Synergies with other projects / programmes

The project has clear synergies with work in the current NPL AIR knowledge base programme where similar measurements, but of higher activity concentrations, are made using radiochemical separation and spectrometric analysis. This project would add value to these activities by extending the range of analytes, concentrations and matrices that can be determined. Synergies also exist with air quality networks operated in the NPL AS Division, on behalf of Defra, where the outputs of this project will provide more accurate determination of pollutants, which currently suffer from isobaric interferences on single quadrupole instruments. The project also has synergies with LGC's work in the current CBM programme within the Environment area (e.g. Methodology for Water Frame Directive critical pollutants) where triple quad technology hyphenated to separation techniques are used for selective and sensitive pollutant quantification at the ng/kg levels in environmental samples.

Risks Whilst the application of the triple quadrupole ICP-MS to radiochemical measurement is novel, the machine itself is well established for other types of measurement. There is extensive experience at NPL and LGC in the development of analytical methods using ICP-MS for environmental applications. We also aim to work with the instrument manufacturer, and the University of Southampton when developing the methods, and therefore any technical risks associated with the project are expected to be very limited.

Knowledge Transfer and Exploitation

Dissemination of knowledge from the projects will from high-impact peer-reviewed publications and presentations at relevant fora. Targeted workshops to communicate developments directly to the nuclear industry and to regulators are also planned. Beyond this timescale and scope of this project, it is envisaged that best practice guides and documentary standards will be an important mechanism for making the techniques available to, and useable by, industry and other laboratories. The radioactivity group at NPL has also just won a competitive PhD studentship (in collaboration with the University of Surrey) funded by the NDA to work on nuclear decay data- this will aid in stakeholder interactions and dissemination of results regarding long-lived radioisotope measurements.

Co-funding and Collaborators

Southampton University will be an unfunded partner in the project. Key stakeholders in the nuclear industry (for example, the Nuclear Waste Research Forum) will be consulted throughout. Participation of other interested organisations such as NNL and Sellafield will be encouraged.

Deliverables			
1	**Start:** 01/04/15	**End:** 31/12/15	**Cost:**
Deliverable title: Literature review and instrument set-up NPL/LGC: Literature review to establish needs of the nuclear industry with regards to radionuclides of interest, and sensitivities required. NPL: Set-up QQQ instrument and establish sensitivities achievable (initially using stable element standards) for accurate metrological instrument operation.			
2	**Start:** 01/04/15	**End:** 31/06/16	**Cost:**
Deliverable title: Method development for detection of key radionuclides by mass spectrometry Initial focus on ^{90}Sr, and an additional, metrologically challenging long-lived radionuclide e.g. ^{93}Zr or ^{135}Cs. LGC: Comparison of instrument performance (for total determination and isotope ratio analysis), using similar ICP-QQQ technology to that available at NPL, and sector field ICP-MS, evidenced by technical report. NPL: Method development of mass spectrometry technique, evidenced by solving key radiochemical measurement problems NPL/LGC: Using diluted samples, or spiked like-for-like matrices, combine MS measurement with specialist radiochemical measurements, enabling direct half-life determination traceable to the Bq. Evidenced by joint peer-reviewed paper and/or conference proceedings.			
3	**Start:** 30/9/15	**End:** 31/03/16	
Deliverable title: Determining the feasibility of laser ablation ICP-MS LGC: Establish feasibility of LA-ICP-MS to achieve quantification and isotope ratio measurement for selected radionuclides in relevant complex samples (e.g. glass) with no need for sample processing, evidenced by technical report.			
4	**Start:** 30/9/15	**End:** 31/06/16	
Deliverable title: Establishment of uncertainty NPL/LGC: Full uncertainty analysis for procedures developed, evidenced by a joint peer-reviewed paper.			
5	**Start:** 01/04/16	**End:** 31/6/16	
Deliverable title: Delivery of results NPL/LGC: Publication of results in joint peer-reviewed papers and/or conference proceedings at relevant international meetings/workshops/conferences. Production of a joint case study or good practice guide. Strategy document outlining future NPL/LGC collaboration to support on-going and future measurement needs of the nuclear industry, evidenced by publicly available document.			

Project No.	IRD/2014/09	Price to NMO	£211,509
Project Title	Characterisation of palladium-based membranes for hydrogen purification	Co-funding target	Approx. £80k in-kind co-funding
Lead Scientist	Arul Murugan (AS)	Stage Start Date	01/10/2014
Scientist Team	Andrew Brown, Alex Shard & Steve Spencer (AS). Eric Bennett, Dave Gorman, Helen Jones & Ken Mingard (MAT).	Stage End Date	31/03/2016
		Est Final Stage End Date	31/03/2016
Sector	Energy	Activity	Low carbon energy
Project Champion	Ben Beake		

Summary

The project will advance the state-of-the-art of membrane characterisation by establishing a new comprehensive test facility for characterising palladium-based membranes incorporating microscopy and surface analysis techniques. This facility will enable the development of improved membranes with superior properties and enhanced performance for hydrogen purification.

The Need

With the roll-out of hydrogen refuelling stations and hydrogen-powered vehicles continuing to increase, it is clear that the UK is committed to advancing a hydrogen economy in order to assist resolving climate change issues. A key challenge that still remains is with regards to hydrogen purity; a recently proposed EC Directive on the deployment of an alternative fuels infrastructure sets out that all hydrogen provided to hydrogen vehicles must comply with stringent standards (such as ISO 14687-2) for hydrogen purity. NPL are currently the leading hydrogen purity analysis laboratory in the UK and provide this service for customers such as ITM Power (UK) and Faber (Italy). Additionally 50 hydrogen samples are to be analysed at NPL by the end of 2015 as part of the Island Hydrogen TSB project. With an anticipated increase in the need for legislated hydrogen purity measurements over the next decade (1,100 hydrogen refuelling stations are expected to be installed in the UK by 2030) NPL needs to make improvements to its purity analysis facilities in order to keep up with this demand. One essential step is the development of NPL's hydrogen impurity enrichment device (HIED) to enable measurement of some of the very low levels of impurities specified in ISO 14687-2 which cannot currently be measured and to reduce the costs of a full purity analysis. Once developed the HIED can also be sold to UK laboratories to allow them to perform full purity analysis whilst still being reliant on NPL for the provision of traceable gas standards. The only issue with the HIED that needs to be resolved is that some impurities adsorb to the palladium-based membrane which affects the accuracy of the device and these physico-chemical interactions are poorly understood. Improved membranes for the HIED, and for a wide range of other applications such as fuel cells, purification of hydrogen, bulk gas and water, can only be developed through further studies of these effects and advanced membrane characterisation. In particular it is important to raise consumers' confidence in fuel cell technology during these early stages by ensuring that the membranes in these systems do not form micro-cracks thus allowing contaminants to degrade the fuel cell.

The Solution

This project will work towards developing an internal comprehensive suite of techniques that can be used to perform membrane characterisation. The techniques selected for the facility, which have never been used to characterise any type of membrane before at NPL, include enhanced microscopy, focused ion beam scanning electron microscopy and x-ray photoelectron spectroscopy. These techniques will be able to measure the small variances in key properties that are required to detect a change in the membrane characteristics; this may not be possible using commercially available techniques that are commonly used in UK laboratories and universities. NPL's expertise in metrology will allow each measurement (such as roughness, micro-crack size, adsorption layer etc.) to be quantified traceably with the highest accuracy. As part of this facility a device will be developed that will be used for carrying out gas testing (allowing the user to subject the sample membrane to high pressures, vacuums, varying temperatures and different gaseous environments). A case study will be performed where the test facility will be used to determine the chemical and structural changes that occur to palladium-based membranes upon interaction with reactive and adsorptive species (such as hydrogen sulphide) and when subjected to vacuum or high pressure environments. The results provided by the techniques will be used to develop improved membranes for use in the HIED and hydrogen purifiers, and will also be the first demonstration of this capability, transferrable to other membrane applications such as bulk gas, air and water purification.

Project Description (including summary of technical work)

The gas metrology group and SAES Group (the world leading manufacturer of hydrogen purification membranes) will take 'fresh' membranes and subject them to different 'harsh' environments that are expected to damage or contaminate the membranes. These tests will represent the conditions that the membranes are subjected to in hydrogen purifiers and in NPL's HIED. Following these tests, the membranes will be characterised and compared to fresh membranes in order to measure any differences in the membrane properties. A key focus of the work will be on metrology including accurate control of impurity levels subjected to the membrane and providing quantified measurements (rather than only qualitative outputs) during surface analysis.

Impact and Benefits

This project will position NPL as a key player in the area of membrane characterisation leading to involvement in future collaborative TSB and Horizon 2020 projects, and additionally open up new opportunities for measurement service focused around membrane characterisation for use by membrane manufacturers. This will allow the manufacturers to develop improved membranes for their purifiers. In particular the improvement of palladium-based membranes to enhance their lifetime and performance will lead to significant reductions in costs for producing high purity hydrogen. This advancement would be timely as over 300,000 hydrogen vehicles are expected to be on the roads in the UK by 2030 and this will require 254,000 tonnes of ultrapure hydrogen per year. This development of a hydrogen economy will lead to economic growth through job creation and reduced climate change. A large benefit to NPL is that the improvement in palladium-based membranes will allow the gas metrology group to further develop their HIED which has the potential to become patented and sold to laboratories. Development of the HIED will in the short term allow NPL to be the first UK provider of a full hydrogen purity service (ISO 14687-2) for UK refuelling stations, a service that would directly impact on the performance of the UK's hydrogen economy.

Support for Programme Challenge, Roadmaps, Government Strategies

NPL's Metrology 2020 - "measurement capability and new standards will be needed for purity, monitoring and metering, to support the hydrogen economy"; the Government's 'Driving success – a strategy for growth and sustainability in the UK automotive sector' document; the UK H_2Mobility roadmap for the commercialisation of hydrogen powered vehicles; the Government's energy strategy 'The Carbon Plan: Delivering our low carbon future'; the draft EC Directive on the deployment of alternative fuels infrastructure; the National Measurement System strategy for 2011-2015 - "The NMO will, through the NMS programs, provide standards for the purity and stability of fuels… (to include…hydrogen)"; and the ChemBio Programme gas analysis theme roadmap target of 'supporting a hydrogen economy'.

Synergies with other projects / programmes

The project strongly aligns with a number of projects in the Analytical Science and Materials Divisions including Island Hydrogen (TSB) – A project where the Isle of Wight is to be powered solely by renewable energy using hydrogen as an energy buffer (for energy storage and powering fuel cell vehicles); Unlocking the Hydrogen Energy Market (TSB) – Development of a new online hydrogen purity analyser for performing quality assurance at the hydrogen refueller; H2FC European Infrastructure (FP7) – Invention and development of NPL's HIED.

Risks

SAES Group withdrawal – SAES Group have provided a letter of support confirming that they are fully committed to the project, however if they withdraw membranes can be purchased from other membrane suppliers.

Lack of visibility of lead scientist track record – Arul has a lot of experience with hydrogen related projects and is currently leading Island Hydrogen, H2FC and will be leading the work for the new Unlocking the Hydrogen Energy Market TSB project. He is additionally work package leader for ENG54 (metrology for biogas). He has independently developed NPL's HIED and a recent paper detailing this work was published in Royal Society of Chemistry's Analytical Methods journal and was featured as a hot article in the journal's blog.

Demand – Currently the demand for this product is from NPL in order to provide measurement services for UK refuelling stations, but as the hydrogen economy develops it is anticipated that the HIED will be sought by other UK laboratories.

Knowledge Transfer and Exploitation

The comprehensive test facility developed in this project will lead to a new measurement service specifically focused on membrane characterisation and will be used to improve the membranes that are used in the HIED. This is essential for NPL so that they can provide a full purity analysis service to hydrogen refuelling stations in the UK, such as those operated by Air Products, ITM Power and BOC. The HIED has the potential to be sold to other laboratories as a device for reducing hydrogen purity analysis costs by lowering the required number of high-end analysers. Any improvement in membranes is likely to lead to a new purifier technology. The work from the project will be published as a peer-review paper in a high-impact journal and future collaborations in related projects such as TSB and Horizon 2020 are expected. In addition, future product development could focus on the next generation prototype of the HIED; an online enrichment device using mass flow controllers that can be used directly at the refueller so that enriched samples can be analysed by an online purity analyser.

Co-funding and Collaborators

SAES Group will contribute 10 membranes (approx. £50k) towards the project as in-kind funding. They will also provide man-power in the form of consultation and additional membranes testing (approx. £30k).

Deliverables

1	**Start: 01/10/2014**	**End: 31/03/2016**	

Deliverable title: Completion of NPL's new membrane characterisation measurement service allowing customers to access internal comprehensive suite of techniques (including XPS, FIB-SEM and enhanced microscopy).

2	**Start: 01/10/2014**	**End: 31/03/2016**	

Deliverable title: Completion of a gas testing device to be used as an additional service to the membrane characterisation facilities to perform pressure/evacuation testing, permeation studies and adsorption testing of customer membranes using traceable gas standards containing impurities in hydrogen at a range of concentrations.

3	**Start: 01/09/2015**	**End: 31/03/2016**	

Deliverable title: Case study report on the feasibility of using XPS, FIB-SEM and enhanced microscopy to perform membrane characterisation of palladium-based membranes and recommendations for developing the HIED

Project No.	IRD/2014/11	Price to NMO	£210,988
Project Title	Contract Management	Co-funding target	N/A
Lead Scientist	Ozlem Lopes	Stage Start Date	October 2014
Scientist Team		Stage End Date	September 2015
		Est Final Stage End Date	
Sector	Management	Activity	Contract Management

Summary

This project will ensure that all operational, financial and reporting requirements for the IRD programme are met to ensure successful delivery of IRD programme. Work in this project will ensure timely invoicing and reporting to the NMO each month and delivery of an annual progress report to the NMO and programme working group.

The Need

Contract management is essential to ensure seamless delivery of the science projects in the programme from the inception with the agreement of financial and technical delivery targets for all projects in IRD programme. Agreement of the final contract with NMO and oversight and review of progress during the delivery phase are essential aspects of this project.

A central point of control is also required for effective operational oversight and governance of the programme.

The Solution

This project will deliver effective contract management through a contract manager dedicated to this programme.
Contract manager will have oversight of :

- Project delivery with maximising the exploitation of the outcomes from the programme;
- Delivery of planned financial performance;
- Establish and build strong relationships with NMO and WG members for the successful delivery of projects and outcomes;
- Invoicing;
- Contract status and variations;
- Monthly and annual reporting.

Project Description (including summary of technical work)

1. Agree and implement financial profile of each project and IRD programme to ensure that all projects are priced appropriately and resources required identified
2. Agree the final contract with NMO, ensure that all programme documentation is finalised and provided to NMO
3. Attend meetings as necessary to support contract delivery and the needs of the NMO
4. Review regularly progress, exploitation and financial performance and ensure corrective actions are identified and addressed by projects managers
5. Prepare reports monthly (invoices, progress report and financial forecasts)
6. Manage delivery of the contract and submit change requests and contract amendments as necessary
7. Analysis of programme performance and revenue forecasts for the financial year
8. Ensure that the contract is managed to NPL's ISO 9001 accredited quality system
9. Establish and build a strong liaison with working group, industrial advisory groups & clubs
10. Deliver annual report and present programme progress to working group and the NMO as required
11. Work with IRD programme manager to ensure that exploitable outcomes are identified and appropriate action taken to maximise the beneficial outcomes from the technical work
12. Support IRD Programme manager to develop and maintain roadmaps and strategy for IRD programme

Impact and Benefits

The work in the programme covers the oversight of delivery from several technical projects and hence this is where ultimate responsibility lies for the success of the programme to meet science quality objectives. Effective management will ensure that maximum beneficial outcomes are obtained for the financial spend.

Support for Programme Challenge, Roadmaps, Government Strategies

Not applicable.

Synergies with other projects / programmes

Not applicable.

Risks
The main risks are the inability to deliver the monthly reports and invoices to the NMO and the failure to deliver the annual report to the programme working group. Both of these risks are mitigated by the availability of a large pool of senior managers who are available to step in to assist or take over delivery if adverse circumstances are causing problems with the completion of the key tasks of this project.

Knowledge Transfer and Exploitation
Not applicable.

Co-funding and Collaborators
Not applicable.

Deliverables

1	**Start: 01/10/14**	**End: 30/09/15**	**Cost: £105,494**
Deliverable title: Contract management including production of monthly invoices and reports to the NMO			
2	**Start: 1/10/14**	**End: 30/09/15**	**Cost: £105,494**
Deliverable title: Produce annual report and present progress to the NMO and working group			

Project No.	IRD/2014/12	Price to NMO	£112,228
Project Title	Programme Management and Formulation for the Innovation R&D Programme	Co-funding target	N/A
Lead Scientist	Helen Compton	Stage Start Date	October 2014
Scientist Team		Stage End Date	September 2015
		Est Final Stage End Date	
Sector	Management	Activity	Programme Management

Summary

This project will formulate a proposal of work for inclusion in the 2014/15 programme and engage with key stakeholders to ensure maximum impact is achieved from the science delivered by the programme. To achieve these objectives the project will:

- Maintain and develop the programme strategy and roadmaps;
- Consult with key stakeholders in government, industry, academia, regulators and other end users in order to determine future measurement requirements or other related issues that need to be addressed by the programme;
- Develop a series of project proposals for prioritisation by the programme working group;
- Develop and maintain a balanced scorecard for the programme as a measure of the impact of the programme.

The Need

New measurement requirements are constantly emerging from all areas of UK life. For example, new technologies require new underpinning metrology and standards, as do new regulations or environmental targets. To underpin areas such as growth in the economy, public health issues or mitigation of environmental impacts these measurement requirements must be successfully addressed as early as possible. In order to achieve these objectives effectively an overview of the research priorities and how to address them is required. Maintaining and developing a programme strategy and roadmaps achieve this objective and allow, in conjunction with knowledge of specific technical requirements obtained through stakeholder consultation, the formulation of a work programme that address UK measurement needs. Both the careful design of any programme of work coupled with the continual review of opportunities for increased impact are essential in order to make sure that the maximum value possible is extracted from the investment made in the technical projects.

The Solution

The views of a wide range of stakeholders from industry, regulators, government and other end users will be sort through a wide ranging consultation process in order to capture current and emerging measurement requirements. This process will include looking at independent evidence of measurement needs as expressed in government reports, foresight activities, industry roadmaps etc. as well as conducting meetings, surveys and interviews as required that focus on specific topics of interest. Collation and assessment of information from all sources will enable the programme strategy and roadmap to be developed which will guide the future direction of the programme. The detailed technical requirements will then be formulated into a series of projects for prioritisation by the independent programme working group. Projects which receive the highest ranking will form a programme of work which will be initiated at the start of the next programme cycle.

In addition to the programme formulation, work will be undertaken to understand and maximise the impact of the research. This will be assisted by the establishment and maintenance of a balanced scorecard for the programme consisting of a number of key metrics.

Project Description (including summary of technical work)

- Horizon scanning, capture and analysis of Industry and Societal needs to feed into current and future programme direction;
- Development and updating of programme roadmaps and strategy;
- Engagement with programme stakeholders to:
  - Realise outputs and maximise benefits to the UK;
  - Ensure alignment of programme with UK Government, Industry and Societal drivers;
- Oversee preparation of project proposals for review and prioritisation by the programme working group;
- Submission of final programme proposal for contracting;
- Liaison with the NMO programme supervisor to deliver maximum impact and efficient delivery;
- Identification of exploitable material for increased impact through channels provided by the Knowledge Exchange programme and other KT avenues;
- Assessment of the impact of the programme through use of a balanced scorecard;

Impact and Benefits

Effective programme management will maximise the outcomes to key stakeholder communities from the outset of the technical work and ensure knowledge transfer activities in the programme are efficient and effective. The programme as a whole addresses many measurement challenges across the broad sweep of the UK economy and society. Therefore, the design of knowledge flows and exploitation plans in technical projects which occurs during the formulation process is essential for delivery of the wide benefits of the programme to the broadest possible audience.

Support for Programme Challenge, Roadmaps, Government Strategies

This project underpins the work of the whole programme through development of an overview of key societal drivers and measurement requirements as captured in the programme strategy and roadmaps. These key programme documents are utilised during development of technical projects to guarantee that all the technical work in the programme is aligned to addressing the metrology needs of the UK.

Synergies with other projects / programmes

This project will interact with the other NMS programmes so that synergies and common goals can be identified to ensure that the maximum value is returned from the investment in the NMS portfolio.

Risks

Not applicable.

Knowledge Transfer and Exploitation

The main functions of this project are to ensure the development of a new programme of work and to measure and increase the impact of the programme. Improvement of the programme impact will be achieved through proactive intervention in the technical projects within the programme rather than through direct knowledge transfer activity in this project.

Co-funding and Collaborators

Not applicable.

Deliverables

1	**Start: 01/10/14**	**End: 30/09/15**	

Deliverable title: Programme Management and Formulation

Project No.	IRD/2014/13	Price to NMO	£146,283
Project Title	Programme Management and Formulation for Strategic Capability Programme	Co-funding target	N/A
Lead Scientist	Neil Harrison	Stage Start Date	October 2014
Scientist Team		Stage End Date	September 2015
		Est Final Stage End Date	
Sector	Management	Activity	Programme Management

Summary

This project will formulate proposals of work for the Strategic Capability programme during the 2014/15 year for inclusion in programme contracts from October 2015 and engage with key stakeholders to ensure maximum impact is achieved from the science delivered by the programme. To achieve these objectives the project will:

- Develop the programme strategy and roadmaps;
- Consult with key stakeholders in government, industry, academia, regulators and other end users in order to determine future measurement requirements or other related issues that need to be addressed by the programme;
- Develop a series of project proposals for consideration for inclusion in the Strategic Capability Programme;
- Commission expert reviews of areas of new science and technology to the NMS to assess requirement for NMS intervention to enable development of future applications and markets;
- Provide independent assessment of proposals through use of non-NPL experts to feed into NMO review process.

The Need

New measurement requirements are constantly emerging from all areas of UK life. For example, new technologies require new underpinning metrology and standards, as do new regulations or environmental targets. To underpin areas such as growth in the economy, public health issues or mitigation of environmental impacts these measurement requirements must be successfully addressed as early as possible. In order to achieve these objectives effectively an overview of the research priorities and how to address them is required. Maintaining and developing a programme strategy and roadmaps achieve this objective and allow, in conjunction with knowledge of specific technical requirements obtained through stakeholder consultation, the formulation of a work programme that address UK measurement needs. Both the careful design of any programme of work coupled with the continual review of opportunities for increased impact are essential in order to make sure that the maximum value possible is extracted from the investment made in the technical projects.

Major unmet needs where the NMS has no current capability or where an existing capability requires a major upgrade to stay competitive and continue to address UK needs have to be identified and tackled with a more strategic approach since the investment required is substantial and usually longer term than achievable within a knowledge base or IRD programme.

The Solution

This project differs from the normal programme management projects in that it is concerned with the development of major new capabilities at NPL offering a major step change to existing capability or the development of substantial new capability to address a need as yet unmet by the NMS. As with the formulation of all NMS technical projects the views of a wide range of stakeholders from academia, industry, regulators, government and other end users will be sought through a wide ranging consultation process in order to capture emerging and future measurement requirements. This process will include looking at independent evidence of measurement needs as expressed in government reports, foresight activities, industry roadmaps etc. as well as conducting meetings, surveys and interviews as required that focus on specific topics of interest. Collation and assessment of information from all sources will enable the programme strategy and roadmap to be developed which will guide the future direction of the programme. A series of outline proposals will be developed as a result of this work and external reviews commissioned. The proposals and reviewers comments will then be fed into the NMO's internal review process.

Project Description (including summary of technical work)

- Horizon scanning, capture and analysis of science and technology trends to feed into current and future programme direction;
- Development and updating of programme roadmaps and strategy;
- Engagement with programme stakeholders to:
  - Realise outputs and maximise benefits to the UK;
  - Ensure alignment of programme with UK Government, academia, Industry and Societal drivers;

- Oversee preparation of project proposals for review and assessment;
- Submission of final projects for inclusion in most appropriate knowledge base or IRD programme contract;
- Liaison with the NMO programme supervisor to deliver maximum impact and efficient delivery;
- Identification of exploitable material for increased impact through channels provided by the Knowledge Exchange programme and other exploitation avenues;

Impact and Benefits

Effective programme management will maximise the outcomes to key stakeholder communities from the outset of the technical work and ensure knowledge transfer activities in the programme are efficient and effective. The programme as a whole addresses many measurement challenges across the broad sweep of the UK economy and society. Therefore, the design of knowledge flows and exploitation plans in technical projects which occurs during the formulation process is essential for delivery of the wide benefits of the programme to the broadest possible audience.

Support for Programme Challenge, Roadmaps, Government Strategies

This project underpins the work of the whole programme through development of an overview of key science and technology trend, societal drivers and measurement requirements as captured in the programme strategy and roadmaps. These key programme documents are utilised during development of technical proposals.

Synergies with other projects / programmes

This project will interact with the other NMS programmes so that synergies and common goals can be identified to ensure that the maximum value is returned from the investment in the NMS portfolio.

Risks

Not applicable.

Knowledge Transfer and Exploitation

The main functions of this project are to ensure the development of a new programme of work and to measure and increase the impact of the programme. Improvement of the programme impact will be achieved through proactive intervention in the technical projects within the programme rather than through direct knowledge transfer activity in this project.

Co-funding and Collaborators

Not applicable.

Deliverables

1	**Start: 01/10/14**	**End: 30/09/15**	**Cost: £146,283**

Deliverable title: Programme Management and Formulation

Project No.	IRD/2014/15	Price to NMO	£1,650k
Project Title	**NanoSpec:** Chemical imaging of solid-liquid interfaces using molecular nanospectroscopy	Co-funding target	£600k
Project Lead	Andy Wain	Stage Start Date	01/12/2014
Project Team	Deb Roy, Vlad Sokhan, Alan Turnbull, Mike O'Connell & external collaborators	Stage End Date	30/11/2017
		Est Final Stage End Date	
Sector	Energy, Sustainability, Advanced Manufacturing	Activity	Strategic Capability
Project Champion		Contractor	

Summary

Our aim is to establish a world-leading capability in molecular nanospectroscopy for the real-time, *in situ* characterization of reaction processes at nanostructured solid-liquid interfaces. Building upon major developments in electrochemical imaging as part of a previous strategic capability project, we will combine pioneering technologies in spatially resolved vibrational spectroscopy and novel electrochemical analysis, whilst establishing a unique capability in atomistic modelling. Together, these tools will enable the comprehensive and unrivalled interrogation of surface molecular reaction dynamics. A key application is in the catalyst industry, where the identification of surface active sites and correlation with interfacial behaviour is a major bottleneck to rational catalyst and process design. Our cutting-edge suite of tools will address this measurement need and stimulate innovation in the catalyst industry by providing the critical link between surface structure and performance. The capability will lead to exciting new science, valuable and diverse expertise, enhanced reputation, and substantial new business opportunities for NPL. Ultimately the insights generated will result in extensive economic and environmental benefits to UK chemicals manufacturing sector and beyond.

The Need

(a) Why is it necessary

Addressing Societal Needs

Interfacial processes are ubiquitous in the modern world and play a central role in a range of applications of strategic importance to the UK. Interest in solid-liquid and solid-gas interfaces ranges from highly active surfaces, for example in heterogeneous catalysis and energy conversion technologies, to chemically inert materials, such as corrosion-resistant alloys. In all of these examples the development of new functional materials with tailored interfacial properties is underpinned by an intimate understanding of how surface structure and chemistry governs behaviour. Whilst huge strides continue to be made in the fabrication of novel materials, significant gaps in our knowledge of how they operate at a fundamental level limit their optimal deployment and present a bottleneck to innovation.

The catalysis phenomenon in particular highlights the impact of interfacial science in industry, chiefly in chemicals production. The chemical industry is one of the UK's leading exporting sectors, generating annual revenue in the order of £55 billion, and directly employing close to 300,000 people [1]. The UK is Europe's fourth largest chemicals manufacturer, and accounts for 2% of global production. Nevertheless, this industry faces major challenges associated with changes in global demand, compounded with the increasing cost of energy, feedstocks and raw materials. Furthermore, pressure on the industry to reduce its carbon footprint and environmental impact in order to meet European targets has never been greater. Doing more with less is a core requirement for sustainable chemicals production and hence evolution of the UK chemical industry is essential for it to remain competitive.

Catalysis lies at the heart of the chemical industry. Catalysts are utilized in over 90% of industrial chemical processes, and are estimated to contribute directly or indirectly to over 35% of global GDP [2]. They play a pivotal role in efficient chemical transformation by binding with reagent molecules and lowering the kinetic barrier to reaction without themselves being consumed. In addition to the above challenges encountered in the chemicals industry, the catalyst business itself faces further obstacles, for example in securing raw materials supply. Sustainability in this industry is at risk due to a dependence on noble metals that are mined from regions of geopolitical uncertainty.

Growth in the catalyst and chemical industries is rooted in the ability to develop and optimize new catalytic materials with the desired interfacial properties. In order to meet the above demands the industry continuously seeks new catalytic processes with: (i) **increased efficiency** (reduced energy intensity and raw materials costs); (ii) **enhanced selectivity** (reduced waste and processing/separation costs); and (iii) **improved sustainability** (reduced dependence on rare materials such as noble metals). Traditionally, catalyst development has been based largely on empirical discovery, but a paradigm shift towards rational design over the last decade has driven the requirement for a deeper understanding of catalyst behaviour. In heterogeneous catalysis, a wide variety of processes are employed but two reactions of major importance are selective hydrogenation and oxidation by supported metal (oxide) nanoparticles:

Selective hydrogenation of unsaturated organics plays a critical role in fine chemicals production and underpins the pharmaceutical and agriculture sectors. A key challenge here is maximizing catalyst activity (i.e. rate of reaction) without compromising selectivity to the desired product (e.g. reduction of alkynes to alkenes without over-hydrogenation to alkanes). Palladium-based catalysts, often modified with undesirable lead promoters, are employed commercially but the industry actively seeks to reduce their dependence on such rare and environmentally unfriendly metals. As an example, recent developments by one of the industry leaders, BASF, have indicated that the use of surfactant modifiers can introduce improved selectivity without loss of activity but the origins of this remain uncertain [4]. Uncovering the secrets of this behaviour is a necessary step in unlocking the potential of this discovery, and the key to this is identification of the active sites on the palladium surface and how they are influenced by modifiers.

Selective oxidation of organic compounds is of rapidly growing importance, most notably for the conversion of waste biomass into fuel and chemical feedstocks. Such applications will play a major role in the future of the catalyst industry, not least to meet various EU targets and legislation on renewable energy, fuel quality and the use of biofuels [3]. In using catalyst technologies with such complex bio-renewable systems, the ability to isolate and characterise the active surfaces will be paramount in understanding de-activation mechanisms.

In both of these examples, modern industry is beginning to turn particular attention to the development of green chemistry and so there is a strong incentive to develop new catalytic processes in liquid media and under mild conditions rather than high temperature gaseous environments. Adapting to such a shift presents a huge challenge for the industry but it is necessary to decrease the UK and Europe’s reliance on energy intensive processes.

The Need for New Metrology

Catalysts operate by providing active molecular binding sites that facilitate the desired (electro)chemical process by lowering its kinetic energy barrier. In heterogeneous catalysis, the binding sites are distributed across a solid surface, thus allowing for simple separation from the product mixture. Such catalytic processes are inherently interfacial, and therefore rely on a complex interplay of mass transport, reagent adsorption, bond breaking/making and product desorption. The goal is to optimize these physicochemical characteristics to support the target reaction without accelerating competing processes.

Rational design of catalysts, and chemically functional materials in general, relies on the unequivocal **identification of surface active sites**, which requires not only measurement of surface structure, but also detailed speciation of interfacial adsorbates, characterisation of molecular intermediates and elucidation of reaction mechanism. The atomic structure of such active sites is typically dynamic and sensitive to environmental conditions and hence *in situ* characterisation is essential. Moreover, the properties of catalytic surfaces are known to be **spatially and temporally heterogeneous** [5], such that many conventional macroscopic characterisation approaches are grossly inadequate to understand the complete role of active sites. Hence there is a major requirement for new measurement science enabling **highly localized, real-time interfacial characterisation under reaction conditions**, as identified by various technology roadmaps [6-8].

Emerging technologies such as spatiotemporal spectroscopy, that enable molecular interrogation with nanoscale resolution, promise to address the above challenges, but such approaches are in their infancy and underpinning metrology and modelling is critical to support their uptake and realize meaningful impact. Furthermore, these novel tools have thus far exclusively been applied to solid-gas systems, whilst the industry urgently demands their extension to solid-liquid catalysis, in which the presence of a solvent adds a further level of complexity.

Required Outputs

The goal is to achieve real-time, *in situ*, molecular level speciation of reaction intermediates at reacting solid-liquid interfaces with nanometre spatial resolution. This will revolutionize our ability to measure and visualise interfacial dynamics, yielding major new insights into the bottlenecks of catalytic and related processes. Identification of the critical reaction sites and required atomic configurations will enable industry to optimize existing systems and rationally design advanced materials through the intelligent, rather than empirical, manipulation of surface structure.

Such a step change can only be achieved by building this measurement capability as part of a novel suite of tools for *in situ* interfacial characterisation, in order to ensure thorough validation. Delivery of the following key outputs is therefore essential to ensure maximum exploitation:

- Novel *in situ* spectroscopic methods enabling molecular speciation at solid-liquid interfaces
- Pioneering technologies for the coupling of interfacial spectroscopy with nanoscale microscopy
- Innovative application methodologies for determining the role of active sites
- New atomistic modelling techniques to simulate molecular binding and support confident data interpretation
- Validation of new capabilities and demonstration of value via industrially relevant case studies
- Provision of guidance on best use in order to ensure reliable and traceable exploitation

[1] The chemical industry in the UK – market and climate change challenges, P. Gilbert, M. Roeder, P. Thornley, Tyndall Manchester, 2013
[2] The North American Catalysis Society, http://nacatsoc.org/educational/about-catalysis/, 2012
[3] Renewable Energy Directive 2009/28/EC; Fuel Quality Directive 2009/30/EC; Biofuels Directive 2003/30/EC
[4] "NanoSelect Pd Catalysts: What Causes the High Selectivity of These Supported Colloidal Catalysts in Alkyne Semi-Hydrogenation?", P. T. Witte *et al.*, ChemCatChem 2013, 5, 582.
[5] "Heterogeneities of individual catalyst particles in space and time as monitored by spectroscopy", B. M. Weckhuysen *et al*., Nature Chemistry, 2012, 4, 973.
[6] Roadmap for Catalysis Research in Germany, German Catalysis Society (2010)
[7] Future Perspectives in Catalysis, Dutch National Research School (2009)
[8] Vision 2020: Reaction Engineering Roadmap, US Department of Energy (2001)

(b) What is the current state of the art?

Experimental Methods

Various approaches have been developed for the spatially resolved chemical characterization of interfaces, and yield differing levels of information across multiple length scales (see Fig.1.). These chemical imaging methods can divided into the following groups [5]:

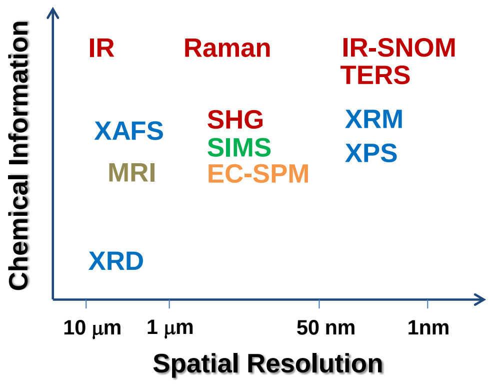


Fig.1. Chemical imaging methods (see text for definitions). Adapted from ref. [5]

X-ray techniques (Fig.1., blue text), such as **x-ray photoelectron spectroscopy (XPS)** and **x-ray absorption fine structure (XAFS)** are common tools for identifying the local chemical structure and elemental composition of materials and surfaces. Whilst highly informative, experimental issues such as the requirement for high vacuum conditions or synchrotron radiation make *in situ* measurement highly challenging. Recent developments in some highly specialized laboratories have enabled XPS measurements under mbar pressures but these are still not equivalent to genuine reactive environments. **X-ray microtomography (XRM)** can also be used to identify the 3D structure of catalyst materials whilst **X-ray diffraction (XRD)** enables precise characterization of lattice parameters. However, such approaches yield limited information on process dynamics and introduce the problem of sampling large enough areas to give a representative analysis.

Vibrational spectroscopies (Fig.1., red text), such as **infrared (IR)** and **Raman** spectroscopy are some of the most powerful techniques for molecular speciation. These are not ordinarily surface-specific but modern adaptations have enabled them to glean a wealth of information about molecular adsorbates at solid-gas or solid-liquid interfaces. The use of attenuated total reflection (ATR) IR spectroscopy compresses the signal sensitivity to within a few microns of a specimen, whilst surface enhanced Raman spectroscopy (SERS) and surface enhanced IR absorption spectroscopy (SEIRAS) shrink this sensitive region to within a few nm of the material. Such plasmon-enhanced techniques are finding wider applications, but are at present lacking in terms of quantitative analysis. Truly surface-specific molecular fingerprinting can be achieved through **second harmonic generation (SHG)** techniques but the application of such approaches to real catalyst samples remains challenging and further work is required for mainstream uptake. Whilst *in situ* measurement is the norm for such spectroscopies, in the absence of enhancement, they do suffer from relatively low sensitivity, especially in the presence of highly absorbing solvents such as water. Kinetic studies can be very challenging and generally require either transient microfluidic reactant flow or ultrafast lasers to measure the time-resolved response. Difficulties also arise in differentiation between spectator species and reaction intermediates, a potential solution to which lies in modulation excitation spectroscopy (MES), in which a periodic external perturbation (e.g. in reactant concentration) is used to stimulate a sinusoidal signal response.

The spatial resolution of IR and Raman microscopy techniques is typically diffraction limited but innovative near field approaches have emerged that enable vibrational spectroscopy at the nanoscale. **Tip-enhanced Raman spectroscopy**

(TERS) combines the spatial resolution of AFM with the chemistry revealed by Raman spectroscopy, thus potentially providing a link between catalyst structure and activity. Similarly, **IR-scanning near field optical microscopy (IR-SNOM)** couples AFM with IR spectroscopy to yield nano-chemical microscopy. Both of these techniques are in their infancy and their application to catalysis science has only very recently been realized.

Magnetic resonance spectroscopy can yield a wealth of chemical information relating to catalyst materials and, when undertaken *in situ*, can generate valuable insights into diffusion, adsorption and reaction processes. Spatially resolved **magnetic resonance imaging (MRI)** gleans such information on a localized scale, although such measurements are at present limited to the micron scale.

Mass spectrometry is a powerful means of chemical identification and can be achieved at surfaces with high spatial resolution using, for example, **secondary ion mass spectrometry (SIMS)**. However, *in situ* mass spectrometry imaging of active solid-liquid interfaces is beyond present capabilities.

Electrochemistry has emerged as a useful tool for surface structure analysis of metal-liquid interfaces, for example using atomic electrodeposition as a means to electrochemically fingerprint surface atomic arrangements. Such techniques at present lack spatial resolution, but recent advances in **electrochemical scanning probe microscopy (EC-SPM)** have enabled electrochemical-topographical imaging of interfacial activity at the 10-100 nm scale.

Atomistic Modelling

The simulation of interfacial processes is a complex and challenging task because of the multiscale nature of the phenomena involved. Despite vast research at the classical level, the accurate description of electronic structure at interfaces is only beginning to emerge. The application of **density functional theory (DFT)**, the *de facto* standard tool for electronic structure calculations, to study surfaces and interfaces is more involved than for homogeneous phases, both numerically and conceptually. Combined with the **Car–Parrinello** approach, this method enables the simulation of molecular dynamics, however it suffers from the inability to capture the weak (van der Waals) interactions important in inhomogeneous systems and is highly computationally demanding (restricting simulations to systems of ~128 molecules and short integration times that captures only the fastest processes). Development of accurate electronically coarse-grained multiscale methods would provide an ultimate solution to such problems with large spatial and temporal dimensions. Recently, NPL in collaboration with IBM and the University of Edinburgh has pioneered development of the **quantum Drude oscillator (QDO)** model to molecular systems and demonstrated unprecedented accuracy and transferability in the test case of water for systems containing thousands of molecules. The model is in active development and one of the immediate tasks is to extend it to include the chemical reactivity, which is not captured at present by the model.

(c) What is the track record of the Research Team?

NPL has a strong background in interfacial chemistry and the present proposal builds upon a previous Strategic Capability project on the theme of chemical imaging using bifunctional electrochemical probes. Through this and other programmes NPL has established a formidable track record in the development of high-resolution electrochemical imaging technologies, enabling the *in situ* mapping of surface activity of solid-liquid interfaces at the 100 nm scale. Recent applications include the electrochemical-topographical imaging of exfoliated graphene [9] and mapping oxygen reduction electrocatalytic activity of Pt at the single nanoparticle level (see Fig. 2 [10]). NPL is internationally leading in the field of TERS, and recently developed a new procedure for the accurate measurement of enhancement factors [11] as well as demonstrating the application of TERS to the spectroscopic mapping of graphene surfaces [12]. NPL also has an excellent track record in molecular dynamics simulations, a recent highlight being the development of an electronically coarse-grained approach based on the QDO [13]. In collaboration with the University of Edinburgh and IBM Watson Centre, and building upon earlier work on noble gases, NPL have developed a highly accurate and transferable molecular model for water, capable of quantitatively describing its properties for all three phases across the broad range of thermodynamic states.

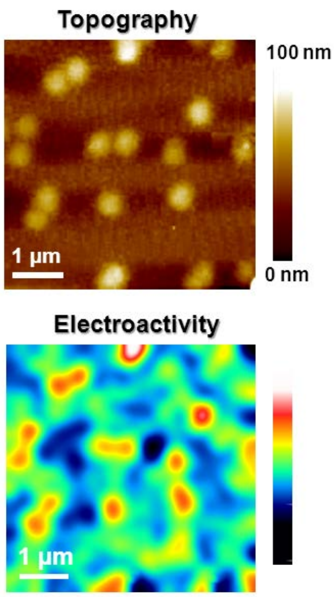


Fig. 2. Topography-Electroactivity mapping of Pt nanoparticles [10]

The research team at NPL comprises the following individuals who bring unique expertise to this project across a broad range of disciplines:

Dr. Andy Wain is a senior research scientist in the electrochemistry group at NPL. His expertise lies primarily in the field of interfacial charge transfer, with a focus on the development and exploitation of innovative approaches to interrogating (electro)chemical reactions and surface processes. He has extensive research experience in localized electrochemistry and has established a cutting-edge capability in multi-scale electrochemical imaging at NPL with a breadth of applications across a range of industries (e.g. fuel cells, corrosion, photovoltaics). In doing so he has led and delivered NMS and third party projects on nanoscale electrochemistry and electrocatalytic activity screening. Prior to joining NPL, he developed and exploited a number of combined electrochemical-spectroscopic techniques for investigating interfacial processes and is now applying this experience to establishing spectroscopic capabilities both within NPL and in collaboration with leading academics at Cardiff and Cambridge. Andy has over 12 years' experience in the field of electrochemistry and has published 39 peer-reviewed papers and 3 book chapters.

Dr. Deb Roy is a principal research scientist in the surface and nanoanalysis group at NPL and is a visiting research fellow at King's College London. He has established key capabilities in TERS and stimulated Raman scattering at NPL. Deb has published 40 journal articles and book chapters with more than 1,500 citations, and received Rayleigh Awards (NPL's award for the best publication) in 2009 and 2012. His primary research interest is in molecular spectroscopy and its applications to interrogate complex systems at the nanoscale. Deb obtained a BTech (Hons) from the Indian Institute of Technology, Kharagpur (IIT-KGP, India) prior to getting his PhD in Raman spectroscopy of carbon nanostructures as a Nehru Scholar from the University of Cambridge (UK). Deb spent two years in Prof Mark Welland's lab at the Nanoscience Centre, University of Cambridge before joining NPL as a Strategic Research Fellow in 2005.

Dr. Vlad Sokhan is a principal research scientist in the mathematics and modelling group at NPL. He joined NPL in 2005 as a strategic research fellow in molecular modelling. His area of expertise is complex fluids at interfaces, where he is developing novel methods for the accurate treatment of manybody polarization and dispersion, and he is a co-developer of the quantum Drude approach to materials simulation His past experience includes the development of methods for the estimation of nonlinear optical susceptibility at the aqueous interfaces. He has published 22 papers that have attracted 570 citations, and is a sole developer of MDL, a general-purpose molecular dynamics code (*ca* 25K lines of code).

Dr. Alan Turnbull is a senior fellow at NPL and is the science area leader for the Electrochemistry group. Since joining NPL in 1973, Alan has produced over 200 publications (about half in peer-reviewed journals) on environment induced cracking of metals and of thermoplastics, on localised corrosion, and on modelling of corrosion processes, and has been the principal author of eight international standards. He is a Fellow of NACE International; the Institute of Materials, Minerals and Mining; and the Institute of Corrosion; a recipient of the T P Hoar Prize from the Institute of Corrosion; the Bengough Prize and Medal from the Institute of Materials; a Technical Achievement Award from NACE International; the Cavallaro Medal from the European Federation of Corrosion; the U R Evans Award from the Institute of Corrosion and the Whitney Award from NACE International. In 2011 Alan was elected as a Fellow of the Royal Academy of Engineering and in 2013 as a Fellow of the Royal Society.

Dr. Mike O'Connell is a higher research scientist in the Electrochemistry group at NPL. He has over 5 years' experience in scanning probe microscopy and, in particular, has contributed to the development of various electrochemical imaging techniques. He also has expertise in the application of advanced interfacial spectroscopy for measuring molecular adsorption kinetics. Mike has published 5 peer-reviewed papers.

[9] "High-Resolution Electrochemical and Topographical Imaging Using Batch-Fabricated Cantilever Probes", A. J. Wain *et al.*, Anal. Chem., 2014, 86, 5143.
[10] "Mapping electrocatalytic activity of individual metal nanoparticles using high resolution SECM-SICM", M. A. O'Connell *et al*., submitted, 2014.
[11] "Accurate measurement of enhancement factor in tip-enhanced Raman spectroscopy through elimination of far-field artefacts", D. Roy *et al.*, App. Phys. Lett., 2014, 104, 123106.
[12] "Visualizing graphene edges using tip-enhanced Raman spectroscopy", W. Su *et al.*, J. Vac. Sci. Tech. B, 2013, 31, 41808.
[13] "Electronically coarse-grained molecular dynamics using quantum Drude oscillators", A. P. Jones *et al.*, Mol. Phys., 2013, 111, 3465.

(d) Why should the work be funded by Government?

The UK has a strong research base in catalysis, and an extensive user industry, but investment is necessary in order to remain internationally competitive. A national injection of funding has recently been advocated by the UK government through the launch of a major new EPSRC Catalysis Hub, which will provide strategic direction to catalytic science in the UK by co-ordinating the research activities of academia and industry. This extensive new programme was endorsed by UK Minister for Universities and Science, David Willets, who highlighted that "catalysis science is *vital* for many areas of the UK economy" [14].

This project will serve to realize NPL's strategic vision as a leading centre of excellence in science, with improved academic and industrial interactions, and will address national challenges as laid out in the NMO strategy [15]. This work falls strongly within government priority areas:

- **Growth** – high value manufacturing, nanotechnologies
- **Energy** – low carbon technologies (fuel cells, biofuels)
- **Sustainability** – new functional materials, alternative feedstocks

The proposed work intersects fundamental and applied science, and promises to bridge academic research with industrial innovation via new measurement science and metrology. It is therefore highly appropriate for this project to be funded by government and led by the UK's national measurement laboratory. Whilst emphasis has been placed on catalysis, the problem of interfacial measurement has much wider impact, for example the understanding and development of:

- Electroactive materials for fuel cells, electrolysers, batteries, supercapacitors and solar energy devices
- Photocatalysts for water splitting, CO_2 reduction and pollutant degradation
- Chemical, biochemical and electrochemical sensor devices
- Passivation layers for materials exposed to aggressive environments (e.g. offshore pipelines, chemical storage)
- Neoteric nanomaterials with functionalised surface chemistry (e.g. 2D materials)

[14] EPSRC Launch of new catalysis Hub, January 2013 http://www.epsrc.ac.uk/newsevents/news/2013/Pages/investmentpromisesgreeneruk.aspx.
[15] The National Measurement System Strategy Document, 2011-2015, July 2011, http://www.bis.gov.uk/assets/nmo/docs/nms/nms-strategy-document.pdf.

Vision

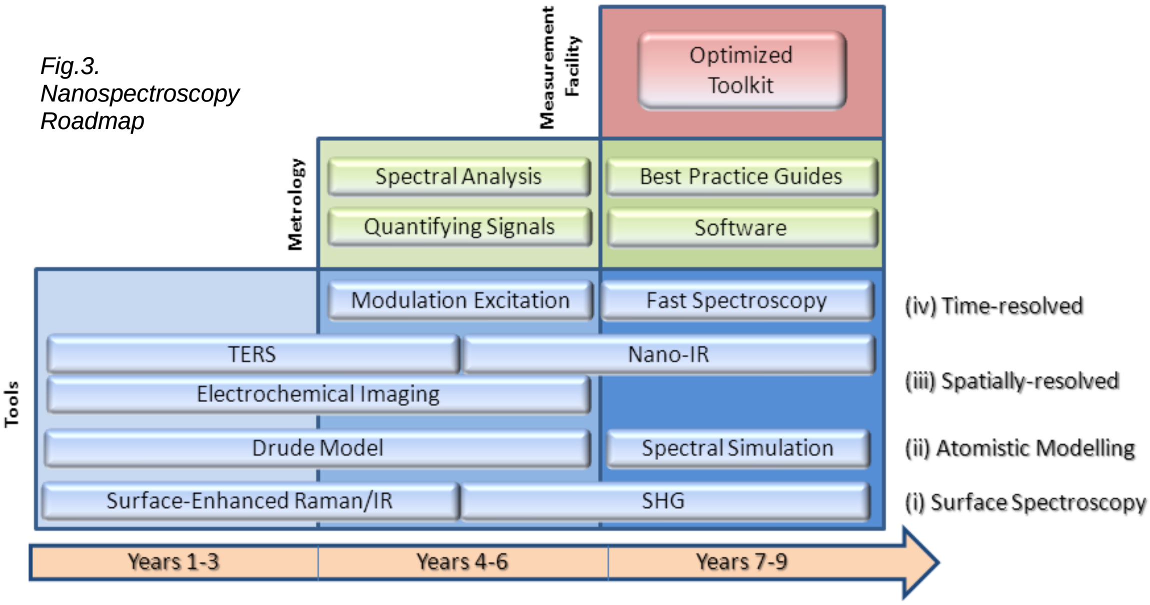
(a) Long term vision (over lifecycle of Capability development)

The vision is to establish a world-leading capability for the characterisation of interfacial reaction dynamics, in order to address the current and future needs of the catalyst industry and beyond. This will be achieved by building unique expertise and novel instrumentation for advanced *in situ* molecular spectroscopy combined with pioneering scanning probe microscopy and innovative electrochemical analysis, and supported by the development of new atomistic models. As laid out in NPL's catalysis roadmap, our strategy is to target solid-liquid interfaces in order to tackle the rapidly growing need for liquid phase catalytic processes under mild conditions.

New Science

This major new capability will be developed through intersecting activities in four key areas, carried out over three phases as outlined in Fig. 3.

Fig.3. Nanospectroscopy Roadmap



(i) Surface Spectroscopy: *We will deliver cutting-edge systems for FTIR, Raman and SHG analysis of solid-liquid interfaces with temperature control, online product analysis and novel signal enhancement*

NPL recently acquired a modern research grade FTIR instrument (Thermo Scientific, Nicolet iS-50) that allows measurement in the ATR mode, and work is currently underway to couple this with electrochemical measurement to enable analysis of molecular adsorbates under controlled surface potential. In Phase 1 we propose to expand this system into a fully state-of-the-art device for measuring catalyst dynamics first by installing an advanced reagent flow-reactor with temperature control and online product analysis and introducing unique plasmonic enhancement methods to improve surface specificity and signal-to-noise beyond current benchmarks by an order of magnitude. This will be achieved in collaboration with experts at Cardiff University, who will make complementary developments in surface-enhanced Raman techniques using innovative non-interfering core-shell particles. In parallel, collaborators at Cambridge will advance *in situ* surface Raman methods towards molecular scale sensitivity via the development of highly novel photonic nanoarchitectures consisting of rigid molecular spacers. Such substrates will form the basis of a new and simplified "on-chip" approach to interfacial spectroscopy with well-characterized measurement uncertainty and the potential for commercial exploitation. In Phases 2 and 3, this capability will be advanced further with the development of SHG spectroscopy, enabling meticulous surface specific analysis of *in situ* catalytic processes.

(ii) Atomistic Modelling: *We will set a new precedent for catalysis theory and the simulation of molecular binding at solid-liquid interfaces via the unique combination of the quantum Drude Oscillator model, pioneered by NPL, and density functional theory (DFT).*

Recent advances by NPL scientists have enabled the application of the Drude model of atoms and molecules to many-body polarization and dispersion (e.g. van der Waals) interactions for atomistic simulation. The highly challenging combination of this model with DFT to calculating electronic structure and interatomic forces at complex solid-liquid interfaces will represent a major step forward for computation in catalysis. We will use this molecular modelling capability to complement spectroscopic measurements by enabling the confident assignment of spectral bands and identification of molecular intermediates by simulating their sensitivity to controlled experimental parameters. Furthermore, the model developed will provide microscopic links between the interfacial structure and calculated spectra, and later a route to analysing transient spectra of short-lived intermediates, thus providing unprecedented access to mechanistic information about fast interfacial processes.

(iii) Spatially-Resolved Interfacial Analysis: *We will demonstrate the first application of spectroscopic imaging to solid-liquid catalytic interfaces with 10 nm resolution and develop a unique tool for simultaneous electrochemical, spectroscopic and topographical mapping*

Interfacial reactions around a single nanoparticle take place within zeptolitre volumes involving a few hundred molecules in total. Our goal is to selectively probe this reaction zone in solid-liquid systems and map chemical speciation and activity with 10 nm spatial resolution. Exploitation of light-matter interactions at the nanoscale to enhance the optical signals in the near field is an emerging approach to probing chemical dynamics at such length scales. Building on NPL's present foundation in TERS in air, and through new probe and cell development, we will establish a unique system for *in situ* spatially resolved molecular speciation at catalytic solid-liquid interfaces. Using similar novel plasmonic enhancement concepts to those developed in part (i) above, innovative probe functionalization with molecular "nanoreactors" will enable molecular probing at the sub-zeptolitre volume level. In Phases 2 and 3 we will further build our capability in optical nanospectroscopy to include IR-SNOM, which will provide a complementary and state-of-the-art measurement approach to highly localized, *in situ* molecular analysis.

Building further on present expertise in electrochemical imaging developed as part of the current SC programme, we propose to integrate localized molecular nanospectroscopy with electrochemical analysis for the first time. Such a combination of nanoscopic topographical imaging, alongside spatially resolved chemical speciation and electroactivity measurement will yield unparalleled interrogation of structure-activity links. We will also develop and implement new potentiodynamic approaches to fingerprinting atomic faceting at nanoparticle surfaces, uniquely targeting palladium surfaces due to their extensive utilization in the catalyst industry. In Phase 2, we will achieve spatially-resolved detection of atomic arrangements by coupling these fingerprinting methodologies with electrochemical scanning probe microscopy.

(iv) Time-resolved Measurement: *We will introduce innovative new methods for transient measurement through novel modulation excitation experiments and ultrafast laser techniques*

Although complete catalytic events take place typically over milliseconds to minutes, chemical bond formation takes place on the picosecond timescale. Hence, rapid data acquisition is essential for true kinetic analysis of dynamic interfacial processes. We will introduce time-resolved molecular speciation in Phase 2 by devising an entirely new system for modulation excitation by driving the transient or periodic electrochemical dosing of catalytic surfaces with reactant molecules (e.g. H_2 for hydrogenation reactions). Monitoring of ultrafast interfacial processes, in particular the identification of short-lived intermediates using picosecond pump-probe measurements, will be the focus in Phase 3.

Critical Mass

Critical mass will be attained through sustained collaboration via joint PhD studentships and postdoc placements with leading academic partners including: Prof. Gary Attard at Cardiff University; Prof. Jeremy Baumberg and Dr. Oren Scherman at Cavendish Laboratory; Glenn Martyna at IBM Watson Research Centre; in addition to close engagement with industry partners and the UK Catalysis Hub. NPL is becoming increasingly integrated into European catalysis networks through participation in Horizon 2020 and EMPIR bids and these will serve to raise NPL's visibility on the international stage. Strong cross divisional interactions at NPL will provide additional support this area; with the backdrop of a world-leading capability in surface analysis and materials characterization, NPL is well-positioned to make a sizeable impact on this field and become a high-profile center of excellence for measurement in catalysis and interfacial science.

Chemical mapping is an exciting area of science that is making groundbreaking steps towards a molecular level understanding of interfacial chemistry. Nanospectroscopy has only recently started to make an appearance in catalyst applications, and so an established capability in this field will be certain attract positive attention. More generally, the requirement for new measurement in catalysis is a view shared by the majority of the catalysis world and so our motives will resonate strongly with this community. NPL has developed a strong network within academia and industry through regular participation in international meetings and we will use this influence to ensure the best researchers are attracted. Our reputation will be enhanced through organization of workshops and various other KT routes described below, ensuring external visibility. The measurement technologies to be developed are also widely applicable to a broad range of problems in interfacial chemistry and so establishing NPL as a leading institute in this area we will draw interest from a diversity of top-level scientists.

(b) Vision for this three-year project segment

The major technical objectives over this three-year project are to:

- Establish a system to enable the plasmon-enhanced spectroscopic interrogation and reaction product analysis of solid-liquid interfaces under controlled conditions
- Assess metrology of plasmonic signal enhancement for semi-quantitative analysis of surface adsorbates
- Build a state-of-the-art capability for TERS measurements at solid-liquid interfaces for *in situ* analysis of reacting catalytic surfaces with sub-50 nm resolution
- Develop new electrochemical methods for determining the predominant atomic arrangements at palladium surfaces (polycrystalline electrodes and nanoparticle-decorated surfaces)
- Establish a new atomistic model combining the Quantum Drude Oscillator model with DFT to simulate binding of molecular adsorbates at solid-liquid interfaces and determine vibrational modes for spectral assignment
- Devise an innovative new tool for combined electrochemical-AFM-Raman spectroscopy

(c) Contributions to Metrology

The primary focus of this project is to develop novel measurement capability to underpin rational materials design by enabling the confident identification of molecules and reaction intermediates adsorbed at dynamic interfaces. In the process of developing interfacial nanospectroscopy, we will take the spatial resolution of *in situ* chemical speciation at catalytic solid-liquid interfaces from the 100 nm range down to 1-10 nm range. The plasmonic enhancement approaches to be developed and employed have yet to be fully characterized in terms of signal quantification and standardization, and hence metrology will play a critical role in establishing the new capability. SHG spectroscopy will help to exclude the interference of non-adsorbed molecular species, but metrology is also lacking in this technique, and so a large part of the early stages will be spent developing methodologies to ensure reliable measurement. The development of robust molecular models will enable technique validation and support the meaningful interpretation of spectral data. The new measurement capabilities developed will be delivered with industry guidance, so as to ensure traceable and reliable exploitation. This will take the form of good practice guides and, where appropriate, measurement standards.

Project Scope

This 3-year project can be broken down into four core elements depicted in Fig. 4 below.

Surface Spectroscopy. The expansion of the FTIR system will begin with the installation and commissioning of a multi-reflection ATR reactor with integrated temperature control. A fluid flow system will then be constructed, including a gas chromatography – mass spectrometry (GC-MS) instrument at the reactor outlet for quantitative product analysis. The use of plasmonic enhancement will be assessed first using gold nanoparticles, and later novel neoteric nanomaterials such as shaped nanocrystals and core-shell systems. A detailed analysis will be performed using a benchmark system in order to evaluate (a) the quantitative enhancement of signal-to-noise and (b) qualitative changes to the lineshape of vibrational bands. Once complete, the new FTIR capability will enable the identification of surface adsorbates under a range of solution chemistries and temperature conditions, in addition to detailed analysis of product distribution. Complementary activities will be initiated at Cardiff and Cambridge for the development of novel substrates for high sensitivity interfacial solid-liquid Raman spectroscopy.

Electrochemistry. A new method for electrochemical fingerprinting the surface faceting at palladium nanoparticle-decorated surfaces using copper metal deposition will be developed. A variety of shaped nanoparticles will be examined in order to assess the sensitivity of the technique, and the results will be validated against crystallographic measurements. We will then explore the first application of this methodology to localised surface analysis by integrating it with our extensive electrochemical imaging facility. This will enable the characterisation of heterogeneous surfaces, especially mixed particle systems, including catalysts provided by our industrial stakeholders. The coupling of electrochemical imaging with confocal Raman spectroscopy will enable unprecedented interrogation of interfacial processes induced by the localized generation of molecular reagents (e.g. H_2) in real time, in addition to determining the role of active sites on conducting catalyst support materials such as carbon. A finite element model will also be developed for extracting quantitative kinetic information from electrochemical current mapping.

Modelling. The spectroscopic measurements will be complemented by atomistic modelling of the binding of unsaturated hydrocarbons and their hydrogenation products to palladium surfaces. This will be accomplished through a set of quantum/classical supramolecular calculations to determine the dynamic properties of a range of potential interfacial intermediates, including the determination of IR absorption cross sections of targeted vibrational bands and their spectral frequencies under varied experimental conditions. This will provide an important link between the spectroscopic response and molecular structure at the interface, whilst enabling the relative stability of intermediate species and competitive binding efficiencies of molecular adsorbates to be determined. Finally, we will investigate the relationships between surface atomic structure and the behaviour of such intermediates as a means to optimise selectivity during catalysis.

TERS. The above three strands of work will provide essential support to the development and demonstration of a new capability for liquid phase TERS, that will enable the real-time identification of surface adsorbed intermediates at the single particle level. This will require the development of a novel cell and environmental chamber for *in situ* liquid phase measurement under controlled chemical conditions, in addition to the development of highly specialised probes in collaboration with partners at NanoWorld Services GmbH. These probes will include a unique thin passivation layer to both shield the underlying metal from the reacting environment and to improve durability. The novel functionalization of TERS probes with molecular nanoreactors will also be explored with collaborators at Cambridge.

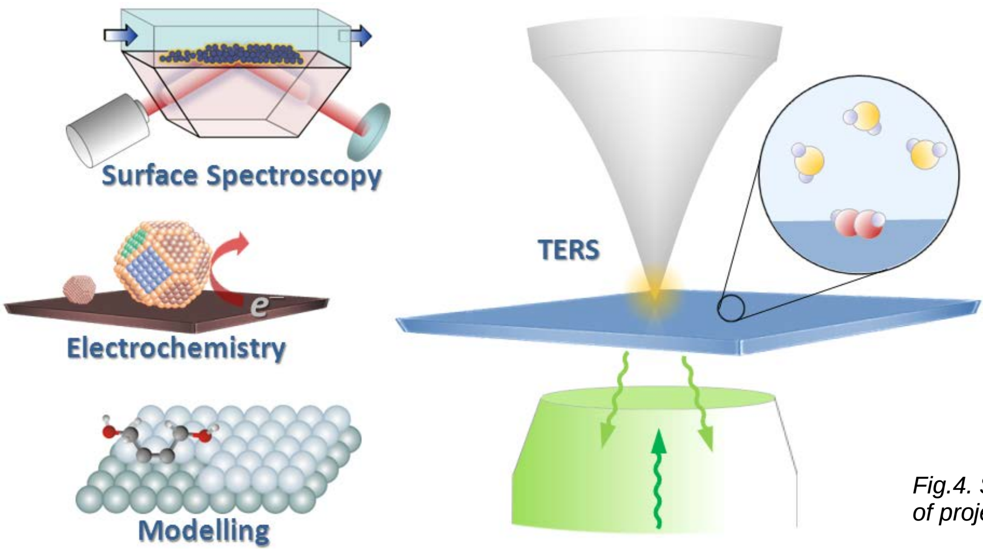


Fig.4. Schematic depiction of project scope

Case Study Systems

The new capabilities will be developed in the first instance with reference to well-defined model adsorptive systems at solid-liquid interfaces. The focus will then shift to exemplar solid-liquid catalytic reactions of key interest to our industry stakeholders by way of three case study systems in which we will draw comprehensive links between activity/selectivity and structure:

1. BASF "NanoSelect" catalyst, a new high profile material for selective alkyne hydrogenation
2. Johnson Matthey supported Pd catalysts for selective carbonyl hydrogenation
3. AFC Energy catalysts for oxygen electroreduction in alkaline media

<u>*Capabilities and Outputs*</u>

Phase 1 *(years 1-3):*

- Multi-reflection FTIR-ATR reactor with temperature control
- Flow system for liquid reagent delivery to ATR device including Integrated GC-MS for product analysis
- Innovative semi-quantitative methodology for plasmonic enhancement of FTIR/Raman signals
- Apparatus and expertise for liquid-phase TERS, including cutting-edge know-how for probing catalytic surfaces
- Novel atomistic model to simulate interfacial molecular binding in liquids
- New electrochemical fingerprinting methodology for metal nanoparticle faceting and build electrochemical system for combined electrochemical-Raman imaging

Phase 2 (years 4-6):

- New system for IR nanospectroscopy at solid-gas interfaces, coupling FTIR with AFM/SNOM
- Technology and underpinning metrology for SHG spectroscopy at solid-gas interfaces
- Plasmonic chip substrates for simplified interfacial spectroscopy and metrology assessment
- Novel electrochemical modulation excitation approach to enable transient spectroscopic measurement
- Extended model including selective oxidation for biofuel applications
- Protocols detailing the reliable analysis of spectra and quantification of signals

Phase 3 (years 7-9):

- Novel cells for SHG and Nano-IR spectroscopy at solid-liquid interfaces
- Pulse laser system for time-resolved spectroscopy of catalytic interfaces
- Computational software for spectral simulation
- Best practice guidance on reliable and traceable use of techniques
- Exploitation of new toolkit in further industry case studies

Benefits

(a) Benefits of the current phase

This project will generate a suite of novel, validated measurement technologies for the benefit of the catalyst and chemical industries as well as commercial instrument manufacturers (specifically our partners BASF, Johnson Matthey, AFC and NanoWorld, along with other interested parties such as Catal International and Clariant). Addressing the measurement needs described will vastly improve our fundamental understanding of the *modus operandi* of catalyst materials, fostering a culture of tailored materials and process design as opposed to empirical catalyst discovery. Short term benefits will include:

- New scientific advances stimulating innovation, adaptability and competitiveness in the chemicals industry
- A state-of-the-art suite of measurement technology that positions NPL for future third party funding (e.g. TSB, EMPIR, Horizon 2020) and lays a solid foundation for a centre for measurement excellence in interfacial science
- New molecular modelling software facilitating the confident analysis of interfacial characterisation data and identification of physicochemical bottlenecks
- New specialized AFM probes with IP potential
- Improved understanding of the origins of selectivity and performance in our case study systems leading to the development of improved catalyst materials
- Unique datasets that will vastly improve NPL's visibility on the world stage and attract direct industry business

(b) Benefits of the completed programme

Beyond this three-year cycle the above benefits will be extended further through the development of transient IR methods and the establishment of SHG and Nano-IR spectroscopy, generating a world-leading capability for measuring interfacial dynamics. Once completed this unique suite of tools will not only promote new scientific discoveries of value to a range of industries, but the development of rigorous test methodologies and dedicated expertise will attract new business opportunities for NPL in the form of collaborative or industry-funded research, in addition to modest levels of direct measurement service work. Based on the size of the accessible catalyst market alone, such a facility could have the potential to generate direct third party revenue in the order of £100k per annum.

In the longer term this capability will lead to broad economic and environmental benefits to the catalyst and chemical industries such as:

- Improved process efficiency and reduced production costs leading to the generation of wealth and jobs (e.g. fine chemicals, biomass refining)
- Increased selectivity in chemicals production leading to reduced waste streams and optimized utilization of feedstocks
- Enhanced energy efficiency and reduced greenhouse gas emissions through less energy intensive processes
- Reduction in active metal content in commercial catalysts leading to greater sustainability in the catalyst industry

The capability will have immense scope for wider applications reaching far beyond heterogeneous catalysis. For example, the combination of electrochemical and spectroscopic analysis at a highly localised scale could be applied to the development of more efficient nanomaterials for energy conversion, leading to better solar cells, fuel cells, batteries, and supercapacitors etc. Similarly, this technology could be used to develop improved coatings, leading to more corrosion-resistant materials, and more robust and reliable platforms for sensing devices.

Collaborators

The proposed work combines high science with impact by bringing together world-leading University collaborators and industry partners. Our academic colleagues will contribute towards the development of innovative plasmon-enhanced molecular spectroscopy and will provide support for establishing the modelling capability, whilst end-user industry participants will provide the application pull *via* collaborating on relevant case studies. In the later stages these case studies are expected to develop into to direct industry-funded research. Also, the involvement of commercial measurement technology developers helps to ensure uptake of new methods developed and offers the potential for future business opportunities through the exploitation of IP, for example through the development of multifunctional nanoprobes. A number of specific collaborators have been identified as follows:

Academia

Professor Gary Attard is Deputy Head of Chemistry at Cardiff University and a partner of the Cardiff Catalysis Institute, the UK's largest collection of academics in this field. Gary has pioneered the application of single crystal electrochemistry to catalysis and, through an ongoing collaboration with NPL, has developed world-leading expertise in the use of core-shell nanoparticles to surface-enhanced Raman spectroscopy. This strong strategic partnership will continue in order to accelerate development of our spectroscopic capability. Cardiff will provide optimized nanomaterials for plasmonic enhancement and knowledge/technology transfer on the fabrication of shaped palladium nanoparticles. Cardiff will also play a key advisory role in the construction of the FTIR flow reactor capability and provide complementary Raman data to validate its performance.

Professor Jeremy Baumberg is a leader in nanoscience and nanotechnology, working for much of his career as an innovator at the interface between academia and industry. He has led interdisciplinary nano-centres at the Universities of Cambridge and Southampton, and developed novel devices within Hitachi, IBM, and his spin-offs Mesophotonics and Base4. He has worked closely with **Dr. Oren A. Scherman** at Cambridge, who is the acting director of the Melville Laboratory for Polymer Chemistry and is internationally-leading in chemically-controlled nano-assembly and sensing. The project will part fund a PhD student shared between the Cavendish Laboratory at Cambridge and NPL to develop and apply the novel nanophotonic architectures. Cambridge will also contribute the equivalent of a 6 month postdoc to the project.

Professor Glenn Martyna is an IBM research staff member at the Watson Research Centre in New York as well as Honorary Professor of Physics at The University of Edinburgh. Glenn's research has focused on atomistic modeling of chemical, biological and materials processes, for which his work has received over 11000 citations. In particular he has developed novel techniques that markedly increase the speed and efficiency of computer simulations and applied these methods to investigate important physical phenomena. Glenn will act as an advisory consultant for the modelling element of the work and the Watson Centre will contribute in-kind computational resources. Given the highly ambitious nature of the model, additional collaborative funding at the PhD/postdoc level will be sought.

Industry

BASF is the world's leading chemicals company with a substantial UK presence. NPL's primary contact, Dr. Peter Witte, is a research chemist in the Catalyst R&D group at BASF Netherlands in De Meern, whose work focuses on the development of heterogeneous catalysts for fine chemicals production. Peter has led the development of BASF's NanoSelect catalyst which will provide an ideal case study for this capability (Case Study 1). Throughout the project, BASF will provide a range of samples, share supporting characterization data, and offer valuable expertise on the exploitation of the new facility. It is our aim to build a strategic relationship with BASF, so as to ensure the maximum realization of industry benefits and receive guidance on future direction.

Johnson Matthey is an international speciality chemicals company, founded almost 200 years ago in London. The electrochemistry group at NPL has a strong partnership with JM, through our fuel cell programme, and this will be expanded to into the heterogeneous catalysis theme as part of the current project. JM will provide test materials including supported palladium catalysts as Case Study 2 and share expertise and feedback on their behavior.

AFC Energy is the world's leading developer of low-cost alkaline fuel cell technologies, focusing on large scale industrial applications. AFC are striving to enhance the performance and durability of their technology through improved electrocatalyst design but presently lack the ability to locally characterize their interfacial properties. Within Case Study 3 we will apply our capability to the characterization AFC catalysts, which will be provided as in-kind support. AFC are also enthusiastic about directly offering resources towards this case study on a commercial basis and discussions are presently ongoing.

NanoWorld Services GmbH is a global manufacturer of Micro-Electro-Mechanical Systems (MEMS) who specialize in the development of microtechnological products based on semiconductor fabrication methods. Previous collaborative work with NanoWorld has led to the successful exploitation of novel batch-fabricated cantilever probes for high-resolution combined electrochemical AFM imaging. This will be developed further as part of the current programme and extended uniquely to the development of novel probes for both TERS and coupled electrochemical-Raman-AFM imaging. NanoWorld will contribute resources and materials to the project (estimated value €200k over three years) through the development and fabrication of tailored multifunction probes.

Complementary NPL Activities

This work will also be complemented by additional projects currently underway at NPL. Specifically, the surface and localized molecular spectroscopy resonates with NPL work on nanoparticle surface characterization, whilst there is overlap between current and future activities in graphene metrology and fuel cells. Furthermore, supporting characterization techniques will be available for undertaking case studies including XPS, SIMS and XRay/FIB-SIMS microtomography.

Fig. 5 depicts a schematic representation of how the various collaborative and complementary elements of the project fit together and feed into the industrial case studies.

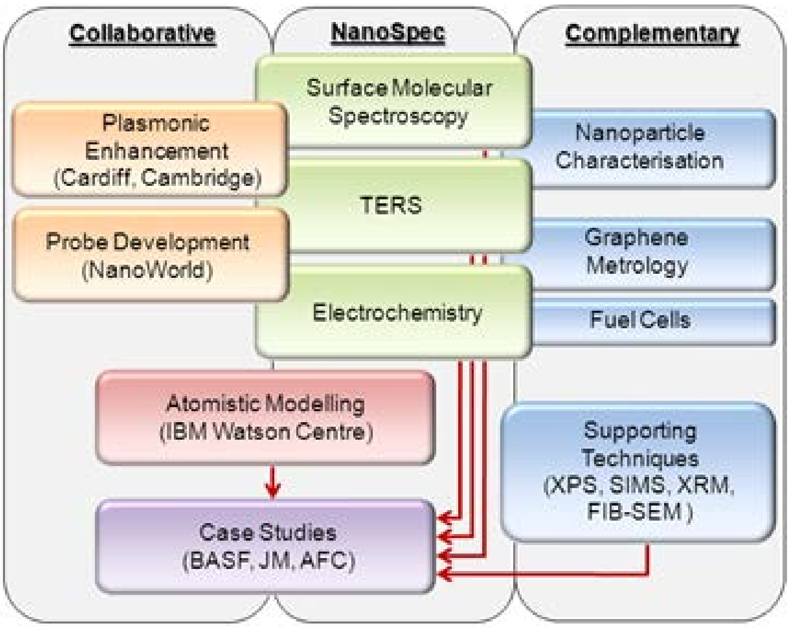


Fig.5. Overview of collaborative and complementary elements

Additional support

Complementary support for developing this strategic capability is currently being sought through various third party funding routes, including:

- Royal Society Industry Fellowship (Vlad Sokhan) on "Building Next Generation Materials Simulation Tools"
- Horizon 2020 bid for a fully funded Marie Curie PhD student (submitted March 2014)

- European metrology programme (EMPIR)
- TSB opportunities to support UK SMEs
- EPSRC CASE studentship bids and further support from academic partners through doctoral training resources
- Direct resources and in-kind support from industry users for further case studies

Knowledge Transfer and Exploitation

(a) Knowledge transfer

KT and dissemination of the scientific advances generated will be achieved via:

- High impact publications and presentations at key international conferences
- Best practice guidance on the exploitation of new measurement technologies
- New software for simulation of vibrational spectra
- Student placements enabling the bi-directional transfer of know-how and capabilities
- Direct interactions with industry and academic collaborators through regular meetings
- Establishment of an Industry Advisory Group (IAG) to review outputs from an applications perspective and steer future activities to maximize commercial value
- A series of NPL-hosted symposia bringing together stakeholders from industry and academia
- Integration into the UK Catalysis Hub through participation in local meetings
- Formulation of a European Network for Measurement Excellence in Catalysis (via EMPIR)

(b) Exploitation plans

Exploitation of the new measurement technologies and expertise will be achieved throughout the development stages by targeting industrially driven case studies and the new data generated will be disseminated via the mechanisms described above. Beyond this we are participating in further funding bids (H2020, EMPIR, TSB) to extend and exploit this capability. In Phase 2 NPL will be well-positioned to participate in the EU SPIRE programme (Sustainable Process Industry through Resource and Energy Efficiency) in addition to future EMPIR Energy and Industry calls. The established capability will serve as a foundation for a leading industry-accessible facility for catalyst interfacial characterization. Our present capability in catalysis and nanoscpectroscopy is relatively modest, and so immediate impact is expected to be relatively minor in the early stages. However, direct industry research funding will be secured in the longer term by building on current partnerships with BASF, Johnson Matthey and AFC Energy, and expanded upon through networking with the UK Catalysis Hub and the UK Chemistry Innovation KTN. The establishment of an IAG will present further opportunity for direct third party exploitation.

Risks

Risk	Mitigation
Plasmonic enhancement may cause complex FTIR signal changes, making interpretation troublesome.	NPL and its collaborators have extensive experience in understanding light-matter interactions. If this is too challenging, less complex plasmonic substrates can be employed.
Some industrial collaborators are direct competitors so there may be some difficulties in data sharing.	NDAs will be signed with all parties. Case studies can be conducted in isolation.
Large gap between model catalyst systems and real industrial catalysts presents a significant challenge	BASF's NanoSelect catalysts are an intermediate type of system that bridge this gap, with a well-defined metal crystallites on an ill-defined support material.
Spatially resolved electrochemical facet fingerprinting has not yet been demonstrated so this is a highly challenging target.	NPL has an extensive capability in localized electrochemistry and significant experience in developing new modes of measurement.
Signal enhancement using TERS technique may be insufficient for unambiguous analysis.	Application of new plasmonic substrates will enable the use of "gap mode" TERS, leading to further enhanced signals.
Underside optics limit the type of substrates that can be employed.	Topside optics are currently being explored as an alternative.
Combining electrochemistry, spectroscopy and imaging is very adventurous.	Lead scientists have extensive expertise in coupling electrochemistry and spectroscopy
Computation of atomistic model may be too demanding for current capabilities	Risk limited by access to world leading computational resources at IBM and associated intellectual support

Deliverables			
1	**Start: 01/12/14**	**End: 30/11/17**	
Surface Spectroscopy: Install and commission FTIR reactor, flow system and GC-MS. Characterize new plasmonic enhancement methods for FTIR and Raman spectroscopy. (Evidenced by characterization data sets, NPL report, 2 peer reviewed publications, international conference presentation, case study).			
2	**Start: 01/12/14**	**End: 30/11/17**	
Electrochemical Spectromicroscopy: Spatially resolved Raman spectro-electrochemistry for the interrogation of electrified solid-liquid interfaces. (Evidenced by 2 peer reviewed publications, international conference presentations, case study).			
3	**Start: 01/12/14**	**End: 30/11/17**	
Atomistic Modelling: Develop a molecular model to simulate reactant adsorption at solid-liquid interface and calculate vibrational bands. (Evidenced by new modelling software, 2 peer reviewed publications, international conference presentations).			
4	**Start: 01/12/14**	**End: 30/11/17**	
Optical Nanospectroscopy: Spatially resolved Raman spectroscopy for the interrogation of nanostructured catalytic solid-liquid interfaces. (Evidenced by 2 peer reviewed publications, best practice guide, draft standard, international conference presentations, case study).			

Project No.	IRD/2014/16	Price to NMO	£4.45M
Project Title	Metrology for Graphene and 2-D Materials	Co-funding target	£2.2M
Project Lead	JT Janssen	Stage Start Date	01/12/2014
Project Team	A. Tzalenchuk, O. Kazakova, L. Hao, T. Sainsbury, A. Pollard, R. Pearce, C. Giusca	Stage End Date	30/11/2017
		Est Final Stage End Date	
Sector	Advanced Materials	Activity	Strategic Capability
Project Champion	Prof. K. Coleman	Contractor	

Summary - This project on graphene and 2D materials is the second-phase of a 10-year capability-building strategy to develop both the measurement capability and standardisation required by industry to commercially exploit graphene and the **focus is on developing metrology for industry to benchmark and grade 2-D materials**. The project continues from the highly-successful first-phase 'Metrology for Graphene' NPL project (see assessment scorecard in appendix 1). The project focusses on the issues required to deliver the commercial potential of graphene and 2-D materials, which are in competition with other technologies. The project supports UK industry needs as outlined by collaborators, the Innovate UK 'GrapheneSIG' work streams, and aligns with the EU Graphene Flagship project.

The NPL multi-disciplinary graphene project team has been identified as a **"world leader"** in characterising and testing graphene in Materials World magazine and by Innovate UK (TSB) as a **"key UK participant in the graphene value chain"**.

Industry players are still developing their knowledge of these advanced materials which are emerging in new chemistries and forms. The actual measurements themselves and the corresponding protocols required are not proven, widely understood, or agreed across the potential supply chain, thus material now being produced commercially cannot be properly evaluated and compared. This "metrology gap" must be overcome to enable the commercialisation of these materials and will be achieved through a collaborative project across three divisions of NPL, which therefore draws upon a broad range of expertise. The main benefit delivered to industry will be the capability to measure electrical, structural, chemical, mechanical and optical properties of 2-D materials and their correlation to understand bulk material and device performance. This will sustain NPL's position as the leading organisation for metrology of graphene and 2-D materials by translating novel research laboratory techniques into formats that can by and are relevant to industry.

The project is expected to deliver the following impacts:
In general, establishing the performance and where applicable traceability of novel and existing methods and techniques will offer validated measurements to give confidence in the performance of new material, devices and systems bringing them closer to production in a shorter time and at a lower price. Technical summaries of metrology methods will be produced to provide recommendations on specific measurement methods, *i.e.* bonding characterisation, contactless resonant microwave resistance, electrical properties of hydrophobic and hydrophilic materials in high humidity conditions, related to the following industry opportunities:

- Graphene production. Large scale production and transfer of graphene using CVD, sublimation of SiC, etc., are a necessary starting point for any graphene application. In this area the new mechanical, electrical and optical methods developed will contribute to the initial quality control of the material, in some cases allowing for inline characterization of the material and dramatically decreasing its cost and batch-to-batch inconsistencies as well as improving reliability of the products. Higher-throughput will be achieved by inline characterisation developed to enable quality control and feedback. The resulting higher rate of consistency and reduced wastage will benefit end-users by reducing cost and guaranteeing quality in areas such as coating materials, energy, automotive, aerospace, and ICT.
- Printable and flexible electronics. New methods of contactless electrical characterization and assessment of functionalization for adhesion will enable assessment and assurance of a product's performance, lifetime and functionality in industrial sectors with large production volumes such as touch panels, lighting, solar harvesting, energy (flexible batteries and storage media).
- Structural and functional materials. Composite materials with outstanding toughness, and strength and thermal conductivity compared to current generation will be enabled by the ability to design and prove the functionality of the interface in nano materials by characterisation of the nature of chemical bonding to 2D materials using repeatable and traceable methodologies.
- Novel opto-electronic devices. The unique combinations of electrical and optical properties will contribute to development of photonic and plasmonic components as well as integrated optoelectronic systems. The impact will be to increase the efficiency of devices such as sensors, photodetectors and photovoltaics components, OLED, solar cells and photodetectors to make them commercially viable in new markets.
- Sensors. Specific methods of measurement of electrical properties of graphene in variable, industrially relevant environments will create a performance index for sensors and coating applications, where reactivity of the material, its affinity to water and other species are crucial in biomedical and environmental sensing, and protective coatings.

The Need

(a) Why is it necessary

Despite significant experimental progress the scientific challenge still exists to understand the physical characteristics of these 2-D materials and this is coupled with a knowledge transfer challenge to make measurement capability and data relevant to industry to enable benchmarking and standardization of materials.

Fundamental property evaluation. Graphene and other 2-D materials have been touted as possible game-changing materials in an ever-increasing range of real-world applications, as detailed in Ref. 1. However new materials cannot compete in the marketplace without their performance and properties being fully characterised. **Without truly knowing the fundamental properties of the materials used in application prototypes, these materials will not progress from laboratory experiments to the factory floor**, as there will be no way for industry to evaluate the real benefits of using these new materials and thus make the commercial decision to invest in production. Confidence in all stages of R & D will only be achieved when accurate and precise measurement techniques have been established and standardised, which in turn will allow both the comparison of these 2-D materials with incumbent technologies, and between rival commercial products.

Confidence in material quality. A major challenge with these emerging materials is understanding what has been supplied. For example there is an abundance of material that is available for purchase and labelled as "graphene" or a specific 2-D material, but the quantity and quality of the key ingredient is not known. The differentiation of product quality is exacerbated by the difficulty in the measurement of atomically thin material, which is further amplified when the material is being produced in industrial sizes, be it kilograms of powder or metre reels of substrate-bound material. Classification of different types of 2-D material through standardisation will therefore be key to commercial exploitation. This project will enable these many metrology problems to be addressed through measurement, standardisation, performance evaluation and benchmarking processes critical for the commercialisation of products using these materials.

UK focus. A decade after the isolation of the first 2-D material, graphene, **the close-to-market opportunities for UK industry are now becoming apparent (see table 1 which gives the view of the UK Graphene SIG work streams)**. All of these opportunties require metrology to make technical progress and validate the properties, performance, lifetime and robustness of graphene and graphene based products. Examples of these markets and industrial players include; Graphene production (Applied Graphene Materials, Thomas Swan, Graphenea, Bluestone Global Tech, Graphene Technologies), sensor systems (Graphene Frontiers, Applied NanoDetectors), printed/flexible electronics (DZP Technologies, Haydale, Nokia) and nanocomposites (Hexcel, DSTL, Airbus).

The "metrology gap" needs to be closed. The metrology of 2-D materials is a new field and the knowledge that is available is scattered across academia who are pursuing these materials primarily for new science rather than to support industry. As there are no agreed methods in this area, the data produced is typically fit for scientific discovery, but is not yet robust enough to support investment, commercialisation and trade. However, much of the instrumentation required for methodical measurements are available from other scientific fields, such as surface-analysis techniques used in the semiconductor industry, and there is great potential to research and standardise these techniques for use by industry and academia in a relatively short period of time to bridge the previously described "metrology gap" and enable commercial uptake.

Sets of properties are required. The need is for measurements of multiple properties of materials to underpin the whole production and supply process from design through to selection of production methods. It is known that the properties are specific to the production method and process but at present the metrology to validate what has been produced is not available. There is also the need for a co-ordinated approach for the measurement of graphene-enabled products, for example: the assessment of distribution, surface bonding characteristics, and the chemical characterisation of any material functionalisation for composites and sensors. The opportunity and need is expanding into the comparison of the properties of a whole new family of 2-D materials, such as molybdenum disulphide and boron nitride, as these materials may be preferred over graphene in some applications, but the appropriate materials can only be selected if benchmarking data is available and based on trusted methods. The opportunity to produce exciting new hybrid materials or heterostructures, based on stacked combinations of atomically thin 2-D materials needs to be underpinned by new metrology relevant to these systems.

The UK Graphene Special Interest Group managed by Innovate UK have assessed the priorities for the UK and the relevance of each project work package to these is shown in the table below.

Innovate UK: GRAPHENESIG strategic development areas	NPL SC Project					
	WP1	WP2	WP3	WP4	WP5	WP6
Structural bulk materials (composites)	X			X	X	
Conductive bulk materials (electrical & thermal)	X		X	X	X	
Coatings (electrical conductive, thermal conductive, barrier)	X	X	X	X	X	
Membranes (separation, barrier)	X		X	X	X	
Energy storage	X			X	X	
Printed electronics & conductive layers	X	X	X	X	X	
Optoelectronic devices	X	X	X	X	X	X
Semiconductor electronics	X		X	X	X	X
Sensors	X	X	X	X	X	
Biomedical functionality	X	X	X	X		X

Table 1 UK Graphene SIG work streams related to project work packages

The relevance of the work packages in this project to the Flagship, which NPL is a partner in, are shown in table 2. The European Graphene Flagship project has a number of priorities that are synergistic with the UK GrapheneSIG work streams. NPL will therefore use the work packages here to exploit these synergies for the benefit of the UK partners in this project. This will accelerate standardization, expand the database of comparable data and enable agreement to be reached across, sectors and Europe to ensure a well-functioning European supply chain.

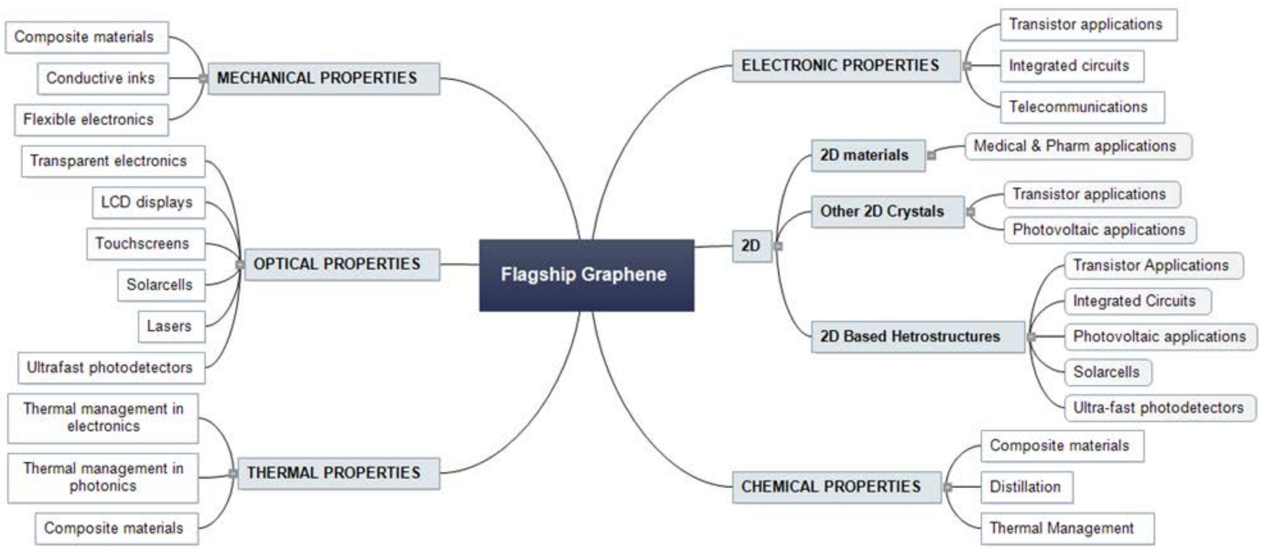


Figure 1 European Flagship Graphene priorities and application areas & NPL Graphene project alignment

Flagship Graphene	NPL SC Project					
	WP1	WP2	WP3	WP4	WP5	WP6
Electronic Properties	X	X	X	X	X	X
2D (Materials, Other 2D Crystals & 2D Hetro structures	X	X	X	X	X	X
Chemical Properties	X			X	X	
Thermal Properties	X		X	X	X	X
Optical Properties	X	X	X	X	X	X
Mechanical Properties	X	X	X	X		X

Table 2 Flagship Graphene priorities related to project work packages

(b) What is the track record of the Research Team?

Dr. T.J.B.M. Janssen, NPL Fellow, is an expert in solid state physics and all aspects of quantum electrical metrology, author of over 100 publications. He has formulated/led a range projects under FP4, 5, 6, and 7. He is the chair of the DC and Quantum Metrology working group of the Euramet TC-EM.

Prof. A. Tzalenchuk, Principal Research Scientist, is an expert in solid state physics and quantum electrical metrology, author of ~90 publications, and a Professor at RHUL.

Dr. O. Kazakova, Principal Research Scientist, is an expert in graphene and 2-D materials and functional SPM techniques. She co-authored more than 100 publications. She has been a WP leader and/or PI in a large number of internal and external projects with a total portfolio of ~ €5M (NPL's share over last 5 years), including participation in 4 EMRP projects. During last 3 years she has also been actively involved in scientific organisation and management of large conferences (~2000 participants).

Prof. L. Hao, Principal Research Scientist, is an expert in metrology of microwave measurements, author of ~120 publications. She is a Fellow of the UK Institute of Physics and a Visiting Professor in the Materials Department at Imperial College, London.

Dr. Toby Sainsbury is a senior research scientist in the Functional Materials group at NPL, researching into the chemical functionalization and manipulation of the surface chemistry of carbon nanotubes, graphene and related 2-D nanomaterials, applied towards the development of nanoelectronic components, sensor platforms, nanocomposites and energy storage materials. Toby has previously worked for nanotechnology start-up companies in the UK and in Silicon Valley, in the chemical industry in Germany and Ireland and completed three post-doctoral fellowships in Ireland and the US.

Dr Andrew Pollard's area of expertise is the chemical and structural characterisation of graphene and 2-D materials (defects and contamination). Andrew has a particular focus on the industrial applications in this field, which requires extensive industrial collaborations to understand and overcome the challenges they face in the real-world commercialisation of 2-D materials. He has published several high-impact publications and has been invited to give presentations at both national and international conferences. He is on the Advisory Board of the Graphene Stakeholders Association and leads NPL's work in international standardisation for graphene and 2-D materials.

(c) **Why should the work be funded by Government?**

Although, the UK government is already supporting R & D in graphene through the National Graphene Institute, And GEIC (University of Manchester and through many other academic research projects via the EPSRC **the pioneering science developed through these programs can only be translated into commercial benefits if there is a coherent measurement infrastructure in place**. Government therefore needs to also support the development of metrology capability that enables the markets and supply chains.

'Advanced materials' is one of the UK Governments eight great technologies and capability in materials science and engineering is a key enabler of industrial innovation. 2-D materials are a platform technology that can drive innovation across industry sectors to stimulate economic growth and can be applied to a number of key government challenges that require innovation, for example, energy, healthcare, environment, the digital economy and security. Given the widespread interest in these materials, coordinated action on the topic of measurement is required and can best be led by NPL as the UK's National Measurement Institute (NMI), with research capability and leadership responsibility for metrology in the UK, but also as the lead NMI in this area in Europe.

Vision

(a) Long term vision (over lifecycle of Capability development)

"The long term vision is to develop industry relevant standardized methods to benchmark graphene and 2D materials to enable the supply chains to function and the market in these materials to grow".

The long term aims are to deliver to industry the metrology capability and standards that they require to be able to use graphene as a "gradable" and tradable commodity for exploitation like steel or semiconductor materials. The metrology will be demonstrated to, and standardised by, these partners to enable the provision of validated data and **metrology knowledge as part of a Graphene core competency for organisations and supply chains**. This approach has been taken based on industry views of the development of Graphene such as the Organic Large Area Electronics (OLAE) vision of "**Bringing together actors along the value chain so that they can define key performance production parameters, run experiments to further improve manufacturing processes or explore the design and development of new manufacturing processes".**

Standards have been shown to be key to bringing together these actors and delivering commercial success. At a strategic level the AFNOR report [2] states that **"whoever sets the standard also makes the market**" with 71.2% of organisations surveyed using standardization to anticipate future market requirements and as an input to decisions on innovation. This is reinforced by evidence [3] that standard setting and benchmarking increases the success of patented technologies

The vision for this capability programme is to enable industry to:

- Make direct comparisons between graphene-based materials from different sources, devices produced by the different companies and by different techniques, and to enable producers to make available graphene that is consistent from batch-to-batch.
- Use agreed best measurement practices for the many different relevant properties (e.g. electrical, chemical etc.) to accelerate the commercialisation of 2-D materials through standardisation.
- Make available agreed benchmarked properties of industrially-relevant graphene materials, leading to investment and innovation in viable real-world applications areas

- Develop other 2-D materials in application areas due to the enablement of comparison across this class of materials

The first phase of this strategic capability development (see appendix 1) has already led to the appointment or secondments of researchers from institutions based in the UK and world-wide, from Universities, graphene companies and national research laboratories. NPL is both nationally and internationally renowned for world-class measurement capabilities over a wide range of research areas, which positions NPL as a 'one-stop shop' for characterisation and leads to interest and collaboration from graphene producers' world-wide. Academics that are typically specialised in one field or technique also understand the benefit of NPL's expertise in measurement science and recognise the importance of the accuracy and clarity. In the graphene field alone, a prime example of this is the XPS capability and expertise at NPL, which has led to collaborations with industry users in the UK and US, as well as the University of Oxford, Cambridge and Manchester.

The continuation in funding for this strategic capability will sustain the critical mass achieved in some parts of this research area through previous funding, as well as initiating newer areas of research at NPL at the forefront of industry's needs, allowing this metrology area to constantly evolve and adapt to this fast-paced field of research.

(b) Vision for this three-year project segment

The approach taken in this project is to integrate the parallel development of measurement methods with technological progress on graphene and 2-D materials rather than a serial method which would delay delivery to market. The end-user companies in application areas such as (flexible) electronics, optoelectronics, energy storage, sensors and composites (sometimes with added functionality), require graphene production companies to have real measurement capability to give end-users the confidence to investment in the commercial exploitation of 2-D materials. The project team are already working with SME's and Industry (see benefits) and these partners will form the industry project Industry steering board (WP7) which will give independent advice on the delivery of metrology.

The vision is to Establish NPL as the international graphene metrology center in partnership with other key players, in particular the National Graphene Institute. This will enable the commercialisation of graphene and 2-D materials through the translation of the fundamental science of metrology into the protocols and standards that gives the confidence and traceability essential for innovation and trade.

Novel instrumentation is required for Quality Control (QC) characterisation of these materials now they are being produced in large-scales, techniques that are both faster and larger in scale than current methods. This will reduce costs and allow high-throughput whilst also ensuring conformity and consistency in industrially-produced 2-D materials, a key enabler for any manufacturing supply chain. These techniques can only be developed through rigorous testing and validation using current state-of-the-art measurement methods, already developed at NPL for the structural, chemical and electrical characterisation of graphene and 2-D materials. Development of IP including that related to the microwave techniques created in the previous Metrology for Graphene project will support relationships with instrumentation provides to deliver new measurement technology to industry.

Existing and new characterisation methods need to be more fully understood for these challenging materials to help bridge the gap between academic research and real-world products. The correlation between different types of properties on length-scales ranging from the macroscale to the nanoscale, for example, how the chemical changes in the material due to functionalisation or contamination change the electrical properties of the material, needs to be better understood using efficient and reliable methods. Collaborations with key academic and industry partners will enable NPL to continue to develop the metrology science in this area and enable the determination of the suitability of these materials for the targeted applications.

State-of-the-art characterisation of 2-D materials and associated applications are still confined to laboratory experiments. By developing a range of measurement techniques, both established and new, NPL will bridge the metrology gap between academic research and real-world applications in areas of core NPL expertise, developing current techniques as explained for each work package in this project.

The project therefore focusses on the issues required to deliver the commercial potential of graphene and 2-D materials in competition with other technologies to support the UK Graphene SIG work streams in synergy with the Graphene Flagship project by:

- Delivering metrology tools to understand the basic science behind the performance of graphene-based materials
- Providing the capability to measure and then correlate different material properties in terms of their effect on product performance and lifetime
- Standardisation of industrially-relevant chemical and structural evaluation methods
- Developing novel and efficient metrology approaches to understand the functionalization of graphene and its

interfaces for composite materials , barrier coatings, and thermal management

- Using the above to enable benchmark data to be provided for design innovation, manufacture and quality control

Size of potential Markets

Printing technologies provide early opportunities to exploit 2-D materials as it is likely that inks can be produced in in the quantities required but the quality needs to be guaranteed**. The Functional inks market** is growing at 22% per year based on printable electronics processes and worldwide will be $14B by the year 2020. These offer low temperature processing, compatibility with several prints processes, and ruggedness. The main target applications are RFID, photovoltaics, batteries, displays, medical devices, lighting and smart packaging. **The composite sector** can use graphene as a high value additive to increase toughness and strength (by 100%) or create multi-functionality beyond just structural applications for example using electrical conductivity, thermal conductivity, or impermeability in new ways. Graphene's superb electrical conductivity and large surface area per unit mass make it an exciting material for **energy storage applications** such as advanced batteries and supercapacitors, which will have a large impact on portable flexible electronics and electric cars. In **optoelectronics** the touch screen application is expected to be one of the first to be commercialized, because the choice of materials is quite limited requiring transparency and high electrical conductivity. Other key markets and the impact of the project are outlined in table 2.

Sector	Annual Market estimate $Bn	Production quality to grade	Electrical / Optical performance	Mechanical performance and adhesion	Reliability and lifetime	Impact
Graphene producers	205 tons (2013) $10M.	High	High	High	High	Ability to trade graded graphene as a commodity.
Printable electronics	77 (2023)	High to medium (performance) High (consistency)	Medium to High	High	High	Improved reliability and design innovation using valid data
Functional composites	1.2 (2018)	Medium	Medium	High	High	Critical to realising technical from the performance in products
Sensors	154 (2020) 32 Biochemical	High to medium performance High for consistency	High	High	High	Reliability, performance and lifetime for commercial success
Flexible power	1.21 by 2017	High	High	High	High	Critical process control of quality and lifetime
OLAE (Organic Large Area Electronics)	50 (2020)	High	High	High	High	Achieve strategic aims of sector

Table 3 Relevance of project to commercialization in World Markets

(c) Contributions to Metrology

Beyond the very early uses of measurements in the discovery of interesting properties of 2-D materials' exploitation on a commercial basis will require a high metrology component similar to that in the semiconductor industry where the measurement content from R+D through to production is higher than in other sectors. These communities are often "ready, willing and able" to adopt new metrology as soon as it is available and have the requirements already highlighted on roadmaps (International Technology Roadmap for semiconductors, Flagship Graphene). The project will therefore deliver new capability directly to these communities expanding their metrology capability.

The demand for measurement services related to Graphene is increasing as more companies initiate research and development programmes and production ramps up. In order to deliver the capability on the scale that Europe requires this project will deliver knowledge transfer to the three most important metrology communities 1) Achieve a critical mass of expertise in different experimental techniques across the European NMIs 2) engage with commercial laboratories who can service industry 3) form alliances with R+D partners to inject validated metrology into research at the point of innovation (e.g. with Manchester University Graphene Institute.)

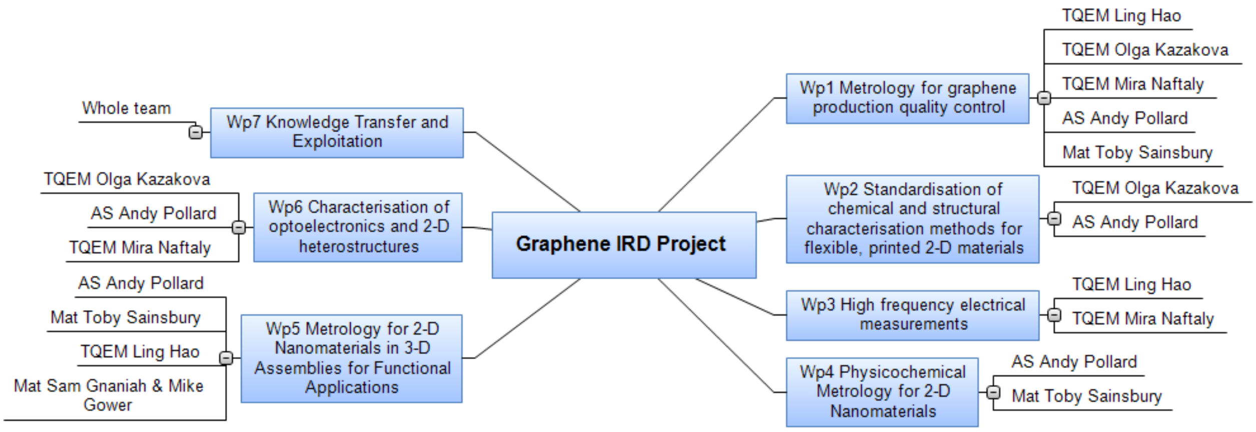
All of the techniques developed in this project require high quality instrumentation some of which can be supplied by UK companies to international markets. Whilst purchasing companies have the capital available for the equipment the time and investment required to develop the know how to make measurements and train staff can be higher than the capital cost. The project will provide support to UK instrumentation companies in transferring this know how as unique selling point to their customers and NPL is already working with Oxford Instruments on the development of instrumentation.

A community of European scientists and engineers with the capability to develop capability in materials production, flexible systems, nanocomposites, and optoelectronics is being developed by the European Flagship Project. NPL is already a member of the Flagship Graphene team and NPL will exploit the knowledge transfer opportunities offered through its membership to bridge the “metrology gap” and ensure that the community developed is also “metrology capable”. A proposal will be submitted to the current Industrial call of the EMPIR programme and this will co-fund some of the work in this project and enable dissemination and collaboration across National Measurement Institutes to underpin an internationally agreed metrology framework for 2-D materials.

Project Scope

The project will deliver new measurement capabilities for graphene and 2-D materials that have been determined through consultation and are outlined in the European Graphene Flagship project in the following application areas :

- Quality Control
- Printed/flexible electronics
- High frequency electronics
- Optoelectronics
- Nanocomposites and 2-D and 3-D structures
- 2-D heterostructures



Work Package 1: Metrology for graphene production quality control

Aim - This work package will provide metrological solutions for rapid and reliable electronic, optical and structural characterisation of graphene and related 2-D materials.

Specific Measurement Need - At present, a number of preparative techniques are used in order to synthesise and fabricate graphene and related 2-D materials to various dimensions, configurations and performance. As the front-running 2-D material, graphene has had considerable industrial development in the pursuit of two key metrics: (i) large area and (ii) low defect density. In conjunction with the industrial pursuit of these metrics, it is essential that there exists defined metrological techniques and protocols for the accurate and traceable validation and standardisation of such 2-D materials which, importantly, may be performed at a rate applicable to industrial production and at viable cost. At present, such techniques do not exist in a manner required by industry, hindering effective quality control (QC) processes. The development of rapid metrological techniques and standardisation for graphene would allow the comparison of both stand-alone and batch-to-batch production and will play a key role in validating graphene as a disruptive technology platform for real-world devices. Electrical transport in graphene is also strongly affected by a large number of external and internal parameters, such as degree of structural uniformity, number of layers, influence of environmental/airborne adsorbates and interaction with the substrate.

State of the art - Analytical techniques which may conventionally be used to characterise the structural and electronic properties of graphene include Raman spectroscopy, scanning tunnelling microscopy (STM), atomic force microscopy (AFM) and transmission electron microscopy (TEM). These techniques offer extremely high quality analytical capability under specific conditions. However, these techniques are expensive, time consuming, require specialised sample preparation and are only feasible for discreet sample geometries. Alternative electrical characterisation of graphene, within a device configuration, typically requires expensive facilities and infrastructure and is coupled with additional issues surrounding the impact of contacts, substrate, contamination and environmental effects. It is therefore clear that there exists a growing need for the development of novel metrological methodologies and techniques which offer solutions to the cost, spatial resolution, through-put and relative ease of analysis for graphene and related 2-D materials. In view of these factors, it is imperative that metrology surrounding 2-D materials is focussed on the development of novel alternative techniques which support the standardisation and traceability of materials. Such techniques would serve to complement both the development of academic and industrial research and to accelerate the fundamental understanding of material platforms which form the technological basis for commercially viable products and technology infrastructure.

Metrology Solutions - In order to address the measurement needs we propose development of rapid, non-contact and non-invasive electrical and structural characterisation methods. The main objective is to develop these methods and subsequently validate them by correlating the results achieved with current state-of-the-art electrical and structural characterisation of graphene-based materials. To achieve this we propose a combination of novel and well-established methods and techniques:

- Rapid, (quasi-)contactless measurements of essential electrical parameters (sheet and contact resistance, R_s=1-10^4 Ohm/sq; carrier concentration, n=±10^{14} cm^{-2}; mobility, 10-10^6 $cm^2V^{-1}s^{-1}$; work function, etc.) using microwave resonance. There is a significant industrial interest in this technique, allowing measurements of key electrical properties without a need of expensive and lengthy device fabrication.
- Validation of QC measurements through 'standard' magnetotransport and local electrical (SKPM) measurements.
- Correlation of measurements to structural properties, and understanding of how the change in these properties affects the results obtained with new methods. E.g. using microwave (electrical) and Raman (structural) techniques.
- Determine how nanoscale changes in properties directly influences macroscopic measurements.
- Correlation of electrical transport and local electrical measurements under controlled environmental conditions, *i.e*. T= -30/+150 ^oC, RH=0-90%, N_2, O_2, NO, NO_2, atmospheres.

Work Package 2: Standardisation of chemical and structural characterisation methods for flexible, printed 2-D materials

Aim To provide the metrology to benchmark and develop the performance and durability of 2-D materials for flexible and printed electronics

Specific Measurement Need - The factors that affect the required electrical and optical performance of 2-D materials need to be understood if flexible, printed electrical devices based on 2-D materials are to be brought to commercial markets. To enable this, the nanoscale structural and chemical variations in 2-D materials, inks and printed films need to be understood and compared to the resultant electrical properties. These measurements and comparisons must also be performed in conjunction with mechanical and durability test methods to understand the degradation and ageing of benchmarked performance characteristics.

State of the art - The measurement of standard electrical properties of flexible and printed electronics are well established, but the currently available methods for structural and chemical characterisation have not been systematically applied to this application area. Degradation processes are understood at the macroscale or product level but development is only possible by combining electrical, chemical and structural characterisation to enable understanding of changes at the nanoscale. Academia has so far focused on the discovery of novel properties but industry requires this complementary approach for flexible and printed electronics to benchmark products.

Metrology Solutions - This work package will demonstrate the following suite of tools to benchmark flexible and printed electronics:

- Techniques to characterise structural properties of 2-D layers and flakes (thickness, lateral size, orientation and stacking of individual graphene flakes, number of layers)
- Methodologies for mapping structural and chemical variations of large-scale and patterned printed electrodes and their relation to the changes in optical and electrical properties, using techniques such as AFM, SEM, Raman spectroscopy, ellipsometry, XPS, SIMS.
- Methods for the benchmarking of electronic properties of competing 2-D materials, to allow comparison with incumbent ITO and other possible disruptive technologies (silver nanowires, PEDOT)
- Protocols for lifetime assessment - Development of methods for measuring lifetime and degradation of flexible electronics in different environments with mechanical deformation incorporating electrical property assessment with mechanical testing.

Work Package 3: High frequency electrical measurements

Aim -The aim of the work package is to provide metrology for the characterisation of graphene and other 2-D materials for high frequency electronic applications by developing new measurement methods capable of measuring the performance of 2-D materials in the GHz to THz frequency range.

Specific Measurement Need - Graphene and other 2-D materials have a great potential for high frequency electron applications such as RF amplifiers, frequency doublers, mixers, field-effect transistors, RF antenna and detectors. The performance of high frequency electronic devices may greatly improve due to the high mobility, high carrier velocity, symmetrical ambipolar conduction and high thermal conductivity of graphene and other 2-D materials. Experimentally however the microwave devices based on graphene have mostly been tested at low frequencies and their performance extrapolated to high frequencies using numeric de-embedding procedures. These procedures rely on the knowledge of material parameters at the specific frequencies. The performance of 2-D devices depends sensitively on the extrinsic perturbations due to microstructures, adsorbates or the substrate for example. In addition, high frequency devices require well-characterised thermal properties as well as high mobility and conductivity. This has become clear as the CMOS limitations are now often thermal in nature, rather than electrical. The need for encapsulation of high frequency devices will also need to be addressed before they can be commercialised since graphene electronic properties can be significantly altered by exposure to trace quantities of gases or even humidity. The high-frequency properties and behaviour of graphene materials, influence of substrates and environment on the mobility, carrier density and thermal conductivity must be determined and understood in order to successfully design high-frequency graphene electronics which fully exploit its unique characteristics. Moreover, robust metrological methodologies need to be established so as to enable reliable inter-comparisons of materials and fabrication techniques.

State of the art - The characterisation of the graphene surface impedance at microwave to THz frequencies is usually carried out using coplanar waveguides (CPW). This approach requires microfabrication to pattern the CPW structures on the graphene. This process may modify the intrinsic properties of graphene, or influence the contact resistance between the graphene and metal strips. This provides the impedance value but does not give an indication of the mobility and thermal properties of the material. New measurement capabilities, especially non-contact, non-invasive methods are needed to measure the mobility and thermal properties as well as the impedance of graphene and other 2-D materials for use in industry. Industry may assess the quality of their high quality, large scale materials for applications in the high frequency electronics.
Measurement of optical constants of materials at THz frequencies using time-domain spectroscopy is a well-established technique that has been applied to a wide variety of substances. Likewise, the derivation of material properties from this data is well-known. Although a number of studies have been published presenting measurement results on individual graphene samples, no systematic work has been carried out on a defined range of 2-D materials (such as MoS_2) and their substrates, especially in relation to high-frequency electronics. Such work is required to establish the dependence of material properties on the fabrication processes. Robust metrology is at present generally lacking in THz spectroscopy, and therefore requires to be established for any industrially relevant measurements.

Metrology Solutions

- Extend the microwave resonance measurement method to enable measurement of carrier density and mobility using non-contact microwave Hall effect.
- Investigate microwave methods for thermal characterisation of graphene and other 2-D materials.
- Determine the THz optical constants of 2-D materials and their substrates at frequencies of 0.2-3 THz using time-domain spectroscopy.
- Establish a robust metrological methodology for such measurements.
- Use the measured optical constants to derive material properties, e.g. conductivity, relaxation times, carrier lifetimes and mobility.
- Relate the optical constants of materials to their structure and composition, thus developing a material characterisation tool.

Work Package 4: Physicochemical Metrology for 2-D Nanomaterials

Aim - To develop metrology tools to characterise the chemical bonding that forms the functional interface in 2-D nanomaterials and within 3-D assemblies, hybrid structures and nanocomposites.

Specific Measurement Need – The chemical interface between materials is one of the fundamental parameters for the utilisation of graphene and 2-D nanomaterials within functional materials and composites across many technological applications. The large-scale bulk-quantity processing and manipulation of 2-D nanomaterials will require controlled chemical compatibilisation and integration strategies in order to form optimal interfaces within intended host matrix materials and solvent systems to enable the development of such applications. Consequently, chemical manipulation of this interface is viewed as a critical enabling technology towards the application of 2-D nanomaterials within commercially relevant sectors such as the global petrochemical industry and derived sectors. There exists a pertinent need to measure precisely the nature of the chemical interface of 2-D nanomaterials. Therefore, chemical metrology for 2-D nanomaterials is required in order to underpin the validation of pristine and chemically derived forms of 2-D nanomaterials and enable traceable research and development through standardization.

State of the art for this need – The chemical functionalization of 2-D nanomaterials is conventionally characterized using combinations of spectroscopic and scanning and electron microscopy techniques. Such characterization techniques are typically non-quantitative and are seldom utilised in a combined fashion in order to form rational understanding of structure-property relationships to optimise design and processing. Techniques are therefore required to provide a reliable indication of the precise location and concentration of chemical functional groups to meet the growing need to control functionalization of 2-D nanomaterials and relate this directly to resulting electrical and thermal properties, mechanical performance, chemical stability, and lifetimes

Metrology Solutions - This work package will develop the physicochemical metrology to characterise the chemical bonding and interactions that produce an effective functional interface. The focus of the work is the determination of chemical composition in terms of the specific nature of the chemistry and location of atoms and molecular groups on the surface of pristine and functionalized 2-D nanomaterials. The new expertise to be developed is the characterization of the chemical composition as a fundamental metric for the assessment of 2-D nanomaterial performance at the nanomaterial interface and will be cross checked against the material bulk properties (mechanical, thermal and electrical) in nanocomposite applications using existing expertise. Molecular modelling techniques will be investigated to examine the nature of the interfacial bonding interactions and to elucidate material performance based on a detailed understanding of the nanomaterial-matrix interface in combination with experimental investigations.

Specifically, approaches in this work package will involve the following:

Physicochemical Metrology

- Determination of the precise chemical bonding structure, location and concentration of intrinsic and engineered surface functional groups, e.g. Graphene and graphene oxide, h-BN and OH-h-BN.
- Development of physiochemical methodologies to measure processing and exfoliation parameters for 2-D nanomaterials as a function of surface chemistry.
- Collaborative research performed with established stake-holder companies to facilitate industrially relevant characterisation and analysis of 2-D nanomaterials: chemical functional group quantification e.g. Haydale, 2-D Tech, Applied Graphene Materials, BAE, and Thales.
- Development of analysis and in-line processing metrology dictated by industrial need, e.g. BAE, Thales, Hexcel, Huntsman, Henkel.
    - Dispersion analysis: electrochemical in-line monitoring.
    - Rheological analysis: in-line viscosity characterisation.

Chemical Performance:

- Establishment of measurement methodology to characterise wettability, chemical resistance and barrier function of 2-D nanocomposites as a function of chemically engineered surface interfaces.
- Development of metrology for assessing gas diffusion barrier properties of nanocomposite systems.
- Correlation of cosmic and UV radiation shielding and protective function of functionalized 2-D nanocomposites with nanomaterial loading and chemical functionality.
- Development of complementary theoretical simulation and models which relate 2-D nanomaterial loading within a composite to gas barrier and radiation shielding performance.
- Development of and validation of metrology techniques for collaborative research projects with MoD DSTL, BAE systems, Thales, Airbus-Astrium and ESA for development of advanced chemically functional composites for de-icing, anti-fouling, hydrophobic surfaces and coatings for industry defined applications.
- Development of industrially applicable chemical metrology for 2-D nanomaterial composites: chemical stability and life-cycle analysis.

Core capabilities developed within this work package will form the basis for the rational understanding of chemical functionalization approaches towards efficient 2-D nanomaterial utilization. Physicochemical metrology developed as part of this work package will serve as framework for nanomaterial analysis and to directly relate surface chemistry and interfacial integration of 2-D nanomaterials to material performance.

Work Package 5: Metrology for 2-D Nanomaterials in 3-D Assemblies for Functional Applications

Aim - To develop metrology tools to validate the relationship between physicochemical functionality and performance in applications using 2-D Nanomaterials .

Specific Measurement Need – The translation of intrinsic material properties of 2-D nanofiller materials across an interface to bulk matrices or substrates requires optimized compatibilisation between materials. Efficient translation of mechanical strain, thermal energy, and electrical potential through a nanocomposite or across a material interface may be achieved by tuning the chemical composition and hence the surface energy of a nanofiller material. There exits a growing need to determine the factors which dictate the efficiency of the interaction. Basic dispersion of pristine 2-D nanomaterials within material matrices needs to be compared with advanced integration strategies. These include manipulation of surface chemistry and concentration in order to facilitate either direct covalent binding or physical interaction as well as the formation of percolation networks. The development of mechanical, thermal and electrical 2-D nanomaterial composites requires traceable studies which can compare and contrast the performance of the materials as a consequence of chemical composition and the type of nanofiller used.

State of the art for this need – The analysis and characterisation of 2-D nanomaterial composites will require traceable and reproducible measurement techniques in order to compare and contrast variability in the nanofillers used and to benchmark against conventional materials. Mechanical and thermal measurement of composite materials is conventionally performed using standardized methodology according to traceable international standards. 2-D nanomaterials may be screened across material production method, type and degree of surface chemistry, nanofiller concentration and mix ratios. The development of new measurement methodologies will be achieved utilising a combined approach including materials characterisation, materials modelling and materials performance evaluation. In this manner, industrially relevant capability will be developed by a cross-divisional approach and will serve as a framework for evaluation of future emerging materials.

Metrology Solutions - This work package will develop metrology to characterise the impact of the interfacial nanofiller-matrix interactions in the context of mechanical, thermal and electrical performance in 2-D nanomaterial composite systems. New measurement expertise will be developed from the preparation of 2-D nanomaterial composite systems in which the key parameters controlling material performance can be assessed. These parameters will include the physical makeup, the chemical composition and the method of material production. In this way, building on quality control methodologies and analysis developed in Work Packages 1 and 4, this Work Package will develop methodologies to assess the material performance in a traceable and comparative fashion. Molecular modelling techniques will be utilized to examine the nature of the interfacial bonding interactions and to elucidate the mechanism of mechanical performance based on a detailed understanding of the nanomaterial-matrix interface in combination with experimental investigations. This will be supplemented by addition molecular modelling in order to determine the impact of 2-D nanomaterial attributes and processing methodologies on thermal and electrical performance. Specifically, approaches in this work package will involve the following:

- **Mechanical Performance:**
- Demonstration of novel metrology approaches to understand the impact of surface chemistry on the interfacial mechanical properties of 2-D nanocomposites and it's translation to the bulk material. E.g. epoxy binding to surface COOH groups.
- New metrology for the combined experimental and theoretical investigation of fundamental physical parameters for individual 2-D nanosheet materials, including modulus and strength determination on the nanoscale. Investigation of the impact of chemical functionalization on intrinsic mechanical properties.
- Development of experimental techniques to Investigate advanced wear, lubricity, friction and adhesive properties of functionalized 2-D nanocomposites as a function of surface chemical functionality combined with modelling validation.
- Development of methodologies to assess rheological and processing parameters for 2-D nanomaterial-fluid systems as a direct function of engineered surface chemical groups.
- Collaborative research with industrial partners in aerospace, defence and energy sectors to perform industry requested development of toughened lightweight nanocomposites for harsh operating environments. E.g. Airbus, EADS-Astrium, MoD, Vestas, Shell, BP.

Electrical Performance:

- Establishment of measurement techniques to assess the electric, dielectric and electrostatic performance of 2-D nanomaterials as a function of chemical functionalization.
- Development of industry requested metrology for the investigation of frequency dependent behaviour of 2-D nanocomposite systems as a function of 2-D nanomaterial composition and surface chemistry.
- Engaging with industry to develop measurement services, protocols and methodologies for electrical measurement of electronically active nanomaterials. e.g. measurement services for Thales.
- Participation in joint development of concept nanomaterial platforms with industrial partners. E.g. CDE project with BAE systems: 3-D printed conductive composites.

Thermal Performance:

- New metrology to determine the impact of interfacial chemical bonding structure on thermal performance of 2-D nanocomposites for thermal management heat-sinking and radiative cooling applications.
- Development of techniques to measure advanced chemically engineered interfaces for ablative and extreme thermal tolerance environments for 2-D nanomaterials.
- Collaborative research with industrial partners targeting relevant applications of thermally conductive nanocomposite materials including joint development of measurement methodologies. E.g. Airbus Defence and Space, ESA, MoD.

Methodologies and protocols developed in this work package will enable the development of tougher stronger composites, improved heat-sinks and thermal management systems, improved smart conducting inks and new forms of chemical filters and sensors. The techniques developed to understand nanomaterial interfaces can be used in complimentary ways for the development of novel multifunctional interfaces, such as solar cells, energy harvesting materials or thermo-mechanical structures for example in satellite technology.

Work Package 6: Characterisation of optoelectronics and 2-D heterostructures

Aim -To develop metrology for characterising 2-D heterostructures and advancing optoelectronics applications of these structures.

Specific Measurement Need - Beyond graphene, there is a growing family of layered materials, such as boron nitride and molybdenum disulphide, which can be exfoliated down to a few layers or even a single-layer. By physically stacking different single- to few-layer 2-D materials (both graphene and others) onto one another, 2-D heterostructures with different functional layers can be created. This new and exciting area of research in nanomaterials is now being heavily investigated due to the ability to partner and/or enhance the exceptional properties of different 2-D materials, with many electronic and optoelectronic applications being envisioned, such as new atomically thin transistors and optoelectronics. However, there are many challenges before these materials structures can be commercially viable due to the recent emergence of these materials; challenges include polymer/ambient contamination between layers and orientation of the different layers.

Graphene itself also shows remarkable optical properties. For example, it can be optically visualised, despite being only a single atom thick. Its transmittance can be expressed in terms of the fine-structure constant. The linear dispersion of the Dirac electrons makes broadband applications possible. Saturable absorption is observed as a consequence of Pauli blocking, and non-equilibrium carriers result in hot luminescence. Chemical and physical treatments can also lead to luminescence. These properties make it an ideal photonic and optoelectronic material, which industries are trying to commercialise. The optical properties of graphene depend sensitively on the carrier density introduced by doping. Measurements of optical absorption and carrier lifetime are necessary in the broad spectral range and in correlation with the local structure and chemistry for both graphene and other 2-D materials.

Of particular interest for optics and optoelectronics are the heterostructures consisting of 2-D semiconductors with direct bandgap, such as monolayer MoS_2, for example hBN/Gr/MoS_2/Gr, which allow development of extremely efficient flexible photovoltaic devices with photoresponsivity above 0.1 A/W (corresponding to an external quantum efficiency of above 30%). Devices based on these materials have passed the proof-of-principle stage. Commercialisation of 2-D optoelectronics requires reliable determination of optical properties enabling a comparison with more conventional materials.

State of the art - Heterostructures are primarily prepared using the mechanical exfoliation technique, which is currently only suitable for research investigations. However, promising optoelectronic devices based on mechanically exfoliated graphene and other 2-D materials have been demonstrated. Little systematic work has been carried out on heterostructures and correlation of the electrical properties of these materials with defects, local chemistry or doping inhomogeneity is required if the viability of these structures for real-world applications is to be proven. Although NPL has the measurement capability required to advance 2-D heterostructures, there has not yet been any research in this area, and thus this area needs to be developed so that NPL is positioned to provide metrological solutions for industry as these materials move higher in TRL.

Metrology Solutions

This work package will perform the following tasks:

- Develop capability, in collaboration with leading academic groups, of creating bespoke 2-D material heterostructures for characterisation experiments
- Determine the local properties of 2-D material heterostructures, including local structure and disorder, work function, doping and chemistry, requiring the development of techniques such as AFM, STM, SKPM, SIMS and TERS.
- Show the optoelectronic characterisation of graphene, other 2-D materials, heterostructures and devices with 10 nm spatial resolution using PC-AFM, SNOM, and THz microscopy and spectroscopy.
- Measure carrier lifetimes directly by time-resolved pump-probe reflectometry. A near-IR femtosecond laser will be used as an interband pump, whereas the probe may be either near-IR or THz, revealing different aspects of carrier behaviour far and close to the Dirac point respectively.

Work Package 7: Knowledge Transfer and Exploitation

Independent Steering Board - A steering board will be formed to ensure that project outputs are tailored to be useable by industry and that the science quality is competitive internationally. This board will consist of industry, academic and NMI partners as well as representatives from the Innovate UK, Graphene SIG and the Graphene Stakeholders Association (GSA). Meetings at 9 month intervals and chaired independently, the group will provide a regular update on industry needs as they develop. NPL is closely involved with the UK Innovate Special Interest Group and GSA and sits on their leadership group and advisory boards respectively, which will enable a direct link to the steering board.

Web presence, new media and publications – NPL will develop a 2-D Material Measurement web space as the "go-to" place for information on measurement for these materials, linked to professional social media options such as LinkedIn, to provide an interactive e-space for academia and industry. The site will provide updates on the work that has been done and access to the outputs, access points for participation in events

Scientific publications
Scientists will aim to publish peer-reviewed research performed in this project in the highest impact-factor journals possible, building on the current track record of the team, who have published in distinguished journals such as Nature Nanotechnology, and other NPG, ACS, AIP, RSC and IoP journals.

Standardisation
There is agreement across industry that there is an urgent need to produce standards for the characterisation and measurement of properties of graphene to support trade, and to provide traceability for benchmarking and data. These cannot be agreed until the underpinning research is performed, and thus can be directly addressed in this project, which will focus on the metrology needed for standardisation of the characterisation of these materials. This project will provide best practice guides, protocols and advice on progress to accelerate the delivery of standards, acting as a conduit for members of the project research team support the following international standardisation committees:

- BSI/NTI/1: Nanotechnologies
- ISO/TC229: Nanotechnologies
- IEC/TC113: Nanotechnology standardization for electrical and electronic products and systems

NPL is already leading a developing standard in Joint Working Group 1 (JWG1) of ISO TC229 and IEC 113 on the vocabulary for 'Graphene and other two dimensional materials'. This will define material terms such as two-dimensional materials, few-layer graphene, etc. It will also define the terms associated with methods to produce 2-D materials.

NPL is currently engaging with other stakeholders in the international community to understand the needs of other standards in this area, which can directly influence this project, with outputs leading to significant contributions to international standardisation. The outputs of this project can also contribute to other graphene standards (committee TC229) in development such as a technical report, led by NIST (USA) and KRISS (Korea) NMIs, on measurement methods to characterise graphene, which will contain a matrix linking graphene characteristics to the measurement methods needed to characterise them.

In addition the outputs will be provided to the Graphene Flagship standardisation group who will have representatives on this project steering group. This will ensure that both the outputs of this project and the Graphene Flagship will be incorporated into international standardisation efforts.

Demonstrator 1 Sensors- The aim is to establish and demonstrate capability to comprehensively characterise performance of a type of sensor based on graphene and supplied from industry. Although the field of sensing is extremely wide, by concentrating on one type of sensor the use of the metrology developed here can be demonstrated to industry. The likely candidate will be based on the graphene field effect transistor, functionalised to give a specific response to a specific input, whether it is a chemical, VOC or biological species in an assay. This full-characterisation and correlation will require the use of nanoscale chemical, structural and electrical surface mapping being developed in other WPs in this project.

Given the almost ubiquitous interest in Graphene the approach taken will have widespread uptake but focussed engagement will create impact in these important sectors

Demonstrator 2 Electrochemical Evaluation of Graphene Flakes for Energy Storage -Graphene and similar derivatives such as graphene oxide and defective/activated graphene, have been targeted by industry as possible components for energy storage products, such as supercapacitors. This application area is of extreme importance globally, as the areas of electric-powered transportation and mobile devices are receiving high-profile attention. However, the fundamental benefits of graphene over nano-graphite have not necessarily been shown in a comprehensive way. The electrochemical variations of these materials will be probed on the nanoscale and compared with graphite, as a first step to determine if these materials are of benefit, which will aid the decision-making of industry in this application area.

A bi-annual workshop on measurement will be held to support the measurement community alternating with a science conference.

Technology translation, standardisation and scientific collaboration – Part of this KT deliverable will include small scale demonstrator industry and standardisation projects (less than £50k) in partnership with industry partners and the international community, where the primary goal is to increase impact through additional technology transfer to meet the needs of end-users, requiring the metrology knowledge to characterise their graphene products and the standards required to measure key material properties.

Benefits

(a) Benefits of the current programme of work.

Alignment of industrial and government strategies for quality management for the nanomaterials sector serves to accelerate progress towards commercial production and viable revenue streams which support the economy.
The graphene project team have a track record in supporting and developing new metrology instrumentation (e.g. microwave patent granted 2014), contracts are in place to deliver measurement services to three UK graphene manufactures and research proposals have been submitted to aerospace industry for structural applications. The benefits of this project will be delivered through interim protocols and good practice guides for graphene and graphene metrology. These will enable industry need to become coherent and using our existing work on ISO, IEEE and IEC organizations standardization committees, and the publication of studies on the use of metrology, we will accelerate the development of test methods for graphene. Detailed information will be collated involving the assessment of electrical, chemical, thermal, and structural properties for graphene and related 2-D materials. Reference spectra and performance data may be disseminated amongst relevant stakeholders. Specific targeted measurement and analysis data will be published in peer reviewed journal format. The availability of such knowledge will directly serve industrial and research entities seeking validation of their in-house characterisation and performance analysis.

(b) Benefits of the completed programme of work.

The development of this overall capability supports innovation and commercialisation in this research area within the UK that is typically centred within the SME community, which itself does not have the resources to develop the urgent and necessary metrology capability.
It is envisaged that the completed programme of work will create long term benefits for NPL/NMS specifically in the context of the approach to emerging technologies relevant to the UK economy and will maintain NPLs position as one of Europe's leading NMIs, as well as enhancing its international presence. The creation of a cross-divisional framework of metrological techniques and methodologies will continue the growth of measurement services in this area that NPL can offer to support industry. This is already developing based on providing characterisation services to some materials suppliers. The research described here expands the scale and scope so that NPL can establish a center of measurement excellence which will be a collaborative center for academic partners and commercial services to industry, in order to directly serve UK industry as these technologies progress from research and development to commercial products.

On a longer time scale, unique products can be developed with graphene and 2D materials as the key component. However, in order to reach this stage through continued research and development, these materials need to become industrially relevant and profitable on a shorter time-scale. Hence, a primary impact of this project will be cost reduction in Quality Control and provision of reliable performance related to graphene-based products to establish the cost/benefits. This will bring forward the tipping point at which graphene becomes commercially viable. The underpinning of the understanding of 2-D materials properties by the development of accurate and traceable metrology will allow performance benchmarking and materials validation to directly influence related technological applications. Stakeholders will benefit directly from the results of this project by utilising core knowledge developed to influence product research and development.

Collaborators
Industry Stakeholders and co-funding targets
NPL is actively engaged in research collaborations and delivering measurement services to a number of academic institutions, UK-based SMEs, major multi-national and government organisations involved in 2-D materials as part of the current programme of work.

These organisations include;
Academic: **UK:** University of Manchester, National Graphene Institute (NGI).University of Cambridge, University of

Oxford, Lancaster University, University of Exeter, University of Nottingham, Loughborough University, University of Bristol, University of Southampton, Imperial College London **, International:** Chalmers University, Linkoping University, Moscow State University, the Fudan University (China)

Industrial: **UK (large):** Airbus, Hexcel, Henkel, Oxford Applied Surfaces, Intrinsiq Materials, DSTL, Bluestone Global Tech, Agilent, AIXTRON Ltd. BAE systems, Thales UK Limited, Oxford Instruments, National Composites Centre (NCC), Graphene Catapult at the Centre of Process Innovation (CPI), **UK (SME):** Haydale Ltd, DZP Technologies, Applied Nanodetectors, Durham Graphene Science?

International (large) Lockheed-Martin (US) Nokia, Optisense, Thales Research & Technology (France), China Innovation Alliance of the Graphene Industry (CGIA) (China). **International (SME)** Graphene Technologies (US), Graphene Laboratories (US), Graphenea (EU), Graphenea (Spain), Graphenesic (Sweden), EPI-lab (Poland)

Government: **UK:** Atomic Weapons Establishment (AWE), Innovate UK, Ministry of Defence (MoD), **International** Korea Research Institute of Standards and Science (KRISS), National Institute of Standards and Technology (NIST) (USA).

Stakeholder organisations: Institute of Physics, IET, Innovate UK GrapheneSIG

The collaborations developed with the organisations above has created the focus that ensures NPL can offer relevant metrology solutions and address the needs of commercial ventures, which are of high importance to the UK economy.

Provision of metrology solutions thus allows NPL to both enhance current collaborations and form new partnerships with leading technology partners. Such collaborations in-turn offer the potential for revenue generation through measurement services and IP, and to attract additional external research funding.

Additional support

The programme of work may seek additional funding streams in order to enhance and leverage deliverable targets and to build strengthened collaborative ventures. It is envisaged that support will be won through EPSRC, EMPIR, Innovate UK, Horizon 2020, Graphene Flagship, DSTL-CDE or ESA funding opportunities and through industrial stakeholders who are already in discussions on direct industry funding to supplement NPL's core NMS funding in this area. Through funding schemes, financial and collaborative scientific outcomes may be achieved throughout the course of the programme of work. Additional value of such support may be in capital equipment and resources and will enhance the value of the scientific outcomes of the project for partners and wider industrial stakeholders.

Current co-funding opportunities

- NPL is already involved in two SME-led Innovate UK projects on graphene conductive inks and printed electronics with a total combined project size of ~£900k
- NPL is a part of Graphene Flagship project (WP on Fundamental science of graphene and 2-D materials beyond graphene) with NPL's budget of £695,988 (incl. co-funding)
- NPL participates in EMRP GraphOhm project on development of quantum resistance standard based on graphene with NPL's budget of £622,855 (incl. co-funding)
- NPL is developing a major bid in the EMPIR 2014 Call on Metrology for graphene industry, which if won will be led by NPL. NPL's income is €520k.
- Graphlaser FP7 project £130k

Knowledge Transfer and Exploitation - The knowledge transfer plan is outlined in work package 6.

Exploitation plans The exploitation strategy for the project is to:

1. collaborate in centers of excellence leading to research projects and commercial services
2. engage with Innovate UK to support the organizations actively participating in the development of the UK work streams leading to grant funded development
3. develop strong relationships that lead to R+D collaborations with groups of companies in key sectors leading to commercially funded and grant funded R+D projects and new on-site facilities
4. maintain the relationship with research consortia (E.g. Graphene Flagship) to create new opportunities for research collaborations
5. develop relationships with new laboratories to initiate an expanding range of research collaborations

Centre of Excellence in metrology of 2-D materials. The exploitation plan of the project is centered on the formation of an international center of excellence in the metrology of Graphene using the hub and spoke model, partnering with Manchester University's National Graphene Institute. The center will develop an international customer base for measurement and characterization services. The formation of this centre will enable access to services, knowledge, traceability and training and NPL's unique multidisciplinary capability, ranging from electrical to mechanical to chemical analysis. The centre will collaborate with and disseminate best practice to and from commercial laboratories and other Universities to close the metrology gap. This project therefore directly supports the NPL strategic business plan for this by developing the technical capability required to provide the services.

Collaboration with the UK National Composites Centre: NPLs composite group are already developing relationships with the UKs national Composites Centre (NCC) and the work in this project provides an opportunity to develop collaborations on Graphene enhanced composites, new concept materials using 2-D materials as components and the concept of functionalization. The aim will be to form a new joint working arrangements focused on these novel ideas to build co-funded research programmes with new industry partners.

Collaborations in new key sectors
A planned approach will be taken to engage with key sectors. For example many UK companies in the Aerospace sector have already indicated requirements that 2-D enhanced novel materials can meet: for example increased toughness, lighting strike resistance, thermal management, and the possibility of combining these enhancements. The team will form a an Aerospace interest group and work individually with partners such as EADES, Astrium, BAe Systems, and ESA to explore the opportunities to exploit the capability developed in this project and secure funding to raise the TRL level of 2-D materials solutions to these requirements.

New Industry/NPL facilities on site. Opportunities to create new facilities at NPL using this capability will be explored including the current prospect with Haydale of siting a graphene research reactor at NPL that uses the capabilities created here to characterize graphene and develop product of consistent quality at lower cost.

Building Strategic relationships with other research organizations
The project provides the technical platform to develop relationships with new research partners worldwide and the team will through a series of well-focused two way strategic secondments create these relationships. For example with Bay Area organizations through Lawrence Berkeley National Laboratory.

Graphene Flagship. The Graphene Flagship project will receive an uplift of funding in the near future and with this project the team will have a technical platform to demonstrate that they are valid partners taking the leadership in metrology issues. The work packages have been carefully constructed to enable the synergies between the flagship priorities and the UK Graphene SIG to deliver benefits to the UK.

Intellectual Property. IP created in the project will be patented and the team have track record with a patent on microwave mobility filed from previous graphene project.

Risks

Risk	Mitigation
The characterisation of graphene flakes and powders is much more difficult than monolayer graphene layers on substrates or mechanically-exfoliated graphene	NPL currently has state-of-the-art techniques and expertise in this area, and have already performed characterisation measurement services on these types of 2-D materials for industry with the current state-of-the-art techniques
Techniques that allow rapid and large-area characterisation of graphene and 2-D materials are not currently available and development will be challenging	NPL has already shown innovative development of a fast, non-contact method for determining the electrical properties of graphene, which shows potential for other properties and large-area measurements
Nanoscale optical measurements of 2-D materials have not been previously investigated at NPL	NPL has extensive experience in measuring the nanoscale variation of photocurrent and photoluminescence using PC-AFM and tip-enhanced photoluminescence mapping and will apply this expertise to 2-D materials
Due to the sample-to-sample variation in printed graphene electrodes the understanding of the correlation of different types of properties is difficult	NPL has successfully produced preliminary and confidential structural, chemical and electrical characterisation measurements of printed graphene electrodes on flexible substrates with an industry partner
Many graphene industrial entities are competitors in the same market and will therefore limit collaboration with NPL and others, hindering standardization	The NPL Graphene Team has extensive experience in collaboration with multiple entities that are direct competitors in this area and will pursue NDAs as appropriate

Risk	Mitigation

The 3-D mapping of chemical species in graphene composites has not been previously shown	NPL already has experience in the 3-D mapping of composite materials, as well as the chemical imaging of graphene films and will use this experience to overcome obstacles in this area	
Heterostructures consist of different materials that vary over the atomic scale and therefore require techniques with extremely high resolution and chemical sensitivity	There are state-of-the-art characterisation facilities at NPL, with high sensitivity and nanoscale resolution, such as TERS, which will be ideally suited for investigating these materials	

Deliverables			
1	**Start: 01/12/14**	**End: 30/11/17**	
Metrology for graphene production and Quality Control			
2	**Start: 01/12/14**	**End: 30/11/17**	
Standardisation of chemical and structural characterisation methods for flexible, printed 2-D materials			
3	**Start: 01/12/14**	**End: 30/11/17**	
High Frequency Electrical Measurements			
4	**Start: 01/12/14**	**End: 30/11/17**	
Physicochemical Metrology for 2-D Nanomaterials			
5	**Start: 01/12/14**	**End: 30/11/17**	
Metrology for 2-D Nanomaterials in 3-D Assemblies for Functional Applications :			
6	**Start: 01/12/14**	**End: 30/11/17**	
Characterization of optoelectronics and heterostructures			
7	**Start: 01/12/14**	**End: 30/11/17**	
Knowledge Transfer and exploitation			

[1] A roadmap for graphene : K. S. Novoselov, V. I. Falko, L. Colombo, P. R. Gellert, M. G. Schwab & K. Kim Nature 490, 192 (2012)

[2] Nesta Working Paper 13/15: The impact of standardisation and standards on innovation, Knut Blind

[3] AFNOR.The economic impact of standardisation, technological change, standards growth in France, June 2009

LGC Projects 2008-

Theme	Health & Biotechnology	**Price to DIUS**	**£1.048M**
Proposal #	**H07**	**Co-Funding Target**	
Proposal Title	**Novel Metallomic Approaches for Improved Disease Treatment**	**Start Date**	Apr 08
		End Date	Mar 15

Vision, Impact and Knowledge Transfer: Major-to-ultratrace elements are contained universally in our human body. Most play essential roles as metalloproteins, metalloenzymes or other metal- containing biomolecules ('metallomes') and have been related to specific diseases (e.g. Se, S & Pt - cancer, Al - Alzheimers, V - diabetes & Cd - Auch-auch). Novel speciation approaches to elucidate biological essentiality and toxicity of the elements on a molecular basis are essential required tools. The UK has a robust cancer research community from basic research (e.g. Cancer Research UK) to applied development programmes, & is well placed to translate this into cancer patient benefit to address the global cancer market, valued at £22bn in 2003. Chemotherapy drugs have been shown *in vitro* to be more effective in the presence of increased levels of elemental species, such as Se/S. Accordingly, this project will initially elucidate the mechanisms by which Se/S-biomolecules may improve cancer outcomes. The work with leading groups in the field will translate, into the clinic, novel intracellular speciation studies in lymphoma cells. This requires administration of relevant elemental species to lymphoma patients before & during chemotherapy at doses that will achieve plasma concentrations at least 10-fold lower than those used *in vitro*. Enabling speciation analysis at very low ppb/ppt levels requires a step-change in the substantial measurement capability LGC has already built in this field. Such sensitivity is also required for analysis of intracellular speciation in circulating blood cells at low microlitre volumes; the identification of specific changes in species- containing proteins and low mass metabolites in limited amounts of bioclinical samples. Such studies are required to identify the elemental species mediating the effects involved & potentially which patients will benefit from intervention early in cancer treatment.

The proposed translation of accurate quantitative measurement & identification of elemental species for cancer studies through approved clinical/supplementation trials is timely, highly relevant to society & assists development of other combination therapies. The partners established track record in KT will continue through high impact peer reviewed journal publications.

Benefits →	Accurate quantitation & identification of Se/S species for cancer studies will help determine the optimum combination treatment or the more efficacious source of Se/S to prevent cancer. Success will have a major impact on the treatment of cancers and help improve the quality of life of those affected.
Innovation →	A novel method for accurate, quantitative ultra-trace Se/S speciation measurement in complex bioclinical samples is vital for understanding the precise mechanism(s) whereby Se/S may improve cancer outcomes, either by reducing incidence in chemoprevention trials or by improving the efficacy of chemotherapy in patients with established cancers.
Technology Solution →	Novel micro-sample extraction, purification/pre-concentration and micro-/nano- flow LC methods, combined with methodologies to enhance the sensitivity of detection of Se/S species using element- & molecule-specific MS techniques. New elemental species enriched with stable isotopes to study, for the first time, metabolic fate of administered Se in patients with cancer using isotope ratio techniques. Demonstration of the approach in human cancer trial samples.
Metrology Challenge →	The simultaneous & accurate quantitative determination & identification of relevant species of Se/S at low ppb/ppt levels in complex samples (e.g. plasma, cells & tissues) is challenging due to the limited amount & complexity of sample, low concentration of target species & instability of target compounds.
Technical Problem →	The mechanism(s) underlying the modulation of activity of cytotoxic drugs by certain elements remains unclear due to a lack of reliable methods to determine the distribution of relevant species in complex biosamples. Identifying intracellular speciation is essential to determine the optimum combination treatment &, therefore, to maximize any interaction observed.

Strategies Supported: TSB Key Technology Area - Bioscience & Healthcare; MSET Roadmaps; LGC's measurement R&D strategy for MS centre of expertise & science initiative 'towards the transparent cell'.

Synergy with other projects: DIUS Chemical & Biological Metrology Knowledge Base Programme- Speciation methods & RMs; EMRP Tracebioactivity.

History: Biochemical & clinical evidence that monomethylated Se metabolites involved in anti-cancer role of Se through Se supplementation (cancer prevention). Specific methyl-Se compounds improve cytotoxic drug activity against cancer in pre-clinical models. Certain similarities between Se & S biochemistry have led to investigation of chemopreventive efficacy of S analogues. Speciation (profiling) methods for Se/S metabolites in chemoprevention & cancer-type models will assist hypothesis testing & development of mechanism-based Se/S status markers for cancer prevention & treatment. LGC has reported the novel measurement & identification of intracellular and volatile methyl-Se species in lymphoma cells exposed in vitro to ppm levels of Se (as methylseleninic acid).

Technical Approach: Sample complexity, low concentration & instability of target species, & the limited amount of biological sample for total element & speciation analysis will be addressed using potential solutions such as carbon-loaded plasma, ultrasonic nebulisation, novel micro-sample extraction, purification/pre-concentration and micro-/nano-flow LC methods, combined with element- and molecule-specific MS techniques. Enriched isotopic tracers will be developed to study metabolic fate of Se in supplementation studies, prior to application of the developed methodologies to clinical cancer trial samples.

Deliverable	**Description**	**Work Package**	**Price / Schedule**	
1 **Deliverable Leader:**	IDMS accurate quantitation & i.d. of heteroatom-containing biomolecules of relevance to cancer research, in bioclinical samples	- Develop micro-extraction methods for (methylated) Se/S biomolecules from micro-biological samples - Develop & validate methodology (CE/2D-LC with ICP-MS) for accurate quantification of Se/S biomolecules at low ppb/ppt levels in micro-volumes of plasma or cell extracts - Evaluate feasibility of ESI/MALDI-MS combined with chromatography for species identification	**Start**	Apr 08
	As evidenced by: Peer reviewed scientific papers & reference methodologies		**Finish**	Mar 10
2 **Deliverable Leader:**	Isotope ratio-based methodology to study fate of Se in cancer & normal cells exposed *in vitro* to isotopically-enriched methyl-selenocysteine or methylseleninic acid, & in supplementation studies	- Preparation & characterisation of novel isotopically-enriched biomolecules (methyl-selenocysteine or methylseleninic acid enriched with Se stable isotopes) as tracers - I.d. of specific changes in the isotopic composition of Se/S-proteins & low mass metabolites in limited amounts of biological samples using methodology from D1 - Evaluation of feasibility & application of D1/D2 to studies	**Start**	Apr 10
	As evidenced by: Peer reviewed scientific papers & reference methodologies		**Finish**	Mar 12
3 **Deliverable Leader:**	Measurement of Se/S speciation in patient blood plasma & tissue/cell extracts from clinical cancer trial	- Evaluation of feasibility & application of D1/D2 to study Se/S speciation of samples generated from cancer prevention/treatment trial - Identify most relevant metallome of interest. Feasibility study to establish relevance of D1/D2 to metallome.	**Start**	Apr 11
	As evidenced by: Measurement support to trial data		**Finish**	Mar 15

Risk and Mitigation:

- Insufficient isotopically enriched biomolecules for method validation. Risk is low as alternative sources likely to become available
- Insufficient sensitivity of existing MS techniques to detect target biomolecules at very low concentration levels. Risk is medium as alternative sample introduction systems available

LGC Projects 2010-

Proposal #	IRD 2010_09	Price to BIS	£335K
Proposal Title	Nanoparticle characterisation methods for food security	Co-funding Target	
		Start Date	Apr 10
		End Date	Mar 15

Vision
The accurate trace element determination and size characterisation of food-relevant nanoparticles (NPs) to underpin food nanotechnology and improve food safety and security.

Impact & Benefits
Nanotechnology is impacting on several aspects of the food industry, from growth to packaging and in the development of novel foods and supplements. Estimates suggest that the nanofood market will reach £12.75 billion by 2010. Two of the key properties of NPs that affect behaviour and toxicity are size distribution and chemical composition. Analytical methods enabling accurate element quantitation and rapid size characterisation of nanoparticles in food are required. This project will enable UK industry to improve their products and enter new markets and consumers to benefit from nutritionally improved and safer food products.

Support for Programme Challenge
Supports IRD Programme Challenge Driven Roadmaps: 6-Security; 2 -Healthcare.

Support for Government Strategies
Supports NMS Draft Strategy through NMS interventions related to Food Security and Healthcare; Government priority area of food safety and strategy for nanotechnologies. Gov Office for Science-"UK Cross Government Food Research and Innovation Strategy 2010"; TSB Agri-Food Innovation Platform.

The Need
The beneficial effects and/or toxicity of nanosized matter are dependent on nanoparticle size distribution and chemical composition. This is crucial for nanoparticles, such as nanosilver (used as an antibacterial) and titanium dioxide, which can adversely catalyse the production of reactive oxygen species and are included into the food directly. The EU intends to publish in 2010 a new strategic action plan related to nanotechnologies for the next five years. The main objective of this will be to address technological and societal challenges and to strengthen research and innovation efforts, with increased emphasis on sustainable development, competitiveness, food, health, safety and environmental issues. It is necessary to advance the fundamental understanding of how nanomaterials behave throughout their life cycle, to ensure product safety and a high level of protection of human health and the environment – while taking full advantage of the benefits of new technologies. Work on effective implementation ofregulation will also continue (http://ec.europa.eu/research/consultations/snap/consultation_en.htm). The Food Standards Agency's strategic plan for 2010-15 (http://www.food.gov.uk/aboutus/publications/busreps/strategicplan/) has set a priority to protect the safety of food manufactured with emerging technologies such as nanotechnology. Finally, the UK Parliament Science and Technology Committee recently reported that the use of nanoparticles in food and food packaging is likely to grow dramatically in the next decade, but too little is known about their safety.
Therefore, it becomes clear that the development of methods to measure the size distribution and elemental composition of nanoparticles of relevance to food nanotechnology is timely and important.

Current State of the Art (NMI and elsewhere)
There is a lack of methodology for the reliable characterisation of inorganic nanoparticles added to food and a lack of knowledge on the stability of such materials. Challenges include: the presence of analytical artefacts caused by sample preparation; lack of resolution of LC methods for colloids with similar hydrodynamic radii; surfactants used in gel electrophoretic separations with ICP-MS detection.

The Solution
A novel technology combination of field flow fractionation (FFF) with UV-Vis and interference-reducing ICP-MS detection for size determination and elemental quantification of nanoparticles in dispersion and to distinguish natural and engineered nanoparticles. FFF has been proven to be a powerful tool for size-fractionation and separation from the relatively low weight molecular components of structures in dispersion. FFF-ICP-MS is able to produce elemental size distributions with a great level of detail in the submicrometer range without the laborious repetitive centrifugation steps of current methods and requires small amounts of material.

Metrology Capability to be Delivered
Aligns with IRD: Security theme "Food production and distribution"; Healthcare roadmap theme "Functional foods; supports Environmental Sustainability theme.

Exploitation/Spin Offs

Methods will be exploited directly by the food industry and regulators and methodology developed will also find applicability in the wider nanotechnology industry. It will also be applicable to elemental nanoparticle speciation in environmental samples and nanotoxicity studies. Use will be made of the new Biosciences KTN, stakeholder networks of the Government Chemist programme and the proposed Agri-Food Innovation Platform.

Synergy with Other Projects
This project relates in general to all ongoing NMS speciation projects but more specifically to CBMIS9 (Methodologies for Cr species in food/supplements) and NB8 (Nanotoxicology-dosimetry).

Summary of Technical Work
Novel sample preparation (e.g. accelerated solvent extraction, microwave-enhanced leaching in aqueous solutions) versus food preparation methodologies to extract/preserve elemental nanoparticles from food matrices will be developed and validated. Methodology based on the use of field flow fractionation (FFF) with UV-Vis and interference-reducing ICP-MS detection for size determination and elemental quantification of nanoparticles in dispersions will be developed. Complementary hydrodynamic chromatographic-based methods will be used for method validation. Total element nanoparticle determination by ICP-MS will be undertaken for mass balance purposes. Isotopically-enriched engineered nanoparticles will be used to investigate the potential of the methodology developed to distinguish between natural and engineered nanoparticles in complex matrices.

Risk
Risk is medium since this project requires the development of new capabilities. However, this is mitigated by the project team's previous experience in the field of hyphenated techniques for element speciation analysis, on the use of collision cell ICP MS for heteroatom interference-reducing measurements and on the development/validation of advanced extraction techniques for food speciation analysis.

Knowledge Transfer Plan
Knowledge transfer of the developed strategies to active parties in the healthcare sector, food industry and academia will be achieved through peer-reviewed publications and presentations at scientific meetings. Methodology transfer through publication on the UK Government Chemist and NMS web-sites will be undertaken and extensive use will be made of links with the relevant Knowledge Transfer Networks and the TSB Agri-food Innovation Platform.

Deliverables

1	Start: Apr 10	End: Apr 11
Methodology based on the coupling of field flow fractionation with ICP-MS for size distribution and elemental composition of elemental nanoparticles in dispersion and mass balance, using accurate dissolved element concentrations in nanoparticle dispersions.		
Evidence: • Validated methods and methodology document and peer reviewed scientific paper(s)		
2	**Start: Apr 13**	**End: Mar 15**
Establishment and comparison of methods based on advanced sample preparation techniques and food preparation procedures using isotopically-labelled nanoparticles (to distinguish between natural and engineered particles).		
Evidence: • Peer reviewed scientific paper(s) and validated methods		
3	**Start: Oct 12**	**End: Mar 13**
Investigation of feasibility of the developed methods for reliable size characterisation and elemental quantitation of nanosize matter in complex foods and food supplements.		
Evidence: • Peer reviewed scientific paper(s) and validated methods		

LGC Projects 2011-

Project No.	IRD/2011/LGC_01	Price to NMO	£698K
Project Title	Ultra Trace Analysis in Bio Matrices	Co-funding target	
Sector	Health and Environment	Stage Start Date	01/04/2011
		Stage End Date	30/06/2015
		Est Final Stage End Date	
		Activity	Methodology for New Capabilities

Summary

This project will provide a chemical/biochemical-based metrological infrastructure to underpin ultra trace detection in biological matrices. Bio-assays are being developed to work with increasing small sample sizes of biological matrices (e.g. whole blood, serum, urine, saliva and sweat) in a wide range of application areas from healthcare monitoring and pharmaceutical development to forensic science and national security. As techniques and platforms capable of handling and employing increasingly smaller biological sample sizes (sub 50 µL) for quantitative analysis are becoming increasingly prevalent, accompanying metrological developments are required to ensure that optimum assay performance is maintained both in the laboratory and upon future transfer to portable/transportable “at-site” detection systems.

The Need

Ultra trace detection offers a wide range of benefits, including reductions in cost, storage space, biohazard exposure, patient stress, chemical usage and disposal during analysis, and increases in throughput via automation. However, reductions in scale are significantly impacting on sample handling and extraction techniques and assay accuracy and precision. These issues become ever more significant when also considering ultra trace detection in emerging portable detection systems.

New sampling strategies include the use of Dried Blood Spots (DBS), capillary blood sampling devices and in-line generated Cell Disintegrated Blood (CDB) either using heat-shock, cryogenic or ultrasonic treatment. These have been driven by improvements in assay techniques such as Liquid Chromatography Tandem Mass Spectrometry (LC-MS/MS) systems, with sufficient sensitivity to analyse ng/mL concentration levels of drugs and their metabolites from sub 10 µL sample volumes.

Emerging electrochemi-luminescence (ECL) methods for protein detection, replacing traditional ELISA techniques, also provide scope for greater sensitivity and more accurate quantitation, resulting from an ability to better tolerate matrix effects within biological fluids and reduce the consumption of test samples, whilst also affording the robust detection of multiple analytes simultaneously.

Ultra trace detection is impacting Drug Metabolism and Pharmacokinetics (DMPK) studies and The Medicines and Healthcare products Regulatory Agency (MHRA) is promoting the use of DBS for animal clinical trials, to reduce numbers used. Over 700,000 new-born babies are screened each year in the UK for a range of metabolic disorders using heel-prick with DBS sampling to minimise infant distress. However, DBS has not been universally adopted for laboratory medicine and estimations from historical data suggest that 6-7 infants die each year as a result of shortfalls in the current procedures for screening for Medium Chain Acyl Dehydrogenase Deficiency (MCADD) alone. Ultra trace analysis is also being investigated in Therapeutic Drug Monitoring (TDM), to enhance patient welfare and avoid the costs associated with regular hospital visits. In the field of sports science, continuous monitoring of a range of biomarkers in athletes is being sought to assess their physiological status and improve wellbeing and performance to underpin competitive advantage.

There is a need, therefore, to address the analytical challenges posed by the complex nature and limited amounts of biological sample coupled with limited detection capabilities. These metrological needs also delay the implementation of portable devices to enable a move away from current biosensors for single analytes (e.g. lactate and glucose) to platforms that provide detection of multiple robust biomarkers.

The Solution

To provide a chemical/biochemical-based metrological infrastructure to underpin ultra trace detection in biological matrices. This will be achieved through the development of; 1) Improved sample extraction techniques for low volume biological samples, 2) Establishment of ultra trace protein and small molecule biomarker detection methods based on ECL and mass spectrometry platforms, 3) Transfer of methods to novel, emerging “transportable” or portable devices.

Project Description (including summary of technical work)

The measurement of ultra trace samples from athletes will be used as a model system for technology development, integration & assessment. Athlete monitoring regimes require frequent low volume samples to be taken and these will be available for this project. Assays will be tailored to the physiological concentration range of the analytes within provided samples. The scope to increase the sensitivity of lab-based assays, and simplification of protocols for more rapid turnaround without compromising robustness, will be evaluated.

Deliverable 1 will assess and develop low uncertainty methodology for mass spectrometry based ultra trace analysis of small molecules in biological fluids. Aspects of the methodology to be developed in order to provide analysis of trace level compounds from limited sample volumes (sub 50 µL) will include: Sample preparation in liquid and DBS samples; Enrichment/extraction techniques (e.g. SPME, MEPS and immunoaffinity SPE); Sample handling robotics and CBD (in-line or off-line); Nano-flow LC separations, including chip based, interfaced with LC-MS/MS; Low Thermal Mass (LTM) columns for GC-MS.

Deliverable 2 will develop multiplexed ECL assays (protein and small molecule) for a range of markers within provided samples and identification and resolution of key measurement issues. Assays will be constructed, optimised and validated in a multiplexed format using the Meso Scale Discovery (MSD) sector 6000 imager platform.

Deliverable 3 Assays will be transferred to emerging portable detection platforms to enable decentralised measurement. Currently anticipated platforms for inclusion include a portable MSD prototype a biosensor that offers the facility for wireless transmission of the information from the portable device back to lab-based analysts.

Impact and Benefits

By introducing methods to underpin and enhance ultra trace detection from low volume biological matrices this project impacts upon key target areas for innovation, including healthcare monitoring, pharmaceutical development, forensic analysis and national security. Immediately related to the project, ultra scale methods for monitoring chemical and biochemical parameters are essential to improve wellbeing and performance of sportsmen/ women and underpin competitive advantage. Other benefits related to general population healthcare monitoring and direct, distinct patient quality of life benefits through reduced sample requirements and patient distress, self-sampling and faster diagnosis will be realised. Outside of these immediate sectors ultra trace measurement of biological samples has clear applicability in the forensic and security sectors.

This project extends and introduces new measurement capability for ultra trace detection within the NMI. It is intended to be one of a series of projects that will develop key lab based platform technologies and exploit potential for portable detection systems (ECL in first phase, MS based in second phase) via the IRD programme coupled to synergistic development of required reference standards via the CBM programme. The ultimate aim is to exploit Olympic legacy opportunities and healthcare applications for portable detection and “wearable” devices for key quality of life and economic impact.

Support for Programme Challenge, Roadmaps, Government Strategies

Supports IRD roadmap and NMO strategic priorities in Healthcare. Complements UK Government funding to support elite sportsmen/ women preparation for the 2012 Olympics and underpins metrological innovation in the UK to support pervasive sensing in elite sports and sustain wider population health and wellbeing. Aligns with TSB key strategic application area of Medicines and Healthcare and Stratified Medicines Innovation Platform.

Synergies with other projects / programmes

Develops previous IRD projects on POC diagnostics (H08) and portable detection technologies (IRD 2009-08). Synergy with CBM OA projects on clinical RM development and IRD project H11 on Single Cell Analysis.

Risks

Nano-LC techniques have historically been more problematic to set up, routinely run and fault find than conventional LC. Mitigation: recent technological advances, such as the chip-based nano-LC have improved robustness.

Biosensors or portable devices may not offer sufficient sensitivity for detection. Mitigation: a range of instruments will be investigated and manufacturers will be intrinsically involved in the project.

Knowledge Transfer and Exploitation

Ensuring the development and assessment of test methods and technologies and help bring them to the marketplace by adding metrological rigour and demonstration of fitness for purpose. Knowledge exchange will be enhanced by interfacing with the relevant KTNs in the sectors impacted including the Medicines and Health Tech and Biosciences KTNs. Key peer review publications and suitable conference presentations will be produced (e.g. International Sports Science and Sports Medicine Conference).

Deliverables

1	**Start: 01/04/11**	**End: 31/12/14**

Evaluation and development of sample format, preparation, extraction and detection for ultra trace analysis

CEW: Multiple sample prep and formats upstream of MS have been assessed. MS based techniques have been assessed in order to obtain necessary sensitivity for analysis of pg levels of “small molecule” analytes in biological fluids.

2	**Start: 01/04/11**	**End: 31/09/13**

Evaluation of the robustness of detecting analytes within distinct matrices by immunoassays with mass validation

CEW: Initial uniplex MSD assays have been developed to evaluate predictive potential of putative biomarkers. Follow on multiplex assays have been developed that incorporate robust biomarkers and been validated by capturing entity using mass spec analysis.

3	**Start: 01/04/12**	**End: 31/03/14**

Portable immunodetection with validation on lab based platform(s)

CEW: Selected assays have been developed on available portable devices. Comparability of portable assays with “gold standard” lab-based assays has been evaluated.

4	**Start: 01/05/13**	**End: 30/06/15**

Novel immunoassays for steroidal target(s)

CEW: Novel immunoassay methodology for steroidal targets has been developed validated and shared with collaborators

LGC Projects 2012-

Project No.	**IRD\2012\14**	**Price to NMO**	£935k
Project Title	Speciation methods for the accurate quantification of metalloproteins	**Co-funding target**	
		Stage Start Date	Jun 12
		Stage End Date	Mar 17
		Est Final Stage End Date	
Sector	Health	**Activity**	Diagnostics

Summary

This EMRP-matched project will develop concepts for future *primary reference methods* for quantifying metalloproteins using the combination of highly selective separation methods combined with ICP-MS detection and isotope dilution calibration. Metalloproteins are especially important in medical diagnosis as they represent around 30% of the whole proteome. Many of them such as haemoglobin (Hb), transferrin (Tf), superoxide dismutase (SOD), selenoproteins and metallodrug adducts are markers for early intervention and treatment of disease. Focus will be on non-covalently bound metalloproteins, e.g. complexes of vanadium (V) with serum transferrin (relevant to Diabetes Mellitus treatment), and covalently bound metalloproteins, e.g. selenoproteins and adducts formed by platinum (Pt) drugs with biomolecules in plasma (relevant to cancer treatment).

The Need

Directive 98/79/EC - in vitro diagnostic medical devices - requires “the traceability of values assigned to calibrators and/or control materials to be assured through reference measurement procedures and/or materials of a higher order”. EN ISO 17511:2003 sets requirements for “traceability of reference measurement procedures for determination of analytes in samples of human origin”. ISO 15193:2009 also sets requirements for “measurement of quantities in samples of biological origin”. Tf is one of the very few plasma proteins that can directly access cells, traversing the blood–brain barrier and intestinal epithelial barrier. This makes it an attractive candidate for developing complex therapies. Although binding of V to Tf *in vitro* in response to V drugs is reported, the mechanisms by which V mediates its observed metabolic effects *in vivo* are not completely understood. Recent evidence indicates an association between selenium (Se), reduction of DNA damage and oxidative stress, together with an effect of selenoprotein genotype on diminished cancer risk. The accurate quantification of plasma selenoproteins after supplementation of Se drugs in clinical trials could be used as a valuable indicator of cancer treatment by Se. The identification and accurate quantification of DNA adducts with metallo-drugs (e.g. Pt drugs) at very low concentrations (ng/kg) is essential to optimise cancer therapy. However, efficacy of Pt drugs (used as chemotherapy agents) is hampered by Pt-binding to intracellular glutathione or specific plasma proteins (e.g. HSA, gamma-globulin, etc.). Mechanisms by which Pt drugs can be made more available for binding DNA with minimal side effects are also of particular interest. This requires methods able to measure the unbound and protein-bound fractions of the Pt drug to elucidate protein-drug interactions and their respective kinetics. (Primary) well-characterised methods are therefore required for the accurate quantification of plasma selenoproteins, Pt-protein complexes, V-Tf and new generation Pt-drug-DNA adducts at ppb levels in bio-clinical samples. This will allow quality control of assays intended for clinical use as well as provide future reference values to PT schemes and in clinical trials.

The Solution

The project will provide (primary) measurement methods for the indicated biomolecules using isotopically-labelled proteins and isotope dilution calibration, through the production and in house characterisation of species-specific spikes (e.g. ^{51}V-enriched Tf), in collaboration with EMRP partners. High resolution separation techniques (e.g. FFF, micro-flow LC) will be developed for coupling to inductively coupled plasma mass spectrometry (ICP-MS) detection of metal, sulfur and phosphorus for the selective and sensitive detection of metalloproteins in the complex matrix. The parallel combination of the derived ICP-MS method with ESI MS/MS will be developed for unambiguous compound identification. The potential of accurate mass measurement MS/MS will be exploited for verification of the structural composition of produced spike materials and potentially for purity determination of separated metallofractions.

Project Description (including summary of technical work)

The quantitative measurement of metallopropteins in bio-clinical samples will be achieved by:

- Production and in-house characterisation of protein/peptide spike materials.
- Method development and validation of; a molecular weight fraction (e.g. size-exclusion or microfiltration membrane) followed by fast protein LC or CE coupled to ICP-MS for IDMS quantification of Tf non-covalently bound with V in plasma or tissue; Plasma selenoproteins (e.g. SEPP1) using a high resolution separation technique (e.g. FFF) for intact proteins or micro-flow reversed phase HPLC (for tryptic selenopeptides) with ICP-MS detection; Accurate quantification of Pt drugs adducts with plasma biomolecules (e.g. proteins vs DNA nucleotides) using off-line fractionation and/or high resolution separation techniques (e.g. FFF) with ICP-MS detection.
- Evaluation of the feasibility of parallel ICP-MS and ESI MS/MS for metalloprotein/ peptide identification.

Impact and Benefits
Diabetes mellitus affects >2m people in the UK equating to ~5% of NHS expenditure; with the cost of insulin almost 2-fold higher than that of potential oral V drugs. Method development and validation that provides identification and quantification of ultra-trace levels of V-biomarkers (e.g. V-transferrin) will enable translation of research practice to UK industry and clinical practice. This will lead to the development of more efficacious V drugs/supplements, with associated decreased cost. The UK's National Cancer Strategy means that the strong research community is well-placed to translate ideas into patient benefit and so address a global market valued at £$54bn in 2009. The accurate quantification of plasma selenoproteins after supplementation of Se drugs in clinical trials could provide a valuable indicator of cancer treatment. The efficacy of Pt drugs as chemotherapy agents has been hampered by unwanted Pt-binding and mechanisms to increase Pt drug binding to DNA with minimal side effects would prove invaluable. Establishing a route for traceability will establish compliance with the EU regulations and so improve the quality of the measurement made on patient samples, allowing reliable diagnosis and therapy.

Support for Programme Challenge, Roadmaps, Government Strategies
Supports NMO Draft Strategy through NMS interventions related to Health - Diagnostics. Underpins the draft Technology Strategy Board Healthcare strategy 2011.

Synergies with other projects / programmes
This project builds LGC's, and the UK NMS, leading recognition in this field developed under IRD HO7 on metallomic approaches for Se, CBM IS9 on methods for V biomolecules, CBM IS7 on the development of analytical methods to quantify metal-containing biomarkers for disease diagnosis and treatment. This work directly aligns with EMRP JRP-17 metrology for metalloproteins.

Risks
The current lack of isotopically-labelled metalloprotein/metallopeptide spike materials presents a low risk since production and characterisation is to be achieved in collaboration with other partners of the EMRP project. This project requires the development of new capabilities, although this risk is mitigated, in part, by LGC's experience in clinical speciation analysis.

Knowledge Transfer and Exploitation
KT will be realised through secondment between collaborators and through the relevant clinical community stakeholders by way of workshop training provision. The developed analytical/methodological strategies will be disseminated to academia and (clinical) stakeholders through peer-reviewed publications and presentations at scientific meetings. Publication in trade journals and on websites consulted by clinical laboratories and producers of medical assays will ensure maximum dissemination of results to relevant communities. Where applicable, methods will also be reported to the metrology community, e.g. Euramet and BIPM.

Co-funding and Collaborators
£354k under EMRP JRP H17: "Metrology for metalloproteins".

Deliverables

1	**Start: 01/06/12**	**End: 01/06/13**
Spike production and characterisation: CEW relevant spike materials have been produced and fully characterised.		
2	**Start: 01/06/12**	**End: 30/12/14**
Methods for the IDMS quantification of V-transferrin/isoforms in biological samples: CEW IDMS methodology based on the combination of two-dimensional separation (size-exclusion or ultra-microfiltration with molecular weight cut off membranes followed by fast protein LC or CE) coupled to interference-reducing ICP-MS have been developed and validated for the IDMS quantification of Tf non-covalently bound with V in biological materials.		
3	**Start: 01/06/12**	**End: 28/02/15**
Methodology for the IDMS quantification of plasma selenoproteins: CEW Methodology for the accurate quantification of plasma selenoproteins (e.g. SEPP1) using a high resolution separation (e.g. FFF) for intact proteins or micro-flow reversed phase HPLC (for tryptic selenopeptide digests) with ICP-MS detection has been developed & validated.		
3b	**Start: 01/03/15**	**End: 31/12/16**
Application of methodology for the identification and quantification of high molecular weight Se species in clinical samples: CEW: methods developed have been extended and feasibility assessed to identify and quantify novel Se species (selenoproteins/ seleno-containing proteins) as potential biomarkers to differentiate between healthy and cancer cells treated with chemotherapy/Se drugs.		
4	**Start: 01/06/12**	**End: 30/12/14**
Methodology for the IDMS quantification of adducts of Pt drugs with plasma biomolecules: CEW Methodology for the accurate quantification of adducts of Pt drugs with plasma biomolecules using off-line fractionation &/or high resolution separation techniques (e.g. FFF) with ICP-MS detection has been developed & validated.		
4b	**Start: 01/04/15**	**End: 31/03/16**
Application of methodology for the identification and quantification of adducts of Pt drugs within clinical samples: CEW methods developed have been applied to identify & quantify Pt drug adducts with DNA & plasma proteins in a pilot clinical study, in order to optimise drug dosage.		
5	**Start: 30/12/12**	**End: 28/02/15**
Compound identification using elemental and molecular MS combined: CEW the feasibility of highly selective separation methods with parallel ICP-MS and ESI MS/MS for metalloprotein/peptide identification has been investigated and		

applied to unambiguous compound identification**.**		
6	**Start: 30/12/14**	**End: 31/03/17**
Publication of scientific peer review papers: CEW Two articles describing the methodology developed have been submitted for publication in peer review journals.		
7	**Start: 01/04/12**	**End: 31/03/17**
Project Management: Project managed on time and to budget.		

Project No.	IRD\2012\15	Price to NMO	£740k
Project Title	Infectious disease detection	Co-funding target	
		Stage Start Date	Jun 12
		Stage End Date	Mar 15
		Est Final Stage End Date	Jun 15
Sector	Health/Security and in part, Environmental sustainability	Activity	Diagnostics/National security

Summary

Infectious diseases account for over 20% of human deaths globally and 25% of all morbidity. Respiratory tract infections (RTI) including pneumonia, influenza and tuberculosis account for almost 50% of all pathogen-associated deaths. Accurate and rapid diagnosis, alongside methods for monitoring transmission and spread in the community and resistance to therapeutic agents, are vital for public health protection.

Molecular approaches, such as qPCR and sequence analysis, offer the potential to improve management of infectious diseases through increased speed, accuracy, sensitivity and information, when compared to conventional microbiological methods. Consequently, the infectious disease testing market is one of the most rapidly growing segments of the in vitro diagnostics industry and is expected to reach €38 billion by 2013. Advances in molecular diagnostic technologies are the main driving force behind the growth. However, issues concerning quality, comparability and traceability of measurements using emerging genomic approaches have been highlighted widely.

This project will therefore develop novel “higher-order” approaches to support assessment and validation of genomic approaches currently being routinely used in clinical and epidemiological laboratories for infectious disease diagnosis, surveillance and monitoring, with a particular focus on RTIs.

The Need

Standard microbiological techniques such as culture are still widely practised, but are involved, time consuming and often subjective. A plethora of molecular approaches have been introduced in both clinical and non-clinical settings in an attempt to speed up the pathogen identification process and avoid reliance on initial culture.

However, in many instances tests are being used in ‘home-brew’ formats. With the detection limits for pathogens present in clinical samples being very low and extraction variability between samples being extremely variable, accurate detection and measurement is challenging. Consequently, issues concerning quality and comparability (and ultimately traceability) have been highlighted widely. Without the measurement capability and development of novel higher-order methods provided though this project, healthcare providers and the biotechnology/diagnostics industry will not be able to demonstrate the reliability of their assays. This is critical for implementation of assays deployed in a wide range of healthcare settings.

The Solution

Provision of an innovative “higher order” measurement capability and validation framework to ensure that current and emerging molecular approaches for the efficient and harmonised rapid diagnosis, surveillance and monitoring of pathogens are “fit for purpose” and applied appropriately. This requires the development of methods with improved accuracy, sensitivity, specificity and quantitative potential over current approaches. These methods should also have potential to be used in the future to assign absolute values to reference materials (as opposed to arbitrary units) which will improve measurement traceability.

Project Description (including summary of technical work)

This project will consider the measurement process as a whole incorporating sample extraction from different matrices and highly accurate and sensitive methods for enumerating single molecules and infectious particles and define the measurement capability of current and emerging molecular approaches. Data interpretation and integration will assure an integral approach of the work. A measurement capability framework will be developed with key stakeholders including healthcare providers, public health laboratories, academics, standards bodies, biotechnology/ diagnostic industries. In particular, the project will:

- Development of quantitative, validated and highly accurate methodologies for the measurement of infectious agents, such as viruses and bacteria
- Development of methodologies for accurately quantifying the performance of commercially available diagnostic assays, ‘in-house’ clinical assays and novel emerging genomic approaches
- Quantitative and comparative evaluation of new and emerging molecular approaches for the surveillance and monitoring of infectious disease load and detection of antimicrobial resistance mutations
- Quantitative and comparative evaluation of new and emerging diagnostic technologies for the rapid detection of infectious agents

Impact and Benefits
The World Bank estimated (2008) that a flu pandemic could cost $3 trillion and result in a 5% drop in world GDP with over 70 million people dying. New threats are emerging; the significant risk to human health was demonstrated during the Severe Acute Respiratory Syndrome (SARS) and *E.coli* 0104 outbreaks that killed >25 people and resulted in sickness in >2,000 others.
Accurate diagnosis, rapid tracing of outbreak source and monitoring of drug resistance, as well as robust approaches for assessing key epidemiological indicators such as disease prevalence and incidence, is therefore vital for public health protection.
The rapid detection and classification of specific bacteria and viruses is important to many sectors beyond that of health: Security – detect contamination from terrorist attacks; Animal husbandry – early detection of diseases, e.g. foot and mouth; Food and drink – detection of food poisoning-causing bacteria; Defence – detection of bio-threats on the battlefield; Environmental sciences – determination of microbial diversity.
Stakeholders and collaborators will support and validate the measurement procedures developed during the lifetime of the project and demonstrate utility through clinical evaluation for assessing/validating end-user assays.

Support for Programme Challenge, Roadmaps, Government Strategies
This work supports the NMS strategy for the "Health" challenge to specifically develop measurement protocols and future standards to enable infectious disease detection technologies to be deployed and utilised with confidence. It aligns with the IRD Programme Health theme: "monitoring and control of pandemics", "next generation sequencing", "and pathogen detection"; Security theme: "epidemics in animal populations", "rapid detection and monitoring methods; and in part Environmental sustainability theme. Support for Government Strategies: 1) TSB Infectious Diseases; 2) OSI Foresight Action Plan "Infectious Diseases: Preparing for the Future".

Synergies with other projects / programmes
CBM BA11- "Sample and library preparation standards for next generation sequencing (NGS)". The development of NGS standards in BA11 will be supported by developed higher order methods and data arising from NGS platforms used here. IRD "Metagenomics"- Methods to profile communities of microbes are being developed in the IRD metagenomics project. This current proposal will build on the expertise developed there to assess newer genomics approaches. BA17- "Isothermal amplification for rapid diagnosis". The current proposal will build on expertise developed under BA17 to enable assessment and novel validation framework to be developed for rapid testing devices. EMRP – INFECT-MET – fully aligned (£447k co-funding).

Risks
1) Methods selected for development into higher order methods prove to be unsuitable. Several measurement procedures will be developed and optimised. LGC has already demonstrated the potential of digital PCR as a higher order method.
2) Data handling complexities of multi-parametric data. Bioinformatics expertise is currently being developed by the NMI skill base and through ongoing projects and collaborations.

Knowledge Transfer and Exploitation
Project outputs will be used directly to inform standards/guidance development by standards bodies. A stakeholder workshop is planned to ensure KT to target stakeholder communities. A series of publications and conference presentations will disseminate the findings to provide maximum benefit to microbial measurement and infectious disease monitoring stakeholders.

Co-funding and Collaborators
EMRP – INFECT-MET collaborators.

Deliverables

1	**Start: 01/06/2012**	**End: 31/05/14**
Development of methods: Develop and evaluate methods for accurate measurement of selected infectious agents with known uncertainties.		
2	**Start: 01/06/12**	**End: 31/05/15**
Emerging epidemiological screening: Investigate the measurement challenges associated with emerging methodologies for surveillance, epidemiology and antibiotic resistance screening.		
3	**Start: 01/06/13**	**End: 31/05/15**
Near-patient testing: Investigate the measurement challenges associated with emerging methodologies for rapid, near-patient testing.		
4	**Start: 01/06/13**	**End: 31/05/15**
Validation for clinical tests: Validate the approaches in WP1, accounting for the considerations encountered from WP2&3, and work with end-user communities/collaborators to improve current clinical PCR approaches.		
5	**Start: 01/06/2012**	**End: 31/05/15**
Knowledge transfer: Maximise by creating links and disseminating knowledge to clinical, industrial and regulatory stakeholders.		
6	**Start: 01/06/2012**	**End: 31/05/15**
Project Management: Project management Project managed on time and to budget.		

Project No.	IRD\2012\16	Price to NMO	£400K
Project Title	Phenotypic Profiling for Stem Cell Manufacture	Co-funding target	
		Stage Start Date	Apr 12
		Stage End Date	Mar 15
		Est Final Stage End Date	
Sector	Health	Activity	Drugs and Therapies

Summary
Stem cells are a class of pluripotent cells that are able to differentiate into any other cell type in the body, giving them the potential to be used for novel medical therapies. Differentiation of these cells involves complex processing as they transform and change their behaviour and function. The ability to measure and track these changes is key to their translation into the clinic and to commercial success. This project will develop a method for quantitatively measuring stem cell phenotype using fluorescent flow cytometry to aid cell characterisation during manufacture. The proof of concept will be carried out in a stem cell model to track differentiation along a hepatic lineage and its application for manufacturing established in line with EU regulatory requirements for cell therapy product characterisation.

The Need
Cell- and tissue-based therapies have the potential to treat many conditions where present conventional treatments are inadequate. This has created a global cell therapy market worth approximately $1 billion with projected growth to $5.1 billion by 2015. In the past 12 months alone autologous, xenogeneic and stem products have been approved for the treatment of a wide range of clinical conditions including prostate cancer (Provenge), myocardial infarction (Hearticellgram-AMI), type-1 diabetes (Diabecell), osteoarthritis (Cartistem) and anal fistula (Cupistem).
As companies develop and commercialise cell therapy products they have to address the major challenges associated with the development of characterisation specifications for products with considerable inherent variability. For example, stem cell products which require some level of differentiation and expansion result in heterogeneous phenotypes as no current protocol is 100% efficient, so manufacturing produces a mix of undifferentiated or partially differentiated cells in the final cell products. This, combined with EU and US regulatory requirements for companies to characterise the cells in their final products for phentypic properties such as identity and purity, creates a significant measurement challenge for cell manufacturers.
Cell phenotype is generally characterised through fluorescent flow cytometry which can analyse a cell's stage of proliferation, differentiation, or activation through cell surface and intracellular markers. These markers are commonly used to identify individual cell populations in heterogeneous samples. However, even for well characterised cells such as human embryonic stem (hES) cells the process of identification can be intensive with a recent report stating that hES cells should be positive for specific markers to maintain their “stemness”. Measuring these markers, among others, during cell manufacture is largely prohibitively expensive and cannot be applied at all for cell models which don’t have well defined markers usable for phenotypic analysis.

The Solution
To develop a novel generic phenotypic fingerprinting approach, which can be applied to stem cells growing and differentiating in a manufacturing scenario, to characterise the population for parameters required for regulatory compliance. By developing a measurement approach applicable to any human cell line used by cell manufacturers, it could be used for process monitoring, optimisation and final product specification. This will be achieved by building upon the successful proof-of-principle work completed under CBM project BA2 and IRD project H1/H10. This project will adapt their approaches to measure phenotype fingerprint changes during stem cell manufacture and differentiation in a 3D environment. Correlating the 3D imaging data to phenotypic profiling data will demonstrate that quantitative analysis of ubiquitous surface markers and tracking fluorescent biomarker expression and cell morphology as stem cells differentiate, can provide a flexible generic identity test applicable to commercial stem cell bioprocessing.

Project Description
The project will be undertaken in three main stages:
Stage 1 – Development of a panel of generic markers for cell phenotype profiling
In this initial stage the application of generic cell surface markers to characterise undifferentiated stem cells and fully differentiated hepatic cells will be examined. Hepatic functional markers analysis will be established to act as a liver potency assay and the minimum number of generic markers required for phenotypic profiling will be investigated.
Stage 2 - Proof of concept for the use of generic surface marker to measure cell differentiation
An optimised model for the differentiation of stem cells into hepatocytes will be established and relevant samples obtained throughout the process. These will be examined using gene and protein expression analysis to measure stage-specific differentiation and population heterogeneity. The use of generic cell surface markers for phenotypic fingerprinting during the differentiation process will be established and optimised.
Stage 3 – Application of the phenotypic fingerprinting to measure cell differentiation during manufacture
Stem cells will be grown in a manufacturing scenario utilising 3D cell culture and the phenotypic fingerprinting approach, in combination with 3D imaging, will be applied to demonstrate its application for industrial cell manufacturing.

Impact and Benefits

Economic: The global cell therapy market has projected growth targets to $5.1 billion by 2015. This growth will increase greatly the demand on companies to develop cell manufacturing strategies, either to produce enough cells for clinical applications or for a contract manufacturing organisation - for a full GMP scale-up process this typically costs >£4.5 million. Having the measurement tools to monitor and optimise these processes and establish product release specification is critical.

Quality of Life: In an ageing population there is an increasing need for new drug compounds, personalised medicine and tissue/organ repair technologies as well as an increasing reliance on the use of cell systems to facilitate the drug discovery process or act as therapies in their own right. Measurement tools to authenticate cell phenotype will help improve cell system reliability, aiding a pragmatic regulatory decision-making process and driving the development of future human therapies.

Science Value: Cell phenotype identification based on surface and/or histocompatibility markers will be a powerful generic measurement tool for cell manufacturers and companies developing therapies for regenerative medicine. Recent European guidelines on the characterisation of allogeneic cells used in tissue engineering recommend phenotypic authentication of cells by histocompatibility markers (CHMP/410869/06) as well as recent guideline documentation produced by BSI (PAS-93).

NMS Capability: Capitalisation on the capabilities established during the current CBM Programme provides the basis for new standardisation (BSI RGM/1 - LGC Chair, ISO TC194/1 - UK representation, and ASTM – LGC technical representation) and enhanced links with cell bank organisations and the UK contract research community.

Support for Programme Challenge, Roadmaps, Government Strategies

Aligns with the NMS strategic theme “The Health Challenge” through innovative measurement research. This project also aligns with the “Health - “Drugs and Therapies” roadmaps and the TSB regenerative medicine roadmap 2011.

Synergies with other projects / programmes

CBM BA2 (Cell Authentication), IRD H1/H10 (Bioreactor Bioprocessing), CBM BA25 (Metrology for Cell Imaging), TSB 101100 (High Throughput Platform for the Discovery of GMP Compatible Stem Cell Manufacturing Protocols).

Risks

The risk for deliverable 1 is Low. The risk for deliverable 2 is medium: if selected markers cannot distinguish cells during differentiation further markers will be added. The risk for deliverable 3 is medium, if the selected phenotyping approach does not distinguish cells during manufacture, then functional and morphological analysis will be added to the approach.

Knowledge Transfer and Exploitation

Outputs will be disseminated through representation on the BSI committee for characterisation and measurement techniques in regenerative medicine (RGM1) and to UK industry through established links with the KTNs and with the TSB Catalyst centre (technology innovation centre) for regenerative medicine when established after the London Olympics.

Co-funding and Collaborators

£65k co-funding through complementary work streams with TSB.

Deliverables

1	**Start: 01/04/12**	**End: 31/05/12**
Set up of cell models and marker identification: Stem cell and hepatic cell models will be obtained and starter culture established. Generic markers suitable for phenotype fingerprinting will be identified and appropriate antibodies ordered.		
2	**Start: 01/06/12**	**End: 31/10/13**
Phenotypic fingerprinting proof of concept: The application of fluorescent flow cytometry for phenotypic fingerprinting of stem cell and hepatic cells will be established.		
3	**Start: 01/11/13**	**End: 31/03/15**
Application to cell manufacture: The use of phenotypic fingerprinting during stem cell manufacture will be established.		
4	**Start: 01/04/12**	**End: 31/03/15**
Knowledge Transfer: Through BSI/RGM, peer reviewed publications and presentations. Methodology and updates will also be published on the LGC NMS website.		
5	**Start: 01/04/12**	**End: 31/03/15**
Project Management: Project delivered on time and to budget with high quality science.		

LGC Projects 2013-

Project No.	IRD13_19	Price to NMO	£740k
Project Title	Metrology for de-risking regenerative medicine and cell therapy	Co-funding target	
		Stage Start Date	Oct 2013
		Stage End Date	
		Est Final Stage End Date	Sept 2016
Sector	Drugs & therapies	Activity	methodology for new capabilities

Summary

Although cell-based therapies are now reaching clinical trials and the first products are starting to emerge onto the market, this is still perceived to be a high risk area due to the large uncertainties associated with their complex and dynamic nature[1]. Measurement solutions have been highlighted[2,3] as the key enabler to move this technology forward and support regulation[4] to ensure product quality and safety. This project will develop a metrologically sound, multi-parametric measurement approach to simultaneously detect genotypic and phenotypic markers to establish critical quality attributes (CQAs) for in-process control, assessing batch variation and release of regenerative medicine products. It will also indicate better surrogate markers of clinical efficacy, to inform product formulation and shelf-life. This project builds on the success of the previous Single Cell project which established relevant protocols, controls and normalisation strategies for the analysis of single and small cell populations.

The Need

In the current evolving regulatory landscape, along with starting material purity and potency assay development, establishing reliable process release criteria is regarded as one of the key measurement challenges to overcome to bring cell therapy products to market. The heterogeneity of the cell population, with different cell-to-cell interactions, spatial distribution and interaction with the extracellular matrix triggering numerous biochemical cues and affecting marker levels, makes for costly testing strategies. There is a need for accepted key markers and robust assignment of specification values for establishing suitable release criteria[3]. The International Conference on Harmonisation (ICH), European Medicines Agency (EMA), & Food and Drug Administration (FDA) have acknowledged the importance of suitable release criteria & associated measurement methods. Although capability exists to provide the minimum information required to release new product batches, currently no one has the capability to bring together cross platform integrated multi-parametric measurement solutions, for safer, faster & more robust testing regimes.

The Solution

This project aims to develop controlled measurement processes, to derive a multi-parametric description of release criteria required for regenerative cell-based products. This will exploit LGC's unique wide range of standardised analytical methods and cross-platform analyses, brought simultaneously together for the first time, to achieve sample characterisation by an integrated approach.

Project Description

A robust cell therapy reference product selected by the consortium will initially be characterised using current standard screening protocols, quantifying such attributes as cell concentration, viability, morphology, function and identity through expression of genomic and proteomic markers[5]. These measurands will be the initial CQAs identified as relevant to the characterisation of the product quality[6]. Timescales and sample size will be important parameters for assessment, as CQAs are highly dynamic properties of live cell products. Single cell and micro-scale cell samples will then be collected by laser dissection microscopy and analysed by a range of advanced analytical platforms, such as: high-throughput dynamic array qPCR for gene expression profiling, digital PCR for accurate quantification of genetic, epigenetic and functional gene expression biomarkers, flow cytometry and superior chemiluminescence protein arrays for antigen and protein biomarker measurements, and mass spectrometry platforms for high resolution measurements of biomarkers. From those techniques found to be suitable standardised approaches and high-throughput procedures will then be developed to allow the parallel analysis of these small cell populations. The multi-parametric data will be integrated and analysed based on system biology principles to map back to the initial CQA's to form an expanded CQA. Project partners will provide access to real cell products and testing in "real life" process conditions the multi parametric measurement approach and expanded CQA definition developed.

Impact and Benefits

The UK is one of the leading countries in Regenerative Medicine, in a market estimated to be worth $5.1 billion by 2014[7], with more highly cited research than the rest of Europe and Asia, outperformed only by North America. The UK public sector has invested over £200m since 2003, whilst the private sector invested £30m between 2005 and 2009, in regenerative medicine research. This project will compliment and support UK activity by improving the quality and

1 Potency assay development for cellular therapy products: an ISCT review of the requirements and experiences in the industry. C. Bravery et al. Cytotherapy, 2013; 15: 9-19

2 Guidelines on Human Cell-Based Medicinal Products. European Medicines Agency, 2008. EMEA/CHMP/410869/2006

3 PAS 93:2011 Characterization of human cells for clinical applications. Guide. BIS/BSI

4 Regenerative Medicine. Report. House of Lord, Science and Technology Committee. 1st Report of Session 2013–14

5 Developing assays to address identity, potency, purity and safety: cell characterization in cell therapy process development. J. Carmen et al. Regen. Med., 2012; 7(1):85–100

6 Precision manufacturing for clinical-quality regenerative medicines. D. J. Williams et al. Phil. Trans. R. Soc. A, 2012 370:3924–3949

7 Taking stock of Regenerative Medicine in the United Kingdom. Research and analysis. Department for Business, Innovation & Skills 18th July 2011. Ref : 11/1056

usability of the data collected from cell therapy products. This will significantly contribute to bridging the gap between potential cell products and actual therapies used in clinical trials, by providing a metrological and regulatory sound framework to ensure product quality and safety. This in turn will promote the development of both documentary and physical reference standards, improving the quality control and safety assessment of cell-based products and speeding up navigation through the regulatory landscape. This project satisfies up to 75% of the technology readiness levels (TRLs) necessary to bring cell therapies to the clinics (short-term return on investment (ROI) is therefore high) and, in time, will contribute to considerably alleviate some of the burden on the NHS, with 80% of today's healthcare costs going towards illnesses which could be cured or better managed using cell therapies (long-term ROI also strong, assuming clinical pathways streamlined for such therapies). The development and optimisation of multi-parametric marker measurement techniques will also be translatable to other important fields such as cancer biology research and diagnosis.

Support for Programme Challenge, Roadmaps, Government Strategies

Aligns with the NMS strategic theme "The Health Challenge" through innovative measurement research. This project also aligns with the "Health Drugs and Therapies" roadmaps, the TSB regenerative medicine roadmap 2011, the TSB Stratified Medicines and Biomedical Catalyst programmes, the Cell Therapy Catapult and the recently announced Joint Industry-Government project on (advanced therapies, biologics and small molecules) medicine manufacturing. It also aligns to the UK/US/Canadian tripartite activity "Building towards a Standard for Mesenchymal Stem Cells.

Synergies with other projects / programmes

This project expands on the previous H11 (Single Cell) project. It aligns with the HT1 and EMRP-JRP4 projects (Regenerative Medicine) through multi-parametric measurements of biomarkers and EMRP Bio-SITrace, through absolute SI traceable quantification of biomarkers. It aligns with BA25 (Metrology for Cell Imaging), BA2 (Generic phenotypic profiling) and IRD 12_16 (Stem cell phenotypic profiling) developing methods to quantify cell specific biomarkers. The project also aligns with the current suite of nucleic acid metrology projects including BA27 (metrology for gene expression profiling), IRD GeneReg (improved methods for epigenetic profiling), BA10 (improved methods and standards for miRNA profiling) and BA28 (trace nucleic acid measurements). BA31 (Strategies for traceable quantification of proteins in biological fluids) will be exploited here too.

Risks

Deliverable 1: medium, mitigated by partnerships and collaborations. Deliverable 2: high, different targets may require screening a range of assays. Deliverable 3: medium. Deliverable 4: high, the selected methods will need to measure simultaneously the same sample, which will require careful evaluation of minimum sample size and workflow optimisation.

Knowledge Transfer and Exploitation

Dissemination through publication of peer-reviewed articles and presentation at national/international conferences (e.g. International Stem Cell Conference and World Congress on Regenerative Medicine) and industry trade journal articles. Knowledge transfer through interactions with the key stakeholders. Particular use will be made of the BIA and Healthcare KTN and the successful CDTs in Regenerative Medicine, for which multi-parametric measurements will undoubtedly improve the understanding and training relating to the mode of action of cell therapies. Where applicable, methods will be taken forward for CCQM-BioAnalysis Working Group (BAWG) study. Translation to other fields such as cancer biology research and diagnosis will be investigated through relevant institutions such as the Institute of Biology etc.

Deliverables

1	**Start: 01/10/2013**	**End: 28/02/2015**
Deliverable title: Identify and source a model cell therapy product, identify initial CQA's through early screens.		
2	**Start: 01/10/2014**	**End: 31/08/2015**
Deliverable title: Evaluate methods across different platforms to measure the CQA's as release criteria.		
3	**Start: 01/05/2015**	**End: 31/12/2015**
Deliverable title: Quantify measurement reproducibility and sources of uncertainty for the successful platforms CQA's to refine release specifications as a function of process control.		
4	**Start: 01/10/2015**	**End: 30/04/2016**
Deliverable title: Select biomarkers and optimise measurement methods for simultaneous analysis of a single cell product. Characterisation of parameters (e.g. sample size, experimental conditions) for which measurements are reproducible.		
5	**Start: 01/10/2013**	**End: 30/09/2016**
Knowledge Transfer: Input to related international harmonisation activities, BSI/RGM, peer reviewed publications and presentations, best practice guide.		
6	**Start: 01/10/2013**	**End: 30/09/2016**
Project Management: Project delivered on time and to budget with high quality science.		

Project No.	IRD13_22	Price to NMO	£439,403
Project Title	Higher order protein structure measurements to support bio-pharmaceutical production and quality control	Co-funding target	
		Stage Start Date	Oct 2013
		Stage End Date	
		Est Final Stage End Date	Sept 2016
Sector	Drugs & therapies	Activity	Methodology for new capabilities

Summary

Analytical tools are vital to ensure purity and structural integrity of bio-pharmaceuticals at each stage of the production process thus ensuring quality and safety of the end product dispensed to the patient. Higher order structural measurements of bio-pharmaceuticals have a critical role in defining quality, safety and efficacy and are also crucial to demonstrate comparability and bio-similarity. This project will address the challenges associated with protein tertiary structural analysis by developing a “gold standard method” based on hydrogen deuterium exchange (HDX) and a novel ion mobility mass spectrometry approach (IMS).These will be used to monitoring high order structural changes of proteins of bio-pharma interest with diverse chemical physical characteristics in stressed and unstressed conditions. The performance of the two methods will be compared with the performance of a number of conventional techniques available through collaborators. The results obtained will address the bias of the methods and support manufacturers in the selection of the most appropriate platform to detect structural changes depending on the characteristics of their bio-products. The project will also investigate the application of these mass spectrometry based approaches to monitor and measure the formation of aggregates.

The Need

The secondary and tertiary structures of bio-products are key quality attributes for the determination of their stability, efficacy and immunogenicity. Higher order protein structure measurements are therefore necessary throughout the product life cycle (ICH Q6B), to demonstrate comparability of bio-products when changes in the manufacturing process occur or biosimilarity when a proposed product has to be proved biosimilar to the innovator product (ICH Q5E). Several physical and analytical methods are available for higher order protein structural analysis; however regulators do not provide any guidelines on the choice of the methods. The only requirement is that the techniques used have to be proved efficient to detect structural variations of the bio-product of interest and that their sensitivity has to be evaluated. This has been highlighted as an area of concern when consulting industrial stakeholders, who would like advice on which methods to be used at different stages of product manufacturing, relative to the product characteristics.

The presence of visible and sub-visible particles in bio-products is also a major regulatory and manufacturing concern due to its potential link to immunogenicity. Particulates, generally protein aggregates, are a major analytical challenge in bio-pharmaceutical development Although many platforms are available to measure soluble aggregates and visible aggregates, very few methods are available to detect the presence of particles between 0.1 and 10µm. Mass spectrometry and separation science methods such as HDX, IMS and field flow fractionation (FFF) have high potential for the analysis of aggregates above 0.1µm.

The Solution

HDX and IMS are powerful platforms for the detection of structural changes of proteins with different chemical physical characteristics. HDX provides exceptionally accurate information related to the location of the structural changes within a protein sequence and has been recognised as an excellent tool in the bio-pharma industry. However its utilisation has been limited due to the low throughput, high sample consumption and high costs associated with the experiments. In contrast IMS provides fast information on global structural changes of proteins, but its potential application in the bio-pharma sector has not yet been explored. LGC will focus on the development of HDX and IMS methods to monitor structural variations of proteins with diverse characteristics. The performance of those platforms will be compared with the performance of conventional platforms and a tabulated guide will be compiled summarising the findings. This will advise regulators and support manufactures in the selection of the most appropriate platform for their measurements and help inform future capital investments in equipment, to gain improved knowledge of their products and reduce risks associated to changes in production

Information on folding thermodynamics, tertiary structure and identification of hot spots in a protein sequence are key for controlling aggregation. Many companies base the identification of hot spots using their knowledge of the molecule in combination with statistical software. HDX is extremely powerful and as can utilised to verify computational predictions. In addition the high potential IMS and FFF require full exploration for their ability to analyse aggregates above 0.1µm.

Project Description

LGC will focus on the development of HDX and IMS capabilities for measuring protein tertiary structure of bio-products A number of model proteins will be selected in consultation with bio-pharma companies and analysed by HDX and IMS. The results will be compared with those obtained on conventional platforms and a tabulated guide will be populated and disseminated. Quantification of protein conformations represents the next step to enable validation of the methods used for tertiary structural analysis. Two feasibility studies will then be performed, the first to establish the potential of IMS to quantify protein folding states. The second to investigate if HDX, IMS or FFF can be applied to the analysis of aggregates.

Impact and Benefits In 2013 bio-pharmaceuticals are expected to represent four of the five top-selling drugs worldwide. The average time required from the discovery to the approval of a bio-product is 9 years. However only a small percentage of bio-products successfully enter the market with obvious economic implications. In 2012 the National Institute for Health and Care Excellence reported that 62% of the anti-cancer drugs evaluated in 2012 were not approved. This project will facilitate the development of methods to reduce costs and risks associated to process manufacturing. It is aimed that the capabilities developed within the project will provide a unique resource, not currently available to UK industry. It is anticipated that this can also be utilised by companies of all sizes develop bioprocesses quickly and cost-effectively.		
Support for Programme Challenge, Roadmaps, Government Strategies The UK bio-pharma sector is comprised of 200 companies, with a portfolio valued at 24bn. Hence, maintaining the UK role as world leaders in the bio-pharmaceutical sector is one the government's priorities. This project aligns with the NMI strategy to support areas where the UK is a word leader by providing tools to facilitate approval of new bio-products and biosimilars, reduce risks during production and improve product knowledge.		
Synergies with other projects / programmes The project is part of a strategy for the development of protein characterisation capabilities within LGC. The project currently aligns with the with a NMS Chemical & Biological Metrology (CBM) Project (BA33) which aims to develop protein characterisation methods to support the production of reference materials and is the outcome of a CBM Programme consultation conducted during 2012/13 by LGC to identify measurement challenges within the bio-pharma area.		
Risks The risk is medium to high. LGC has experience in performing both HDX and ion mobility analysis and the proposed external collaboration with one of the leading academics in protein structural analysis significantly reduce project risk. However the success of the feasibility study on the potential use of ion mobility for quantifying folding states of a protein and for detecting aggregates above 0.1µm is unknown due to the novelty of the approach.		
Knowledge Transfer and Exploitation An industrial steering group will be formed to ensure the delivery of the project aligns with industrial requirements and to help disseminate the outputs of the project. We will also disseminate to UK communities through established links with the Healthcare KTN, Centre for Process Innovation's (CPI's), National Industrial Biotechnology Facility (NIFB) and the National Institute for Biological Standards and Controls (NIBSC). Findings will also be reported in peer review publications and presented at relevant conferences and meetings.		
Deliverables		
1	**Start: 01/11/2013**	**End: 31/05/2014**
Development of mass spectrometry based methods for protein structural analysis by using a model system: When HDX and IMS methods have been developed to detect structural changes of a known protein such as human growth hormone in stressed and unstressed conditions.		
2	**Start: 01/03/2014**	**End: 30/11/2015**
Tertiary Structure Platform Comparison: When proteins have been selected in consultation with stakeholders, and analysed stressed and unstressed conditions on a number platforms.		
3	**Start: 30/04/2014**	**End: 30/09/2016**
Feasibility study on quantification of protein structure by ion mobility mass spectrometry: When at least one protein will be analysed by ion mobility mass spectrometry, its folding states will be relatively quantified and the results obtained in two different labs will be compared.		
4	**Start: 01/04/2014**	**End: 30/09/2016**
Feasibility study on the potential application of HDX and IMS to protein aggregate analysis: When the feasibility of using HDX, IMS and FFF for the analysis of aggregates is evaluated.		
5	**Start: 01/01/2014**	**End: 30/09/2016**
Knowledge transfer: Attendance at relevant conferences and meetings. Peer reviewed publications and tabulated guide produced. An industrial steering group will be formed with regular meetings organised to discuss progress.		
6	**Start: 01/10/2013**	**End: 30/09/2016**
Project Management: Project managed on time and to budget, including studentship and secondments.		

<u>LGC Projects 2014-</u>

Project No.	IRD/2014/14	Price to NMO	£850k LGC/£80k NPL
Project Title	A metrological platform to study the bio-distribution of metals/metallospecies in µ-samples for the treatment & diagnosis of disease	Co-funding target	
		Stage Start Date	Dec 2014
		Stage End Date	
		Est Final Stage End Date	Sept 2017
Sector	Health (“Diagnosis” & “Drugs & therapies”)	Activity	Development of existing capabilities

Summary

With the support of the NMS over the past 5 years, LGC has cemented a lead metrological position for the determination of metals & metal species in food & clinical applications. Additionally it has established a metal imaging capability that forms part of a national centre for mass spectrometry imaging. It is the combination of this expertise that is now being sought for further development in line with the needs of a stakeholder group, to study bio-species distribution in µ-bio-clinical samples, from tissue sections to single cells.

Metallodrugs &/or targeted drug delivery vehicles (nano-particle tagged drugs) are widely used for the treatment of many diseases including cancer & diabetes. Metal species are also increasingly being linked, either causally or by association, to the diagnosis of many diseases, including those of the eye, pancreas & brain. However new disease diagnosis &/or therapeutic strategies require new traceable measurement methodology to determine drug uptake & transformation within individual cells, small cell populations & tissue sections. Such bio-species distribution information is essential in establishing the presence or absence of key biomarkers for the successful development of improved targeted therapies & diagnostics. This project will develop a metrological platform to accurately determine the distribution of target elemental species (metallodrugs &/or nanoparticles & metabolic intermediates) in µ-samples (small cell populations, tissue sections, single cells) relevant to disease diagnosis & treatment (focusing on diagnosis of Alzheimer’s disease (AD) & treatment of cancer with metallodrugs).

The Need

The effects of neurodegenerative diseases & cancer, is increasing & changing with the changing demographics of our society. Although cancer still remains the primary cause of death in the UK (29% in 2013) & has an annual health & economic costs of ~£12bn, the equivalent cost of dementia is already ~£23.6bn, with Alzheimer’s disease (AD) accounting for 2/3 of cases and the number of people diagnosed with dementia in Western Europe is set to double by 2050. For the effectiveness of cancer therapies to be truly understood & optimised, techniques to allow the monitoring of penetration, distribution & metabolism of the drug within the target tissue/tumour are essential. The same approaches are also required to monitor species transformation for many different disease states including the progression of AD. Traceable methodology to accurately determine & characterise the distribution of target elemental species is scarce, yet would be invaluable for the development of improved combined and targeted therapies. Based on discussions with stakeholders, examples of current clinical interest include the link of proteins of Fe & Se with the risk/progression of AD disease & the distribution/metabolism of drugs of Se & Pt in tumours & cancer cell models. It is also known that chemotherapy drugs have been shown *in vitro* to be more effective in the presence of increased levels of elemental species such as Se species. In terms of neurodegenerative disease diagnosis/prevention, Selenoprotein M & Selenoprotein P have been shown to have an important neuroprotective role. Another feature of AD is amyloidosis i.e. the accumulation of ß-amyloid which binds & accumulates transition metals such as Fe. The ability to assess Fe-containing species is vital for predicting clinical outcome. Finally, inorganic nanoparticles have been used as anti-cancer therapeutic agents (e.g. by enhancing the efficacy of radiation, inhibiting protein activity, etc.).

The Solution

This project will make use of a novel analytical platform based on highly sensitive laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) to map the elements of interest, followed by laser dissection, combined with wet or off-line speciation techniques &/or solid state (on tissue) speciation (to be carried out by NPL) to study specific species. This will establish the bio-distribution of metallodrugs &/or nanoparticles & their metabolic intermediates & key biomarkers in µ-samples (e.g. small cell populations, tissue sections, single cells) from selected disease models.

Project Description

The development & clinical application of traceable metal/bio-species distribution methodology will be achieved by:

- Development & validation of LA-ICP-MS based methodology to determine the distribution of elements & elemental ratios in model tissue/cell samples.
- Development & validation of methodology combining laser dissection with wet speciation techniques &/or MS (for on tissue speciation) for the determination & characterisation of bio-species. Species/disease combinations of interest include Se proteins & AD; Se/Pt drugs & metabolic intermediates in cancer treatment &/or inorganic nanoparticles used in the treatment of cancer & neurodegenerative diseases.
- Investigation of the feasibility of the approach developed for application to relevant clinical samples provided by collaborators.

Impact & Benefits

This project will enhance LGC’s metrology know-how to facilitate inorganic speciation measurement at the single cell level, generating a unique capability within the UK. It will also increase LGC’s leadership role in Metallomics worldwide. The application of this capability to disease treatment will provide the basis for the development of new & more efficacious combined therapies & diagnostics to improve front-line clinical decisions allowing better diagnosis/treatment of the high impact diseases under study (AD & cancer). It will also be significant to many others, such as diabetes & Parkinson's disease, thus helping to improve the quality of life of those affected. The lead by clinical & industrial stakeholders, & provision of clinical trial samples, will validate the developed approach & ensure their clinical relevance & impact. The provision of a metrological approach will assist the bringing of more effective therapeutic & diagnostics products to market in years to come, thereby supporting the UK life sciences & its contribution to the UK economy.

Support for Programme Challenge, Roadmaps, Government Strategies

This project is in line with the "Cell Biology" & "Speciation" roadmaps re: µ-sample/single cell imaging technologies. It builds on existing capability for elemental imaging & speciation analysis & extends such capability to monitor/quantify the distribution of low concentration of metallospecies in µ-samples. This project directly addresses the Government Industrial Strategy for the UK to become a global hub for Life Sciences, bringing together business, researchers, clinicians & patients, to translate discovery into clinical use; for medical innovation within the NHS & to contribute to sustained UK economic growth. It also addresses policy initiatives to make England the best country in Europe for people to live with dementia. Government funded dementia research has increased from £28.2m 2009/10 to £52.2m in 2012/13, with the TSB highlighting neurodegenerative diseases in its Health & Care action plan 2014-15.

Synergies with other projects / programmes

The project aims to develop novel bio-speciated imaging capabilities within LGC which can be applied beyond the clinical area to environmental safety & biopharmaceutical areas. The project currently aligns with both the CBM IS12 project which aims to develop improved calibration strategies & candidate standards for traceable quantitative elemental tissue imaging & the current EMRP 'Metallomics' project which aims to develop traceable methods for the accurate quantification of metalloproteins relevant to Health/Disease Treatment in clinical samples. This project also draws in knowledge from the NPL project "AIMS HIGH" in the CBM programme (CB/2012/NB12).

Risks

Insufficient isotopically enriched biomolecules for method validation. Low risk as alternative sources available; Insufficient sensitivity of existing MS techniques to detect target biomolecules at very low concentration levels in µ-samples. Risk is medium as alternative sample introduction systems & advanced technologies are available.

Knowledge Transfer & Exploitation

KT & impact will be achieved through the collaborative partners involved in the healthcare sector & who have led the identification of the need in this project & by dissemination within the NMI structure through joint working with NPL, as well as international secondments with other NMIs. E-webinar, conference presentations & associated workshops, peer reviewed publications & publication on the UK NMS web-site will be undertaken.

Deliverables

1	**Start: 01/12/2014**	**End: 01/01/2016**

Development of LA-ICP-MS methodology for the imaging of multiple elements/elemental ratios in tissue/cell samples: Methodology based on LA coupled to ICP-MS for the determination of multiple elements & elemental ratios distribution in tissue/cells has been developed & validated.

2a	**Start: 01/12/2014**	**End: 01/10/2016**

Development of MS speciation methodologies for the analysis of metal species of interest in specific regions tissue/cell samples-wet chemistry: Methodology based on the combination of laser dissection (of tissue sections identified in D1) with wet speciation techniques.

2b	**Start: 01/12/2014**	**End: 01/10/2016**

Development of mass spectrometry on tissue speciation methodologies for the analysis of metal species of interest in specific regions tissue/cell samples: MS based methodology (for on tissue speciation in samples from D1) for determination & characterisation of bio-species distribution have been evaluated & protocols developed.

3	**Start: 01/10/2016**	**End: 31/07/2017**

Feasibility study & application of developed LA-ICP-MS & speciation methodology to clinical samples of relevant to disease treatment: Feasibility of the methodology developed & validated in D1 & D2 has been investigated for application to relevant clinical samples in collaboration with stakeholders.

4	**Start: 01/12/2014**	**End: 30/09/2017**

Knowledge Transfer & Impact: Stakeholder network established for the project, at least two workshops, at least three scientific publications of the developed analytical platforms & their application to relevant clinical samples have been submitted & at least three presentations at scientific conferences or clinical meetings have been accomplished.

5	**Start: 01/12/2014**	**End: 30/09/2017**

Project Management & sub contract management: Project managed on time & to budget.

Project No.	IRD/2014/15	Price to NMO	£55K
Project Title	Programme Management and Formulation	Co-funding target	N/A
		Stage Start Date	01 October 2014
		Stage End Date	30 September 2015
		Est Final Stage End Date	
Sector	Underpinning metrology	Activity	Programme Management

Summary

This project supports the LGC management and co-ordination activities that are necessary to ensure that the Innovation Research and Development (IRD) Programme is delivered effectively and seamlessly.

- To provide co-ordinated management and reporting on all IRD projects contracted to LGC and to ensure the delivery of work to quality, time and budget
- To enable effective co-ordination and collaboration with NPL in order to deliver a seamless programme.

This project also underpins the stakeholder consultation and formulation of future project work to be delivered under the programme.

The Need

The IRD programme is one of a portfolio of programmes within the National Measurement System. Effective programme management and liaison with NMO, and other NMS contractors (NPL, NEL) as applicable, is essential to ensure the programme is delivered to quality, time and budget and co-ordinated with other NMS initiatives and programmes.

Programme formulation requires close liaison with NMO and their expert advisors and collaboration with others (both in UK and overseas) to ensure that the technical specifications reflect stakeholder needs, and also to ensure that project proposals are prepared in accordance with NMO strategy and policy. Proactive input to the formulation of EMPIR projects is vital in order to influence and secure strong involvement and payback for UK plc.

Programme formulation involves stakeholder consultation exercises to inform the production and revision of a series of project specifications which evolve during the course of the programme development process. The draft programme is presented and reviewed by the NMO/IRD WG at a Decision Conference after which the final programme is agreed and contracted.

The Solution

A set of related and appropriate programme management and formulation activities.

Project Description

- Programme planning and monitoring: Preparation of delivery plans, budgets and invoice forecasts. Internal progress and financial monitoring, including meetings between programme and project managers to review progress.
- Production of monthly reports for NMO which summarise highlights and exceptions and provide invoice forecasts for each project.
- Production of annual reports and attendance of LGC staff at annual progress reviews.
- Programme formulation involving the stakeholder consultation, production and revision of a series of project specifications which form the draft programme presented and reviewed by a Decision Conference, after which the final programme is agreed and contracted.

Impact and Benefits

This project ensures that work contracted to LGC is delivered to quality, time and budget. Well-founded project specifications that are representative of requirements and address priority needs are essential to maximising the future impact of the NMS. Provision of timely and accurate information helps NMO manage the overall NMS programme portfolio and ensure that NMO delivery targets are achieved.

Support for Programme Challenge, Roadmaps, Government Strategies

This project directly supports the development and updating of programme roadmaps.

Synergies with other projects / programmes

N/A

Risks

N/A

Knowledge Transfer and Exploitation

N/A

Co-funding and Collaborators

N/A

Deliverables		
1	**Start: 01/10/2014**	**End: 30/09/2015**

Programme Management including:

- **Monthly Reporting:** Monthly reports and invoices, submitted to NMO within one month of period end.
- **Contract Review Meetings:** Regular meetings between LGC (Programme Manager) and NMO (Programme Supervisor) to review contract delivery.
- **Annual Report:** Annual report, produced in collaboration with NPL, submitted to NMO within two months of year end.
- **Progress Review and Decision Conference:** Annual progress review meeting and decision conference held to the satisfaction of NMO.
- Production of IRD project proposals and specifications.

Project Amendment Annex NPL

IRD PROGRAMME - NPL Project Amendment Annex 2013-2014

Project / Deliverable	Revision notes	Requested By	Page	Original		Revised		Authorised By/Date
				Start Date	End Date	Start Date	End Date	
IRD/2013/9; Sensor networks:data to knowledge	Request to remove £90,000 for the initiation of a new project. Request to create **NMS/IRD13/ESA** for the amount of £90,000 for the co-funding for ESA Feasibility Study to develop a Transport Infrastructure Integrity Management (TIM) Service . Request to remove £45k from original Deliverable 2 (from £170k to £125k) and Deliverable 3 (from £245k to £200k) amounts to be reduced. IRD/2013/09/ESA project will start on the 6.1.2014 and finish 6.1.2015. Project timelines remain the same.	Helen Murphy/Elena Barton				06/01/2014	06/01/2015	SKJ 9/1/2014
IRD/2013/19; Certification of biometric systems to support innovation and interoperability (Co-funding for **HECTOS**)	Request to create new project IRD/2013/19 for the amount of £190,000 for the co-funding for FP7 European project 'Harmonized Evaluation, Certification and Testing Of Security products' (HECTOS) which applies measurement capability and standardisation for innovative measurement solutions in biometric evaluation to support the European Market in security product development and systems interoperability.	Ozlem Lopes				01/07/2014	30/06/2017	SKJ 9/1/2014
IRD/2013/05; Metrology for CCS validation and leakage detection	Request to remove IRD/2013/05 project from IRD 2013 contract. This project was subject to EMRP co-funding approval which was not succesful and will need to be removed from IRD 2013 contract.	Ozlem Lopes	20					SKJ 9/1/2014
IRD/2013/03; Methodology for characterizing radiobiological impact of Au nanoparticles for diagnostic and therapeutic applications.	Request to be substituted into the 2013 contract via a formal amendment. Project IRD/2013/05 did not win its EMRP co-funding. Both projects are of the same value and due to start in April 2014.	Ozlem Lopes	22			01/04/2014	30/03/2017	SKJ 9/1/2014
IRD/2011/3: Metrology for Nano-engineered thermoelectrics	The project co-funds an EU project. The EU contract has an end date of May 2014, this revision is requested to bring the two projects in line.	GMcG		Apr-11	Mar-14	Apr-11	May-14	SKJ 9/1/2014
IRD/2011/11, Advanced metrology for enhanced lifetime of organic diodes, Deliverable 3	Change of scope proposed for D3: This deliverable proposed a Good Practice Guide. However, following discussion at Project Board 3 Dec 2013, it was agreed that it is too early in the development of these techniques for a GPG to be useful. Consequently it is proposed to change this deliverable to produce a Restricted NPL Report on the User Protocol for the tests being developed at NPL. No date changes are proposed.	Lesley Henderson/ Fernando Castro		Jun-13	Sep-14	Jun-13	Sep-14	SKJ 9/1/2014
IRD\2013\15: Strategy for support to addivitive layer manufacturing	Due to delayed feedback from external organisations the final report will be delayed and completed in February. NPL would like to extend end date to 28th February 2014	Ozlem Lopes	87/89	Oct-13	Jan-14	Oct-13	Feb-14	SKJ 27/1/2014
IRD/2011/2: OWEL Marine Wave Power demonstrator: Del 1: Co-fund TSB Specification of instrumentation for control and monitoring	After phase 2 being on hold, now got TSB go-ahead, but revised build schedule is Nov 15	Andrew Smith		Jan-11	Dec-14	Jan-11	Nov-15	SKJ 24/3/2014
IRD/2011/2: OWEL Marine Wave Power demonstrator: addition of Del 2: Co-fund for DECC Deep Green wave energy project	New DECC project: £22k NMS co-fund (65% grant)	Andrew Smith				Mar-14	Feb-15	SKJ 24/3/2014
IRD\2011\1: Scalable, low cost organic photovoltaic devices (SCALLOPS OS0032011 P01)	At the Q11 partner meeting this month, NPL became aware of a discrepancy in project completion date between the industrial and academic partners, with the academic partners expecting to complete 3 months after the industrial ones. Consequently TSB may need to extend the completion date for the industrial partners by 2 months to end June 2014. We therefore request that this project completion date is also extended to end June 2014	Lesley Henderson		May-11	Apr-14	May-11	Jun-14	SKJ 24/3/2014
IRD2012/13 D2 & 4 Development of wide area measurement tools for the electrical characteristics of graphene.	2 month time extension for Time, Quantum and Electromagnetics - extension to reduce the margin by lengthening the time of the deliverables. The deliverables are all on track to meet their objectives.	Stephanie Kitchen		Aug-12	Aug-14	Aug-12	Oct-14	SKJ 24/3/2014
IRD/2012/13 D3 & 5 Development of wide area measurement tools for the structural characteristics of graphene.	2 month time extension for Analytical Science - disruption in their staff utilisation as a new recruit left. The deliverables are all on track to meet their objectives.	Stephanie Kitchen		Aug-12	Aug-14	Aug-12	Oct-14	SKJ 24/3/2014

IRD PROGRAMME - NPL Project Amendment Annex 2014-2015

Project / Deliverable	Revision notes	Requested By	Page	Original		Revised		Authorised
				Start Date	End Date	Start Date	End Date	By/Date
IRD/2012/4, Nanostrain; Del 2 (WP2) : Piezo-NEMS near-field microwave resonator for strain measurement in nanoscale devices demonstrated. Wp2 end date extension request.	It would be beneficial to have that date extended to 31st March 2015. The project itself ends on 31st March 2015; the impact of the extension of our deliverable is small. The rationale to ask for this time increase to deliver WP2 is to be found in the fact that it is becoming more difficult to access to equipment needed to do the project.	Ozlem Lopes	86	Apr-12	Sep-14	Apr-12	Mar-15	SKJ 7/4/2014
IRD/2013/03; Methodology for characterizing radiobiological impact of Au nanoparticles for diagnostic and therapeutic applications. Authorisation reqest to start D2 (Development of a methodology and critical infrastructure for rapid multi-aparmeter screening of specifically functionalsed nanoparticles of clinical interest) in July 2014	Following on from the Project kick-off meeting, team now envisages WP2 activities starting in July 14 – not April 15 as originally indicated, largely due to the need to progress cell studies earlier.	Ozlem Lopes	14	Apr-15	Mar-17	Jul-14	Mar-17	SKJ 7/4/2014
IRD/2012/5 D2 and D3	We request extension of this project by one month, to end October, so as to provide continuity into the expected strategic capability project which will start in November; no additional money is needed.	Lesley Henderson		D2: 1 April 2103 D3: 1 Jan 2013	30 Sept 2014 30 Sept 2014	D2: 1 April 2103 D3: 1 Jan 2013	31 Oct 2014 31 Oct 2014	SKJ 1/9/2014
IRD/2011/11 D2 and D3	During this penultimate month of the project, there have been some significant equipment problems in both fabrication and with the solar simulator. Progress is now underway again but the completion of the test plan (running 100% time) and assessment of the data cannot now be completed by end of September. Consequently we request an extension of the project by one month to end of October.; no additional money is needed.	Lesley Henderson		D2: 1 Mar 2012 D3: 1 Jun 2013	30 Sept 2014 30 Sept 2014	D2: 1 Mar 2012 D3: 1 Jun 2013	31 Oct 2014 31 Oct 2014	SKJ 1/9/2014
IRD\2012\3: (115938) Nanoferroelectrics II **Deliverable 1**	a) New facility – Measurement apparatus for evaluation of the piezoelectric coefficients of piezoelectric thin films – DELIVERED and publication available. b) Completed VAMAS pre-standards report on Piezoresponse Force Microscopy (PFM) – In progress. For the VAMAS pre-standards report we are conducting an inter-laboratory comparison study with the partners participating on a voluntary basis. With the current finishing deadline (Dec. 2014) we expect the report will include contributions from 4 partners. Extending this by a further 6 months will allow contributions from a further 4 partners. This will make for a much stronger pre-standards report.	GMcG	39	Apr-12	Dec-14	Apr-12	Jun-15	SKJ 23/9/2014
IRD\2012\3: Nanoferroelectrics II **Deliverable 2**	New facility: sub-ps pulsed electrical and optical measurement of fast dynamic switching in ferroelectrics. [NPL, Surrey] This workpackage is used to fund work at NPL from an EngDoc student registered at Surrey University (Till Buchacher) and supervision and assistance from Serban Lepadatu and Markys Cain (NPL). The funding for WP2 is due to finish in April 2015, however the EngDoc project arranged with Surrey University is due to finish Dec. 2015. We are currently on track to deliver the ultrafast switching in ferroelectrics measurement facility by April 2015. Further time is needed however to commission this facility by way of measurements on a range of materials and publications. Extending this workpackage is necessary to ensure the collaboration with Surrey University and this project is delivered with maximum impact.	GMcG	39	Aug-12	Mar-15	Aug-14	Dec-15	SKJ 23/9/2014
IRD\2012\3: (115938) Nanoferroelectrics II **Delieverable 3**	Models of ultrafast dynamics to simulate the switching characteristics measured in Task 2. This workpackage is coordinated by Anna Kimmel (NPL). This workpackage needs to be extended in order to complement WP2 – publications arising out of WP2 work will need a theoretical model. This is currently being developed by Anna Kimmel together with Jacob Chapman (PhD student) and will need to be applied to the results obtained from measurements using the completed facility in WP2. Again, extending this workpackage is necessary to deliver maximum impact from the completed ultrafast measurement facility by way of publications.	GMcG	39	Dec-12	Mar-15	Dec-12	Dec-15	SKJ 23/9/2014
IRD/2012/12 (115947) Verification of Carbon Savings for Smart Infrastructure	Reduce value of Deliverable 2 by 28K and add to value of Deliverable 3.	H Murphy	P30 of pdf	01-Apr-13	Feb-15			
IRD/2012/12 Verification of Carbon Savings for Smart Infrastructure	Purpose of revision: to strengthen industrial impact of project. Move 28K form deliverable 2 to deliverable 3 & revise Deliverable 3 to read as follows: Title: Engage Industry & Deliver Impact: A) Produce Carbon Savings reports for industry (e.g. for BT, KIWI Power, ENWL). B) Secure backing for the improved Transform Model from OFFGEM C) Engage DNOs in use of Transform Model. Decision point: If successful extend end date of project beyond Jun 2015 (with no additional NPL finance) & proceed to D. D) Secure £100K industrial funding to fund creation of PAS document (£70K PAS fee+ £30K estimated writing costs). Working with partners including BSI, to finalise the standard (PAS document) which will set this methodology as the standard for the Verification of Carbon Savings for Smart Infrastructure.	H Murphy	P30 of pdf	01-Oct-13	31-Mar-15		30-Jun-15	SKJ 14/10/2014
IRD/2013/09/ESA01	To align end date of this IRD co-funding project with the end date of the ESA TIM project which now has an end date of 31-Jan-15 (was originally 31-Dec-14)	H Murphy		01-Jan-14	31-Dec-14		31-Jan-15	SKJ 14/10/2014
IRD/2013/09/ESA02	To align end date of this IRD co-funding project with the end date of the ESA TIM project which now has an end date of 31-Jan-15 (was originally 31-Dec-14)	H Murphy		01-Jan-14	31-Dec-14		31-Jan-15	SKJ 14/10/2014
IRD\2012\9: Metrology for Structured Surfaces. Del 3: Modelling and prediction of functional performance of patterned surfaces-2 scientific papers	Progress in this deliverable has been slower than expected due to the need to make sure of the best overall approach. An abstract is being prepared for submission to the Interdisciplinary Surface Science Conference in March 2015. We would like to extand this deliverable due to delays in progress caused by illness of a senior project scientist being off sick for 3 months.	Ozlem Lopes		Apr-14	Mar-15	Apr-14	Jul-15	SKJ 14/10/2014
IRD\2012\9: Metrology for Structured Surfaces. Del 4: Dissemination, management and exploitation- NPL Good practice guide, meeting of stakeholder group	A stakeholder meeting took place in September with the support of the IOP with a total attendance of 38 with 26 from industry. The Good Practice Guide is now being written. We would like to extend this deliverable due to delays in progress caused by illness of a senior project scientist being off sick for 3 months.	Ozlem Lopes		Apr-14	Mar-15	Apr-14	Jul-15	SKJ 09/12/2014
Multiprobe Metrology (IRD\2011\4b)– Part 1 [Nanomotion]	To bring closure date in-line with co-funding project; there has been an extension to the Nanomotion project by the co-ordinator	Ozlem Lopes	19	Nov-11	Jun-15	Apr-11	Dec-15	SKJ 09/12/2014

Project Amendment Annex LGC

LGC INNOVATION R&D PROGRAMME - Project Amendment Annex

Project / Deliverable	Revision notes	Requested By	Page	Original		Revised		Authorised By/Date
				Start Date	End Date	Start Date	End Date	
H07 Novel metallomic approaches for improved disease treatment /D3/	Clinical Trail samples will not be received until the end of the summer 2014. therefore by the project will need to go on hold following the completion of deliverable 2. Once the samples have arrived at LGC it will take a number of months to measure them, analyse data and report findings.	Paula Domann		May-11	Sep-14	May-11	Mar-15	SKJ 18.2.2014
H09/Novel spatial metal mapping & molecular imaging of tissues/D3	Work is on hold until the acquisition of a new laser system takes place (in November 2013) since a fault on the current laser system is providing RSD in the region of 40%.	Paula Domann		Apr-11	Sep-13	Apr-11	Dec-13	SKJ 18.2.2014
H09/Novel spatial metal mapping & molecular imaging of tissues/D3	As above- The new laser system with enhanced sensitivity and robustness took longer to install than originally envisaged.	Paula Domann		Apr-11	Sep-13	Apr-11	Mar-14	SKJ 18.2.2014
H07 Novel metallomic approaches for improved disease treatment /D2/	Deliverable 2 has been delayed in order to complete a peer reviewed publication on the findings of the Se Precise Clinical Trial. The knowledge transfer component of this deliverable (D3) is therefore ahead of planned delivery however the end date of D3 remains unchanged.	Paula Domann		Nov-12	Dec-13	Nov-12	Jun-14	SKJ 18.2.2014
2010_09/Nanoparticles/D2	Availability of material produced by collaborators from the Hungarian academy of Science has delayed this deliverable however this material has added value to the project.	Paula Domann		Apr-11	Mar-13	Apr-11	Jun-14	SKJ 18.2.2014
2010_07/Metagenomics/D5	Completion of peer reviewed publications taking longer than originally envisaged.	Paula Domann		Jan-14	Mar-14	Jan-14	Jun-14	SKJ 18.2.2014
2010_09/Nanoparticles/D2	LGC has been invited to submit a paper for a special edition of JAAS (Journal of Analytical Atomic Spectrometry) on Nanoparticles. To enable wider dissemination of project outputs, LGC request that D2 be extended from June 14 until October 2014.	John Black		Apr-11	Jun-14	Apr-11	Oct-14	SKJ 14.7.2014
IRD\2012\14 - Speciation methods for the accurate quantification of metalloproteins/D3b	**New Deliverable added (3b)** - Application of methodology for the identification and quantification of high molecular weight Se species in clinical samples. As agreed by the Working group at the Decision Conference on 04 Sept 2014.	John Black		n/a	n/a	Jan-15	Dec-16	SKJ 22.9.2014
IRD\2012\14 - Speciation methods for the accurate quantification of metalloproteins\D4b	**New Deliverable added (4b)** - Application of methodology for the identification and quantification of adducts of Pt drugs within clinical samples. As agreed by the Working group at the Decision Conference on 04 Sept 2014.	John Black		n/a	n/a	Jan-15	Dec-15	SKJ 22.9.2014
LGC_01/Ultra Trace Analysis in Bio Matrices/D1	Technical issues with the Agilent chip-cube nano-electrospray platform has delayed completion of work to lower the limits of quantification (thus permitting lower initial sample volumes), and evaluation of the chip-cube ability to reduce matrix suppression effects. We now expect work to be completed by Dec 2014.	John Black		Apr-11	Sep-14	Apr-11	Dec-14	SKJ 8.10.2014
IRD13_19/Metrology for de-risking regenerative medicine and cell therapy/D1	Primary mesenchymal stromal cells (MSCs) sourced from our collaborators at Loughborough University are growing slower than expected. In order to culture suitable quantities for the remaining project work, we request an extension of this deliverable to Feb 2015. To mitigate the risk of further delays alternative sources of MSCs will also be investigated. Fibroblast cells will also be used to work up the different methods to be investigated during this period.	John Black		Oct-13	Sep-14	Oct-13	Feb-15	SKJ 8.10.2014
2010_09/Nanoparticles/D2	Initial characterisation of the isotopically enriched silica nanoparticles from the Hungarian Academy of Sciences showed that the particles differed slightly from that of the silica nanoparticles in samples of the coffee creamer and that further modification was required in order to fully investigate their feasibility for IDMS purposes. This has therefore delayed completion of work to develop and validate an IDMS method to quantify silica particles in the coffee creamer matrix and an extension to D2 is required from Oct 14 to Dec 14.	John Black		Apr-11	Oct-14	Apr-11	Dec-14	SKJ 27.11.2014

Glossary

AFM	Atomic Force Microscopy
BOA	British Olympic Association
BRITS	British Regenerative Industry Tool Set
CCQM	Comité consultatif pour la quantité de matière – métrologie en chimie
CPT	Coherent Population Trapping
CSAC	Chip Scale Atomic Clock
DFB	Distributed Feedback Laser
DITS	Dark Injection Transient Spectroscopy
EA-IRMS	Elemental Analyser Isotope Ratio Mass Spectrometry
EC	Embryonic Carcinoma
EMRP	European Metrology Research Programme
ESI	Electro Spray Ionisation
FAMEs	Fatty Acid Methyl Esters
FE	Finite Element
FFF	Field Flow Fractionation
GC	Gas Chromatography
GC-FID	Gas Chromatography-Flame Ionisation Detection
HCF	Hollow Core Fibre
HDAC	Histone Deacetylase
HDPE	High-Density Polyethylene
HPLC	High Performance Liquid Chromatography
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
IDMS	Isotope Dilution Mass Spectrometry
IOC	International Olympic Committee
IRMS	Isotope Ratio Mass Spectrometry
ISO	International Organisation for Standardisation
JIP	Joint Industry Research Project
KCL	Kings College London
LA	Laser Ablation
LAMP	Loop-Mediated Isothermal Amplification
LNE	Laboratoire national de métrologie et d'essais
LOD	Limit of Detection
MALDI- MS	Matrix Assisted Laser Desorption Ionisation Mass Spectrometry

MALS	Multiangle-light scattering detector
MC-ICP-MS	Multi Collector Inductively Coupled Plasma Mass Spectrometry
ME	Manganese Enhanced
MEMS	Micro-Electro-Mechanical Systems
MFI	Measurement For Innovators
miRNA	micro RNA
MMSSA	Methicillin-Sensitive Staphylococcus Aureus
MNP	Manufactured nanoparticle pollutants
MRI	Magnetic Resonance Imaging
mRNA	messenger RNA
MRSA	Methicillin-Resistant Staphylococcus Aureus
MS/MS	Mass Spectrometry/Mass Spectrometry
MSA	Methylseleninic Acid
MSD	Meso Scale Discovery (platform)
NGS	Next Generation Sequencing
NIM	Chinese National Measurement Institute (part per thousand)
NIM	Chinese National Measurement Institute
NIMT	National Metrology Institute Thailand
NIST	National Institute of Standards and Technology
NQR	Nuclear Quadrupole Resonance
OFETs	Organic Field Effect Transistors
OLEDs	Organic Light-Emitting Diodes
OPVs	Organic Photovoltaic Solar Cells
P3HT	Poly(3-Hexylthiophene)
PCA	Principle Component Analysis
PCR	Polymerase Chain Reaction
PE	Plastic Electronics
PFA	Paraformaldehyde
PLA	Proximity Ligation Assay
POC	Point of Care
PTB	Physikalisch Technische Bundesanstalt
QC	Quality Control
qPCR	Quantitative Polymerase Chain Reaction
qRT-PCR	Quantitative Real Time Polymerase Chain Reaction

RF	Radio Frequency
RNA	Ribonucleic acid
RSC	Royal Society of Chemistry
RT	Reverse Transcription
RT-qPCR	Real Time Quantitative Polymerase Chain Reaction
SAW	Surface Acoustic Wave
SeMet	Selenomethionine
SERS	Surface Enhanced Raman Spectroscopically
SHM	Structural Health Monitoring
SIMS	Secondary Ion Mass Spectrometry
SKPM	Scanning Kelvin Probe Microscopy
SME	Small and Medium-Sized Enterprises
SoGAT	Standardisation of Genome Amplification Techniques
STI	Sexually Transmitted Disease
TSB	Technology Strategy Board
UCL	University College London
UCLH	University College London Hospital
UHV	Ultra High Vacuum
UKCRC	UK Clinical Research Collaboration
UPS	ultraviolet photoelectron Spectroscopy
VEGF	Vascular Endothelial Growth Factor
VSCEL	Vertical-Cavity Surface-Emitting Laser
XPS	X-ray Photoelectron Spectroscopy (part per thousand)
‰	per mil

National Measurement System

The National Measurement System delivers world-class measurement for science and technology through these organisations

National Measurement Office

The National Measurement System is the UK’s national infrastructure of measurement Laboratories, which deliver world-class measurement science and technology through four National Measurement Institutes (NMIs): LGC, NPL the National Physical Laboratory, TUV NEL The former National Engineering Laboratory, and the National Measurement Office (NMO).