National Measurement System

National Measurement System Programme

for

Acoustics and Ionising Radiation Metrology

Programme document:

contracted projects in progress during 2014

Contract references:
X0101/0002/15, X0101/0002/16, X10101/0002/18

Version 1 – April 2014

(For Public Release)

National Measurement Office

NPL National Physical Laboratory

LGC Setting standards in analytical science

nel technology for life

National Measurement System Programme

for

Acoustics and Ionising Radiation Metrology

Programme document: contracted projects in progress during 2014

(For Public Release)

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NPL Report: AIR (RES) 085
(For Public Release)

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EXECUTIVE SUMMARY

The Acoustics and Ionising Radiation Metrology (AIR) Programme forms part of a larger portfolio of Programmes which contribute to the UK National Measurement System (NMS) operated by the National Measurement Office (NMO), an Executive Agency of the Department for Business, Innovation and Skills (BIS).

This report contains project definitions for all projects in progress during Jan 2014 that were in the National Measurement System Knowledge Base Programmes for Acoustics and Ionising Radiation, specifically all projects that were in progress prior and continuing into January 2014 or contracted to start in 2014.

Introduction

The AIR programme as a whole maintains and develops the measurement infrastructure for acoustics and ionising radiation that primarily:

- Enables the healthcare, energy generation and defence sectors to comply with regulations and codes of practice.
- Supports healthcare and environmental sectors to improve quality of life.

The AIR programme provides the infrastructure including the development of new measurement techniques to underpin new technology and facilitate innovation.

The AIR programme aims to enable:

- Optimised and effective application of ionising radiation and acoustics in medicine
- Continued safe operation of industries that use ionising radiation
- Better understanding and mitigation of the effects of personal and environmental noise exposure
- Compliance with international obligations in acoustics and ionising radiation
- More accurate sentencing of nuclear waste
- A maintained metrology base to support national nuclear energy options and hydrocarbon exploration
- Optimised application of ultrasound in detection and processing
- Internationally accepted and accessible measurement standards

Projects Summary - 2012 contract

Acoustics projects

Ref	Title	Start Date	End Date	Price £k
AIR/2012/A7	Metrology for a universal ear simulator and the perception of non-audible sound	Jan 2012	Dec 2014	135
NMS/AIR12003	Cofunding for EMRP H11 Metrology for a universal ear simulator and the perception of non-audible sound (Linked to AIR/2012/A7)	May 2012	Jun 2015	198
AIR/2012/A8	Optically based primary standard for sound in air	Oct 2012	Dec 2014	164
AIR/2012/A9	Noise metrology for anthropogenic sources	Jan 2012	Dec 2014	431
AIR/2012/A10	Next generation of metrology for acoustic properties of materials and optical methods	Jan 2012	Dec 2014	217
AIR/2012/A11	Metrology for target strength and active sonar calibration	Jan 2012	Dec 2014	143
AIR/2012/A12	Metrology for therapeutic ultrasound	Jul 2012	Sept 2014	100
NMS/AIR12034	Cofunding for EMRP H12 Metrology for therapeutic ultrasound (Linked to AIR/2012/A12)	Jul 2012	Jun 2015	460
AIR/2012/A14	QUS for osteoporosis assessment	Jan 2012	Dec 2014	230
AIR/2012/A16	Towards a unit for cavitation	Jul 2012	Dec 2015	350
AIR/2012/A17	A new generation of reference and user-focused cavitation sensors (	Oct 2012	Sept 2015	225

Dosimetry Projects

Ref	Title	Start Date	End Date	Price £
AIR/2012/D4	Dosimetry for IMRT & small fields	Jan 2012	Jun 2015	367
AIR/2012/D5	Dosimetry for Complex Hadron Therapy	Jan 2012	Jun 2015	194
NMS/AIR12016	Co-funding for EMRP H14 Metrology for radiotherapy using complex radiation fields (Linked to AIR/2012/D4 and AIR/2012/D5)	Jul 2012	Jun 2015	589
AIR/2012/D6	Dosimetry for Molecular Radiotherapy	Jul 2012	Jun 2015	101
NMS/AIR12018	Co-funding for EMRP H13 Metrology for molecular radiotherapy – Dosimetry element (Linked to AIR/2012/D6)	Jul 2012	Jun 2015	365
NMS/AIR12021	Cofunding for EMRP S04 Biologically weighted quantities in radiotherapy (BioQuaRT)	Jun 2012	May 2015	442

Neutrons Projects

Ref	Title	Start Date	End Date	Price £
AIR/2012/N2	Cosmic Ray and High Energy Dosimetry	Jan 2012	Dec 2014	208
AIR/2012/N3	Develop low energy neutron calibration fields	Jan 2012	Dec 2014	246

Radioactivity Projects

Ref	Title	Start Date	End Date	Price £
NMS/AIR12027	Co-funding for EMRP 18E Metrology for radioactive waste management (MetroRWM)	Jan 2012	Sept 2014	220
AIR/2012/R5	Metrology for Quantitative Imaging and MRT	Jul 2012	Jun 2015	199
NMS/AIR12029	Co-funding for EMRP H13 Metrology for molecular radiotherapy – Radioactivity element (Linked to AIR/2012/R5)	Jul 2012	Jun 2015	201
AIR/2012/R6	Development of capability for radioactive aerosol monitoring	Jan 2012	Dec 2014	190

Projects Summary - 2013 contract

Acoustics Projects

Ref	Title	Start	End	Price (£k)
AIR/2013/A1	Traceability, standardisation and international equivalence for airborne noise and human hearing conservation	Jan 2013	Dec 2015	316
AIR/2013/A2	Provision of standards for underwater acoustics	Jan 2013	Dec 2015	573
AIR/2013/A3	Provision of traceable standards for medical ultrasound	Jan 2013	Dec 2015	654
AIR/2013/A4	Provision of traceable standards for industrial ultrasound	Jan 2013	Dec 2015	151
AIR/2013/A5	Development of next generation of acoustical primary standards based on optical methods	Jul 2013	Jun 2016	265

Dosimetry Projects

Ref	Title	Start	End	Price (£k)
AIR/2013/DC1	Provision of therapy level and protection level primary standards	Jan 2013	Dec 2015	1150
AIR/2013/DC2	Provision of irradiation facilities and mathematical modelling capability	Jan 2013	Dec 2015	2198
AIR/2013/DD1	Provision of the small field and IRMT calorimeter	Jan 2013	Dec 2014	147

Neutron Projects

Ref	Title	Start	End	Price (£k)
AIR/2013/N1	Primary neutron standards	Jan 2013	Dec 2015	1456

Radioactivity Projects

Ref	Title	Start	End	Price (£k)
AIR/2013/R1	Maintenance of primary standards	Jan 2013	Dec 2015	1056
AIR/2013/R2	Secondary Measurement Standards and Systems	Jan 2013	Dec 2015	833
AIR/2013/R3	New primary standards for radiopharmaceuticals	Jan 2013	Dec 2014	207
AIR/2013/R4	New reference materials for nuclear decommissioning	Jan 2013	Dec 2014	100
AIR/2013/R5	Metrology for processing materials with high radioactivity (EMRP MetroNORM proposal; i13: Metrology for processing materials with high natural radioactivity)	Jun 2013	Aug 2016	316
AIR/2013/R7	Development of a mobile radiochemistry laboratory	Apr 2013	Dec 2014	210

Projects Summary - 2014 contract

Acoustics projects

Ref	Title	Start	End	Price (£k)
AIR/2014/U1	Novel detectors for enhanced ultrasound computed tomography – TSB cofunding	Jan 2014	Dec 2016	262
AIR/2014/U2	Exploiting photoacoustic (PA) techniques	Jul 2014	Dec 2015	132
AIR/2014/U4	New measurement methods for kHz-frequency ultrasonic cleaning systems	Jan 2014	Jun 2015	75
AIR/2014/U5	Correlated flow cavitation sensors	Oct 2014	Sept 2016	125
AIR/2014/SA2	In-situ acoustic measurement and calibration	Jan 2014	Dec 2016	280
AIR/2014/UA1	Extension of free-field standards for transducers and materials to lower frequencies	Jan 2014	Dec 2016	151
AIR/2014/UA2	Establish metrology for underwater noise measurement for marine renewables including wave and tidal	Oct 2014	Dec 2016	150
AIR/2014/UA5	Feasibility study of measurement methodologies for vector field quantities and calibration standards for vector sensors	Jan 2014	Jun 2015	50

Dosimetry projects

Ref	Title	Start	End	Price (£k)
AIR/2014/DS1	Development of specialised phantoms for audit	Jan 2014	Dec 2015	182
AIR/2014/DS2	Development of a primary standard for electronic brachytherapy	Jan 2014	Dec 2014	20
AIR/2014/DS4	Dosimetry and radiobiology for new MRI-radiotherapy facilities	Jan 2014	Dec 2016	396
AIR/2014/DS5	Dosimetry for novel radiation processing applications	Jan 2014	Dec 2016	196
AIR/2014/DS7	A new Code of Practice for MV X-ray therapy dosimetry	Jul 2014	Jun 2017	311

Neutron projects

Ref	Title	Start	End	Price (£k)
AIR/2014/N1	Portable fast-neutron spectrometer	Jan 2014	Dec 2016	211
AIR/2014/N2	Neutron-producing target study	Jan 2014	Dec 2015	133
AIR/2014/N3	Thermal neutron field standardisation	Jan 2014	Dec 2014	139
AIR/2014/N5	Improved tissue equivalence of sensors for personal neutron dosemeters	Jan 2014	Dec 2016	190
AIR/2014/N7	Neutron dosimetry based on radiobiology	Jan 2014	Dec 2015	67

Radioactivity projects

Ref	Title	Start	End	Price (£k)
AIR/2014/R2	Nuclear decay data	Jan 2014	Dec 2016	354
AIR/2014/R3	Improved radionuclide metrology for decommissioning and remediation of the UK Nuclear Industry – EMRP MetroDECOM cofunding	Sept 2014	Aug 2017	569
AIR/2014/R6	Metrology for radiological early warning networks in Europe – EMRP MetroERM cofunding	Sept 2014	Aug 2017	279

Facility review, regulatory, management and knowledge transfer projects

Ref	Title	Start	End	Price (£k)
AIR/2014/M01	Review of neutron facility	Jan 2014	Jul 2014	41
AIR/2014/M02	Regulatory Compliance (Radiation Safety)	Jan 2014	Dec 2014	364
AIR/2014/M03	AIR National and International Representation	Jan 2014	Dec 2014	386
AIR/2014/M04	Contract Management	Jan 2014	Dec 2014	204
AIR/2014/M05	Programme Management and Formulation	Jan 2014	Dec 2014	169

Acoustics Projects 2012

Project No.	AIR/2012/A7	Price to NMO	£135k
Project Title	Metrology for a universal ear simulator and the perception of non-audible sound	Co-funding target	NIHR EMRP
Lead Scientist	Richard Barham	Stage Start Date	01-Jan-12
Scientist Team	Richard Jackett. Janine Avison, Rob Pocklington	Stage End Date	31 Dec-14
		Est Final Stage End Date	31-Dec-15
Sector	3.1 Diagnosis 3.3 Health & safety	Activity	Challenge-driven R&D

Summary

This project is aligned with AIR12003 project "Cofunding for EMRP H11 Metrology for a universal ear simulator" and aims to produce prototype advanced ear simulators, representative of neonates, children and adults, simulating oto-acoustic emission and evoked brainstem responses, providing specific traceability for these types of measurement.

The Need

Ear simulators underpin the traceability of measurements required for the diagnosis of hearing disorder, and are used both to establish normative hearing thresholds and in the routine calibration of audiometric equipment. However the metrological underpinning currently relates primarily to pure tone audiometry for adults. Screening programmes for neonates and children are now in place to capitalise on the benefits of early diagnosis and treatment of hearing disorders, which of necessity require alternative objective methods suited to the patient being unable to respond voluntarily or reliably to a stimulus. Consequently hearing assessment methods based on evoked brainstem responses and oto-acoustic emissions (OAE), are now mainstream, with around 800,000 neonatal screening tests being carried out routinely per year. In contrast developments of ear simulator devices for neonates and children has only just been initiated and needs to progress to keep pace with current practices, and no recognised devices exist for simulating objective modalities. This situation has led to the emergence of proprietary methods for calibrating such equipment that hinders comparison of data from different centres and different equipment models, and raises concerns about traceability. Ear simulators for evoked brainstem responses and oto-acoustic emissions, and associated methods of calibration, are therefore required, in addition to basic ear simulators specifically for neonates. All need to be supported by corresponding IEC/ISO specification standards. The frequency range of human hearing has long been regarded as extending from 20 Hz to 20 kHz (though 16 kHz is a more realistic upper limit). However, concerns exist that inaudible sound above this range present a hazard to hearing. Evidence for this is difficult to establish, but the need for mitigating safety criteria and a risk assessment protocol has been identified nevertheless. Many types of machinery emit airborne ultrasound either intentionally for a specific process, or as a by-product of their operation. Producer of such machinery require noise emission regulations to be well founded and not unnecessarily restrictive, while those responsible for workplace safety also need reliable safety criteria and risk assessment processes. However primary standards do not yet exist in this frequency range. Only when the metrology infrastructure of primary standards and methods of calibrating measuring devices have been established can any damaging effect of airborne ultrasound be quantified and legislation to limit exposure be put in place. The first step in determining safety criteria is to establish perception thresholds (as opposed to hearing thresholds) for inaudible airborne ultrasound.

The Solution

Existing ear simulators can be regarded as devices simulating the outer ear (up to the ear drum), whereas the objective modalities under consideration originate at points beyond this in the hearing process. It is therefore feasible to consider a modular design for these advanced ear simulators, where the simulation of the particular modality can be added to existing outer ear simulators. This provides for a great degree of flexibility, since the approach remains valid as alternative designs for the outer ear simulator evolve. The microphone signal from the outer ear simulator would then be used to elicit the type of response to be simulated, which may be generated either acoustically (for OAE) or electrically as a result of signal processing (for evoked responses).

Project Description (including summary of technical work)

In this project a prototype oto-acoustic emission simulator and a prototype auditory evoked response simulator will be developed for use in conjunction with the IEC 60318-4 occluded ear simulator and any similar devices suitable for neonates and children that may emerge (in conjunction with project NMS/AIR12003). The project will begin with consultation of users and manufacturers of equipment featuring the advanced modalities, to establish appropriate functionality and performance specification. The main project activity will see prototype devices designed and produced for evaluation in the laboratory, and the development of appropriate means of calibration. Recommendations to standardisation bodies for the specification of such devices will also be made. Immediately following the end of this project stage (Dec-14) the prototypes will also be made available for evaluation in user environments.

<u>Summary of technical work</u>

- User consultation and literature review to establish functional and performance specifications
- Feasibility evaluation of proposed technical solutions leading to preferred option for each type of device
- Design specification for a prototype oto-acoustic emission simulator and a prototype auditory evoked response simulator
- Experimentation with system components leading to construction of prototype devices

- Laboratory evaluation of each prototype device and development of calibration methods
- 2 peer reviewed papers on the development and performance of the prototype devices
- Preparations of recommendations to standardisation bodies for the specification of such devices

Impact and Benefits

The new ear simulators enable the validation of equipment used in the screening of every newborn child in the UK (around 800,000 per year), enhancing measurement quality. It is estimated that just over 1 in 1000 neonates are diagnosed with hearing disorders, but with reliable detection at this early stage, 40% do not develop risk factors. Oto-acoustic emission testing is used as the first stage in NHS hearing screening programmes in the UK and evoked response audiometry is used in the second stage for referred or at risk cases (e.g. premature births). Improved calibration and traceability for these modalities is therefore vital for achieving the programme's objective for screening and diagnostic services to be effective and delivered to a high standard. Traceability in the field of hearing assessment is strongly geared, with a single ear simulator calibration underpinning 100,000s of hearing tests. Scientifically the project puts NPL at the forefront of ear simulator development. Currently, risk assessment of airborne ultrasound is hindered by a lack of authoritative, scientifically based criteria and no underpinning metrology, but is nevertheless necessary in many industrial applications involving for example, ultrasonic cleaning, sonochemistry, pumping, drilling, and cutting. Metrology and safety criteria issues are both addressed by this project. Understanding of the risks from airborne ultrasound also enables informed regulations to be put in place on emissions from equipment and machinery, avoiding unnecessarily conservative limits and consequent excessive safety measures, while at the same time protecting users, particularly in the workplace.

Support for Programme Challenge, Roadmaps, Government Strategies

The concept of a universal ear simulator is a roadmap deliverable. Inclusion of these objective modalities addresses a key aspect within this. The ultrasound region is now the most significant omission from the roadmap target to have full range calibration capability. Primary standards in this area are required to establish new workplace health and safety regulations relating to exposure to airborne ultrasound. This work will inform future developments in Noise at Work regulations. This project will deliver on the NMS strategy 2011 - 2015 to optimise diagnostic health technologies in clinical practice.

Synergies with other projects / programmes

NPL has a track record for introducing new ear simulators into the field of audiometry. The devices for air-conduction and bone-conduction found in mainstream practice were developed at NPL in the 1970s and 1980s respectively. More recently NPL has led the upgrade of specifications in IEC standards to increase confidence in the use of the devices. If previous trends are repeated, these devices will be adopted into standard in the IEC 60318 series and ISO 389 series, be produced commercially, and used widely in the field. The NHS have established extensive protocols associated with the hearing screening programmes. This project will enable the measurement quality aspects to be improved by better calibration.

Risks

The proposed ear simulators are novel and while technical solutions have been conceived, their suitability as references devices can only be determined once they are produced. Such issues will be part of the considerations in selecting the preferred technical option to develop. NPL is currently alone in seeking to develop such an ear simulator which could hold back future standardisation. This risk can be mitigated by encouraging international partner involvement in evaluating and developing calibration methods for the devices, e.g. through EURAMET and direct links with other NMIs.

Knowledge Transfer and Exploitation

The project is set to conclude, ready for a series of user evaluations of the ear simulators, which represents a useful but limited means of dissemination. Wider activities will include the publication of peer reviewed papers on each device, and presentations at conferences targeting key user groups (e.g. British Society of Audiology). Project outputs will also feed directly into new IEC specification standards. Expectation is that the prototypes will be developed into commercial devices.

Co-funding and Collaborators

This project is aligned and cofunds project NMS/AIR12003, EMRP H11 "Metrology for a universal ear simulator". The EMRP project adds significant cash co-funding with collaborators including PTB, Germany (Lead); DFM, Denmark; Brűel and Kjær, Denmark, UME, Turkey; LNE, France and Aalto U., Finland. The project also requires collaboration with users of ear simulators and calibration centres to establish specifications and to test project outputs. This will be in the form of in-kind contributions rather than cash. However there may be interest from instrumentation manufacturers prepared to support the development of the devices. Funding from NIHR (e.g. i4i funding) will also be pursued for the development of the advanced ear simulators.

Deliverables

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

Deliverable title: Prototype ear simulators for the verification of OAE and ABR systems, suitable for neonates and children, described in peer-reviewed papers

Project No.	NMS/AIR12003	Price to NMO	£198k
Project Title	Cofunding for EMRP H11 Metrology for a universal ear simulator and the perception of non-audible sound (Linked to AIR/2012/A7)	Co-funding	EMRP
Lead Scientist	Richard Barham	Stage Start Date	01-May-12
Scientist Team	Richard Jackett. Janine Avison, +1	Stage End Date	30-Jun-15
		Est Final Stage End Date	
Sector	3.1 Diagnosis 3.3 Health & safety	Activity	Challenge-driven R&D

Summary

The work proposed contributes to the EMRP Health project "Metrology for a universal ear simulator". This EMRP project, aligned with project NMSAIR12002, will develop a universal ear simulator for which new calibration methods will also be developed along with new specification standards. The EMRP project will also examine human perception thresholds for inaudible sound, including the development of the first primary standards for airborne ultrasound. Consequently sensors systems operating in the ultrasound frequency range will be developed. Since these will also be used *in fMRI* and similar environments, the non-metallic nature of MEMS devices will be exploited.

The Need

The frequency range of human hearing has long been regarded as extending from 20 Hz to 20 kHz (though 16 kHz is a more realistic upper limit). However concerns exist that inaudible sound outside of this range still presents a hazard to hearing or creates annoyance. Evidence for this is difficult to establish, but there is strong and growing support that there is a real problem to be solved and an urgent need for mitigating safety criteria and a risk assessment protocol. New technologies and industrial processes emit infrasound or airborne ultrasound either intentionally or as a by-product of their operation. Examples include wind turbines, heat pumps, sonochemical reactors, ultrasonic cleaning and dentistry. Producers of such machinery require noise emission regulations to be well founded and not unnecessarily restrictive, while those responsible for workplace safety also need reliable safety criteria and risk assessment processes. However primary standards do not yet exist in this frequency range. Only when the metrology infrastructure of primary standards and methods of calibrating measuring devices have been established can any damaging effect of airborne ultrasound and infrasound be quantified and legislation to limit exposure and protect the population be put in place. The first step in determining safety criteria for inaudible infrasound and ultrasound is to establish perception thresholds (as opposed to hearing thresholds). A second thread of this EMRP project addresses needs arising in the hearing assessment community, where modern audiological practices are underpinned by ear simulators that are not fit-for-purpose. Hearing tests of newborn children are now carried out routinely and extensively throughout the EU, yet the underpinning metrology (embodied in specification and use of ear simulators) is based on data derived from the adult population. Consequently stimulus levels applied to neonates and children are ambiguous, and the process of diagnosis made less certain as a result. There is an additional need to rationalise the number of ear simulator types available. Four types are currently standardized each having variants and particular usage requirements. This JRP will develop a new universal ear simulator suitable for all age groups, and for use with the variety of transducer types and test stimuli used in clinical practice. Together with new reference threshold data and IEC and ISO standards governing the use of the universal ear simulator, the JRP addresses the need for improved reliability in neonatal hearing screening and for simplifying the calibration of audiometric equipment across all hearing assessment practices.

The Solution

The project aims to support preventative strategies to hearing conservation through two major interdisciplinary research and development activities. The first (WP1 – WP3) aims to establish new understanding of human perception of non-audible sound as well as the metrology infrastructure necessary to put in place effective safety criteria. The second (WP4 & WP5) aims to improve the relevance of metrology in modern audiological practices, to bring about improved quality and reliability of results.

Project Description (including summary of technical work)

WP1 will develop new methods and technology for the determination of brain responses using magnetoencephalography (MEG) and functional magnetic resonance imaging (fMRI) to non-audible sound. New transducers appropriate for delivering and measuring the acoustic stimuli will also be developed.

WP2 will develop new measurement methods and calibration techniques for non-audible sound, including a new primary standard for airborne ultrasound, thereby providing traceability for noise measurement in this part of the frequency range

WP3 will compare brain response measurement and hearing thresholds which will generate new understanding of the perception mechanisms and underpin the determination of safe exposure limits for non-audible sound.

WP4 will follow a process of user requirement, specification, modelling, design and production of a new prototype universal ear simulator

WP5 will develop new calibration methods and determine reference equivalent threshold sound pressure level values for the universal ear simulator. A selection of clinical users will then be engaged to evaluate the new device in audiological practice and provide valuable feedback on usability, and the standardization process will be initiated.

WP6 contains a variety of mechanisms for creating maximum impact, using existing and new contacts with medical and industrial stakeholders, policy formulators, standardization and regulatory bodies, and the wider scientific community.

Impact and Benefits

The new ear simulators enable the validation of equipment used in the screening of every newborn child in the UK (around 800,000 per year), enhancing measurement quality. It is estimated that just over 1 in 1000 neonates are diagnosed with hearing disorders, but with reliable detection at this early stage, 40% do not develop risk factors. Oto-acoustic emission testing is used as the first stage in NHS hearing screening programmes in the UK and evoked response audiometry is used in the second stage for referred or at risk cases (e.g. premature births). Improved calibration and traceability for these modalities is therefore vital for achieving the programme's objective for screening and diagnostic services to be effective and delivered to a high standard. Traceability in the field of hearing assessment is strongly geared, with a single ear simulator calibration underpinning 100,000s of hearing tests. Scientifically the project puts NPL at the forefront of ear simulator development. Currently, risk assessment of airborne ultrasound is hindered by a lack of authoritative, scientifically based criteria and no underpinning metrology, but is nevertheless necessary in many industrial applications involving for example, ultrasonic cleaning, sonochemistry, pumping, drilling, and cutting. Metrology and safety criteria issues are both addressed by this project. Understanding of the risks from airborne ultrasound also enables informed regulations to be put in place on emissions from equipment and machinery, avoiding unnecessarily conservative limits and consequent excessive safety measures, while at the same time protecting users, particularly in the workplace.

Support for Programme Challenge, Roadmaps, Government Strategies

The concept of a universal ear simulator is a roadmap deliverable. Inclusion of these objective modalities addresses a key aspect within this. EMRP funding takes this concept further and aims to produce a universal simulator of the outer ear. The two together therefore fully realises this deliverable. These advanced ear simulators help NHS hearing screening programmes achieve their objective to be effective and delivered to a high standard. The ultrasound region is now the most significant omission from the roadmap target to have full range calibration capability. Primary standards in this area are required to establish new workplace health and safety regulations relating to exposure to airborne ultrasound. This work will inform future developments in Noise at Work regulations. This project will deliver on the NMS strategy 2011 -2015 to optimise diagnostic health technologies in clinical practice.

Synergies with other projects / programmes

NPL has a track record for introducing new ear simulators into the field of audiometry. The devices for air-conduction and bone-conduction found in mainstream practice were developed at NPL in the 1970s and 1980s respectively. More recently NPL has led the upgrade of specifications in IEC standards to increase confidence in the use of the devices. If previous trends are repeated, these devices will be adopted into standard in the IEC 60318 series and ISO 389 series, be produced commercially, and used widely in the field. The NHS have established extensive protocols associated with the hearing screening programmes. This project will enable the measurement quality aspects to be improved by better calibration.

Risks

The proposed ear simulators are novel and while technical solutions have been conceived, their suitability as references devices can only be determined once they are produced. Such issues will be part of the considerations in selecting the preferred technical option to develop. NPL is currently alone in seeking to develop such an ear simulator which could hold back future standardisation. This risk can be mitigated by encouraging international partner involvement in evaluating and developing calibration methods for the devices, e.g. through EURAMET and direct links with other NMIs (e.g. there is strong interest in ear simulator technology in China and Japan). Development of transducers for airborne ultrasound is challenging, and the additional requirement for these to operate in MRI environments adds to the technical risk. NPL has a collaboration agreement with a manufacturer of silicon microphones which may offer a solution.

Knowledge Transfer and Exploitation

The project is set to conclude, ready for a series of user evaluations of the ear simulators, which represents a useful but limited means of dissemination. NPL will also lead the EMRP work package on dissemination. Proposed activities include 2 dissemination workshops, a project website, at least 6 peer review publications, conference presentations targeting key user (e.g. British Society of Audiology), and recommendations to health and safety bodies. Project outputs will also feed directly into new IEC specification standards. Expectation is that the prototypes will be developed into commercial devices.

Co-funding and Collaborators

This project comprises NPL's input into the EMRP Health Metrology for ear simulators project. Collaborators include PTB, Germany (Lead); DFM, Denmark; Brűel and Kjær, Denmark, UME, Turkey; LNE, France as well as researchers from the EAR Institute at UCL.

NPL Deliverables

1	**Start: 01/05/12**	**End: 30/06/15**	

Deliverable title: Cofunding for EMRP H11 Metrology for a universal ear simulator and the perception of non-audible sound

Project No.	AIR/2012/A8	Price to NMO	£164k
Project Title	Optically based primary standard for sound in air	Co-funding target	
Lead Scientist	Triantafillos Koukoulas	Stage Start Date	01-Oct-12
Scientist Team	Rob Pocklington, Pete Theobald	Stage End Date	31-Dec-14
		Est Final Stage End Date	31-Dec-16
Sector	7.1 Traceability & uncertainty	Activity	Challenge-driven R&D NMS infrastructure

Summary

Research towards a fundamental realisation of a primary standard for sound pressure using optical techniques, eliminating reliance on commercial transducers, and expanding the range of devices that can be calibrated at the level of precision offered at the current primary level. This work follows up the research work undertaken in the measurement of particle velocities due to airborne sound and expands it into very challenging free-field conditions.

The Need

Primary standards for sound in air are currently reliant on the continued availability of laboratory standard microphones supplied commercially from a single manufacturer. While there is currently no threat to continued production, this does present a risk with high impact. In addition, realisation of the primary standard is in terms of the sensitivity of these microphones as determined by reciprocity calibration, rather than in terms of the primary quantity of sound pressure. A direct realisation, as offered by optical methods therefore removes the artefact-based nature of the primary standard. NPL is the first NMI to investigate modern optical alternatives to reciprocity calibration, offering direct traceability to the unit of acoustic pressure rather than electrical standards. Accepting the need to displace existing primary standards with an optically based realisation, the same top level requirement for primary standards also applies; i.e. airborne sound impacts the whole hearing population and its measurement is vital to protect the environment we live in, and to control the risk of hearing damage and annoyance caused by noise.

The Solution

Optical measurement provides an opportunity for direct realisation of primary standards. Experimental methods based on the Doppler effect (frequency shift due to particle scattering) and derived from photon correlation spectroscopy have been applied successfully to oscillatory particle motion, enabling particle velocity in air to be determined. When the acoustic impedance is also known, as in a free sound field for example, the sound pressure can be determined. The research work has been successful in the accurate and non-intrusive measurement of particle velocities due to sound in enclosed spaces (such as standing wave tubes). However, for a potential primary standard applicable to microphones of standard and non-standard dimensions, this approach needs to be instated in a fully anechoic acoustical chamber (free-field conditions). In this case, having determined the acoustic pressure at a point in space, the microphone under calibration can be placed in the same point and its response acquired directly as a function of the acoustical Pascal. This approach also poses a number of significant research challenges in order to be fully validated. These include, amongst others, accurate optical alignment over such large distances (3-4 metres), especially in fringe formation due to focused beams, sufficient scattered photon counts using collecting optics at similar ranges, significant mean flow vector components resulting in velocities comparable to those due to sound, amount of particle seeding to counter-balance the mean flow and properties of seeding particles that relate to their scattering efficiency and size that dictate the upper frequency limit to which the technique is applicable. This project extends work in the current programme by the establishment of an optically based primary standard with an uncertainty comparable with reciprocity calibration, initially over a limited frequency range, and then seeks to expand that range in stages beyond 2014.

Project Description (including summary of technical work)

Continued research on the optical technique will demonstrate the calibration of a laboratory standard microphone in free-field conditions at frequencies not higher than 4 kHz by comparison with reciprocity. The results of this comparison will be published in a peer-reviewed journal and work in 2014 will establish the frequency range over which the optical method can provide an alternative primary standard method.

Summary of technical work

- Complete comparison with the reciprocity primary method over a limited frequency range using standard B&K pressure microphones
- Publish peer-reviewed journal paper describing the technical details of the optical system and comparison results with reciprocity
- Establish frequency range over which the optical method is capable of being instated as a new primary standard
- Establish the primary calibration methodology and determine uncertainties.

Impact and Benefits

One of the major impacts of establishing such a new standard relates to the traceability of the measurement itself; the unit of sound is the acoustical Pascal and therefore a standard traceable to the acoustic pressure rather than electrical standards, as is this case up to now, would be a more robust, and approach to be adopted by an NMI. In addition, this would bring NPL to the unique global position of becoming the first NMI to provide calibrations directly traceable to the unit of sound with similar uncertainties to those offered by the current reciprocity technique. It would also mark a return to a primary standard directly realised in terms of sound pressure, but at significantly higher technical level than in the 1950s when this was last the case. Moreover, accurate acoustic measurements have a direct impact on environmental quality through reliable measurements of noise leading to informed decision making and noise policy, and in diagnosis and treatment of hearing impairment, both avoiding enormous detriment to quality of life. Benefits of switching to an optically based realisation are primarily to the NMS. Through moves towards a non-artefact based primary standard the high impact risk of those artefacts becoming unavailable is removed. However, the means by which the primary standard is realised has, in principle, little impact on the general user. Conversely, optical methods place very few restrictions on the type of transducers that can be calibrated, which is of benefit to the general user.

Support for Programme Challenge, Roadmaps, Government Strategies

The project directly addresses the roadmap target for optically based primary standards. Once implemented as a viable means of establishing a new primary standard, it supports the same Government strategies or initiatives as the current 'Core' projects.
Environmental Sustainability – Pollution: Healthcare – Diagnostics and therapeutics:
Specifically, it provides calibration and test capabilities for noise measurement and nuisance assessment, and hearing assessment, conservation and treatment. It underpins measurements for a wide range of initiatives including; environmental noise reduction targets, built environment strategic objectives, renewable energy agenda, noise at work act, and national hearing screening programmes.
This project will support the NMS's drive to develop next-generation metrology, in turn supporting growth and innovation in UK business. It also links up with the measurement and calibration requirements of MEMS microphones.

Synergies with other projects / programmes

The optical calibration of microphones has a common theme, of primary standards based on optical methods, with projects to base the primary standard for marine hydrophone calibration on heterodyne optical interferometry and with the primary standard for medical hydrophone calibration already being based on homodyne optical interferometry. Optical methods are necessary for the calibration of non-standard microphones and this project therefore has linkages with current and future projects on MEMS technology. This project would effectively enable NPL to provide optical calibrations covering the entire acoustic range.

Risks

Free-field calibration of microphones using optical photon correlation methods is of relatively high technical risk, particularly in the technical challenges that influence uncertainty. This risk will be mitigated by partnering with the leading experts in this field and by collaborating with other NMIs where possible. Research staff with experience in the application of optical techniques in the measurement and assessment of sound from the universities of Edinburgh (UK), Le Mans (France), Southampton University (UK) and California Polytechnic State University (USA) have also offered their technical expertise.

Knowledge Transfer and Exploitation

Research in this area at NPL Acoustics has been carried out over the last few years. As a result, NPL has established itself as the leading NMI in this exciting and highly challenging field. The work has produced so far a number of internal and external presentations, in addition to one peer-reviewed journal publication and four international conferences publications. This particular spectroscopy technique has also been applied in the area of materials characterisation (loading and dispersion) that has also produced a further peer-reviewed journal publication and one international conference publication, in addition to featuring in a high profile industrial magazine. Progress on the optical based primary standard will be disseminated through presentations at suitable international conferences and through at least one publication in a peer-reviewed journal. There is strong NMI interest in this project, especially from those with limited capacity to carry our research. Opportunities to present at EURAMET and CCAUV, and at higher levels within these metrology organisations (e.g. at EURAMET General Assembly and BIPM JCRB meetings) will therefore be taken to highlight these achievements, and to indicate the world-leading nature of this research.

Co-funding and Collaborators

This is a pure metrology and significantly research-based project with the objective of instating a new calibration and measurement capability. There are therefore no expectations of collaborators apart from other NMIs. At present NRC, Canada and DFM, Denmark have approached NPL about initiating research in this field.

Deliverables

1	**Start: 01/10/12**	**End: 31/12/13**	
Deliverable title: An optically based research demonstrator calibration facility, demonstrating free-field pressure measurement over the frequency range from 500 Hz to 4 kHz			
2	**Start: 01/01/14**	**End: 31/12/14**	
Deliverable title: Demonstrate the free-field calibration of a secondary microphone and improve the uncertainties to match those of a secondary microphone calibration over a limited frequency range			

Project No.	AIR/2012/A9	Price to NMO	£431k
Project Title	Noise metrology for anthropogenic sources	Co-funding target	
Lead Scientist	Stephen Robinson	Stage Start Date	01-Jan-2012
Scientist Team	Pete Theobald, Lian Wang, Gary Hayman	Stage End Date	31-Dec-2014
		Est Final Stage End Date	31-Dec-2014
Sector	7.3 Traceability & uncertainty 2.2 Pollution & waste reduction 1.3 Low carbon energy	Activity	Challenge-driven R&D Statutory & policy obligations

Summary

The aim is to provide metrology to underpin the protection of the marine environment from anthropogenic noise. This will involve establishing in-situ methods for underwater noise measurement of anthropogenic sources, and for ocean ambient noise. The sources of concern include shipping, and both construction and operational noise from marine renewables. The work will feed into development of international standards, and will provide robust acoustic metrology to underpin the Good Environmental Status (GES) indicators described by the EU Marine Strategy Framework Directive (EU MSFD).

The Need

There has been increasing concern about underwater anthropogenic noise affecting marine life, leading to legislation at both national and European level. EU Habitats' Directive 92/43/EC, and the EC Directive 2001/42/EC govern the protection of the marine environment in Europe (both adopted into UK legislation). DECC issue licences for oil and gas exploration work, and the Marine and Fisheries Agency (MFA) of DEFRA issues around 300-400 licences under the Food and Environment Protection Act 1985 (FEPA) and Coast Protection Act 1949 (CPA) each year for a range of activities including: construction works; land reclamation; renewable energy development (wind, wave and tidal); aggregate dredging; and construction of sea defences. Environmental Impact Assessment (EIA) is now routinely required before the commencement of offshore activities which may generate underwater acoustic noise, but standard methodologies to measure such noise sources in-situ have not yet been developed. The EU Marine Strategy Framework Directive adopted in 2009, requires all EU Member States to achieve Good Environmental Status (GES) by 2020. One of the descriptors of GES is to ensure the *'Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment'*. EU MSFD requirement for Good Environmental Status has led to development of noise pollution indicators which need underpinning with robust metrology. The whole field of underwater noise metrology and impact assessment is relatively immature, with even the meaning of some familiar terms ill defined. There is a strong case for improved metrology infrastructure in this rapidly evolving area to ensure that decisions are based on robust metrology and sound science. The metrology for offshore noise measurement needs to catch up with the rapidly evolving legislative framework. At present, Directives exist which require measurement, but no standards exist to govern the methods.

The Solution

We will build on the NPL work of the last 4 years to establish metrology for in-situ noise measurement, feeding into key stakeholder committees and working groups in which NPL is already taking a leading role. Agreed acoustic metrics for defined impacts must be developed with appropriate definitions. Accepted methodologies for measurement and characterisation of noise sources must be provided, establishing in-situ methods for underwater noise measurement of anthropogenic sources, and for ocean ambient noise. The feasibility of measuring other important field parameters such as particle velocity must be assessed. The sources of concern include shipping, and both construction and operational noise from marine renewables. The work will feed into development of international standards, and will provide robust acoustic metrology to underpin the Good Environmental Status indicators described by the EU Marine Strategy Framework Directive. This will improve understanding of the nature and effect of anthropogenic noise and will reduce barriers to offshore development of marine renewable energy, whilst also protecting the environment (UK Government strategy).

Project Description (including summary of technical work)

The proposed work builds on work started in the current programme to establish methods for in-situ noise measurement in shallow water, and to investigate the possibilities offered by noise measuring buoy technology. In the work proposed here, NPL will engage with other experts in the UK and Europe to obtain consensus, representing UK on international standards committees, and EU Technical working groups (appointed by DEFRA in the UK) to develop guidelines for implementation of the EU MSFD indicators. NPL will also work to develop measurement methodologies for sources of concern such as shipping, marine renewable energy developments (construction and operational noise), and ocean ambient noise. The work will involve:

1. Contribution to international standards groups to devise guidelines for noise measurement. This will include representing UK at the EU Technical Sub-Group on underwater noise looking at implementation of GES indicators for EU MSFD). Guidelines are required not only for specific sources, but also for measurement of ambient noise.
2. Developing measurement methods for nose sources associated with marine renewable energy developments. This requires a better physical understanding of radiation mechanisms for some sources such as marine piling and covers and operational noise as well as construction noise during installation. There are some specific issues with regard to wave and tidal energy systems, which are distinct from offshore wind developments, and there is a need to measure the acoustic particle velocity and seabed vibration (for fish species in particular). NPL is sponsoring a PhD student at ISVR (University Of Southampton) to

work in the above area.

3. Developing measurement and monitoring methodologies for noise from shipping and other contributors to ambient noise. One of the GES indicators for the MSFD covers trends in ambient noise, with a specific emphasis on shipping noise. There is as yet no real agreement on the methods for monitoring such noise, the role of modelling in such assessment, and the analysis methods by which trends may be determined. There is also work required to standardise the methodology for measuring ship noise so that the source data may be used in appropriate models to derive noise maps.

Impact and Benefits

One area of benefit is marine renewable energy which is growing rapidly driven by environmental concerns and the transition to a low carbon economy. Enormous investments are required to achieve the ambitious targets being set by governments (the UK government is investing £180 million in marine renewable energy alone in the next few years in order to reach the target of 30% of electricity from renewable sources by 2020, a five-fold increase from the current value, with independent estimates that the offshore wind could by then be worth £2 billion a year to the UK economy). Among the measures designed to stimulate expansion of renewable power are: up to £120m to advance the offshore wind industry and up to £60m to stimulate progress in wave and tidal technologies. Around 7,000 new wind turbines may be erected by 2020, providing more than 33 GW from offshore wind alone. UK policy is to *drive delivery and clear away barriers* whilst *protecting the environment* and natural heritage through the *application of relevant controls*. The success of this work will ensure that decision-making about anthropogenic noise and environmental impact assessments are based on sound metrology. In particular, the implementation of the EU Marine Strategy Framework Directive must be informed and underpinned by good acoustic metrology to ensure a robust legislative framework which protects the environment without placing unnecessary barriers to developments.

Support for Programme Challenge, Roadmaps, Government Strategies

This area has direct alignment with NMS Strategy 2011-205, with key areas being metrology for *environmental monitoring, renewable energy technologies,* specifically *wind and marine energy.* The work is directly in accord with stated strategy of UK Government, in particular with the DEFRA Marine Bill, the EU Marine Strategy Framework Directive 2008, and with UK Renewable energy strategy. The applicable sectors are Environmental Sustainability, and Energy.

Synergies with other projects / programmes

The work on noise is likely to feature in the NMS programme for a number of years – extending beyond the three-year horizon envisaged here. To address the enormous challenges within marine environmental acoustics, collaboration is essential and the intention is to apply for funding for complementary projects from UK OGD, EPSRC, and EU FP7. The work here is in accord with the research priorities of DEFRA and DECC, and a complementary project is being funded at Cefas. Research work in the Netherlands and Germany will complement the work described here, where collaborative partners are being sought.

Risks

There is inevitably some technical risk but the risk is strongly mitigated by the choice of collaborative partners that are experts in their field. These include: Loughborough University, ISVR (University of Southampton), St Andrews University (Sea Mammal Research Unit), TNO, and Gardline Environmental Ltd.

Knowledge Transfer and Exploitation

Several journal papers and papers at international conferences,(the majority will be collaborative); input to standards bodies such as ISO, BSI and ANSI, and input to scientific committees such as UK Marine Science Coordination Committee; representing UK on the EU Technical Sub-Group for descriptor number 11 (underwater noise) of the Marine Strategy Framework Directive.

Co-funding and Collaborators

In kind collaboration will come from ISVR – University of Southampton; Loughborough University; TNO (Netherlands), SMRU – St Andrews University; National Oceanographic Centre, Southampton; Gardline Environmental Ltd, European Marine Energy Centre (EMEC). This field is too challenging to be addressed solely by NPL with NMS funding, and funding is being sought for joint complementary projects from UK OGD, EPSRC, and EU FP7.

Deliverables

1	**Start: 01/01/2012**	**End: 31/12/2014**	

Deliverable title: Establish international standards and guidelines for ambient noise measurement (feeding into GES indicators for EU MSFD) contributing to publication of at least two standards/guidelines.

2	**Start: 01/01/2012**	**End: 31/12/2014**	

Deliverable title: Develop measurement methods and physical understanding of radiation mechanisms for installation and operational noise for marine renewable energy, including the feasibility of vector field measurement, resulting in at least one joint paper in refereed journal.

3	**Start: 01/01/2012**	**End: 31/12/2014**	

Deliverable title: Develop measurement and monitoring methodologies for noise from shipping and other contributors to ambient noise resulting in at least one joint paper in refereed journal.

Project No.	AIR/2012/A10	Price to NMO	£217k
Project Title	Next generation of metrology for acoustic properties of materials and optical methods	Co-funding target	
Lead Scientist	Pete Theobald	Stage Start Date	01-Jan-12
Scientist Team	Stephen Robinson, Triantafillos Koukoulas, Graham Beamiss, Gary Hayman, Justin Ablitt, Lian Wang	Stage End Date	31-Dec-14
		Est Final Stage End Date	31-Dec-14
Sector	5.1 National Security 7.1 Traceability & uncertainty	Activity	Challenge-driven R&D NMS infrastructure

Summary

This project builds on work funded under the previous and current NMS programmes, with the aims being to develop the next generation sensing methodologies for characterisation of acoustic properties of materials at simulated ocean conditions, primary calibration of hydrophones by optical methods, and improved methods for acoustic field characterisation. The work will include development of measurement methods for characterising structured materials and accurate material sound speed determination at simulated ocean conditions (in the NPL Acoustic Pressure Vessel), and research into future primary standard methods for hydrophone calibration based on optical methods and improved methods for sonar near-field characterisation.

The Need

Traceability is required for calibration and performance testing of underwater acoustic transducers and systems, requiring national standards to be maintained for the UK, and satisfying the requirements of the Mutual Recognition Arrangement (harmonised standards across borders). The current primary standard for marine hydrophone calibration is based on the classic method of three-transducer spherical wave reciprocity, which provides only an indirect method of realising the acoustic pascal, and relies on the availability of suitable reciprocal transducers. Particularly at frequencies of hundreds of kilohertz, this method does not provide the accuracy needed for the most demanding user requirements, with at maximum only a factor of two between the primary standard uncertainty, and that of secondary methods and field measurements. An increasing requirement for accuracy and speed applies to the characterisation of high frequency sonar arrays used for imaging in oil and gas, oceanographic and security applications. Current field characterisation methods based on hydrophone scans or open water measurements are time-consuming and have limitations with regard to accuracy due to artefacts introduced by the hydrophone, and lack of environmental control in open water facilities.

Traceable measurements are also required for acoustic characterisation of materials for underwater acoustics. Viscoelastic materials are commonly used as acoustic windows, barriers and absorbers (including for stealth applications). The acoustic properties of such materials vary with temperature and depth and therefore the materials require testing over a range of such environmental conditions. Advanced acoustical materials used for acoustic stealth (e.g. in defence applications) and for incorporation into sonars are continually improving in performance and it is difficult to measure high performance materials accurately, especially at low kilohertz frequencies. In particular, inhomogeneous materials containing internal structure such inclusions, or an internal sensing array, pose severe challenges due to the requirement to measure in the acoustic far-field of the test panel. Furthermore, the testing of layered materials pose considerable challenges, in particular with regard to accurate determination of sound speed.

The Solution

We will build on the NPL work of the last 6 years to establish the next generation of metrology for underwater acoustics based on optics and for acoustic characterisation of materials at simulated ocean conditions. This has resulted in several peer-reviewed papers in the Journal of the Acoustical Society of America. The proposed solution builds on the foundations laid by the work of previous programmes, where NPL has provided an international lead in both the areas of materials testing and optical techniques applied to acoustical metrology. The previous work on optical calibration methodologies has demonstrated the hydrophone calibration method which will be adopted as the primary standard for hydrophone calibration in the hundreds of kilohertz range. In addition, optical techniques have been used to characterise the acoustic near-field of high frequency sonar array transducers, and the limits posed by the acousto-optic effect have been studied successfully with a sponsored PhD at ISVR (University of Southampton). The proposed project builds on this work by looking to extend the frequency range of the optically-based primary standard to determine its lower limiting frequency, and by finally validating it as a primary standard through inclusion an international key comparison. The previous work on optical methods for near-field transducer field characterisation will be further developed to provide rapid, non-invasive, high-resolution imaging of acoustic fields and extend this to lower frequencies. The NPL's APV provides a unique facility (outside of the USA) for characterising the acoustic properties of materials (in the form of panels) at simulated ocean conditions. The existing methods such as the array sensor technique will be further developed for measuring structured inhomogeneous materials, optical methods will be investigated, and methods will be developed for accurate material sound speed determination at simulated ocean conditions. This work will be jointly undertaken with partners who will provide considerable co-funding in kind, including NUWC-USRD (USA) who will undertake joint comparison exercises.

Project Description (including summary of technical work)
The proposed work consists of two main deliverables:

(i) Develop improved measurement methods for characterising structured materials and accurate methods for material sound speed determination at simulated ocean conditions. The existing array sensor technique will be further developed, and optical sensing techniques will be investigated. Methods will be developed for accurate material sound speed determination at simulated ocean conditions, including for layered materials. The work will be the subject of a peer-reviewed journal paper.

(ii) Determination of the limitations of optical techniques for hydrophone calibration and near-field characterisation including limiting frequency range. Building on previous work, NPL will look to extend the frequency range of the optically-based primary standard down in frequency, validate it as a primary standard through inclusion an international key comparison, and further develop optical near-field scanning to provide rapid, non-invasive, high-resolution imaging of acoustic fields. This work will be the subject of at least one peer-reviewed journal paper.

Impact and Benefits
This project contains state-of-the-art developments in the field of underwater acoustic measurement, which consolidate NPL's position as an internationally leading NMI in underwater acoustic metrology. They are the continuation of longer term research to provide the next generation of calibration techniques to address the anticipated future requirements. The developments will underpin the accuracy of end user measurements and equipment in a wide range of sectors including oil and gas exploration, offshore renewable energy development, oceanographic measurements and defence. The work will also support the future requirements of the UK's extensive underwater acoustic equipment manufacturing base. The project enables NPL to meet the more demanding requirements of industry into the future.
There are only two facilities in the world (including NPL) that have the capability of measuring the acoustic properties of these materials at simulated ocean conditions (the other being in the USA). The development of methods for materials characterisation using the APV has removed the requirements for expensive sea-trials, and enabled savings of up to a factor of ten in costs. The services for testing of panels have proved among the most popular acoustic services and have shown high utilisation over the last five years.

Support for Programme Challenge, Roadmaps, Government Strategies
The project to develop optical techniques directly addresses the roadmap target for optically based primary standards. Once implemented as a viable means of establishing the primary standard it underpins the same Government strategies and initiatives as the current 'Core' projects to provide standards.
The developments in sensing for material testing directly address the developments for acoustic materials topic in the NMS road map for underwater acoustics.

Synergies with other projects / programmes
The project follows a major theme in NPL acoustical metrology for basing the next generation of primary standards on optical methods. Other projects include developing a primary standard for microphones based on optical methods, with the primary standard for medical hydrophone calibration already being based on optical interferometry. The project results in work which will eventually form the basis of NPL's core NMI activity.

Risks
Whilst the project poses some significant technical challenges, NPL have, over recent years built up significant internal expertise and established partnerships with other leading organisations in this area. This will mitigate the risk in the project.

Knowledge Transfer and Exploitation
Progress on the optically based measurement methods and acoustic materials testing will be disseminated through a presentation at a suitable international conference and through at least two publications in a peer-reviewed journal. There is a significant NMI interest in this project, especially from those with limited capacity to carry out research. Opportunities to present at EURAMET and CCAUV, and at higher levels within these metrology organisations (e.g. at EURAMET General Assembly and BIPM JCRB meetings) will therefore be taken to highlight these achievements, and to indicate the world-leading nature of this research.

Co-funding and Collaborators
This project will be delivered through a collaborative effort including NUWC-USRD and Applied Polymers Ltd for the materials work, and ISVR (University of Southampton) and HAARI (China) for the optics work. This will be through in-kind contributions where the collaborators have an interest in the success of the project.

Deliverables

1	**Start: 01/01/12**	**End: 31/12/14**	
Deliverable title: Develop measurement methods for characterising structured materials and accurate material sound speed determination at simulated ocean conditions resulting in at least one publication in a peer-reviewed journal			
2	**Start: 01/01/12**	**End: 31/12/14**	
Deliverable title: Develop optical methods for field characterisation of sonar transducers and hydrophones over an extended frequency range resulting in at least one publication in a peer-reviewed journal.			

Project No.	AIR/2012/A11	Price to NMO	£143k
Project Title	Metrology for target strength and active sonar calibration	Co-funding target	
Lead Scientist	Pete Theobald	Stage Start Date	01-Jan-2012
Scientist Team	Lian Wang, Stephen Robinson, Justin Ablitt	Stage End Date	31-Dec-2014
		Est Final Stage End Date	31-Dec-2014
Sector	5.1 National Security 7.1 Traceability & uncertainty	Activity	Challenge-driven R&D

Summary

The initial aim of the work is to establish a capability for target strength measurements so that specific acoustic targets may be characterised in terms of their backscattering cross-section. In parallel to this will be the development of calibration capability for active sonars and echosounders using standard sonar targets. The capability will be developed at the NPL open water test facility at Wraysbury.

The Need

There is a need to calibrate sonars and echosounders for use in a variety of applications. For example, scientific echosounders used in fisheries acoustics and oceanography require calibration in order to utilise the data for quantitative analysis. Sonars and multi-beam echosounders (MBES) used in hydrographic surveying require functional testing before use in surveying, in particular for safety critical surveying such as that for ship navigation in shallow water (approaches to ports, etc). In the latter case, the International Hydrographic Organisation (IHO) specifies a methodology in Standards for Hydrographic Surveys Special Publication No. 44 (5th Edition, February 2008) which uses a concrete cube of dimension 1 metre placed on the seabed as a standard target to test performance. This is a crude and unsatisfactory choice of target for high frequency sonars due to the dependence of backscatter on aspect angle, and better test methods are required. Many sonars and echosounders require the calibration to be undertaken in-situ without removing the system from the vessel (often it is fixed to the vessel hull and is not easy to remove). In addition, characterisation of targets generally in terms of their backscattered radiation is of scientific interest to those wanting to classify objects that have been detected by sonars or echosounders, ranging from fish to seabed features to mine-like objects. Established techniques already exist to provide solutions to the above calibration problems, in particular there are techniques developed to calibrate scientific echosounders using standard targets. The goal of a standard-target calibration of an active acoustical device is determination of the overall frequency response function of the device by measurement with a standard target. In some important special cases, the goal is determination of a simple scaling factor that effectively integrates the frequency response function. For determination of the combined transmit- and receive-sensitivity of a scientific echosounder, the standard target is suspended at a known position in the beam of the echosounder transducer. This may be done by moving the target or moving the transducer. In the case of a stationary transducer mounted on the hull of a vessel, for example, a three-point suspension is typically used. This may be done in-situ with the active acoustic system installed on the vessel. The standard targets for calibrating active sonars are typically solid elastic spheres, made from copper, tungsten carbide, or aluminum alloys.

The Solution

The use of the existing techniques is limited to the scientific community, and there is no service offered within the UK for this type of calibration. The aim of the work proposed here is not to replace the existing calibration techniques, but instead to build upon them, establishing a capability using the NPL open water test facility, launching a service, and undertaking in-situ measurements as a demonstrator. Working with partners, NPL will then seek to demonstrate the extension of the technique to other types of sonars and sonar users not commonly benefiting from the calibration techniques.

Project Description (including summary of technical work)

The well-established calibration techniques for active sonar calibration using standard targets will be implemented at NPL's open water test facility. Initially, a capability to characterise any target for backscattering cross-section will be established. Then standard targets will be acquired for use in active sonar calibration, and a capability for full calibration will be established. Investigations will be conducted into novel retro-reflective targets for use in performance testing of hydrographic surveying using MBES systems. A service will be launched, and the technique will be demonstrated in-situ on suitable vessels supplied by partners. Working with partners, NPL will then seek to demonstrate the extension of the technique to other types of sonars and sonar users not commonly benefiting from the calibration techniques. There are two deliverables envisaged:

1. Establish capability for target strength measurements for target characterisation and launch service;
   This will establish a service using the NPL open-water test facility for characterisation of target strength of objects, including objects placed on the seabed, and suspended targets where characterisation must be done as a function of aspect angle;
2. Establish capability for active sonar calibration with standard targets and launch calibration service.
   A service will be established for calibration of echosounders and sonars using standards targets, both at the NPL open-water test facility and based on in-situ measurements. The method will utilise standard spherical elastic targets. Investigations will also be undertaken into developing retro-reflective targets for use in functional testing for hydrographic MBES systems.

Opportunities for publications will be pursued, and it is envisaged that at least one peer-reviewed paper is likely from this work.

Impact and Benefits
The UK has a highly active sonar and transducer manufacturing industry, with over 30 companies involved in the manufacture of underwater acoustic systems. The work here will provide a service to the UK not routinely available elsewhere. Those benefiting are likely to be those users of scientific echosounders and MBES systems requiring performance checking, or full calibration for quantitative data analysis. These include users with applications such as fisheries acoustics and oceanography, hydrographic surveyors, researchers interested in seabed classification, and those interested in mine hunting for defence applications.
In addition, manufacturers of sonars, echosounders and MBES systems will benefit from the services developed in product testing and performance benchmarking.
The active sonar calibration method when applied to traditional imaging sonars could provide a paradigm shift in the method for in-situ performance testing – essentially offering a cost effective alternative to decommissioning the sonar from the vessel and testing in a tank or open water facility.
The establishment of a target strength facility at the NPL open water test facility will provide a test and benchmarking service for those interested in classification of seabeds and objects close to them.

Support for Programme Challenge, Roadmaps, Government Strategies
This work is relevant to items on the NMS Underwater Acoustics Roadmap such as *full sensor transfer function determination*, and *improved in-situ characterisation*.

Synergies with other projects / programmes
There is considerable synergy with the work of Woods Hole Oceanographic Institute (WHOI), where Professor Ken Foote is a leading expert on the techniques in question. Precise seabed geophysical data is essential for ship safety and is a priority for the MCA and UKHO where the safety-related nature of this type of survey means accuracy is of paramount importance.

Risks
The work would build on techniques that are already well established, reducing the technical risk. Working with a world expert such as Prof Foote would reduce the technical risk even further.

Knowledge Transfer and Exploitation
New calibration services would be launched using the NPL open-water test facility at Wraysbury reservoir.
A joint peer-reviewed journal paper would be published.
NPL will seek to exploit any IPR from novel acoustic targets developed during the project, making these available commercially through a partner supplier.
NPL will seek to demonstrate the extension of the technique to other types of sonars and sonar users not commonly benefiting from the calibration techniques by undertaking in-situ tests of systems using vessel-deployed targets.

Co-funding and Collaborators
Professor Ken Foote of Woods Hole Oceanographic Institute (WHOI) is keen to collaborate in this work as a con-funded partner.
As part of the project, an outward guest worker visit for an NPL staff member would be arranged to Woods Hole Oceanographic Institute in the USA. This would allow first hand experience to be gained of conducting the active sonar calibrations. To partly cover the costs of this visit, an application will be made to ONR (Office of Naval Research) Global.
For the application in hydrographic surveying, NPL will work with the UK Hydrographic Society, and contacts in industry familiar with performance testing of surveying systems (Associated British Ports, Marine Coastguard Agency).

Deliverables

1	**Start: 01/01/2012**	**End: 31/12/2014**	
Deliverable title: Establish calibration methods for autonomous underwater noise recorders (Amendment, 2 April 2013, see below)			
2	**Start: 01/01/2012**	**End: 31/12/2014**	
Deliverable title: <u>Characterise uncertainties in</u> <u>standardised method for active sonar calibration with standard targets and contribute to ISO/IEC</u> (Amendment, 2 April 2013, see below)			

Changes to AIR/2012/A11 "Metrology for target strength and active sonar calibration"

Existing deliverables:
D1: Establish capability for target strength measurements for target characterisation and launch service
D2: Establish capability for active sonar calibration with standard targets and launch calibration service
Start date: 01-Jan-2012 End date: 31-Dec-2014 Project value: £143,226

Progress
It was always envisaged that the effort for this three year project would start slowly with the majority of the work taking place in year 2 and year 3 (2013-2014). In the first year, the main activity within the project was to undertake scoping activity to determine the exact nature of the metrology requirement, and then plan the remaining project tasks accordingly. Accordingly, NPL has been involved in discussions with stakeholders from industry and academia with regard to the most effective work to undertake to produce the most impactful project outputs. As a result of this consultation NPL would like to suggest significant changes to this project in the light of new developments in underwater acoustic metrology. The proposed changes are cost neutral.

Changes proposed to AIR/2012/A11 D1
NPL has scoped the requirements for target strength measurements using the open water facility, and though there is still demand, it is not currently significant enough to warrant the development of a calibration service. Such demand as there is originates from relatively few customers. The need for the capability could be addressed in the future by direct collaboration or, should the need develop more widely, by a future NMO project which would be subject to approval by the NMO WG at that stage. Instead of progressing this project further, NPL recommends that this deliverable be terminated and the funding used to support another project aiming to develop standard methods for the calibration of autonomous noise recorders for ocean noise measurement.

Changes proposed to AIR/2012/A11 D2
NPL has now scoped the requirements for scientific echo-sounder calibration, having consulted with UK academia, Woods Hole Oceanographic Institute (WHOI) in the USA, and researchers active in the working groups of the International Council for the Exploration of the Sea (ICES), which represents the main user community. We have now reached significant conclusions with regard the future direction of the work. The methodology used for such calibration is already well established and has the feature that it is designed for an *in-situ* procedure on-board the vessel on which the echo-sounder is deployed. Therefore, there is little scope for significant utilisation of a calibration service using the NPL open-water facility. However, in discussion with Professor Ken Foote of WHOI (the world expert in the technique) and other researchers, there is a real need to standardise the method and feed the findings though to international standards via ISO or IEC. Therefore, NPL propose that the output of this deliverable be changed to reflect that the work will contribute to standardisation of the methodology and feed into ISO/IEC. The proposed new wording for the deliverable is: "Characterise uncertainties in standardised method for active sonar calibration with standard targets and contribute to ISO/IEC".

New project (replacing AIR/2012/A11 – D1)
The aim of this new project is to develop methods suitable for the calibration and characterisation of autonomous recorders used in measurement of underwater noise, thus providing traceability for underwater noise monitoring to underpin the protection of the marine environment from anthropogenic noise, for example in response to the EU Marine Strategy Framework Directive (MSFD). This was proposed as a new project for the 2012 NMO Decision Conference, but just missed out on funding. However, since the original proposal was formulated, the need has become even more acute, a fact which has been recognised by the EU MSFD Technical Sub-Group on Underwater Noise. At both the October 2012 and the February 2013 meetings, the calibration of autonomous recorders was highlighted as a problem requiring urgent solution, and the issue was specifically raised in the committee progress report to the Commission. As Member States consider their proposals for noise monitoring programmes in response to the MSFD, the calibration of the autonomous recorders must be underpinned by robust metrology. This will be addressed by the proposed new project. The methods developed will provide the ability to determine the key acoustic performance characteristics of the recorders, including the self-noise of the hydrophone and system, the hydrophone and system sensitivities, and the effect of any diffraction around the recorder body. The work will result in publications and feed into development of international standards and EU guidelines. The work will benefit from strong collaboration and in-kind co-funding, which has been offered by 10 suppliers and users of the technology within UK and Europe, with contact having been made with many of them only in the last three months. It will provide much-needed acoustic metrology to underpin the Good Environmental Status (GES) indicators described by the EU Marine Strategy Framework Directive (EU MSFD). The title of the new project would be: "Establish calibration methods for autonomous underwater noise recorders Start: 01-Apr-2013; End: 31-Dec-2014 (NMS/AIR12035)

Project No.	AIR/2012/A12	**Price to NMO**	£100k
Project Title	Metrology for therapeutic ultrasound	**Co-funding target**	
Lead Scientist	Adam Shaw	**Stage Start Date**	01-Jul-2012
Scientist Team	Mark Hodnett, Pierre Gelat, Elly Martin, Christian Baker, Ian Butterworth, Neelaksh Sadhoo, Minh Hoang	**Stage End Date**	30-Sep-2014
		Est Final Stage End Date	30-Sep-2014
Sector	3.2 Drugs & therapies 3.3 Health and Safety 7.1 Traceability & uncertainty	Activity	Challenge-driven R&D

Summary

To enhance measurement capabilities for HITU equipment and develop measurement services for HITU equipment. As well as the experience of previous NMS AIR programmes, this project builds in part on the knowledge gained from a previous IMERA+ EMRP project "External Beam Cancer Therapy" with more than 20 published papers. This project is linked to the AIR project NMS/AIR12034 "Cofunding for EMRP HLT0312 Dosimetry for Ultrasound Therapy" and will enable NPL, collaborating with Institute for Cancer Research, to begin biological dose/response studies.

The Need

Ultrasound is used for a wide range of different treatments: physiotherapy, enhanced bone repair, high intensity focused ultrasound (HIFU), lithotripsy, fat removal, and various cosmetic purposes. The optimum 'amount' of ultrasound to achieve a successful treatment outcome is generally not known and, if there is any treatment planning, it is currently based only on time and intensity measured in free-field conditions, not in tissue. Support for manufacturers for equipment development and standards compliance requires a suite of field measurement facilities which also underpin more fundamental research into dose and treatment planning.

The Solution

To address this need, the solution is to establish not just an internationally recognised measurement standards infrastructure, but also a dosimetry infrastructure (including base quantities, measurement methods and modelling methods) along the lines of those used for ionizing radiation. This project will focus on the former, in particular, draft measurement standards for High Intensity Therapeutic Ultrasound (HITU) have been written but these have to be implemented experimentally and tested more thoroughly, as well as being modified as best practice improves.

Project Description (including summary of technical work)

Measurement services for HITU equipment: to include the consolidation of established but separate techniques into an integrated measurement process (which includes the new scanning tank, infrared field mapping, thermal methods and optical techniques); the establishment of a measurement service based on draft IEC62556; and a critical review of the draft standard with suggested improvements submitted to IEC TC87. This will result in a measurement service and contributions to IEC standards.

Impact and Benefits

This project will assist the wider acceptance of new therapeutic ultrasound applications, which is currently hindered by the lack of underpinning metrology. The integration of a range of techniques into a coherent measurement service will also improve the efficiency of future work and benefit customers requiring testing of diagnostic and non-HITU therapy devices. The project will also result in improved IEC standards.

Support for Programme Challenge, Roadmaps, Government Strategies

The project is aligned to the NMS Strategy and AIR Programme Roadmap "Metrology for medical applications of ultrasound to support improvement in healthcare of EU citizens" and also the UK's Cancer Strategy.

Synergies with other projects / programmes

NMS AIR Programme research in the Industrial Ultrasound area and Underwater Acoustics.

Risks

No major technical risks are envisaged as the project builds on already well established internal expertise in this area.

Knowledge Transfer and Exploitation

Delivery will be through the IEC TC87 and provision of enhanced measurement services and consultancy to companies and the health services.

Deliverables

1	**Start: 01/07/2012**	**End: 30/09/2014**	

Deliverable title: Measurement services for HITU equipment: as evidenced by a measurement service based on draft IEC62556, and text improvements to the standard submitted to IEC TC87.

Project No.	NMS/AIR12034	Price to NMO	£460k
Project Title	Cofunding for EMRP HLT03 Dosimetry for Ultrasound Therapy (Linked to AIR/2012/A12)	Co-funding target	
Lead Scientist	Adam Shaw	Stage Start Date	01-Jul-2012
Scientist Team	Mark Hodnett, Pierre Gelat, Elly Martin, Christian Baker, Ian Butterworth, Neelaksh Sadhoo, Minh Hoang	Stage End Date	30-Jun-2015
		Est Final Stage End Date	30-Jun-2015
Sector	3.2 Drugs & therapies 3.3 Health and Safety 7.1 Traceability & uncertainty	Activity	Challenge-driven R&D

Summary

The work proposed here is aligned with AIR project A12 and contributes to a wider body of research in the European Metrology Research Programme “Dosimetry for Ultrasound Therapy (DUTy)” project HLT03. The aim is to conduct research for the definition and metrological underpinning of a dose concept in therapeutic ultrasound and to develop dose modelling and measurement methods for proper treatment planning and risk assessment. As well as the experience of previous NMO programmes, this project builds in part on the knowledge gained from a previous IMERA+ EMRP project “External Beam Cancer Therapy” with more than 20 published papers. The project will enable NPL, collaborating with ICR, to begin biological dose/response studies; successful EMRP cofunding will greatly enhance this.

The Need

Ultrasound is used for a wide range of different treatments: physiotherapy, enhanced bone repair, high intensity focused ultrasound (HIFU), lithotripsy, fat removal, and various cosmetic purposes. The optimum ‘amount’ of ultrasound to achieve a successful treatment outcome is generally not known and, if there is any treatment planning, it is currently based only on time and intensity measured in free-field conditions, not in tissue. This project will establish definitions related to dose for ultrasound and to develop modelling and measurement methods to determine the delivered dose according to these definitions. Proper treatment planning and risk assessment require metrological input to develop and validate methods for determining the correct dose. In the longer term, this will provide a solid metrological basis for the verification of treatment planning systems and will contribute to the benefit of the patients.

The Solution

To address this need, the solution is to establish not just an internationally recognised measurement standards infrastructure, but also a dosimetry infrastructure (including base quantities, measurement methods and modelling methods) along the lines of those used for ionizing radiation. For dosimetry, the variety of mechanisms for interaction with tissue (e.g. thermal, cavitation, radiation force) needs to be considered, although the main emphasis will be on thermal mechanisms. To achieve this, the project will establish a set of defined dose quantities which will be presented for international scrutiny, and will develop measurement methods to determine the highest priority quantities. Modelling is seen as an essential aspect of the work to estimate dose to tissue, in the same way as Monte Carlo simulations underpin a great deal of ionizing radiation dosimetry. So ultrasound modelling capabilities at NPL will be enhanced to include more detailed interaction with tissue and the developed models will be validated against the new measurement methods. We will carry out comparisons with methods used in other NMIs. In addition, we will be able to begin to implement some of these methods on commercial equipment (for instance looking at treatment planning), and explore experimentally the relationship between dose and tissue or cellular response to permit more precise treatment planning.

Project Description (including summary of technical work)

The main aspects to the work include:

Definitions and quantities for ultrasonic dose: to include the evaluation of potential dose quantities and methods for measurement and modelling resulting in a scientific workshop, at least 1 peer reviewed paper and contribution to IEC standards.

Measurement methods for ultrasound dose: to include development and evaluation of systems for the measurement of dose quantities related to thermal and non–thermal mechanisms. This will result in at least 2 peer reviewed papers describing the preferred systems and at least 1 commercially exploitable system.

Modelling methods for ultrasound dose: to include specification and commissioning of computer hardware for nonlinear, 3d modelling; development and validation of improved models for nonlinear propagation and interaction with tissue; calculation of dose quantities and evaluation of associated uncertainties. This will result in at least 1 peer reviewed paper.

Intercomparison of dose determination methods: including carrying out measurement and modelling of agreed set of transducers and realistic exposure conditions. This will result in a peer-reviewed paper summarising the results and comparing with methods used at PTB, INRIM and UME.

Tools for commercial therapy systems: to include development of dose measurement phantoms/systems for hospital use; evaluation in at least 3 clinical centres; peer-reviewed paper. This will result in at least 1 commercially exploitable system.

Application to clinical treatment: the development of a prototype system for delivering precisely quantified thermal dose to different cells and tissues (durations between 0.1 and 20s) and a study of their responses over a range of timescales; the calculation of treatment dose maps for clinical HIFU patients; evaluation of clinical therapy equipment. This will result in at least

3 peer reviewed papers and a database resource for other researchers. Note: some aspects of this deliverable anticipate securing further European funding in addition to the main EMRP project funding.

Impact and Benefits

This project will assist the wider acceptance of new therapeutic ultrasound applications, which is currently hindered by the lack of underpinning metrology. In consequence techniques like high intensity therapeutic ultrasound, offering the potential for increased survival rates in a wide range of cancers and improved quality of life, are not accessible for all. In addition, the use of properly validated dose quantities will enable a better understanding of the dose-response of different tissue types, leading to treatments (including routine physiotherapy) which can be more precisely tailored to the individual patient – reducing costs and improving outcome. Entering the areas of biological dose/response studies will bring NPL's metrological expertise to a wider range of disciplines in medical ultrasound with anticipated benefits to patients. The project will also result in improved IEC standards.

Support for Programme Challenge, Roadmaps, Government Strategies

The project is aligned to the NMS Strategy and AIR Programme Roadmap "Metrology for medical applications of ultrasound to support improvement in healthcare of EU citizens" and also the UK's Cancer Strategy.

Synergies with other projects / programmes

NMS AIR Programme research in the Industrial Ultrasound area and Underwater Acoustics.

Risks

The major risk is that the computer models cannot be made sufficiently realistic to provide useful results for complex (non-circular) nonlinear fields. In this case, modelling will be restricted to either circular nonlinear fields or to linear non-circular fields. We will also make use of collaborations with UCL to make use of their computer cluster. We will look for further European funding to address the dose-response effect and improved patient imaging aspects mentioned, which would benefit from researches with existing experience in these areas.

Knowledge Transfer and Exploitation

Delivery will be through the IEC TC87, scientific publication and provision of enhanced measurement services and consultancy to companies and the health services. A number of exploitable measurement systems are expected to arise: we will pursue these with commercial partners (such as Precision Acoustics) as appropriate.

Co-funding and Collaborators

Anticipate contributions in kind, and access to specialist facilities and equipment from Institute for Cancer Research, Oxford University, Imasonic, US FDA, and participants in IEC TC87/WG6 and WG14. Possible cofunding through EPSRC and other research proposals especially with ICR.

EMRP project includes partners: Physikalisch-Technische Bundesanstalt (Germany); INRIM (Italy), UME (Turkey); CSIC (Spain); ICR (UK); Moscow State University (Russia); NIM (China); University of Merseburg (Germany) - together with any of their local collaborators.

Deliverables

1	**Start: 01/06/2012**	**End: 31/05/2015**	

Deliverable title: Cofunding for EMRP project HLT03 Dosimetry for Ultrasound Therapy

Project No.	AIR/2012/A14	Price to NMO	£230k
Project Title	QUS for osteoporosis assessment	Co-funding target	
Lead Scientist	Bajram Zeqiri	Stage Start Date	1-Jan-2012
Scientist Team	Srinath Rajagopal, Christian Baker	Stage End Date	31-Dec-2014
		Est Final Stage End Date	31-Dec-2014
Sector	3.1 Diagnosis, 3.4 Disease prevention & management	Activity	**Challenge-driven R&D**

Summary:
This project will investigate and establish a metrological framework designed to underpin the clinical development of Quantitative Ultrasound techniques as an effective screening tool for osteoporosis.

The Need:
Quantitative Ultrasound or QUS is correlated to bone properties and osteoporosis. Bone Mineral Density (BMD) measurement is underutilized as a screening tool within the majority of European Countries. Reasons for this include the limited availability of densitometers, restrictions in personnel able to perform scans (due to the use of *x*-rays) and poor awareness of the usefulness of BMD measurements. As a result of this, osteoporosis remains one of the most prevalent under-diagnosed diseases in the world today. Statistics related to the disease are compelling, underlining the huge personal and economic toll caused by the disease [1]. In Europe, disability due to the disease is greater than that caused by cancers (with the exception of lung cancer) and is comparable with or greater than that lost to a variety of chronic non-communicable diseases such as rheumatoid arthritis, asthma and high blood pressure related heart disease. By 2050, the worldwide incidence of hip fracture is projected to increase by 310% in men and 240% in women. In 2000, within Europe, there were an estimated 4 million new (hip) fractures, or one every eight seconds. The total direct costs of hip fractures were estimated to be €31.7 billion, a bill expected to increase to €76.7 billion in 2050 based on anticipated demographical changes in Europe. Within the UK, of the 70,000 people who have osteoporotic hip fractures each year, 30% will die within a year from causes directly related to the fracture. There has been strong interest in QUS management of osteoporosis: equipment is relatively inexpensive and there is significant evidence that it is able to predict hip fractures in elderly women as accurately as the 'reference' technique DXA (dual energy x-ray absorptiometry). Over the last three years, within the Pacific Rim region, 4 million QUS scans have been completed using a GE system alone. Despite its potential, clinical use of QUS remains very poorly defined, with uncertainties over long-term stability, cross-calibration, reference databases, precision issues, technical diversity of equipment and its clinical deployment [2]. A range of commercial systems employ QUS technology for osteoporosis screening and it is well documented that results vary significantly across systems. There is a clear need to inject metrology and standardization into the field, enabling the diagnostic capability of QUS to be fully exploited [3].

1] http://www.iofbonehealth.org/facts-and-statistics. [International Osteoporosis Foundation (IOF)].
2] *Quantitative Ultrasound in the Management of Osteoporosis*: The 2007 ISCD Official Positions, Journal of Clinical Densitometry: Assessment of Skeletal Health, vol. 11, no. 1, 163-187, 2008.
3] Quantitative Ultrasound – It is time to focus research efforts, Bone, (2007) 9-13.

The Solution:
The QUS screening process involves positioning two piezoelectric transducers either side of the calcaneum (heel) and measuring the characteristics of sub- 1 MHz ultrasound transmitted through bone. Typically, attenuation of the acoustic signal is measured, and used to derive a quantity known as Broadband Ultrasound Attenuation (BUA) that has been correlated with the degree of osteoporosis. The complex nature of the interaction between the ultrasound and the heel structure makes the measurements variable, and this is exacerbated through phase-cancellation artefacts caused by the use of large area phase-sensitive detectors. The objective is to apply a metrological approach to the QUS screening process, supporting development of standardised protocols. The project will leverage off NPL's IP related to phase-insensitive detection of ultrasonic fields, using the pyroelectric effect.

Project Description (including summary of technical work):
For QUS assessment, the objective of this work will be to develop a critical metrological understanding of the use of ultrasound to assess the disease potentially through modelling, phantom design and the employment of novel transduction methods.
Activities include:

- Scoping phase: contacting manufacturers and clinical users, literature review, formation of Steering Group.
- Development of phantoms and characterisation methods.
- Understanding 3-D acoustic fields transmitted through bone or bone-like materials (including potential modelling), and how this affects the measurement properties (BUA or speed of sound values).
- Development of new detection schemes and analysis techniques, based on phase-insensitive measurements.
- Development of Standards for performance assessment of QUS equipment.

Impact and Benefits:
Successfully completing the work will provide manufacturers and clinicians with specification standards, methods and tools required to overcome existing technological barriers to success, enabling them to develop and deploy cost-effective and specific

treatment vehicles for conditions increasingly affecting our ageing society. Validated QUS technology, enabling measurements to be carried out in a standardised, traceable and repeatable way, will impact hugely on disease management. Improved precision measurements will be crucial in recognising patients with a sufficiently high probability of fracture risk that would benefit from medication. This would enable much wider screening for the disease, driven crucially by the non-ionising nature of ultrasound radiation, making it a safe, portable technology, bringing screening into GP practices and even people's homes. For *Patients* these relate to a) improved diagnostic techniques, leading to better and less traumatic disease management, and b) fewer hip fractures and a reduction in costly and traumatic procedures. For *Healthcare providers*, benefits from the project are: increased range of reliable equipment available; enhanced information guiding equipment procurement and underpinning patient care; access to flexible measurement tools & reduced healthcare costs. *Manufacturers* will benefit from access to validated phantoms and performance standards as well as the availability of validated measurement, testing and QA tools and services.

Support for Programme Challenge, Roadmaps, Government Strategies

Healthcare – Diagnostics. The project is relevant to the NMO Roadmap "Metrology for medical applications of ultrasound to support improvement in healthcare of EU citizens", with particular relevance to the Target - *Modern ultrasound methods for improved diagnostic and therapeutic modalities* and the Technology Module - *Test objects (phantoms) for determining the performance of medical diagnostic equipment*. It is a strong fit to the Measurement Priority: Health Challenge in the NMS Strategy 2011-2015 which states "Health priorities will be driven by predicted changes in population demographics and the increasing prevalence of age-related health issues....There is a need to introduce more efficient clinical practices and (early) prognostic and diagnostic techniques...These new practices and technologies must be validated as safe and effective".

Synergies with other projects / programmes:

The scientific knowledge gained from the project is more generally relevant to the detection of ultrasound transmitted through complex biological media, and diagnostic imaging. Currently, National Institute of Health Research (NIHR) funding has been won for a project entitled "Enhanced through-transmission ultrasonic tomography for breast imaging using novel phase-insensitive pyroelectric detectors" (Reference number: II-FS-0909-13081) through the Invention for Innovation (i4i) scheme. This project is due to be completed in September 2011, and following establishment of proof-of-concept, other funding routes will be explored to move the development towards a clinical instrument. An EPSRC-funded PhD at ISVR (University of Southampton), is currently under way investigating the potential of the new detection method. NPL, through its internal Strategic Research Programme, has already supported proof-of-concept projects in this area. With suitable clinical partners, NIHR support may also be sought to establish proof-of-concept of any novel ideas for bone density measurement systems based on ultrasound.

Risks:

The project concerns research and the technical risks of the objectives not being met i.e. that the improved metrological understanding of the QUS process does not lead to an improvement in its clinical application, are considered to be small. It is important, however, that the solutions and outputs are of clinical relevance, and this will be ensured through a detailed scoping phase involving interaction with the manufacturing and clinical communities (potentially through a Questionnaire process) and by establishing a Project Steering Group (PSG) comprising clinical users (University of Cambridge have expressed and interest in the project, through Dr Jonathan Reeves).

Knowledge Transfer and Exploitation:

New phantoms could be spun out to potential manufacturers. A QUS User Forum, probably held at NPL, will be organised early in Year 3. Newly developed protocols will be disseminated through relevant standardisation and professional organisations. The project is likely to generate new potentially patentable detector systems and new clinical systems, which again may ultimately be exploited by manufacturers. IP will be carefully managed throughout the process during interaction with collaborators.

Co-funding and Collaborators:

Providing 'in-kind' support relevant to the development of new detectors, the UK SMEs, Acoustic Polymers Limited and Precision Acoustics Limited (PAL will contribute to the design of new detector concepts). Members of the PSG will provide their time for meetings (once a year). Professor Christian Langton of the Queensland University of Technology, the originator of the QUS concept, has agreed to contribute the project, through several short-term secondments at NPL. Further funding will be sought from proof-of-concept sources, possibly through the NIHR i4i "Early Stage" scheme, as the project progresses.

Deliverables

1	**Start: 1/1/2012**	**End: 30/9/2012**	
Deliverable title: Scoping report generated through interaction with the equipment manufacturing and clinical user base, identifying detailed work-plan.			
2	**Start: 1/10/2012**	**End: 30/06/2014**	
Deliverable title: Paper submitted to a peer-reviewed Journal detailing metrological aspects of the QUS technique.			
3	**Start: 1/3/2013**	**End: 30/09/2014**	
Deliverable title: Acoustically characterised phantom for deployment with clinical systems.			
4	**Start: 1/7/2014**	**End: 31/12/2014**	
Deliverable title: User protocol/ guidelines disseminated to the clinical user community.			

Project No.	AIR/2012/A16	Price to NMO	£350k (to Dec-15)
Project Title	Towards a unit for cavitation	Co-funding target	
Lead Scientist	Mark Hodnett	Stage Start Date	01-July-2012
Scientist Team	Bajram Zeqiri, Gianluca Memoli, Pierre Gélat, Lian Wang	Stage End Date	31-Dec-2015
		Est Final Stage End Date	31-Dec-2015
Sector	6. 2 Process control & efficiency 7.1 Traceability & uncertainty	Activity	Challenge-driven R&D

Summary:

This project will establish a new capability: the metrological framework for defining a traceable unit of cavitation, to underpin and support advanced manufacturing and healthcare applications that exploit high power ultrasound, through provision of a reference single bubble/controlled cloud acoustic cavitation facility. The proposed work significantly extends the published progress made in establishing reference cavitation vessels, and strengthens NPL's world-leading position In cavitation metrology.

The Need:

High power ultrasound is applied across a large number of industries, ranging from established practices such as ultrasonic cleaning (a $4bn pa business worldwide, covering surgical instrument cleaning to microelectronics manufacture) to emerging applications such as the preparation of materials for pharmaceutical manufacture and food processing (where the EU has invested over €10m in ultrasound projects under FP7), and where there is strong European growth, driven by innovation. Cavitation is also harnessed in biofuel production, where ultrasound application can improve biomatter yields from feedstocks by 50%, and in treatment of secondary sewage sludge to accelerate biological decomposition and enhance methane production. In healthcare, high power ultrasound is being postulated for targeted gene and drug therapies (see AIR/2012/A12). These applications are all driven by acoustic cavitation - the nucleation, growth, oscillation and collapse of micro- and nano-scale bubbles in fluids due to an applied acoustic field. Despite widespread user need, no acoustic cavitation measurement standards exist, and attempts by IEC to provide such methods have been unsuccessful. Cavitation detection techniques based on acoustical, optical, chemical and thermal methods have been developed, and fundamental scientific understanding of cavitation has progressed in recent years; however, the barrier to the objective comparison of methods, and their take-up, is the absence of measurement units and the corresponding facilities for disseminating standards. This deficit is preventing the effective scale-up of advanced cleaning, and of novel processing technologies, in a technical area where the UK has a pre-eminent position (Ultrawave, Prosonix, Sonic Systems), and of new medical therapies. There is a clear need to provide metrology and standardisation for this challenging field, to generate facilities and validated methods that will underpin scientific understanding of cavitation, enabling manufacturers and users to fully exploit cavitation technologies, enhancing UK competitiveness.

The Solution:

The project will build on the findings of current NMO work, and incorporate the leading-edge metrology emerging from NPL's Strategic Research (SR) project on Microbubbles (harnessing acoustical and optical methods for coated bubble manipulation and measurement), to develop a controlled reference facility which can generate **repeatable single-bubble and multi-bubble cavitation fields, in free fields, and at surfaces**. These bubble fields will be characterised systematically under a wide range of environmental conditions, using sensors developed under AIR/2012/A17 , and other techniques, to build a fundamental understanding in industrially-relevant cavitation conditions, and generate standards, protocols and new units of measurement.

Project Description (including summary of technical work)

- Scoping phase: examining literature, applications and consulting with manufacturers: early stage experimental work;
- Formation of Steering Group of end-users, spanning manufacturing industry, healthcare and academia;
- Design, manufacture and commission bubble facility, using generation techniques from SR project and Scoping Study, and reflecting industrial needs;
- Systematic study of cavitation fields comparing existing and developed methods, incorporating metrological findings from SR Projects and external collaborators;
- Disseminating findings through enhanced measurement services, a User Forum, peer-reviewed papers and conference presentations and via positions of influence in Ultrasonic Industry Association (UIA) and IEC, to develop international consensus for standardisation

Early on in the project, under the auspices of EURAMET, a bilateral comparison of current cavitation measurement methods (exploiting existing NPL IP in cavitation detection) will be carried out with PTB.

Impact and Benefits:

Successfully completing the project will develop new measurement capabilities, and provide users and manufacturers with standardised methods, facilities and protocols for measuring acoustic cavitation, enabling them to overcome scale-up barriers that are inhibiting full commercial exploitation of high power ultrasound in sonoprocessing, cleaning and healthcare. NPL's internationally-leading position in cavitation metrology will be strengthened significantly by the new facility, and by the dissemination of cutting-edge research through peer-reviewed publications and user interactions. The metrological framework will enable users to innovate manufacturing processes in phenomena such as sonocrystallization and should position the UK strongly in exploiting acoustic cavitation on a commercial basis (this is a fledgling industry in the UK of around £20m: traceable sono-processes could see this grow to £100m p.a. as large-scale high power ultrasound facilities will be lower-risk, and realisable). The availability of objective measures for cavitation will also improve procurement decisions and QA for ultrasound cleaning systems in the NHS. Developed specification standards will be taken up by users directly, and also through enhanced Measurement Services at NPL, for high power ultrasound system characterisation and sensor calibration.

Support for Programme Challenge, Roadmaps, Government Strategies

1) *Healthcare – Therapeutics*. The project is relevant to the NMO Roadmap "Metrology for medical applications of ultrasound", Target "Modern ultrasound methods for improved diagnostic and therapeutic modalities" and Deliverable "Contrast agents for combined physical and pharmaceutical therapy"; and 2) *Advanced Manufacturing – Process Control and Instrumentation*; *Underpinning Metrology – Traceability*. Here, it is strongly relevant to the NMO Roadmap "Metrology for industrial applications of ultrasound", Target "International standard for quantifying the degree of cavitation and cleaning effectiveness" and the Technology "Single bubble cavitating facility for evaluating cavitation detection". Through enabling high value, traceable manufacturing in pharmaceuticals, it fits the Measurement Priority: Health Challenge in the NMS Strategy *2011-2015*, to "Enable new drugs and therapies…to be brought to the market quicker and at lower cost, consistent with regulation". The project is also applicable to government energy strategies on biofuel production, for which cavitation has known beneficial effects on yields.

Synergies with other projects / programmes:

The project builds strongly on previous and current NMO-funded work, and leverage from NPL's track record for innovation, adding value by extending scientific robustness and strengthening measurement services. The new capability will also support the project in *Sensor development*. The current NPL SR project "Bubbles: Sensors for the micro-world" will be both a beneficiary of, and a co-funder to the project: it is investigating the dynamic use of bubbles as microsensors, and runs until 2014. EU R4SME funding has been won for the project "TOPHONEY" (concluding December 2012), investigating non-thermal methods for improving honey quality, and its findings in application of cavitation to full-scale commercial processes will be invaluable in scoping the project. Future Technology Strategy Board funding is a strong ongoing route for extending the science to industry.

Risks:

The project is research-based, and so the main technical risk is that a suitable reference system and measurement capability is not established. This is considered to be of low-medium scale, and will be mitigated through a thorough scoping study, involving literature review, engagement with academia, experimental evaluation and synergising knowledge with the Microbubbles SR project. It is vital that the developed capability and methods are relevant to industry, and the Steering Group (with representatives from pharmaceutical manufacturing, sonoprocessing, and cleaning) in the early stages, will ensure applicability.

Knowledge Transfer and Exploitation:

The new scientific capability will be disseminated through peer-reviewed publications and conference presentations (particularly the UIA, where NPL holds the Presidency for 2012), by two Cavitation Users' Forums at NPL, and by regular technical progress updates through the Measurement Network on TSB's _connect platform. Take-up will be by users and manufacturers of cavitation-producing systems via the development of international specification standards through IEC, and by enhanced measurement services established at NPL. The project may generate novel cavitation production and sustainability techniques, which could be applied by users: IP will be critically examined and managed, particularly with collaborators.

Co-funding and Collaborators:

The SR and R4SME projects described above will both contribute to the project: each will extend scientific developments and quality, and the latter will provide critical input on commercial applicability.. The Steering Group members will provide time and access to facilities, and in-kind science input will result from the EURAMET interaction with PTB, which should see an NPL staff member seconded to Germany for one month.

Deliverables

1	**Start: 01/07/2012**	**End: 30/03/2013**	
Deliverable title: Completed scoping study on the specifications for a controlled-cavitation facility, including EURAMET intercomparison with PTB on cavitation detection methods, formation of a Steering Group and a Cavitation User Forum			
2	**Start: 01/04/2013**	**End: 30/06/2014**	
Deliverable title: Designed, commissioned and acceptance-tested facility for controlled single and multi-bubble cavitation			
3	**Start: 01/5/2014**	**End: 30/06/2015**	
Deliverable title: At least two peer-reviewed papers and at least two conference presentations on detailed system characterisation, comparing formation methods and multi-parameter measurement methods on single and multi-bubble cavitation.			
4	**Start: 01/11/2014**	**End: 30/12/2015**	
Deliverable title: Drafted specification standard on cavitation measurement; project outcomes disseminated through a Cavitation User Forum and establishment of new measurement services.			

Project No.	AIR/2012/A17	Price to NMO	£225k (to Sep-15)
Project Title	A new generation of reference and user-focused cavitation sensors	Co-funding target	
Lead Scientist	Mark Hodnett	Stage Start Date	01-Oct-2012
Scientist Team	Bajram Zeqiri, Ian Butterworth, Lian Wang	Stage End Date	30-Sept-2015
		Est Final Stage End Date	30-Sept-2015
Sector	6.3 Advanced instrumentation & sensors 3.3 Health & safety	Activity	Challenge-driven R&D

Summary:
This project will generate two intimately-linked outcomes: initially, leveraging NPL's existing IP to design and develop new reference 'gold standard' cavitation detection sensors to extend NPL's measurement capability for meeting future industry requirements; and the development of simple, low-cost user-focused sensor methods for cavitating systems. These will be trialled extensively by the user base, and disseminated through peer-reviewed publication and online networks.

The Need:
High power ultrasound is applied across a large number of industries, ranging from established practices such as ultrasonic cleaning (a $4bn pa business worldwide, around £75m UK, covering surgical instrument cleaning throughout the NHS; automotive and aerospace components manufacture; and cleaning PCBs in microelectronics). Emerging applications such as the novel use of sonocrystallization in food production and preparation of raw materials for pharmaceutical manufacture are also gaining traction. These applications are all driven by acoustic cavitation - the nucleation, growth, oscillation (and collapse) of gas and vapour bubbles in fluids due to an applied acoustic field. Through previous NPL Strategic Research and NMO funding, spatially-sensitive cavitation sensors applicable in the range 20-60 kHz, based on acoustic emission have been developed, yet the use of these is restricted to ambient temperatures and aqueous environments. Many advanced manufacturing and cleaning processes frequently use solvents or concentrated acids, at elevated temperatures, and in addition, new cleaning and processing applications are now operating at frequencies up to 2 MHz, harnessing non-inertial cavitation and microstreaming. To characterise cavitation in these environments is beyond the scope of current NPL measurement capability, and this drives the need for a new generation of broadband sensors of high sensitivity and low perturbation.

At the user scale, there is a clear need for simple measurement methods that produce outputs relevant to the application: e.g. the required qualification of ultrasonic cleaning systems in the NHS is described in HTM2030, and recommends the use of aluminium foil for cavitation observation and record-keeping. This method is clearly non-quantitative, such that QA of cleaning systems employed during sterilisation of re-usable surgical instruments is not meaningful, increasing the likelihood of biological contamination. Also, as processing applications of cavitation are researched and become established in advanced manufacturing (food and beverage industries; pharmaceuticals), there is an emerging need for routine measurement methods that may be used for online monitoring and system feedback, to provide real-time data on processor performance, efficiency and product quality: indeed, for pharmaceutical applications of cavitation (where the UK has a strong technical lead through companies such as Prosonix), such monitoring is a regulatory requirement. Robust *in situ* cavitation measurement methods providing system feedback are needed to provide manufacturers and users with tools for developing new processes, and to monitor product quality and processor performance during manufacture. Providing user-focused quantitative measurement methods will increase confidence in cleaning and manufacturing processes, enhancing patient safety and underpinning innovative manufacture.

The Solution:
The project will build on previous NMO work and **NPL's patented IP in cavitation detection**, and extend current NPL capability: to firstly develop **'gold standard' cavitation sensors**, with characteristics of low-noise (potentially using bilaminar or shielded PVDF films), low perturbation and suitable for aggressive environments (by developing new materials) and applicable to a broad operating frequency range. The resulting design will be tested against existing and new reference cavitation facilities (see *Towards a unit for cavitation dose*), refined, and then combined with a novel application of commercial pressure-sensitive film, to develop a second, **dual-mode sensor** that will provide **simultaneous numerical and visual indication of cavitation.** This new sensor approach will be trialled at user sites, in cleaning and advanced manufacturing applications, and will result in a device specification for users to implement.

Project Description (including summary of technical work)

- Review and design stage: examining current measurement capability, discussing with industry, and refining NPL requirements; testing existing ruggedisation technologies and pressure-film concept;
- Realisation and testing of gold-standard sensors against reference and commercial cavitating systems;
- Realisation and testing of user-focused dual-mode sensors against reference systems, and trialling with commercial collaborators;
- Disseminating findings through the User Forum (see AIR/2012/A16), peer-reviewed papers, conference presentations, online platforms and through trade articles, and production of a Good Practice guide in cavitation monitoring.

Impact and Benefits:
Successfully completing the project will provide 'gold standard' sensors that can be deployed in broad range of cavitation fields and environmental conditions. This will develop an advanced measurement capability for NPL, significantly extending the scope of the present measurement portfolio, and will form a key part of the proposed new metrological infrastructure for cavitation research. This enhanced capability will in turn benefit measurement service users through a broader scope of characterisation facilities, better tailored to their specific application needs. NPL's internationally-leading position in cavitation metrology will be further enhanced by the 'gold standard' sensors. Developing and trialling the second aspect, the novel dual-mode sensor, will provide a new measurement approach for industry which is accessible, strongly end-user focused, and which will, for the first time, provide quantitative methods for QA of ultrasonic cleaning and advanced manufacturing. This will enable cleaning system users to define new standards for device performance, and equip developers of cavitation-driven processes to monitor cavitation activity directly, underpinning novel formulation technologies.

Support for Programme Challenge, Roadmaps, Government Strategies
Advanced Manufacturing – Process Control and Instrumentation. The project is strongly aligned to the NMO Roadmap "Metrology for industrial applications of ultrasound", with particular relevance to the Deliverables "Reference sensors and methods for measuring acoustic cavitation", "Robust methods of quantifying cleaning ability appropriate at the industrial level" and the Technology "Novel robust sensors for cavitation detection". Through enabling high value, traceable manufacturing in pharmaceuticals, it fits the Measurement Priority: Health Challenge in the NMS Strategy 2011 - 2015 to "Enable new drugs and therapies…to be brought to the market quicker and at lower cost, consistent with regulation".

Synergies with other projects / programmes:
The project outcomes will build strongly on previous and current NMO-funded work, adding value by extending scientific robustness and strengthening measurement services, and ensuring that the sensor capability at NPL is at the leading technical edge to keep abreast of scientific progress in cavitation applications. The new sensor developments in this project will also support the proposed NMO work "Towards a unit for cavitation". NPL has won EU R4SME funding for the project "TOPHONEY" (concluding December 2012), investigating non-thermal methods for improving honey quality, and the research undertaken in the application of cavitation to commercial processes will contribute to defining both the gold standard and user-focused sensors proposed here. Future Technology Strategy Board funding is a potential ongoing route for extending the science to industry, as is National Institute of Health Research (NIHR) funding, to QA cleaning processes in healthcare applications .

Risks:
The project is research and development based, and so the main technical risk is that suitable sensor designs, at either a 'gold standard' or user level, are not developed: this deficit could lie in aspects such as technical performance, or applicability. This risk is considered to be at a low level, and will be mitigated by detailed initial reviews for the sensor requirements, and of the available technologies for ruggedisation. Selecting a wide user base for the trialling phase will also ensure that the dual-mode sensor is tested on representative systems, and by engaging with representative bodies and associations (such as the Institute of Physics and Engineering in Medicine) will raise awareness and accessibility of the technology.

Knowledge Transfer and Exploitation:
The new user-focused sensors will be disseminated directly through the trialling process, and the research for both sensor types will generated peer-reviewed publications and conference presentations (particularly the UIA, where NPL holds the Presidency for 2012), at two Cavitation Users' Forums at NPL (proposed in AIR/2012/A16), and by regular technical progress updates through the Measurement Network on TSB's _connect platform. Both aspects of the project are likely to generate novel material developments, and so IP will be systematically reviewed for potential exploitation.

Co-funding and Collaborators:
The R4SME project described above will contribute in part to the project, providing input on commercial applicability of the developed sensors (and a potential trialling outlet). At least four trialling sites will be targeted (manufacturers and users), and this will contribute in-kind support. Both sensor types will be designed and manufactured in collaboration with UK SME's Precision Acoustics and Acoustic Polymers Ltd, each of whom will also provide in-kind support through expertise and facilities.

Deliverables

1	**Start: 01/10/2012**	**End: 30/06/2014**	
Deliverable title: Report detailing the scoping, design and manufacture at least two designs of 'gold standard' cavitation sensors, and tests against two reference cavitation systems at NPL			
2	**Start: 01/06/2013**	**End: 31/12/2014**	
Deliverable title: Report detailing the scoping, design and manufacture of a novel dual-mode (acoustical/surface impact) cavitation sensor, tests against two reference cavitation systems at NPL, and trial at least three user sites			
3	**Start: 01/09/2014**	**End: 30/09/2015**	
Deliverable title: Two peer-reviewed papers, at least two conference presentations and a trade journal article on sensor developments.			

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Dosimetry Projects 2012

Project No.	AIR/2012/D4	**Price to NMO**	£367k (to Jun 15)
Project Title	Dosimetry for IMRT & small fields	**Co-funding target**	
Lead Scientist	Simon Duane	**Stage Start Date**	1st Jan 2012
Scientist Team	Simon Duane, Hugo Palmans, Catharine Clark, Peter Sharpe, David Shipley, Russ ell Thomas, Mark Bailey, Julia Pearce, Nigel Lee, Florian Graber	**Stage End Date**	30th June 2015
		Est Final Stage End Date	30th June 2015
Sector	3.2 Drugs & therapies 7.1 Traceability & uncertainty 7.3 Standards & regulation	**Activity**	Challenge-driven R&D Knowledge Transfer

Summary

Advanced radiotherapy is increasingly reliant on the use of very small fields (in stereotactic radiotherapy, SRT, and stereotactic radiosurgery, SRS) and composite fields (in intensity modulated radiotherapy, IMRT). According to recent estimates[1], 35% of all radiotherapy patients would benefit from the most advanced forms of radiotherapy. This would bring widespread benefit to a significant number of cancer patients, with the likelihood of increased survival rates and improved quality of life. As in all radiotherapy, success is critically dependent on accurate delivery of the specified absorbed dose. The extension to small and composite fields of established reference dosimetry, which is based solely on measurements of dose at a point and on central axis depth dose data, introduces unacceptable measurement uncertainty. This research will develop dosimetry techniques, reference conditions and protocols for small and irregular beams as well as for flattening filter free (FFF) beams. The project will provide recommendations as to required changes to the relevant IPEM code of practice as well as providing relevant audit techniques and training.

The Need

Intensity Modulated Radiotherapy is a relatively new modality and a number of clinical trials designed to test IMRT are currently in progress or in development. However preliminary studies already indicate that IMRT: gives improved tumour control with better side effect profiles versus conventional techniques; gives good sparing of adjacent radiosensitive organs such as, in breast radiotherapy, the heart; gives reduced damage to normal tissue; gives reduced late effects; gives excellent dosimetric profiles with improved dose homogeneity within the tumour; and can further improve local control when used in conjunction with chemotherapy. The optimisation of IMRT involves the use of complex algorithms to calculate the planned three-dimensional dose distribution within the patient, based on high-resolution volumetric imaging, in combination with computer-controlled beam shaping and intensity modulation of the x-rays used to deliver the treatment. The fields required to deliver the optimal treatment are generally very different, being small and/or irregular and having regions with steep dose gradients, from the fields that are used for traceable reference dosimetry.

Stereotactic radiotherapy, SRT, involves the use of a large number of very small beams precisely directed at the target volume from many independent directions. This makes possible, for example, the non-invasive treatment of tumours in surgically inaccessible regions of the brain. The exceptionally good sparing of adjacent normal tissue in stereotactic treatments makes it possible for the required dose to be delivered in very few fractions, including even single-fraction treatments, i.e. Stereotactic radiosurgery (SRS). In SRS it is especially important that the correct dose is delivered and to the correct location.

The measurement of absorbed dose at a point, in the presence of steep dose gradients and/or in the absence of electron equilibrium, is subject to significant uncertainty associated with volume averaging effects, detector perturbation effects and, for non-absolute detectors (i.e. those that require calibration), sensitivity to the energy spectrum of secondary electrons. Yet these conditions are routinely present in the small fields used for stereotactic radiosurgery (SRS) and stereotactic radiotherapy (SRT), and in the irregular and often small fields of which IMRT treatments are composed. Furthermore, flattening filter free beams that are often used in these treatment modalities have a different energy spectrum and beam profile causing dosimetry protocol assumptions to fail.

The Solution

a) Dosimetry for IMRT & small fields Development of dosimetry techniques, reference conditions and protocols for small and irregular beams.

b) Dosimetry for FFF beams Development of the required traceable and relevant dosimetry for FFF beams additionally providing recommendations as to required changes to the relevant IPEM code of practice.

c) Audit and training Development of audit protocols for complex radiotherapy and delivery of extended Practical Course on Reference Dosimetry.

Project Description (including summary of technical work)

1 Cooper, T., UK Dept. of Health, at BIR meeting on ‘Expansion of IMRT in the UK’, Feb 2011

a) Dosimetry for IMRT & small fields First primary measurement using IMRT calorimeter developed in previous NMS project in Elekta VMAT at NPL and subsequently offsite; Design, construct and commission new device(s) for the absolute measurement of integral dose in a range of conditions relevant to SRS, SRT and IMRT; Building on already significant expertise in alanine dosimetry further develop to optimise dose required and/or pellet size; Validation of alanine and other dosimeters against IMRT calorimeter at NPL and in the clinic; Collaborate with IPEM to revise UK Code of Practice.

b) Dosimetry for FFF beams Measurements with new primary standard calorimeter in FFF beams at NPL and with new "proton beam" calorimeter in FFF beams in selected hospital(s), pilot measurements have been carried out at one UK hospital to date; Measurements with alanine and with existing secondary standard for dissemination to FFF beams elsewhere; Monte Carlo simulation of all types of FFF beams used; Identify and recommend changes to IPEM Code of Practice.

c) Audit and training Building on existing expertise developed auditing reference and non-reference radiotherapy beams, finalise protocols used for pilot audit of complex radiotherapy including rotational and dynamic deliveries; To undertake national audit of advanced rotational radiotherapy; Collaborate with IPEM and RTTQA group in further audit development; Deliver Practical Course on Reference Dosimetry, with content revised as needed, e.g. to cover small and composite fields.

Elements a) and c) continue from previous discretionary subprojects.

Impact and Benefits

Facilitate the effective and efficient application of innovation in the use of IR for imaging and treatment systems supporting improved quality, reliability and comparability of individually optimised therapy for patients undergoing IMRT, SRS, and SRT leading to increased cancer survival rates and improved quality of life for cancer survivors.

Support for Programme Challenge, Roadmaps, Government Strategies

Healthcare (Therapeutics)

DH – Cancer Reform Strategy

Supports the Government priority set out by Public Service Agreement Targets (PSAT) 4 'Promote world-class science and innovation in the UK' as well as 18 'Promote better health and wellbeing for all'.

Synergies with other projects / programmes

Relies on and applies the small field / IMRT and proton calorimeters developed in previous programmes. Deliverables that cover dosimetry for IMRT and small fields and FFF beams depends on and maximises the impact of the NPL clinical linac. All of these deliverables align with projects currently being formulated for submission into the EMRP Health II call.

Risks

This project relies on access to new and novel facilities not available at the NPL; the existence of already established collaborations should mitigate this risk.

Knowledge Transfer and Exploitation

As improvements in the dosimetry for these advanced radiotherapy modalities are realised, the expertise developed within NPL will be transferred to hospital users in the collaborative development of dosimetry protocols, audit procedures and IPEM codes of practice as well as in the provision of advice to users and the development of new calibration services. NPL will develop training materials, which extend the scope of the existing Practical Course in Reference Dosimetry to cover measurements in the complex fields used in IMRT; this course is currently run annually with 24 participants. It is also expected that this work would result in a number of papers that would be published in peer review journals.

Co-funding and Collaborators

This project cofunds and is aligned to NMS/AIR12016 project EMRP Health Metrology for radiotherapy using complex radiation fields.

Funding in kind by partners for collaborative research effort and use of facilities not available at NPL.

Collaborations with: RSCH and other hospital RT Departments in the UK and elsewhere in the EU; NMI partners in EMRP Health II Radiotherapy Trials QA group (RTTQA); IPEM; linac manufacturers.

Deliverables

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

Deliverable title: Dosimetry for IMRT and small fields

Development of dosimetry techniques, reference conditions and protocols for small and irregular beams to support recommendations for revisions to IPEM code of practice and supporting development of new calibration services.

2	**Start: 01/01/12**	**End: 31/12/13**	

Deliverable title: Dosimetry for FFF beams

Development of the required traceable and relevant dosimetry for FFF beams additionally providing recommendations as to required changes to the relevant IPEM code of practice and supporting development of new calibration services.

3	**Start: 01/01/12**	**End: 30/06/15**	

Deliverable title: Audit and training

Development of audit protocols for complex radiotherapy and delivery of extended Practical Course on Reference Dosimetry.

Project No.	AIR/2012/D5	Price to NMO	£194k
Project Title	Dosimetry for Complex Hadron Therapy	Co-funding target	
Lead Scientist	Hugo Palmans	Stage Start Date	1st January 2012
Scientist Team	Hugo Palmans, Peter Sharpe, David Shipley, Russell Thomas, Mark Bailey, Nigel Lee, Rebecca Nutbrown, Simon Duane	Stage End Date	30th June 2015
		Est Final Stage End Date	30th June 2015
Sector	3.2 Drugs & therapies 7.1 Traceability & Uncertainty	Activity	Challenge-driven R&D

Summary

The number of clinical centres applying proton and carbon ion beam therapy is increasing worldwide and the number of patients that are treated with these modalities undergoes at present an exponential growth. Scanned proton and ion beams form a category of complex dose delivery modalities that are more and more used given the lower neutron production as compared to scattered beams. All new proton therapy centres, like those planned in the UK, will use scanned beams.

The project will contribute to the improvement of the accuracy of dosimetry for light ion beams and in particular for scanned and high-dose-per-pulse beams by simulating and measuring the effects of time and spatially dependent dose deposition patterns, phantom materials and detector energy dependence on the dose response of calorimeters ionisation chambers and alanine.

The Need

Cancer is a major disease accounting for 13% of all deaths worldwide in 2008. The total number of deaths from cancer is projected to rise by 50% over the next 20 years and the demand for all modern radiotherapy modalities will grow accordingly. The use of protons and ion beams for radiotherapy has only recently become a mainstream treatment modality mainly because of the recent establishment of proton and carbon ion therapy as a commercial product by a limited number of companies. The number of patients treated worldwide with this modality is growing exponential having increased from about 3000 patients per year in 2005 to about 8000 patients per year in 2009.

However, despite the intrinsic advantage of a lower total body dose as compared to conventional high-energy x-ray treatments, the dosimetry of light ion beams has not reached the same level of accuracy as that of x-ray beams, potentially jeopardizing part of the advantage of the treatment technique. This is illustrated by the higher uncertainty assigned to proton and carbon ion reference dosimetry (2.0%-2.3% and 3.0%-3.4%, respectively) as compared to high-energy x-rays (1.5%). Scanned and pulsed beams have added further uncertainties due to the poorly characterised response of calorimeters and ionisation chambers to the high and instantaneously inhomogeneous dose rate patterns.

Primary standards for proton and ion beams do not exist and in particular for scanned and high-dose-per-pulse beams many dosimetric aspects have been poorly understood. For the reference ionisation chambers used in clinical practice ion recombination corrections and perturbation factors in scanned and high-dose-per-pulse beams are poorly known. The same holds for phantom materials where in some cases significant corrections on dose distributions in different media have been demonstrated but this topic has not undergone systematic investigation for a range of commonly used water or tissue substitutes.

In order to measure a beam quality correction factor, k_Q, for an ionisation chamber in a scanned particle beam, one must understand the response of the primary calorimeter instrument and the correction of the ionisation chamber readings for influence quantities such as ion recombination. For the comparison of experimental k_Q values with theoretical ones the capability to calculate perturbation factors is needed. All these are complicated by the time dependent and instantaneously inhomogeneous distribution of energy deposition.

The Solution

a) Applying calorimetry to scanned and high-dose-per-pulse proton and ion beams
b) Applying ionometry to scanned and high-dose-per-pulse proton and ion beams
c) Water equivalence and energy dependence of detector and phantom materials in scanned and high-dose-per-pulse particle beams

Project Description (including summary of technical work)

a) **Applying calorimetry to scanned and high-dose-per-pulse proton and ion beams** Developing the capability to calculate corrections for heat transfer in scanned and high-dose-per-pulse particle beams by coupled 4D Monte Carlo simulations and finite element heat transfer simulations and validating calculated corrections by detailed experiments.
b) **Applying ionometry to scanned and high-dose-per-pulse proton and ion beams** Modelling and experimental investigation of ion recombination in ionisation chambers for time-dependent dose deposition patterns that include partial irradiation conditions encountered in scanned particle beams and high-dose-per-pulse conditions. Measurement of relative perturbations for ion chambers in a broad field and in fields composed of small beamlets that deliver the same dose.
c) **Water equivalence and energy dependence of detector and phantom materials in scanned and high-dose-per-pulse particle beams** Experimental investigation and Monte Carlo simulations of fluence correction factors for plastic phantoms and solid detector materials like alanine and the investigation of the energy dependence of the absorbed dose response of alanine.

This project will build on previous projects that have developed a calorimeter specifically for use in scattered proton beams and the considerable existing expertise in ionometry measurements, alanine dosimetry and Monte Carlo modelling of these beams.

Impact and Benefits

Facilitate the effective and efficient application of innovation in the use of IR for treatment systems supporting improved quality and reliability for patients undergoing proton therapy leading to increased cancer survival rates and improved quality of life for cancer survivors.

Support for Programme Challenge, Roadmaps, Government Strategies

Healthcare (Therapeutics)

DH – Cancer Reform Strategy

Supports the Government priority set out by Public Service Agreement Targets (PSAT) 4 'Promote world-class science and innovation in the UK' as well as 18 'Promote better health and wellbeing for all'.

Synergies with other projects / programmes

Relies on and applies the proton calorimeter developed in previous programmes. All of these deliverables align with project NMS/AIR12014 and 12016.

Risks

Access to hadron therapy beams will be required; mitigated to some extent by pre-existing collaborations that allow NPL access to such facilities.

Knowledge Transfer and Exploitation

Advice will be provided to users on dosimetry to support proton therapy. It is also expected that this work would result in a number of papers that would be published in peer review journals. This work would lead to new NPL calibration services.

Co-funding and Collaborators

Funding in kind by partners for collaborative research effort and use of facilities not available at NPL.

Collaboration with NMI partners and co-funding from EMRP Health II call project: Metrology for radiotherapy using complex radiation fields.

Collaborations with: CCO, RSCH, QEHB and other hospital RT Departments in the UK and elsewhere in the EU;

EPSRC case studentship awarded: Graphite calorimetry for scanned and pulsed particle beams, to start before October 2012.

Deliverables

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

Deliverable title: Applying calorimetry to scanned and high-dose-per-pulse proton and ion beams

Capability developed to calculate and validate corrections for heat transfer in scanned and high-dose-per-pulse particle beams and results published.

2	**Start: 01/01/12**	**End: 30/06/15**	

Deliverable title: Applying ionometry to scanned and high-dose-per-pulse proton and ion beams

Investigation of ion recombination in ionisation chambers for time-dependent dose deposition patterns and measurement of relative perturbations for ion chambers; and results published.

3	**Start: 01/01/12**	**End: 30/06/15**	

Deliverable title: Water equivalence and energy dependence of detector and phantom materials in scanned and high-dose-per-pulse particle beams

Investigation of fluence correction factors for phantoms and solid detector materials like alanine, investigation of the energy dependence of the absorbed dose response of alanine and results published.

Project No.	NMS/AIR12016	**Price to NMO**	£589k
Project Title	Cofunding for EMRP H14 Metrology for radiotherapy using complex radiation fields (MetrExtRT) (Linked to AIR/2012/D4 and AIR/2012/D5)	**Co-funding target**	
Lead Scientist	Simon Duane and Hugo Palmans	**Stage Start Date**	01/07/2012
Scientist Team	Catharine Clark, Peter Sharpe, David Shipley, Russell Thomas, Mark Bailey, Julia Snaith, Nigel Lee, Florian Graber	**Stage End Date**	30/06/2015
		Est Final Stage End Date	30/06/2015
Sector	Health: Drugs and Therapies Traceability and Uncertainty	**Activity**	Challenge Driven R&D

Summary
The work proposed contributes to the European Metrology Research Programme (EMRP) Health project, "Metrology for radiotherapy using complex radiation fields (MetrExtRT; JRP-HLT09)". It will develop traceable measurement systems for the verification of dose and dose distributions and establish "dose area" primary standards for intensity modulated radiotherapy (IMRT), rotational and stereotactic modalities (high energy) and introduce absorbed dose to water for medium energies in such complex fields. This work builds on activity within AIR Programme projects AIR/2012/D4 and AIR/2012/D5.

The Need
The need for effective radiotherapy is demonstrated by the fact that each year, there are about 4 million new cases of cancer in Europe. These figures are predicted to increase in the future due to the improvement of diagnostic methods and the global ageing of the population in Europe. The goal of radiotherapy is to kill the tumour cells and simultaneously achieve a high survival rate of the surrounding healthy tissue. About 75% of cases are treated using radiotherapy (alone or with chemotherapy and/or surgery), it is estimated that about 50% of successful treatments can be attributed to radiotherapy. In the dose range over which the effect on tumour cells varies most rapidly, the highest accuracy of the applied dose is required. In this range a change of the dose by 5% can result in a change of the tumour control probability of 50% and can result in a normal tissue complication probability of 20% to 30%. The International Commission on Radiation Units and Measurements recommend a standard uncertainty for the dose applied to the tumour of less than 2.5% for teletherapy, and less than 5% for brachytherapy. Today, in modern photon radiotherapy uncertainties of about 8% can be achieved in high-energy photon, electron and hadron therapy while for brachytherapy the uncertainties are up to 20%. These discrepancies emphasize the urgent demand for further advancements in dosimetry in radiotherapy. In addition, from the regulation point of view, EU Directive 97/43/EURATOM is now widely interpreted as making *in-vivo* dosimetry mandatory for all radiotherapy patients. However, the lack of convenient and effective *in-vivo* dosimetry systems has contributed to an increased risk of error in patient treatment, with a consequent reduction in therapeutic efficacy and patient safety.

The Solution
To address the stated needs, the MetrExtRT project aims to:

- Establish new standards of absorbed dose to water, instead of previous standards of air kerma, so avoiding the use of costly conversion factors in terms of uncertainty for low and medium energy X-rays, and addressing the problem of new miniature X-ray brachytherapy sources and superficial external radiotherapy;
- Study a new integral quantity to reduce the uncertainty of the dosimetry of small beams used in modern radiotherapy modalities based on high energy photons (IMRT, stereotactic and rotational radiotherapies);
- Study new radiation quality indexes for improving the traceability of standards for these modalities;
- Develop metrological methods for scanned proton beams by measuring and calculating corrections for calorimeters and ion chambers;
- Develop methods for verification of treatment planning systems (TPS) via internal and external quality control of the clinical radiation fields and for *in vivo* dosimetry beyond use of point dose measurements, which in complex treatments show a large associated uncertainty in the presence of steep dose gradients. The high-resolution information provided by two-dimensional and three-dimensional dose maps enables a more robust basis for the verification of complex dose distribution;
- Characterise the new miniature X-ray brachytherapy sources, establishing a primary standard in terms of absorbed dose to water and giving recommendations on a calibration chain.

Project Description (including summary of technical work)
NPL's contribution to the EMRP project will build on work as described in the AIR/2012/D4 and AIR/2012/D5 projects:

- *Extend the dosimetry for IMRT, small fields and flattening filter free beam*: Identifying the limits, in terms of treatment beam size and field complexity, beyond which measurement uncertainty prevents point-like and central axis dosimetric parameters from meeting the needs of radiotherapy. Determining the scope of integral quantities, such as dose area product (DAP) and DAP radiotherapy, in the specification and accurate delivery of stereotactic radiosurgery, stereotactic radiotherapy and IMRT. To define such a quantity or quantities, determine optimal geometrical reference conditions and suitable commercial or non-commercial detectors for their measurement, to identify how TPS beam model parameters can be based on the measurement of integral quantities and to make recommendations on the use of integral quantities for absorbed dose and beam quality specification—in place of absorbed dose at a point and central axis depth dose data—in radiotherapy which is based on small and irregular fields.

- *Protocols for rotational and dynamic complex radiotherapy*: Identify effective methods for multi-dimensional verification of complex dose distributions; develop suitable protocols for Europe-wide verification of rotational treatment deliveries; validate protocols for 2D and 3D dosimetry audit of complex radiotherapy including rotational and dynamic deliveries; and undertake pilot studies of effective and efficient audit of advanced rotational radiotherapy.
- *Develop 4D Monte Carlo capability*: Develop 4D Monte Carlo capability of dose deposition patterns (including time dependence) for scanned and high-dose-per-pulse particle beams. Developing an interface to use 4D Monte Carlo simulated dose deposition patterns into finite element heat transfer simulations to calculate corrections due to heat transfer corrections in graphite calorimeters. A systematic experimental investigation of the response of a graphite calorimeter to individual pencil beamlets hitting different components of the calorimeters to enable an analytical analysis of heat transfer and to validate the model calculations. Experimentally evaluate and compare the response and performance of graphite calorimeters in scanned and high-dose-per-pulse particle beam
- *Monte Carlo simulations of dose distributions*: These simulations in the cavity of ionisation chambers will be used for the calculation of ion recombination under partial and time dependent irradiation conditions in scanned and high-dose-per-pulse particle beams. Experimental investigation of ion recombination under partial irradiation conditions in proton pencil beams. Experimental investigation of ion recombination under time dependent and high-dose-per-pulse irradiation conditions to validate model calculations. Monte Carlo simulations and experimental investigation of ion chamber perturbations in a broad proton beam and in a beam composed of multiple abutting beamlets providing a similar overall dose distribution.
- *Energy dependence of alanine in scanned particle beams*: Determination of the energy dependence of alanine in scanned particle beams from 30MeV to 250 MeV by comparing the response to that of the graphite calorimeter and ionisation chambers. Experimental investigation of the water equivalence of plastic water and tissue substitutes in scanned particle beams from 30 MeV to 250 MeV by comparing the fluence in those phantom materials with the fluence in water and compare the results with Monte Carlo simulations.

Impact and Benefits

This EMRP project will enable the international codes of practice for radiotherapy to be updated, producing good practice guidelines for quality controls and *in vivo* dosimetry that will be distributed to the radiotherapy services. At the end of the project, the use of absorbed dose to water and its dissemination will be standardized for all types of radiation. The first step towards the application of an integral quantity for very small fields (i.e. establishment of reference, new quality index, secondary standard, and TPS- calculation) will have been completely evaluated. Therefore, medical physicists will have more reliable and convenient tools available for quality control and *in vivo* dosimetry allowing validation of the treatment plan. The consequent benefit to cancer patients of this improved dosimetry will come from better treatment outcomes and reduced costs.

Support for Programme Challenge, Roadmaps, Government Strategies

This project is aligned with: the NMS Strategy 2011 – 2015; the AIR Programme Strategy’s Healthcare drivers and challenges and the Dosimetry Radiotherapy roadmap; and the Department of Health’s Cancer Reform Strategy (2011).

Synergies with other projects / programmes

The work builds on developments made in previous AIR Programme projects e.g. small field/IMRT and proton calorimeters and is aligned with AIR/2012/D4 and AIR/2012/D5 projects.

Risks

The project relies on access to new and novel facilities not available at NPL e.g. hadron therapy beams; the existence of already established collaborations should mitigate this risk

Knowledge Transfer and Exploitation

Dissemination of the project’s outputs will be through: Publications (reports and scientific papers); oral presentations at leading international conferences; a project website; and provision of training workshops to relevant stakeholders. Further dissemination will be through the development of international standards through, for example, ISO TC85 SC2 WG2 (radiation reference) and ISO TC85 SC2 WG22 (dosimetry and related protocols in medical applications of ionizing radiation).

Co-funding and Collaborators

This project comprises NPL’s input into the EMRP Health MetrExtRT project. The project is led by CEA Laboratoire National Henri Becquerel (France) with other partners including CMI (Czech Republic), ENEA-INMRI (Italy), MKEH (Hungary), PTB (Germany), SMU (Slovakia), STUK (Finland), VSL (the Netherlands), and DTU (Denmark) as an unfunded partner. Collaborators include Carl Zeiss Meditec, PTW, University of Mannheim, Clinical Centre for Radiation Therapy (Offenbach), NuTeC, XIOS hogeschool Limburg, Thérapie ciblée combinatoire en onco hématologie, Helsinki University Central Hospital, Tampere University Hospital.

Deliverables

1	**Start: 01/06/2012**	**End: 31/05/2015**	

Deliverable title: Cofunding for EMRP project “Metrology for radiotherapy using complex radiation fields (MetrExtRT; JRP-HLT09)”

Project No.	AIR/2012/D6	**Price to NMO**	£101k (to Jun 2015)
Project Title	Dosimetry for Molecular Radiotherapy	**Co-funding target**	EMRP
Lead Scientist	Vere Smyth	**Stage Start Date**	1st July 2012
Scientist Team	Simon Duane, Hugo Palmans, Peter Sharpe, David Shipley, Russell Thomas, Florian Graber, Clare Gouldstone	**Stage End Date**	30th June 2015
		Est Final Stage End Date	30th June 2015
Sector	7.1 Traceability & uncertainty 3.2 Drugs and therapy 3.1 Diagnosis	**Activity**	Challenge-driven R&D

Summary

Molecular Radiotherapy (MRT) is expanding as a cancer treatment modality as new therapeutic radiopharmaceuticals are developed. Currently radioactivity is administered on the basis of nominal measured activity or patient mass, without knowing the dose received by critical tissue within individual patients, despite evidence that treatment effect is dependent on the dose delivered to tumours and critical organs. But the metrology is difficult, and there is no consensus approach to the problem. This project will investigate the basic metrological problems associated with obtaining a measurement of absorbed dose from a radionuclide within a patient traceable to a primary standard, and the possibility of developing a practical dosimetry protocol.

The Need

Cancer is a major disease accounting for 13% of all deaths worldwide in 2008. The total number of deaths from cancer is projected to rise by 50% over the next 20 years and the demand for all modern radiotherapy modalities will grow accordingly. For the majority of currently available cancer treatment options the approach is to destroy cell populations that are growing uncontrollably. This potentially leads to a non-selective treatment that can damage rapidly dividing cells that are non-cancerous. More recently there is increasing interest in developing "targeted therapies" such as Molecular Radiotherapy (MRT) that kills cancer cells by delivering a lethal dose of radiation, usually attached to a 'carrier' that selectively attaches to tumour cells or localises in the host tissue. As with external beam radiotherapy, MRT offers the advantage of delivering high radiation doses to a specific target; however in common with chemotherapy it can deliver the treatment systemically, attacking multiple sites throughout the body, and additionally it has relatively few side-effects. Unfortunately, the culture of treating patients with MRT on the basis of administering a "dose" rather than determining how much radiation dose is actually absorbed by the tissue being treated has persisted. Accordingly the potential of MRT has not been fully exploited, because rigorous treatment planning has been unavailable and has led to non-optimal MRT implementations. When comparing Molecular Radiotherapy (MRT) with conventional external beam radiotherapy, in which the dosimetry is strictly controlled according to agreed protocols providing full traceability to primary standards and addressing legal requirements for accurate dosimetry, it is clear that MRT is urgently in need of metrological support in order to bring dosimetry to a comparable standard.

The Solution

Development of a practical measurement procedure that can be adopted widely in clinical departments, and is supported both by metrology laboratories in the provision of calibration and verification services and by the consensus of the nuclear medicine community.

Project Description (including summary of technical work)

a) Investigation of possible primary standards and development of possible dosimetry technology/ies to be used in the construction of a secondary standard of absorbed dose to an appropriate medium from selected radionuclides;

b) Development and performance testing of one or more prototype instruments, as proof of principle for the recommended approach.

c) Benchmarking and validation of calculation methodologies for determining absorbed dose from the decay schemes of selected radionuclides, by comparison with direct measurements of absorbed dose.

d) Use of validated Monte Carlo simulations to calculate dose to target treatment volumes and to organs at risk, based on specified radionuclide distributions within the patient.

This is a new area of work for NPL, however an ongoing NMS funded feasibility study is looking into the potential to develop an accurate dosimetry protocol for TRT, traceable to a primary standard. This will provide a sound basis for ongoing work. Furthermore NPL possesses expertise in a number of relevant areas including expertise in Monte Carlo simulations and in the development of absorbed dose primary and secondary standard technologies. Strong collaborations that already exist with IPEM, the RT trials QA group and the user community will maximise uptake of protocols developed within this project.

Impact and Benefits

This project will provide the metrological basis for development of a practical dosimetry protocol that can be developed and widely adopted within the UK to improve the quality of routine clinical MRT and support the development and clinical trials for MRT. This will have the following positive impacts: It will improve cancer treatment results by ensuring an effective dosage is administered; It will improve patient safety by ensuring that no more radiation is administered than is needed; It will enable new treatments to be trialled and introduced more easily; It will enhance the value of clinical trials testing the efficacy and safety of new therapeutic radiopharmaceuticals by reducing the uncertainty in the dose to the target tissue; It will support the development of new therapeutic radiopharmaceuticals providing a metrological basis for demonstration of the safety and efficacy.

As the potential of dosimetry-based MRT is realised it is likely that this treatment will be more commonly used at an earlier stage in the patient's treatment, rather than in later stage patients as is currently often the case, and that it will be increasingly used in conjunction with chemotherapy and radiotherapy to provide synergistic treatment.

Support for Programme Challenge, Roadmaps, Government Strategies
Healthcare (Therapeutics)
DH – Cancer Reform Strategy
Supports the Government priority set out by Public Service Agreement Targets (PSAT) 4 'Promote world-class science and innovation in the UK' as well as 18 'Promote better health and wellbeing for all'.

Synergies with other projects / programmes
This project aligns with the EMRP Health project NMS/AIR12018: Metrology for Molecular Radiotherapy – Dosimetry element and with project AIR/2012/R5. This project also relies on expertise developed in core NMS projects in the areas of Monte Carlo modelling and measurement of absorbed dose.

Risks
The development of new technologies for measuring absorbed dose to an appropriate medium from selected radionuclides will be very technically challenging. Collaboration with other NMIs through EMRP partnership will reduce this risk, as this will allow many more techniques to be investigated than would otherwise have been possible.

Knowledge Transfer and Exploitation
As improvements in dosimetry for MRT are realised, the expertise developed within NPL will be transferred to hospital users in the collaborative development of dosimetry protocols and audit procedures. In the longer term this work would be expected to lead to the provision of new NPL calibration services. Advice will be provided to users on dosimetry to support MRT. It is expected that this work would result in a number of papers that would be published in peer review journals.

Co-funding and Collaborators
Collaborations with: RMH and other hospital RT Departments in the UK and elsewhere in the EU; Cofunding has been obtained from the EMRP Health project: Metrology for Molecular Radiotherapy – Dosimetry element (NMS/AIR12018); Radiotherapy Trials QA group (RTTQA); IPEM.

Deliverables

1	**Start: 01/07/12**	**End: 31/12/13**	
Deliverable title: Investigation and development of potential primary and secondary standards Investigation of possible primary standards and development of possible dosimetry technology/ies to be used in the construction of a secondary standard of absorbed dose and summary report.			
2	**Start: 01/07/12**	**End: 31/12/14**	
Deliverable title: Development and performance testing of prototype instrument(s) Development and performance testing of one or more prototype instruments and summary report.			
3	**Start: 01/01/14**	**End: 31/12/14**	
Deliverable title: Benchmarking and validation of calculation methodologies Benchmarking and validation of calculation methodologies by comparison with direct measurements of absorbed dose.			
4	**Start: 01/01/14**	**End: 30/06/15**	
Deliverable title: Monte Carlo simulations to calculate dose to target treatment volumes and to organs at risk Use of validated Monte Carlo simulations to calculate dose to target treatment volumes and to organs at risk and publication in peer-reviewed journal.			

Project No.	NMS/AIR12018	Price to NMO	£365k
Project Title	Cofunding for EMRP H13 Metrology for molecular radiotherapy (MetroMRT) – Dosimetry element (Linked to AIR/2012/D6)	Co-funding target	EMRP
Lead Scientist	Vere Smyth	Stage Start Date	1 Jul 2012
Scientist Team	Rebecca Nutbrown, Lena Johansson	Stage End Date	30 Jun 2015
		Est Final Stage End Date	30 Jun 2015
Sector	7.1 Traceability & uncertainty 3.2 Drugs and therapy 3.1 Diagnosis	Activity	Challenge-driven R&D

Summary

This project, linked with NMS/AIR12017, contributes to an EMRP Health MetroMRT project that aims to address the lack of any consistent methodology for measuring the absorbed dose to the treated tissues in the clinical use of molecular radiotherapy (nuclear medicine therapy). Using formal metrology it will formulate MRT dosimetry as a chain of measurements traceable to primary standards linked by procedures whose uncertainty contribution can be evaluated. The result will be procedures for calibrating and auditing the dosimetry procedures used in a clinic, and an objective evaluation of the accuracy of different dosimetry methods, and the implications of not performing dosimetry.

The Need

For decades MRT treatments have been prescribed on the basis of the administered activity of the radiopharmaceutical, ignoring the degree of uptake in the treated tissues. This is now known to cause an uncertainty in the therapeutic radiation dose of more than 2 orders of magnitude. There are currently no established procedures for measuring the uptake, or the radiation dose from an estimated uptake, that can be calibrated or evaluated for uncertainty. Because of the pre-existing culture of activity-based treatments, there has been no development of this metrology by NMIs. While there are research clinics in the UK working to develop accurate in-house dosimetry, this does not address the problem of the need for individual patient dosimetry as the standard for all clinics. Only a government-funded body will be able to address the problem nationally, so the health system as a whole can benefit.

The Solution

In the short term the project will develop validated measurement methods for each link of the MRT dosimetry chain together with a full uncertainty analysis of the dosimetry process as a whole in order to provide a robust metrological basis for the widespread implementation of clinical dosimetry. This will lead to standardised and validated methods, and to recommendations for a dosimetry protocol that can be adopted nationally. The protocol will be supported by calibration and audit procedures that will assist clinics newly implementing dosimetry, and routinely as a means for maintaining quality.

Project Description (including summary of technical work)

The project is an EMRP Joint Research Project and will involve an international consortium of 6 NMIs, 9 unfunded clinical research partners, and initially one other collaborating NMI (NIST). It will investigate each aspect of the dosimetry chain as follows:

- Activity measurement: investigation of critical aspects of the measurement of key beta-emitting radionuclides that are used for MRT, both in terms of the primary standards, and transfer of activity measurements to the clinic;
- Quantitative imaging measurements: investigation of the accuracy of the various methods that have become available with current imaging technologies, and development of equipment and procedures for validation and calibration of the measurements;
- Absorbed dose measurement: development of techniques for direct measurement of absorbed dose from unsealed radionuclides in order to validate methods for deriving absorbed dose to tissue from cumulative activity;
- Uncertainty analysis: construction of a mathematical model of the entire dosimetry chain so that the contribution of the uncertainty from each component on the end result can be determined;
- Impact and recommendations: the findings from each part of the project will be used to develop recommendations for best practice based on an objective evaluation of the uncertainty implications of various methodologies, including failure to implement individual dosimetry in favour of the current activity-based treatment methods.

Impact and Benefits

It is expected the project will create an impact on:

- Individual patients, improving management of cancer treatment;
- National Health Departments, saving scarce funding resources by making MRT a more effective treatment modality;

- Radiopharmaceutical companies, by allowing more effective evaluation of new products;
- Clinical research, by giving access to dose data that will improve statistics in clinical trials.

Furthermore, since MRT dosimetry has not been addressed by NMIs up till now, the project will lead to new capability, particularly in the fields of quantitative radionuclide imaging, and measurement of absorbed dose from unsealed radionuclides. The contribution from the clinical research partners will be essential to the development of new technologies and methodologies.

Support for Programme Challenge, Roadmaps, Government Strategies

This project aligns with the NMS Strategy document 2011 -2015 and the AIR Programme Strategy and roadmaps. It complies directly with the Grand Challenge for Health set out in the 2008 EMRP Outline. It also supports the Government initiatives for improvement of cancer treatment, and improvement of quality and safety of therapy in general.

Synergies with other projects / programmes

The project will use and extend current NPL expertise in the activity measurement of beta-emitters. Measurement of absorbed dose distributions from unsealed radioactive sources will have synergy with work in the Dosimetry Group on radioactive brachytherapy sources, and small field measurements in external radiation beams.

Risks

MRT dosimetry is complex and has not been addressed before from a formal metrological viewpoint. There is a great variety of different clinical applications for quantitative imaging. It may be difficult to define sufficiently representative reference conditions for verification procedures. Direct measurement of absorbed dose from unsealed radionuclides is an undeveloped field. It may be difficult to establish traceability directly to a primary standard. Less direct methods will be developed to cover this possibility.

Knowledge Transfer and Exploitation

Dissemination will be through the usual routes of publications and conference presentations. In particular, the Chairman of the Dosimetry Committee of the European Association of Nuclear Medicine will be the scientific representative of one of the unfunded partners, so there will be good communication with the EANM members. There will also be close contact with the UK Institute of Physics and Engineering in Medicine (IPEM) for presentation of results and recommendations to the UK clinical MRT community. It is planned that the results of the project will provide recommendations and guidelines for development of new MRT dosimetry good practice guides and protocols in collaboration with IPEM and the British Nuclear Medicine Society.

Co-funding and Collaborators

This project comprises NPL's input into the EMRP project MetroMRT. NPL is leading the project. The consortium consists of funded partners CEA (France), CMI (Czech Republic), ENEA (Italy), PTB (Germany), and (VSL (Netherlands), unfunded partners RMH-ICR (UK), UCL-CI (UK). IFO (Italy), SMGH (Italy), SAH (Italy), ISS (Italy), MRP-LUND (Sweden), CHRISTIE (UK), and VELINDRE (UK). NIST will be a collaborator.

Deliverables

1	**Start: 01/07/12**	**End: 31/06/15**	

Deliverable title: Cofunding for EMRP project "Metrology for molecular radiotherapy (JRP-HLT11)" – dosimetry element

Project No.	NMS/AIR12021	Price to NMO	£442k
Project Title	Cofunding for EMRP S04 Biologically weighted quantities in radiotherapy (BioQuaRT)	Co-funding target	EMRP
Lead Scientist	Hugo Palmans	Stage Start Date	01/06/2012
Scientist Team	Sebastian Galer, Ling Hao, Caterina Minelli, Peter Sharpe, Clare Gouldstone	Stage End Date	31/05/2015
		Est Final Stage End Date	2021
Sectors	1. Health: Drugs & Therapies 2. Underpinning metrology: Extension of SI	Activity	Methodology for New Capabilities

Summary

The work proposed contributes to a wider body of research in the European Metrology Research Programme (EMRP) SI Broader Scope "Biologically weighted quantities in radiotherapy (BioQuaRT; JRP-SIB06)" project. The purpose of this project is to develop measurement and simulation techniques for determining the physical properties of ionising particle track structure on different length scales, and to investigate at the cellular level how these track structure characteristics correlate with the biological effects of radiation with the long term aim of defining and realising a new dosimetric quantity which, contrary to the currently used quantity absorbed dose, represents the biological effects of radiation in an unambiguous way from a physical perspective. NPL's involvement consists of two major contributions: (i) the development of micro-calorimeters that directly measure energy deposition spectra and participation in comparisons with tissue-equivalent proportional counters and silicon based micro-dosimeters and (ii) the development of methods for measuring the production rate and 3D distribution of reactive oxygen species in tissue exposed to proton and ion beams.

The Need

Given the announcement that the clinical application of proton therapy in the UK will be expanded (with two large scale high-energy proton facilities going beyond the low-energy facility now available in Clatterbridge) there is increasing urgency to develop a consistent metrological basis of dosimetric concepts used in proton and ion beam treatments. The present approach of using absorbed dose to water and an overall biological weighting is insufficient for providing a generic method to quantify the administered radiation dose. Given the complexity of radiation induced biological processes on various scales, a multi-scale approach is needed which can only be realized by a European consortium with the necessary wide range of expertise since the expertise of any single laboratory is restricted to only one or a subset of the metrology capabilities required for covering all processes and scale levels involved. On the micro scale all present microdosimetric devices measure ionization rather than energy deposition and at the cellular level the distribution of radical formation linked to indirect DNA damage has been poorly understood and quantified.

The Solution

NPL contributes by the investigation and development of methods addressing the measurement at the micro scale and the measurement of radical distributions. Based on a feasibility and design study that was performed in collaboration with the University of Surrey and the Royal Surrey County Hospital a SQUID based micro-calorimeter will be developed that provides a direct measurement of energy deposition at the micrometer scale. The design consists of an absorber with radiological properties close to that of tissue, grown on a superconducting film surrounded by a micro-SQUID loop. Monte Carlo simulations and heat transfer simulations will be performed in support of the characterisation of the device in the Surrey Ion beams. Comparisons with a miniature tissue-equivalent proportional counter and a silicon micro-telescope will be performed to establish the relation between ionization and energy deposition on the micro scale. Concerning the measurement of radiation induced radical distributions, the literature of radiation chemical yields of biologically significant reactive species in aqueous environments will be reviewed, particularly the effect of radiation type and energy on the relative amounts and spatial distribution of different species produced. Based on this specific probes / techniques will be identified that can be used to determine the relative amounts and distributions of species produced and relate these quantitatively to biological effectiveness.

Project Description (including summary of technical work)

In the first phase of the micro-calorimeter development demonstrator prototypes, built with previous NMS and external funding (NIHR-i4i), will be characterised concerning their basic performance (response time, recovery time, transition temperature, absorber and superconductor poisoning and radiation hardness) by experiment, Monte Carlo and finite element heat transfer modelling. The knowledge obtained from this first phase will lead to the design and production of a generation of improved devices with emphasis on flexibility, transportability and versatility to be used in a clinical environment. In the third phase the equivalence of ionisation and energy absorption at the micro scale by will be investigated by comparing microdosimetric lineal energy spectra measured with micro-calorimeters, proportional counters and silicon micro-telescopes. Concerning the quantification of radical induced indirect effects, methods will be developed to quantify radiation induced biologically significant reactive species, particularly reactive oxygen species (ROS), by the use of specific probes. An essential aspect will be a critical literature review of the information gained over many decades and will concentrate on the identification of successful techniques and the consistency of data relating radiation chemical yields to radiation type and energy. The feasibility of methods for determining the spatial distribution of those reactive species will be evaluated theoretically, among which direct imaging methods, or by techniques, such as EPR and NMR, that characterise the environment surrounding radiation induced species, and a test system will be developed based on a selected method.

Impact and Benefits

The results of this project will contribute to lay the metrological foundations for a new measurand of ionising radiation that is based on measurable physical properties of particle track structure at different length scales and allows a more robust quantification of dosage across all modalities of radiotherapy. The work will assure a leading role for NPL in the areas of microdosimetry and the quantification of indirect radiation effects as part of a wider effort to realise a new dosimetric quantity which represents the biological effects of radiation.

Support for Programme Challenge, Roadmaps, Government Strategies

The iMERA roadmap for ionizing radiation metrology “New Physical Concepts and Metrology for Quantifying Radiation Interaction with Matter” considers “Biological quantities for radiation dose” as an important future trend in dosimetry.

The BIPM’s Consultative Committee of Ionising Radiation has expressed strong support for defining such a new quantity, particularly for treatments involving the use of one or more multiplying factors to describe the corresponding biological effects of the absorbed dose.

A recent joint report of the International Atomic Energy Agency (IAEA) and the International Commission on Radiation Units and Measurements (ICRU), entitled “Relative Biological Effectiveness in Ion Beam Therapy” points out that the growing use of radiotherapy modalities whose biological effect differs from that of high-energy photon beams heightens the need for consistency across the different radiotherapy modalities and propose a "universally agreed approach for the use of weighting factors ... (to) ...facilitate exchange of information and improve collaboration between centres and within the radiation oncology community".

Synergies with other projects / programmes

SR project UniS: Development of a microbolometer for microdosimetry

NIHR-i4i project II-ES-0511-21007 (The development of a novel detector for the measurement of radiobiological effect of ion beams)

Risks

Delays in the production of micro-calorimeters will be mitigated by prioritisation of this effort and by the possibility to fall back on existing devices which have not been specifically designed for the purpose (with sub-optimal performance). The devices are anticipated to be used in broad clinical beams but if this is technically not possible mitigation of the work to micro beams is possible. Setup of proportional counters and silicon micro-telescopes at our beam line may not be possible in which case the mitigation constitutes of performing indirect comparisons (at different beams but with the same energies). Sensitivity of specific ROS probes may be too low in which case we can fall back on less specific probes.

Knowledge Transfer and Exploitation

The outcomes of the research will be disseminated by publications in peer-reviewed journals, EMRP workshops, and presentations at scientific conferences organised by target user groups outside the metrological community, such as medical and clinical physics. The establishment of a report committee with the ICRU will be initiated within the framework of the BioQuaRT (JRP-SIB06) project.

Co-funding and Collaborators

Co-funding from EMRP SI Broader Scope project “Biologically weighted quantities in radiotherapy (BioQuaRT; JRP-SIB06).

Collaborators will be the Ion Beam Centre of the University of Surrey, Surrey Ion Beam Centre, Royal Surrey County Hospital, Gray Institute and the EMRP partners, Institut de Radioprotection et de Sûreté Nucléaire (France), Instituto Tecnológico e Nuclear (Portugal), Politecnico di Milano (Italy), Istituto Nazionale di Fisica Nucleare (Italy), PTB and ENEA.

Deliverables

1	**Start: 01/06/12**	**End: 31/05/15**	

Deliverable title: Cofunding for EMRP project “Biologically weighted quantities in radiotherapy (BioQuaRT; JRP-SIB06).

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Neutrons Projects 2012

Project No.	AIR/2012/N2	Price to NMO	£208k
Project Title	Cosmic Ray and High Energy Dosimetry	Co-funding target	
Lead Scientist	Graeme Taylor	Stage Start Date	1st January 2012
Scientist Team	David Thomas, Graeme Taylor, Neil Roberts, Nicola Horwood	Stage End Date	31st December 2014
		Est. Final Stage End Date	31st December 2014
Sector	3.3 Health & Safety 7.3 Standards & Regulation (future)	Activity	Challenge-driven R&D

Summary

Continued measurements on transpolar flights aim to improve understanding of doses from solar particle events and their impact on air travel. Commissioning of NPL high energy spectrometry capability and subsequent characterisation of high energy standard neutron fields at ISIS will offer UK-based testing for single event effects for the first time.

The Need

Exposure to high energy neutrons (i.e. > 20 MeV) is becoming an increasing part of our everyday lives for certain occupationally exposed groups. The most prevalent source of high energy neutrons is galactic cosmic radiation, which we are exposed to every time we fly. Although nowadays the impact of galactic cosmic radiation is quite well understood, there is much less understanding about the mechanisms and effects of solar cosmic radiation, particularly solar particle events, which have the capability to increase in-flight dose rates by factors of ten or more. However, they can also decrease dose rates, and the lack of understanding regarding the production and propagation of these events results in a lack of knowledge regarding the energy and spatial distributions of the radiation fields at aircraft altitudes, leading to wildly different estimations of in-flight doses. Differences of factors of three or higher have been known to occur in estimates for transatlantic flight doses from solar particle events. In addition to the potential health effects of exposure to cosmic radiation, there are the potential effects on electronic systems as well.

Another source of high energy neutrons which is also becoming more commonplace, is secondary neutron radiation from high energy accelerators such as those used for proton therapy. As the UK seeks to commission its first high energy proton therapy facilities and develop a high energy facility for studying single-event effects in electronic devices (CHIP-IR at ISIS), the absence of high energy neutron spectrometry capabilities in the UK becomes increasingly significant. Developments in this area will be undertaken in cooperation with PTB in Germany, IRSN in France, and INFN in Italy.

The Solution

The only way to improve understanding and consequently improve the models for predicting doses from solar particle events is to provide the experimental data required for benchmarking these models. Continued participation in the PolarHawk collaboration, flying instruments on ultra-long-haul, transpolar routes offers the best available opportunity to capture such measurement data. However, given the sporadic and transient nature of particle events, any opportunity to expand the measurement network will be investigated.

In order to extend NPL's neutron spectrometry capabilities to higher energies, additional Bonner spheres with increased sensitivity to high energy neutrons will be constructed and characterised. These will be complementary to the existing NPL Bonner sphere set. The extended neutron spectrometry capability will then be used to characterise the CHIP-IR high-energy neutron standard fields in collaboration with ISIS, providing traceability of neutron standards over an increasing range.

Project Description (including summary of technical work)

1: Continue to develop measurement network for solar event dosimetry. Continued *participation in the PolarHawk project*, monitoring transpolar routes for the evaluation of instrumentation and increasing understanding of solar particle event dosimetry, backed up with calculations performed with codes such as MCNPX, QARM and FLUKA. (In collaboration with SolarMetrics, QinetiQ and United Airlines).

2: High energy standard neutron fields. A high energy standard neutron facility is being set up at ISIS, and NPL's role is the measurement of the neutron spectrum using high energy Bonner spheres based on gold foils. A complex analysis procedure is necessary to determine the spectrum. (In collaboration with ISIS). The Bonner sphere set will also be useable with active detectors and will thus have applications at proton therapy facilities both in the treatment room and outside shielding.

Impact and Benefits

Better solar particle event dosimetry.

Improved protection of the public and radiation workers from neutron radiation from an ability to satisfy regulatory requirements. Measurements will be possible for the first time around high energy accelerators including proton dosimetry facilities.

The development of a facility for testing electronics for single event effects from high energy neutrons, which will be the first in the UK, will lead to improvements of civil and military aircraft electronic components.

Overall it will maintain NPL as one of the top neutron metrology labs in the world by increasing the range and quality of its standards.

Support for Programme Challenge, Roadmaps, Government Strategies
This project aligns with the current NPL Neutron Metrology Roadmap:
"Improved cosmic ray dosimetry for radiation protection"
"Radiation hardness testing"
Programme Challenge: Health protection – improvements to neutron dose measurements.
Government strategies: Improved radiation protection for nuclear workers, flyers and MoD staff.

Synergies with other projects / programmes
NPL has been involved in cosmic ray dosimetry since 2000, resulting in several peer-reviewed publications (e.g. Taylor et al., Radiat. Prot. Dosim. 110(1-4), 381-386 (2004), Beck et al., Radiat. Prot. Dosim. 131(1), 51-58 (2008)), contribution to an EC Report (Radiation Protection 140, 2004), memberships of the UK Cosmic Ray Advisory Group (CRAG) and EURADOS working group on high energy dosimetry (WG 11).
NPL has been active in the field of Bonner sphere neutron spectrometry since the 1970s, but only recently identified a need for developing a high energy spectrometry capability. Design studies are currently under way (2010-2011 programme), with finalised designs planned for December 2011.

Risks
The current solar cycle is behaving in an uncharacteristic manner, hence it is possible that no significant solar particle event will affect air travel during the life of this project. The higher risk, however, is that anything less than having instruments airborne 100% of the time carries a risk of missing an event (estimated medium risk).
There is a low-to-medium risk that the CHIP-IR facility at ISIS will not be ready for characterisation during the lifetime of this project.

Knowledge Transfer and Exploitation
Intended routes of knowledge transfer for all deliverables are:

- Presentations at national / international conferences and meetings (e.g. NEUDOS, EURADOS, CRAG) and NPL clubs
- Peer-reviewed publications in appropriate journals, e.g. Radiat Prot Dosim, NIM A
- Extension of NPL field measurement capabilities (high energy neutron spectrometry)
- Development of high energy single event effects testing facility (CHIP-IR at ISIS)

Outputs will be taken up by all sectors with an interest in radiation protection against high energy neutrons, e.g. Energy, Health and Aviation.

Co-funding and Collaborators
Collaborations will consist of work in-kind, providing expertise not available at NPL, plus routine management of instrumentation including data downloads, battery replacement, flight transfers, etc. in the case of the PolarHawk project.
Solar event dosimetry: SolarMetrics, QinetiQ and United Airlines
High energy standard neutron fields: ISIS

Deliverables

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

Continue to develop measurement network for Solar Event Dosimetry: Continued participation in the PolarHawk project making measurements on transpolar routes during Solar Maximum, a period associated with increased solar activity; analyse measurement data and correlate with solar activity, publish any data on particle events annually; final report in Dec 14

2	**Start: 01/01/12**	**End: 31/12/13**	

High energy standard neutron fields: Continue development of high energy standard neutron fields in UK (at ISIS).
Year 1: commission HE Bonner spheres designed during 2010-2011 programme and write report
Year 2: perform characterisation measurements at CHIP-IR / ISIS and publish results

Project No.	AIR/2012/N3	**Price to NMO**	£246k
Project Title	Develop low energy neutron calibration fields	**Co-funding target**	
Lead Scientist	David Thomas	**Stage Start Date**	1st January 2012
Scientist Team	David Thomas, Nigel Hawkes, Graeme Taylor, Andrew Bennett, Neil Roberts, Sarb Cheema	**Stage End Date**	31st December 2014
		Est. Final Stage End Date	31st December 2014
Sector	3.3 Health & safety 7.1 Traceability & uncertainty	**Activity**	NMS infrastructure

Summary

This project will extend NPL neutron fluence and dose equivalent standards to lower energies and help maintain NPL as one of the top three neutron metrology labs in the world by extending the range of its standards into an area of the neutron energy range that is important for radiation protection.

The Need

Radiation protection devices, i.e. area survey instruments and personal dosemeters, tend to always miss-read at low neutron energies. Moderator based survey instruments over-read, one commonly-used instrument reaches an over-reading of a factor of 9 in the intermediate energy region. Tissue equivalent proportional counters, commonly used for area monitoring, under-read, as do the majority of personal dosemeters used in the UK. There is, however, a type of personal dosemeter (an albedo dosemeter) which may over-read at low energies. This information on the device responses comes from calculations, and from measurements with reactor filtered beams. These beams are no longer available and reliable calculations are difficult for personal dosemeters. Developers of area survey instruments and personal dosemeters thus need standards in the intermediate (thermal to low-keV) energy region for acceptance testing of both production devices and devices under development. In many workplace fields the low energy neutrons dominate the fluence spectrum.

One type of test field developed at NPL simulates a workplace where there are large numbers of low energy neutrons. As no two workplace fields are alike, the continued development of additional simulated fields to complement the existing NPL facility will widen the potential customer base for such irradiations and also extend their usefulness in terms of identifying the problems with dose measurements. Experiments with the existing NPL simulated field have shown that both personal and area dosemeters, can give readings which are badly wrong if used in fields which are very different to those in which they were calibrated. The response functions of many dosemeters are such that the degree of misreading is very sensitive to the precise spectrum of the simulated field and this needs investigating by having available simulated fields with different spectra.

The Solution

Irradiation facilities will be extended via two deliverables.

1: Monoenergetic standards will be developed at ~1 keV (i.e. lower than any currently offered), providing traceability of monoenergetic neutron standards over an increasing range.

2: New simulated workplace fields and/or fields with a broad energy distribution in the intermediate energy region will be developed.

Project Description (including summary of technical work)

1: The most likely reaction to use for producing low-energy monoenergetic neutron fields is ^{65}Cu(p,n). This has been investigated briefly at NPL in the past and it is clear that neutrons in the 1 keV region can be produced using this reaction. The major problem, however, is the very low yield. There are a couple approaches to improving the neutron production. In the previous measurements a natural copper target was used. The option of using a target isotopically enriched in ^{65}Cu did not originally seem feasible since it would have been prohibitively expensive to buy enough material to produce a target by evaporation. However, recent developments in target preparation using ion-implantation now make isotopically pure targets possible. (Ones have already been made for another laboratory). The other approach is to use high beam currents. This approach was investigated for the ^{45}Sc(p,n) work in recent programmes and the knowledge learnt there can be used for copper targets. Once a target is available the neutron output will be characterised using available fluence measuring devices. Some work will also be required to extend the calibration of these to lower energies. The 1 keV neutrons from the ^{65}Cu(p,n) reaction are produced at 0^{o} to the proton beam. At other angles the energy is even lower so the deliverable would also include work to characterise the angular distribution of the neutron intensity allowing measurements to be made at several energies simultaneously.

2: Monte Carlo modelling during the current programme has provided valuable insights into what is possible in terms of broad energy fields produced by moderation of accelerator-produced neutrons. The existing simulated workplace field has to date only been experimentally characterised at 0^{o} to the charged particle beam, but the calculations indicate that different spectra, with useful characteristics, are available at other angles. There is also the possibility, by absorbing the thermal neutrons of producing a 1/E broad-energy field with neutrons solely in the intermediate energy region. Both options would provide useful additional test fields. In the 2012 programme detailed calculations with will be performed to investigate the optimum designs of moderators and/or collimators that produce the desired energy spectra. Once a suitable design is found it will be manufactured, tested and characterized.

Impact and Benefits

Improved protection of the public and radiation workers from neutron radiation by ensuring that devices meet specifications. The project will provide facilities which will help device manufacturers prove that their devices satisfy the requirements laid out in international standards. With climate change issues making new build very probable these are essential capabilities for the UK. In the long run this project will enable the development of better instruments for measuring neutron dose equivalent.

Support for Programme Challenge, Roadmaps, Government Strategies

All elements of this project align with the current NPL Neutron Metrology Roadmap (i.e. better characterisation of instruments, improved dosemeters and extended neutron dosimetry, broad energy range spectra). Programme Challenge: health protection – improvements to neutron dose measurements.

Government strategies: Improved radiation protection for nuclear workers (including new-build), MoD staff, oil well loggers, and all individuals exposed to neutrons..

Synergies with other projects / programmes

1: Deliverable 1 is a logical extension of the previous work to develop standards at lower energies which started with 8 and 27 keV from the $^{45}Sc(p,n)$ reaction.

2: Continues the work in the current programme developing new fields, and a 1/E intermediate field fits in with deliverable 2 in providing standards in a region where currently there are none.

Risks

Reliable operation of the Van de Graaff accelerator is essential for both deliverables. The maintenance of the accelerator is covered in a core project. Equipment failure is always a risk issue requiring careful management of essential project funding to ensure obsolete units are identified and replaced.

It may turn out that the low yield from the $^{65}Cu(p,n)$ reaction will limit its usefulness, however, there are instruments with sufficiently high responses in the 1 keV region that useful measurements can be made.

Knowledge Transfer and Exploitation

Intended routes of knowledge transfer for all deliverables are:

- Presentations at NPL forums such as the Neutron Users' Club and the Ionising Radiation Metrology Forum (IRMF).
- Presentations at conferences, particularly the three-yearly Neutron Dosimetry Symposium (NEUDOS).
- Publication in journals such as Nuclear Instruments & Methods or Radiation Protection Dosimetry.
- Publication of NPL Reports.
- The NPL web site.

Exploitation occurs through our measurement services via customers' improved products in Energy, Defence and Health.

Co-funding and Collaborators

For deliverable 1 collaboration is proposed with IRMM, IRSN, and PTB who, together with NPL, have a working collaboration agreement. The Sc(p,n) work was undertaken via collaboration with this group, the IRSN providing a PhD student and the other labs experimental facilities.

Deliverables

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

Develop monoenergetic standards at ~1 keV:

Year 1: Develop targets and investigate yield, optimise backing material.

Year 2: Characterise target output in terms of the energy and angle dependence.

Year 3: Perform calibrations at these low energies.

2	**Start: 01/01/12**	**End: 31/12/13**	

Development of broad energy range spectra:

Year 1: Detailed modelling, design, and manufacture of the moderator assembly and target based on the ideas developed in the current year's programme.

Year 2: Characterisation of the yield and the energy spectrum at different angles to the charged particle beam.

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Radioactivity Projects 2012

Project No.	NMS/AIR12027	Price to NMO	£220k
Project Title	Cofunding for EMRP 18E Metrology for radioactive waste management (MetroRWM)	Co-funding target	EMRP
Lead Scientist	Julian Dean	Stage Start Date	1 Jan 2012
Scientist Team	Simon Jerome, Hilary Phillips, John Sephton, Julian Dean	Stage End Date	30 Sept 2014
		Est Final Stage End Date	30 Sept 2014
Sector	3.3 Health and Safety 2.2 Pollution and Waste reduction	Activity	Challenge Driven R&D

Summary

The aim of the project is to improve two aspects of radioactive waste management, namely (i) efficiency of monitoring of α- and β-emitting radionuclides in nuclear site wastes, and (ii) monitoring of gaseous emissions from organic waste in repositories.

Radiochemical analyses of contaminated materials from nuclear sites involve sampling and transfer to a remote laboratory, resulting in delays, additional costs, and potential exposure to staff and lack of flexibility in sampling protocols. One aim of this project is to develop and test a portable, integrated radiochemical analysis system to address these problems.

Increasing quantities of radioactive waste are being stored in repositories; many of the waste products contain organic materials with the potential to produce radioactive gases and vapours. There are radiological aspects of this that need to be considered. Another aim of this project is to develop and test methods for the monitoring of gaseous radioactive emissions from such wastes. The requirement is to assay gaseous radionuclides in specific chemical forms, so systems for radioactive gas separation will require development and integration with suitable commercially available radiation detectors.

The Need

There is a need to develop capability for the direct measurement of α- and β-emitting radionuclides wastes arising from nuclear site decommissioning. Such measurements are normally carried out at a radiochemical analysis laboratory remote from the site. This introduces measurement problems because of the need to take representative samples of the waste and because it is impractical to modify the sampling and analysis strategy in real time. Sending samples to a laboratory also introduces additional costs due to the need to transport, register, process, analyse and dispose of the samples taken.

In-situ radiochemical analyses are needed. NPL already has experience in evaluating small-scale radiochemical analysis platforms and, with the capabilities of partner NMIs, is well positioned to integrate this with a commercially-available portable radioactivity detector to form a prototype portable assay system.

At the post-storage stage, there is a need to measure gases and vapours containing ^{3}H, ^{14}C, ^{222}Rn and non-radioactive 'bulk' gases arising from radioactive wastes stored in repositories. This is because radioactive species can potentially constitute a radiological hazard to workers (and, ultimately, the general population); moreover, the dose delivered depends on the chemical form of the species, therefore it is necessary to differentiate between concentrations of different forms of radionuclides. A better understanding of waste degradation mechanisms is also required, and for this, the concentrations of the non-radioactive bulk gases are needed to enable determination of the specific activity of a radionuclide in its bulk gas.

Short-term measurements (e.g. over hours) are required to estimate doses to workers, whilst longer-term measurements (e.g. over weeks or months) are needed to inform studies of waste degradation and environmental modelling. Such measurement techniques have other applications (e.g. for waste package acceptance tests). The current state-of-the-art is that there are existing commercial monitors (e.g. portable liquid scintillation counters), which could potentially measure the radioactive species, but these were not designed for this type of remote application. Gas trapping and separation techniques exist for the radioactive species of interest, but not with fluid transfer capability nor a traceable calibration. There are existing commercial monitors for the 'bulk' gases at the concentrations of interest, but not integrated into a system suitable for this type of application. However, NPL and its partner NMIs have expertise in areas such as radioactivity detection, fluid separation and chromatography which can be brought to bear to address the above needs.

The Solution

NPL will lead work with other European NMIs to build and test a field-deployable integrated radiochemical analysis system based on a radiochemical separation platform and a commercially-available portable detector. This will provide capability for rapid in-situ measurements of α- and β-emitting radionuclides. To address the repository-monitoring requirement, NPL and its partner NMIs will also build and test gas separation and fluid transfer manifolds integrated with radiation detectors. This will provide a capability for real time dose assessments and support the development of monitoring systems capable of remote measurement.

Project Description (including summary of technical work)
The technical work for the in-situ measurement project will consist of (i) extending laboratory techniques for initial sample processing to develop protocols suitable for in situ processing, (ii) designing, building and validating a prototype in situ radiochemical analysis system, and (iii) calibrating, validating and integrating with the analysis system a portable radioassay system.

The technical work for the gaseous effluent monitor project will consist of (i) developing a time-integrating gas-in-air monitoring system with installed gas-collection and assay instrumentation, (ii) developing an ionization chamber based real-time gas-in-air monitor with associated gas separation unit (using a novel approach), and (iii) developing ancillary methods for rapid gas sampling from wastes. (i) and (ii) will enable the activity concentration of different radioactive species to be determined. There is also a requirement to include computer interfaces to enable remote monitoring of air quality at more than one location.

The technical work will involve building gas separation and fluid transfer manifolds, testing them and then integrating with existing radiation detectors. The equipment will be tested using standard radioactive gases at NPL and the partner NMIs. The low-level ^{3}H and ^{14}C gas standards required for the system calibrations will be developed at NPL. The project will also involve testing gas trapping devices for collecting samples from wastes.

Impact and Benefits

In-situ measurement capability will significantly reduce costs and doses to personnel by reducing the need to transport radioactive material off-site and the time required to sample, transport, register, analyse, assay, manage and dispose of radioactive samples. In addition, the close proximity of such an analysis system to waste that requires sentencing introduces far more flexibility to modify sampling strategies in real time.

The gaseous effluent monitor deliverables will contribute to better radiation safety for waste repository workers by enabling better real time dose assessments from airborne species, a better understanding of waste degradation mechanisms and the development of monitoring systems capable of remote measurement of small increases in levels of gaseous radioactivity. It will expand measurement capability by enabling NPL to develop separation methods for individual gases and low level radioactive gas standards, with the potential to develop new measurement and instrument testing/calibration services in radioactivity.

Support for Programme Challenge, Roadmaps, Government Strategies
This project area is in the radioactivity roadmaps and supports the Ionising Radiation Regulations 1999 and the Radioactive Substances Act 1993. It also addresses the UK National Challenge: Sustainability.

Synergies with other projects / programmes
The project will build on NPL's expertise in radiochemical analysis and in radioactive gas and vapour counting/handling (by adding gas separation technologies). These could be applied to our measurement services in this area. The project relies on core capabilities generated by the primary and secondary standards projects in radioactivity.

Risks
For the in-situ analysis deliverables, there is a risk that the system will not completely process and analyse a field sample, resulting in lack of usable data. This risk can be mitigated by, for example, characterizing the system for a wide range of materials and radionuclides of importance. For the gas monitoring project, the fluid separation and transfer mechanisms may be difficult to develop, potentially increasing costs and reducing impact. The risk can be mitigated by tapping into the experience of instrument companies and partner NMIs and ensuring the best components and methods are used.

Knowledge Transfer and Exploitation
This will be done via conferences (e.g. ICRM), the literature (e.g. Applied Radiation and Isotopes) and EMRP media.

Co-funding and Collaborators
Co-funding will be obtained from EMRP. Collaborators will be BEV/PTP, CMI, ENEA, SMU, PTB and ENVINET.

Deliverables

1	**Start: 01/01/12**	**End: 30/09/15**	
Deliverable title: Co-funding for EMRP project JRP18: MetroRWM			

Project No.	AIR/2012/R5	Price to NMO	£ 199k
Project Title	Metrology for Quantitative Imaging and MRT	Co-funding target	EMRP
Lead Scientist	John Keightley	Stage Start Date	1st July 2012
Scientist Team	Lena Johansson, Michaela Baker, Andrew Fenwick, Andy Pearce, Joel Gasparro	Stage End Date	30th June 2015
		Est Final Stage End Date	30th June 2015
Sector	3.1 Diagnosis 3.2 Drugs & Therapies	Activity	Challenge Driven R&D

Summary

Each year in the UK, there are in excess of 750,000 radiopharmaceutical administrations to patients, the vast majority of which are related to the use of diagnostic nuclear imaging techniques (PET, PET-CT, SPECT). This project addresses metrological issues related to improvements in the quality, reliability and comparability of activity measurements for administered radiotracers utilised in quantitative imaging and molecular radionuclide therapy (MRT). By developing metrological tools for nuclear medicine departments to improve in their dose planning capability in two ways; firstly by providing new measurement techniques for the activity determination in case of therapeutic treatments and secondly, by developing methods for the hospitals to test their accuracy in dose estimation from quantitative imaging.

The Need

Under current European guidance, nuclear medicine departments are required to ascertain the activity of delivered patient doses to within an uncertainty of 10%. Demonstrating activity measurement traceability is problematic for most positron-emitting radionuclides used in nuclear imaging (due to their short half-lives) as well as for beta-emitting nuclides used for radiotherapy, in part due to the wide variety of physical forms employed (colloids, micro-spheres) combined with the short range of the associated ionising emanations.

The current state of the art reveals that dose planning for MRT is mostly ineffective with uncertainties sometimes as large as 100%, compared to, for example, external beam therapy where dose planning systems are utilised and doses to the target area can be determined within less than ±10%. Currently, there is a relatively small selection of software available for hospitals to perform dose planning for MRT and this software is not always validated. The EANM (European Association of Nuclear Medicine) is currently considering how to standardise the dose planning on a European level; traceable phantom measurements and/or images are needed to support this standardisation.

Quantitative Imaging refers to making quantitative measurements of activity within defined volumes from tomographic radionuclide images, providing information about the 3D activity distribution within the target volume as well as any sensitive organs and the retention of the activity in the body (the dose delivered is a function of time), i.e. the biological half-life, which might vary significantly between patients. Any metastasis can also be evaluated by imaging and sometimes successfully be treated. From the images, which are normally taken using PET/CT or SPECT/CT cameras, a dose estimation can be derived.

The primary need is for a practical measurement procedure that can be adopted widely in clinical departments, and is supported both by metrology laboratories in the provision of calibration and verification services and by the consensus of the nuclear medicine community.

The Solution

a) Develop a traceable method for determination of the activity used for PET and SPECT imaging, as they are mostly very shortlived (in the order of minutes).
b) Develop a method to accurately determine activity administered to patients for therapeutic purposes, utilising the knowledge NPL has on Cerenkov counting. Development of a Cerenkov counter based on the TDCR (triple to double coincidence ratio) principle to improve accuracy in therapeutic administrations of pure beta emitting radiopharmaceuticals, with specific emphasis on the measurement of Y-90 microspheres, alongside a study of the associated measurement uncertainties.
c) Develop or select a suitable standard phantom for calibration of PET-CT and SPECT cameras, together with a procedure that will achieve a traceable measurement chain from an activity standard to a PET or SPECT measurement of activity within a volume of a tomographic image.
d) Perform a comparison exercise of phantom measurements and/or phantom images from PET and SPECT cameras

Project Description (including summary of technical work)

a) Provision of a re-entrant ionisation chamber system to be used for the in-situ calibration of short-lived photon emitting isotopes used in nuclear imaging (calibrated against NPL's primary activity standards).
b) Development of a TDCR Cerenkov counter, facilitating the in-situ calibration of beta-emitting radiopharmaceuticals used in palliative treatments and targeted radionuclide therapy. Validated via a series of international comparison exercises between collaborating NMIs. This will include a primary activity standardisation of solution/s containing the two existing types of Y-90 microspheres (resin and glass).

c) An anthropomorphic phantom (and associated measurement procedures) will be developed to enable quantitative, and traceable, data (such as standard uptake values) to be inferred from nuclear medicine imaging devices. Improvement of implementation of correction factors (e.g. scatter correction, reconstruction, camera resolution, efficiency …) for both planar and tomographic imaging techniques.

d) Comparison exercise of suitable phantom with standardised radionuclide and/or images from camera(s).

Development and dissemination of suitable protocols for making and interpreting measurements, for a) – c) above.

Impact and Benefits

The provision of measurement protocols and methodologies, linked to a sound metrological basis for calibration of imaging scanners, associated instruments and the interpretation of results will have a profound impact on the quality of patient dosimetry for targeted radionuclide therapy, and diagnoses made with multi-modal imaging techniques, leading to increased cancer survival rates and improved quality of life for cancer survivors.

Support for Programme Challenge, Roadmaps, Government Strategies

Support for Programme Challenge: Healthcare - Diagnostics: Medical Diagnostic Techniques for accurate and earlier diagnosis of disease.

Support for Government Strategies: Supports the Government priority Public Service Agreement Targets PSAT 18 “Promote better health and wellbeing for all”

Supports the Government priority PSAT 4 ‘Promote world-class science and innovation in the UK’

Synergies with other projects / programmes

Relies on and applies to the:

- Ongoing preliminary project on guidance for measurement of Y-90 microspheres.
- The proposed Cerenkov detector was initially investigated in an SR Exploratory Research project at NPL, funded in 2010.

The deliverables align with and complement the AIR Programme/EMRP projects around “Metrology for Molecular Radiotherapy”.

Risks

Development of methodologies for the primary standardisation of Y-90 microspheres is new and technically challenging.

Knowledge Transfer and Exploitation

As improvements in quantitative imaging and targeted radionuclide therapy are realised, the expertise developed within NPL will be transferred to hospital users in the collaborative development of measurement protocols and audit procedures. NPL will develop training materials to cover measurements.

Co-funding and Collaborators

Funding in kind by partners for collaborative research effort and use of facilities not available at NPL.
Co-funding from EMRP Health II project “Metrology for Molecular Radiotherapy” (Radioactivity element; project NMS/AIR12029).
Collaborations with IPEM, and Royal Marsden Hospital, and other Nuclear Medicine Departments in the UK and EU.

Deliverables

1	**Start: 01/07/12**	**End: 30/06/15**	

Deliverable title: Traceability for PET nuclides
A transfer instrument based on the NPL secondary ionisation chamber will be produced for in-situ measurements at the clinic.

2	**Start: 01/07/12**	**End: 30/06/15**	

Deliverable title: Activity determination of therapeutic nuclides by TDCR/Cerenkov counting
A new technique employed to the existing NPL TDCR system will provide a possible metrological solution to measuring therapeutic beta-emitters in-situ and directly in the sample. Test will be done on the current TDCR system.

3	**Start: 01/07/12**	**End: 30/06/15**	

Deliverable title: Quantitative Imaging of Radionuclide Phantom
In collaboration with UK Hospital, a suitable phantom for PET and/or SPECT camera imaging will be determined and NPL will provide standardised activity solutions and take a sequence of images which will involve traceability

4	**Start: 01/07/12**	**End: 30/06/15**	

Deliverable title: Comparison exercise of phantom/imaging at UK hospital
The image of a phantom with a well-known activity distribution will be circulated amongst a few of the main UK hospitals and the capability will be evaluated as a function of software used. A report will be produced

Project No.	NMS/AIR12029	Price to NMO	£201k
Project Title	Cofunding for EMRP H13 Metrology for Molecular Radiotherapy (MetroMRT) – Radioactivity element (Linked to AIR/2012/R5)	Co-funding target	EMRP
Lead Scientist	Lena Johansson	Stage Start Date	1st Jul 2012
Scientist Team	John Keightley, Michaela Baker, Andrew Fenwick, Andy Pearce, Sean Collins	Stage End Date	30th Jun 2015
		Est Final Stage End Date	30th Jun 2015
Sector	3.1 Diagnosis 3.2 Drugs & Therapies	Activity	Challenge Driven R&D

Summary

The work proposed builds on project NMS/AIR12028 and contributes to the EMRP Health project, "Metrology for molecular radiotherapy (MetroMRT) and will support metrological issues related to improvements in the dose estimations of medical treatments using radionuclides, i.e. molecular radionuclide therapy (MRT). The current state of the art reveal that dose planning is mostly ineffective in these kind of treatments and uncertainties are sometimes as large as 100%, which is a significant uncertainty for a treatment compared to for example external beam therapy where dose planning systems are utilised and doses to the target area can be determined within less than ±10%. This project is hence developing metrological tools for nuclear medicine departments to progress in their dose planning capability in two ways; firstly by providing new measurement techniques for the activity determination in case of therapeutic treatments and secondly, by developing methods for the hospitals to test their accuracy in dose estimation from quantitative imaging.

The Need

Each year in the UK, there are in excess of 750,000 radiopharmaceutical administrations to patients, the vast majority of which are related to the use of diagnostic nuclear imaging techniques (PET, PET-CT, SPECT). This project addresses metrological issues related to improvements in the quality, reliability and comparability of activity measurements for administered radiotracers utilised in quantitative imaging and targeted radionuclide therapy.

Under current European guidance, nuclear medicine departments are required to ascertain the activity of delivered patient doses to within an uncertainty of 10%. Demonstrating activity measurement traceability is problematic for most positron-emitting radionuclides used in nuclear imaging (due to their short half-lives) as well as for beta-emitting nuclides used for radiotherapy, in part due to the wide variety of physical forms employed (colloids, micro-spheres) combined with the short range of the associated ionising emanations.

The primary need is for a practical measurement procedure that can be adopted widely in clinical departments, and is supported both by metrology laboratories in the provision of calibration and verification services and by the consensus of the nuclear medicine community.

The Solution

a) Develop a method to accurately determine activity administered to patients for therapeutic purposes, utilising the knowledge NPL has on Cerenkov counting. Development of a Cerenkov counter based on the TDCR (triple to double coincidence ratio) principle to improve accuracy in therapeutic administrations of pure beta emitting radiopharmaceuticals, with specific emphasis on the measurement of Y-90 microspheres, alongside a study of the associated measurement uncertainties.

b) Develop or select a suitable standard phantom for calibration of PET-CT and SPECT cameras, together with a procedure that will achieve a traceable measurement chain from an activity standard to a PET or SPECT measurement of activity within a volume of a tomographic image.

c) Perform a comparison exercise of phantom measurements and/or phantom images from PET and SPECT cameras

Project Description (including summary of technical work)

a) Development of a TDCR Cerenkov counter technique, facilitating the in-situ calibration of beta-emitting radiopharmaceuticals used in palliative treatments and targeted radionuclide therapy. This will include a primary activity standardisation of solution/s containing the two existing types of Y-90 microspheres (resin and glass).

b) An anthropomorphic phantom (and associated measurement procedures) will be developed to enable quantitative, and traceable, data (such as standard uptake values) to be inferred from nuclear medicine imaging devices. Improvement of implementation of correction factors (e.g. scatter correction, reconstruction, camera resolution, efficiency …) for both planar and tomographic imaging techniques.

c) Comparison exercise of suitable phantom with standardised radionuclide and/or images from camera(s).

Development and dissemination of suitable protocols for making and interpreting measurements, for a) – c) above.

Impact and Benefits

The provision of measurement protocols and methodologies, linked to a sound metrological basis for calibration of imaging scanners, associated instruments and the interpretation of results will have a profound impact on the quality of patient dosimetry for targeted radionuclide therapy, and diagnoses made with multi-modal imaging techniques, leading to increased

cancer survival rates and improved quality of life for cancer survivors.
Support for Programme Challenge, Roadmaps, Government Strategies Support for Programme Challenge: Healthcare - Diagnostics: Medical Diagnostic Techniques for accurate and earlier diagnosis of disease. Support for Government Strategies: Supports the Government priority PSAT 18 "Promote better health and wellbeing for all" Supports the Government priority PSAT 4 'Promote world-class science and innovation in the UK' as well as 18 'Promote better health and wellbeing for all'.
Synergies with other projects / programmes Relies on and applies to the: • On-going preliminary project on guidance for measurement of Y-90 microspheres. • The proposed Cerenkov detector was initially investigated in an Exploratory Research project at NPL, funded in 2010. The deliverables align with, and complement, project NMS/AIR12028 Metrology for quantitative imaging and MRT.
Risks Development of methodologies for the primary standardisation of Y-90 microspheres is new and technically challenging.
Knowledge Transfer and Exploitation As improvements in quantitative imaging and targeted radionuclide therapy are realised, the expertise developed within NPL will be transferred to hospital users in the collaborative development of measurement protocols and audit procedures. NPL will develop training materials to cover measurements.
Co-funding and Collaborators This project comprises NPL's input into the EMRP project MetroMRT. NPL is leading the project. The consortium consists of funded partners CEA (France), CMI (Czech Republic), ENEA (Italy), PTB (Germany), and VSL (Netherlands). Collaborations will also include: IPEM, and Royal Marsden Hospital, and other Nuclear Medicine Departments in the UK and elsewhere in the Europe.
Deliverables

1	**Start: 01/07/12**	**End: 30/06/15**	
Deliverable title: Cofunding for EMRP project "Metrology for molecular radiotherapy (JRP-HLT11)" – Radioactivity element			

Project No.	AIR/2012/R6	Price to NMO	£ 190k
Project Title	Development of capability for radioactive aerosol monitoring	Co-funding target	
Lead Scientist	Julian Dean	Stage Start Date	1 Jan 2012
Scientist Team	Hilary Phillips, Julian Dean	Stage End Date	31 Dec 2014
		Est Final Stage End Date	31 Dec 2014
Sector	3.3 Health & safety 2.2 Pollution & waste reduction	Activity	Challenge Driven R&D

Summary

Nuclear plants are required by legislation to perform routine monitoring of airborne radioactivity. This project will develop NPL's expertise in the generation and measurement of radioactive aerosols, and perform studies, which will lead to correction factors for the calculation of activity collected on filter media leading to more accurate dose exposure calculations for nuclear industry workers. This will enable better compliance of the employer with the Ionising Radiations Regulations (IRRs) and also with international requirements on testing of radioactivity-in-air monitors as laid down in IEC standards.

The Need

The nuclear industry must comply with legislation such as the IRRs (1999) (requiring monitoring of radiation doses to workers) and the Radioactive Substances Act (1993) (requiring assay of radioactive wastes prior to disposal). Compliance is required under normal operating conditions, during de-commissioning activities and after sudden unplanned release of airborne radioactivity.

A significant source of worker dose exposure is alpha emitting airborne radioactive particulate generated in the workplace. The dose is estimated from measurements of alpha activity on the filtered samples of air. The activity of the collected particulate as determined using air-sampling monitoring instruments is often significantly less than the true activity. This has been demonstrated by radiochemical assay of monitored filters. Actual and monitored alpha activities can differ by up to a factor of 20. The size of the radioactive particulate, the depth it has penetrated within the collection filter, the dust loading on the filter and the presence of radon in the monitored area can all contribute to under-estimation of the activity concentration of alpha emitting aerosols. Calibration of the instrumentation used in the nuclear plant is performed using solid calibration sources, but these sources are physically very different from the samples typically assayed and there is uncertainty within the industry over the suitability of such sources for filter assay. There is a clear and important need for 'correction factors' for monitor's response to alpha activity on filters under various conditions (e.g. different dust loadings and filter types). Also, instruments must comply with IEC standards, which stipulate tests in the presence of alpha-loaded aerosols with known particle sizes and radon-222 decay product levels; a recent NMO survey has confirmed specific UK user requirements.

There are currently only two institutions worldwide that have a capability to generate radioactive aerosol atmospheres for studies on airborne monitoring instrumentation. NPL already has a well-respected non-active aerosol measurement capability within its Environmental Measurement Group. This group currently operates the UK Particle Network on behalf of Defra and could work in tandem with NPL's radioactivity group. This project would enhance NPL's airborne measurement expertise by introducing new knowledge in the radioactive field.

The Solution

Project objectives include the production of radioactive aerosols with a defined particle size; the collection of these particles on filter media to prepare well-defined filters for subsequent studies; the comparison of apparent activity as measured by commercially available instrumentation to the activity as determined by radiochemical analysis. The effect of radon progeny on these measurements will be determined; we will also quantify the effect of dust loading on instrument response to alpha activity. The production of filters containing uniformly distributed particulates of known size, shape, activity and dust loading would enable comparison of instrument response to activity from filter media and calibration standards.

Project Description (including summary of technical work)

The production of well-characterised alpha aerosol particulate and its collection on filter media enables the determination of correction factors leading to greater accuracy in the estimation of dose from airborne radioactivity in the workplace. A basic radioactive aerosol generation and exposure rig suitable for the production of active filters (and also for instrument exposures) is proposed. A radon generator and aging chamber attached to the rig would enable simultaneous collection of radon daughters and active aerosol. The fabrication of active filters using synthetic glass milled to the required particle size as an alternative to the aerosol generation rig will be investigated. The correction factors (e.g. measured activity to total activity) and attenuation due to dust loading would be derived from studies using the particulate produced. Equipment for the addition of dust layers is already available at NPL. The introduction of radon daughters to the active aerosol would enable evaluation of instrument compensation protocols used to determine activity in the presence of interfering radon peaks. A rig for aerosol generation and instrument exposure will be designed, built and tested using in-house expertise in handling radioactive gases and inactive aerosols. The project will involve input from the radioactivity group and aerosol experts in the analytical science group.

Impact and Benefits

The project will enable users to comply with the Ionising Radiations Regulations (1999) (radiation protection of workers) and will enable instrument manufacturers to comply with IEC standards (e.g. IEC 61578) stipulating required tests for radioactive aerosol assay instruments. It will expand NPL's technical capability to include radioactive aerosol generation and radioactive aerosol instrument testing. The impact on the nuclear industry will be that worker doses can be more accurately determined, thus improving worker safety and the efficient management of the nuclear workplace.

Support for Programme Challenge, Roadmaps, Government Strategies

Primary Standards for radioactive aerosols is on the Radioactivity Measurement for Environmental, Energy and Radiation Protection Roadmap

This project supports the Sustainability Challenge: continuing need to measure pollutants in air (NMS Strategy)

Synergies with other projects / programmes

The Environmental Measurement Group (Analytical Science Division) currently operates the UK Particle network on behalf of Defra and has successfully conducted a biological aerosol project for Defra. This group has expertise and facilities for the generation, collection and measurement of aerosol particulate.

The aerosol deliverable would build on the recent NMO-funded study of metrology of activity on air filters, would enhance NPL's existing expertise in aerosol science and add diversity to NPL's airborne radioactivity capability. External partners would be sought to assist with rig fabrication. The equipment and procedures developed would be used in the future to establish further filter correction factors and to contribute to the type testing of radioactive aerosol assay instruments.

This deliverable is reliant on the core capabilities generated by the primary and secondary standards projects in radioactivity.

Risks

Radioactivity Group has little experience at present with radioactive aerosol generation or measurement. This risk can be mitigated by collaboration with the Environmental Measurement Group at NPL.

Knowledge Transfer and Exploitation

The aerosol project equipment and procedures will be disseminated to user communities via an NPL Report, possibly a PhD thesis, and also via the literature in peer reviewed journals such as the Journal of Radiological Protection and at conferences. It is envisaged that the equipment and procedures will form the basis of a type-testing facility and/or measurement service for radioactive aerosol monitors

Co-funding and Collaborators

Co-funding will be sought e.g. from a Research Council (funding a PhD student). The loan of commercially available radioactivity-in-air monitors for the project would be sought.

Deliverables

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

Deliverable title: Production of calibrated filters with radioactive aerosols

This includes: Generation of radioactive aerosols with well characterised properties. Production of a rig for the transfer of aerosol to filter and for the exposure of instrumentation to active aerosol.

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

Deliverable title: Filter measurement corrections

This includes: Determination of the relationship between measured and true activity for increasing filter dust loading and particulate filter penetration and generation of correction factors. Evaluation of instrument response to solid calibration sources and well characterised filters and generation of correction factors. Study of the effectiveness of manufacturers' radon compensation techniques. NPL Report and external papers on project findings

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Acoustics Projects 2013

Project No.	AIR/2013/A1	**Price to NMO**	£316k
Project Title	Primary standards , traceability, and international equivalence for airborne noise measurement and human hearing conservation	**Co-funding target**	
Lead Scientist	Richard Jackett	**Stage Start Date**	01-Jan-13
Scientist Team	Janine Avison, Ben Piper, Dan Simmons, Sue Dowson, Richard Barham	**Stage End Date**	31-Dec-15
		Est Final Stage End Date	On-going
Sector	7.1 Traceability & uncertainty 3.1 Diagnosis 2.2 Pollution & waste reduction	**Activity**	Provision of Standards & Maintenance of Capabilities; International obligations

Summary

Provides traceability for sound pressure measurement in the UK, to support NMS research in sound in air, and to meet demands from the diverse range of applications spanning hearing conservation and noise pollution in the environment. Demonstrate international equivalence through CCAUV key comparisons, and participation in the MRA.

The Need

Noise is the second largest form of environmental pollution (after air quality) and estimated by *DEFRA* to cost £7 billion to £10 billion per year, and affect over 40% of the population. An *Action on Hearing* (formerly *RNID*) report that 10 million people in the UK have a hearing loss, representing 16% of the population. This rises to 70% in the over-70 age group. Slightly more than 1 per 1000 neonates are also diagnosed with hearing impairment through NHS screening programmes. The measurement of airborne sound is vital to protect the environment we live in, and to control the risk of hearing damage and annoyance caused by noise. Acoustic measurement also underpins widespread hearing assessment practices. NPL currently implements a world-class primary standard for sound pressure based on reciprocity calibration. This supports a number of secondary facilities for working standard microphones, sound calibrators and ear simulators, in many cases providing the only UK source for such calibrations. Those involved with making acoustic measurements or tasked with enforcing regulations, and organisations that are part of the traceability chain (e.g. UKAS labs and hospital departments) rely on the NMS for confidence in the reliability and traceability of those measurements. Dissemination is via direct calibration and through 11 UKAS-accredited calibration laboratories and over 30 testing laboratories.

The Solution

The project provides a primary calibration facility for microphones and secondary calibration facilities for microphones and other types of acoustical instrumentation, and dissemination with ISO 17025 accreditation. International consistency will be assured through active participation in CCAUV and EURAMET key comparisons including the piloting of CCAUV.A-K5 which began in Jan-12 and the submission of data to the database of Calibration and Measurement Capabilities (CMCs) maintained by BIPM.

Project Description (including summary of technical work)

Provision of key facilities will be assured and operated within the requirements of ISO 17025, as independently assessed by UKAS. International equivalence of primary standards will be verified by participation in international key comparisons including the continued piloting of CCAUV.A-K5. The resulting degrees of equivalence and CMCs supported by the key comparison will be updated in BIPM databases.

<u>Summary of technical work</u>

Realising the primary standard for sound pressure in air, ensuring that the facility remains operational, fully traceable to base units and fully compliant with the requirements of ISO 17025, and that it remains accessible to the measurement community.

Dissemination for noise measurement by provision of secondary calibration facilities for microphones and sound calibrators.

Dissemination for hearing assessment by provision of calibration facilities for ear simulators and mechanical couplers.

Demonstrate international consistency through completion of reporting on CCAUV.A-K5 and further participation in one new key comparison on primary microphone calibration.

The project outputs will include:

Continued availability of the primary standard and secondary calibrations for microphones, sound calibrators and pistonphones and a range of ear simulators, all of which play a part in ensuring accurate acoustical measurement. In all, this project supports 6 accredited measurement systems and the world-class test facilities on which they are built.

A final report on CCAUV.A-K1 presenting new key comparison data on the degree of equivalence of primary measurement standards from all metrology regions. A protocol for a EURAMET key comparison, fulfilling an obligation as a CCAUV key comparison pilot laboratory, to extend the linking of data to the EURAMET region.

Impact and Benefits

Accurate acoustic measurements have a direct impact on environmental quality through reliable measurements of noise leading to informed decision making and noise policy and diagnosis and treatment of hearing impairment, both avoiding enormous detriment to quality of life. Six key measurement systems and a suite of test facilities provide support for 11 UKAS calibration

laboratories and over 30 UKAS testing laboratories and UK health and environmental sectors users. Many calibration certificates are issued annually which in turn provide extensive traceability across the UK. Dissemination of traceability is particularly widespread in the field of hearing assessment, with ear simulator calibrations supporting many 100,000s of measurements annually.
Support for Programme Challenge, Roadmaps, Government Strategies Project links with the AIR Programme strategy and Sound in air theme roadmap target for calibration facilities covering the full range of frequencies and levels found in sound-in-air measurement. It addresses government priorities on Environmental Sustainability – Pollution, Healthcare – Diagnostics and therapeutics. This project supports the national infrastructure of measurement standards and services for sound in air as defined in the NMS Strategy 2011-2015. Specifically, it provides calibration and test capabilities for noise measurement and nuisance assessment, and hearing assessment, conservation and treatment. The project underpins measurements for a wide range of initiatives including; environmental noise reduction targets, built environment strategic objectives, renewable energy agenda, noise at work act, and national hearing screening programmes.
Synergies with other projects / programmes All other sound-in-air projects will depend on this project for calibration and traceability. Other NMIs share the same need to ensure international consistency of measurement standards and benefit from the data made available under the MRA. UKAS laboratories benefit from improved dissemination and access to the latest measurement techniques. This project underpins the EMRP hearing studies through provision of calibrated microphones and artificial ears. This proposal includes international collaboration through a CCAUV and EURAMET key comparisons and is therefore partly dependent on the activity and contributions from overseas NMIs.
Risks Risks associated with provision of key measurement facilities are well understood and recent attention has put in place mitigation measures such as provision for replacement of specialised equipment. Where NPL works collaboratively there is a medium degree of risk in that NPL has little formal control over delivery; mitigated by ensuring project delivery is not dependent on any single NMI.
Knowledge Transfer and Exploitation Calibration services, technical guides and information are published on the NPL website. Training in calibration techniques is offered to existing customers and via the website. UKAS accredited measurement services. Publication of CMCs and degrees of equivalence with other NMIs in MRA database. Publication of CCAUV key comparison report and a EURAMET key comparison protocol.
Co-funding and Collaborators Collaborators in this work include EURAMET and CCAUV member NMIs, and UKAS calibration laboratories. NMIs would contribute resources each matching that of NPL. Key comparisons are collaborative by their nature.

Deliverables

1	**Start: 01/01/13**	**End: 31/12/15**	
Deliverable title: Provision of traceable standards for airborne noise and hearing assessment Support for 6 UKAS accredited calibration facilities, available to meet 100% of user demand within the agreed service delivery periods for each facility			
2	**Start: 01/01/13**	**End: 31/12/15**	
Deliverable title: CCAUV key and regional comparisons A final report on CCAUV.A-K5 and a protocol for a EURAMET key comparison linking to this.			

Project No.	AIR/2013/A2	**Price to NMO**	£573k
Project Title	Provision of standards for underwater acoustics	**Co-funding target**	
Lead Scientist	Stephen Robinson	**Stage Start Date**	01-Jan-2013
Scientist Team	Underwater Acoustics Team	**Stage End Date**	31-Dec-2015
		Est Final Stage End Date	Ongoing
Sector	7.1 Traceability & uncertainty; 5.1 National security; 2.2 Pollution & waste reduction; 6.3 Advanced instrumentation & sensors	**Activity**	Provision of Standards & Maintenance of Capabilities; International Obligations

Summary

Provision and dissemination of traceable standards in support of the UK industry, consolidating the UK position at the forefront of marine acoustic technology in Europe. This includes provision of traceable *free-field* primary standards and dissemination via measurement services (using the laboratory tanks and open-water facility) , provision of *low frequency* pressure calibration standards, provision of existing services and facilities for the standards at *simulated ocean conditions* (using the Acoustics Pressure Vessel; APV), and provision of services for acoustic characterisation of materials. The standards provision includes a major update to obsolete equipment and legacy software. In addition, there is the validation of standards by participating in (and piloting) new free-field CCAUV key comparison.

The Need Traceability is required for calibration and performance testing of underwater acoustic transducers and systems, requiring national standards to be maintained for the UK, and satisfying the requirements of Mutual Recognition Arrangement (harmonised standards across borders). This provides underpinning support for UK manufacturing industry for underwater systems – the UK is a highly active European country for underwater acoustics with more than 30 companies involved in manufacturing transducers, hydrophones and systems for sonar, positioning, navigation, surveying, communication and monitoring marine life, a business worth hundreds of millions of pounds per annum. Traceability is required for calibration and performance testing of underwater acoustic transducers and systems at simulated ocean conditions, and for acoustic characterisation of materials for underwater acoustics (properties of such materials vary with temperature and depth). Traceability is also required to underpin legislation and regulation where *absolute* acoustic measurements are made in support of environmental impact assessments for anthropogenic noise, and in support for offshore energy and oceanographic applications. Access to unique national facilities enables the accurate measurement of system performance that is crucial for ensuring unambiguous specification and acceptance testing, an important consideration when many UK companies need access to overseas markets.

The Solution

Current primary standards and measurement facilities will be maintained and services provided according to the requirements of ISO 17025 and assured by UKAS accreditation. Facilities realising the primary standards and used for measurement services include the laboratory tanks, the Acoustics Pressure Vessel, and the open-water calibration facility. Current low frequency pressure standards for hydrophones will also be maintained. The facilities are used for services provided for transducer and sonar calibration, and materials characterisation. The facilities are also used in support of other research projects including those funded by NMS and third-parties. Opportunities will be taken to validate and improve capability through CCAUV key comparison.

Project Description (including summary of technical work)

This project involves the continued provision of primary calibration facilities for hydrophones and transducers, and of services and calibration facilities covering the frequency range 250 Hz to 1 MHz, replacing ageing instrumentation and software as required. International consistency will be assured through active participation in CCAUV and EURAMET and take a leading role in key comparisons. The project will include the following:

- Provision of primary free-field and pressure standards for underwater acoustic measurements;
- Dissemination of standards via calibration services offered through maintained national facilities (open-tank facilities and open-water test facility, air-pistonphone facility);
- Provision of standards and services at simulated ocean conditions using the national facility of the Acoustic Pressure Vessel for transducer and sonar calibration, and for characterisation of materials in the form of test panels.
- Maintaining ISO 17025 accreditation for services (via assessment by UKAS);
- Completing the replacement of the obsolete acquisition instrumentation and legacy software for the test facilities;
- Taking a leading role in the validation of standards by participation in and piloting key comparison CCAUV.W-K2, and contributing data to the BIPM Key Comparison database.

Impact and Benefits

The traceable standards provided by NPL directly <u>support the UK industry</u>, the UK being one of the most active European countries in the field with more than 30 UK-based companies involved in manufacturing products and developing and using marine acoustic systems, many requiring rigorous calibration and testing to internationally-recognised standards (especially when accessing overseas markets). The overall business in underwater acoustic systems is worth hundreds of millions of pounds per annum. The ability of industry, academia and OGDs to assess the full performance of underwater acoustic systems by use of the world-class national facilities maintained by NPL provides cost savings to industry (as opposed to maintaining their own facilities or conducting expensive sea-trials). The cost of using the APV is approximately a factor of 10 lower than undertaking equivalent sea-trials, and the APV offers considerably more environmental control than is available in sea-trials (a crucial factor in testing devices and materials whose performance varies with depth and temperature). Most of the NPL facilities are unique in the UK (and in case of the APV in Europe) and are enablers of research with much of our research work utilising them.

NPL provides over 250 calibrations per year to a variety of customers and industry sectors. Underwater acoustics is a crucial underpinning technology in the offshore oil and gas industry, in maritime defence and in oceanographic exploration, with applications such as sonar, positioning, navigation, surveying, communication and monitoring marine life. The standards provided by NPL also underpin marine environmental regulation with regard to the absolute acoustic measurements required to support environmental impact assessments of the influence of anthropogenic noise (e.g. EU Habitats Directive). With incipient legislation in this field requiring the assessment of impact thresholds and long-term trends, it is vital that decisions are made based on robust metrology. NPL is the leading NMI in the underwater acoustics field, and leads the way in international fora such as CCAUV, EURAMET, ISO, and IEC. A measure of NPL's impact in the field is the utilisation of services (which remains high), and the commercial income in this area, which has shown substantial increase in recent years.

Support for Programme Challenge, Roadmaps, Government Strategies

The work is in direct accord with the NMS Strategy 2011-2015 and NMS AIR Programme Strategy theme roadmap for underwater acoustics. It is also directly aligned with the EURAMET TC-AUV roadmap. The work underpins the requirements of the DEFRA Marine Bill (marine environment strategy), the UK Renewable Energy Strategy, and the EU Marine Strategy Framework Directive. The work is relevant to the following sectors: Environment; Instrumentation and Test Laboratories, Defence & Security; Advanced Manufacturing, Energy.

Synergies with other projects / programmes The work underpins the rest of the underwater acoustic metrology projects in the NMS programme. The facilities are an enabler of research, without which much of the benefits of that research could not be realised. Externally, there are synergies with the work of EURAMET and CCAUV member NMIs, with the work programmes of DEFRA, and with the research programmes of academia (universities such as Southampton, Loughborough and St Andrews). Other NMIs share the same need to ensure international consistency of measurement standards and benefit from the data made available under the MRA. Calibration laboratories benefit from improved dissemination and access to the latest measurement techniques.

Risks Major facility failure is a risk, but this is mitigated by careful planned maintenance. Risks associated with provision of key measurement facilities are well understood and recent attention has put in place mitigation measures such as provision for replacement of specialised equipment. International collaboration presents a medium degree of risk in that NPL has little control over delivery. This can be mitigated by ensuring project delivery is not dependent on any single NMI.

Knowledge Transfer and Exploitation The main knowledge transfer in this project comes from direct services to customers (providing calibration services and certificates), draft IEC and ISO standards and eventually, the published documents (available in the UK via BSI). In addition, the NPL web-site provides valued technical guidance on a range of topics (ocean sound speed, sound absorption, uncertainties, etc.). The project also underpins the research of the group, and so contributes to the scientific publications produced. It is estimated that over the three years of the project, at least 12 peer review papers will be submitted from work undertaken directly using the facilities.

Co-funding and Collaborators Co-funding in kind available from EURAMET and CCAUV member NMIs; NPL Modelling Group (MMM programme); Universities (Southampton, Loughborough).

Deliverables

1	**Start: 01/01/13**	**End: 31/12/15**	
Deliverable title: Provision of free field primary standards, and provision of free-field services and facilities for calibration and testing of hydrophones and transducers			
2	**Start: 01/01/13**	**End: 31/12/15**	
Deliverable title: Provision and dissemination of standards at simulated ocean conditions using the APV and coupler, including services for materials characterisation			
3	**Start: 01/01/13**	**End: 31/12/14**	
Deliverable title: Replacement of obsolete hardware and software for facility data acquisition systems and validation.			
4	**Start: 01/01/13**	**End: 31/12/15**	
Deliverable title: Piloting and participating in free-field CCAUV.W-K3 Key Comparison and KC database entry			

Project No.	AIR/2013/A3	**Price to NMO**	£654k
Project Title	Provision of traceable standards for medical ultrasound	**Co-funding target**	
Lead Scientist	Bajram Zeqiri	**Stage Start Date**	1/1/2013
Scientist Team	Adam Shaw, Srinath Rajagopal, Neelaksh Sadhoo, Christian Baker	**Stage End Date**	31/12/2015
		Est Final Stage End Date	Ongoing
Sector	3. Health (3.1 Diagnosis, 3.2 Drugs and therapies & 3.4 disease prevention and management).	**Activity**	Provision of Standards and Maintenance of Capabilities

Summary

This project will provide the UK and much of the rest of the World with traceability for measurements of acoustic output (pressure and power) at medical frequencies, underpinning the metrological requirements of medical ultrasonic applications. It will also provide support for innovative developments in the medical ultrasound industry, both diagnostic and therapeutic.

The Need

Ultrasound has transformed medical practice since its introduction in the mid-1960s and it is now one of the most commonly used imaging modalities. From Department of Health figures, over 7.1 million ultrasound examinations were carried out in NHS trusts during the period April 2007 to March 2008. About a third of these (2.4 million) were obstetric and gynaecological (O/G) examinations (DH, 2008) and today nearly all pregnancies in the UK are subject to at least one ultrasound-screening. There has been a steady annual growth in ultrasound examinations over the last decade: 43% for O/G since 1995, but the dominant increase has been in non O/G examinations which have doubled over the same period. These involve applications such as neonatal, muscularskeletal, ophthalmological and breast examinations. In addition, it is estimated that the UK has around 30 lithotripters, 2,500 ultrasound scanners, 10,000 ultrasonic foetal heart-beat detectors and 20,000 physiotherapy units. The capabilities of diagnostic equipment are rapidly improving aided by advances in technology, improvements in transducer technology and a higher acoustic output levels. This underlines the need to underpin traceable measurement methods for determining key exposure quantities over an increasingly wider range of frequencies. The ability to undertake these measurements in a meaningful, traceable, way is pivotal to ensuring both safety and efficacy of medical ultrasound applications. Additionally, its non-ionising nature and the relative low cost of the technology, makes medical ultrasound an active area in terms of innovative emerging applications. There are an increasing number of new therapeutic modalities involving the application of extremely high acoustic intensities, essentially to kill cancerous tissue; as well as elastography and the application of contrast agents within drug delivery and imaging. Realising the intended benefits of these technologies requires access to reliable, traceable measurements and characterisation techniques, which frequently provide significant measurement challenges.

The Solution

Primary and secondary measurements to support safety are undertaken within industry and hospitals using measurement devices such as hydrophones and radiation force balances. This project will provide the underpinning measurement infrastructure required to ensure UK users can make traceable measurements of key acoustic exposure quantities. It will also assist in ensuring UK patients are treated with ultrasonic equipment, which complies with appropriate safety and performance standards.

Project Description (including summary of technical work)

The capability of the primary standards for the free-field realisation of the acoustic pascal and the acoustic watt in water and the associated secondary dissemination facilities will be secured. Specific activities are as follows:-

- Free-field realisation of the acoustic pascal through the primary standard interferometer – addressing the degradation in the transducer & hydrophone positioning capability and improving the immunity of the primary standard to background environmental disturbance (2013);
- Annual calibration of secondary standard membrane hydrophones to underpin calibration services;
- Ensuring facilities and services are continuously operational, providing customers with UKAS-accredited hydrophone calibrations;
- Piloting of the CCAUV Key Comparison for calibration of ultrasonic hydrophones (2014);
- Provision of primary standard for power measurement and dissemination through secondary standards and a range of services to industry and hospitals;
- Ensuring facilities and services are continuously operational, providing customers with output power measurements and power meter calibrations;
- Replacement of ageing hardware including reference ultrasound power source;
- Support for a broad range of facilities providing measurement services to industry and hospitals and underpinning capability to research projects: acoustic output characterisation to international standards, materials characterisation facilities and Thermal Test Rig (including Thermal Test Objects);
- Annual renewal licence of the finite element software package PAFEC, providing essential theoretical modeling capability that is utilized within a broad range of NMS and third-party funded projects;

Supporting the training of new staff, or existing staff who are developing new skills, to ensure the project portfolio is delivered effectively;

Meeting COSHH, safety and NPL quality system requirements.

Impact and Benefits

This project will deliver traceable and harmonised measurements ensuring compliance with the EU MDD and the FDA 510(k). Primary beneficiaries are: UK manufacturers of medical ultrasonic devices and test equipment who will have better tools and services for product development thus enabling access to markets; clinical users will have greater confidence in the diagnostic and therapeutic equipment they use; healthcare patients will benefit from the latest developments in medical ultrasound whilst having confidence in its effectiveness and safety; other NMS and 3rd party customers will have access to high quality measurement capabilities**.** Take-up will be measured through the number of Certificates and Test Reports generated.

Support for Programme Challenge, Roadmaps, Government Strategies

The project is relevant to the NMS Roadmap "Metrology for medical applications of ultrasound" and the Government Cancer Reform strategy.

Synergies with other projects / programmes

The facilities maintained in this project are important to NMS research in the Industrial Ultrasound area & Underwater Acoustics. Capabilities have been utilised through collaborative projects related to safety of medical ultrasound funded through the Department of Health (Radiation Protection Programme), EMRP and the National Institute of Health Research Invention for Innovation Programme. Future developments in terms of new capability required by the user community will be through Discretionary projects, with appropriate co-funded support, for example from EMRP or other funding organisations, being sought.

Risks

Work identified with this project relates to the provision of a range of Measurement Services which have been in place for a number of programme cycles. Consequently it is considered to be low risk. The piloting of the CCAUV ultrasonic hydrophone Key Comparison (KC), brings with it some small risk regarding the robustness and stability of the membrane hydrophones employed. NPL piloted the original KC and so is well placed to mitigate these risks through careful project management and ensuring the availability of suitable quality back-up devices.

Knowledge Transfer and Exploitation

The main route for dissemination of the capability supported by this project will be through Test Reports and Calibration Certificates. NPL is one of the two leading world NMIs providing such services to medical equipment and test instrumentation manufacturers world-wide. Evidence suggests that the majority of acoustic output measurements undertaken world-wide are traceable to NPL.. Other services provided include: power measurement and power balance calibration, provision of tissue-mimicking materials (about 15 customers annually), acoustic output and acoustic property of materials measurements (8 - 10 customers annually); metrology-related consultancies (3-5 customers annually). The CCAUV ultrasonic hydrophone Key Comparison will be written up as a peer-reviewed paper, within the third year of this project (2015). Additionally, NPL hosts Guest Workers from other NMIs and this provides a further mechanism where knowledge is transferred to countries that are developing metrological capability in the medical ultrasound area.

Co-funding and Collaborators: The CCAUV ultrasonic hydrophone Key Comparison will involve collaboration several world NMIs such as PTB (Germany), NIM (China) and AIST (Japan).

Deliverables

1	**Start: 1/1/13**	**End: 31/12/15**	
Deliverable title: Provision of ultrasonic pressure standard facilities achieving 90% availability throughout period (includes piloting by NPL of the CCAUV ultrasonic hydrophone			
3	**Start: 1/1/13**	**End: 31/12/13**	
Deliverable title: Interferometer			
4	**Start: 1/1/14**	**End: 31/12/14**	
Deliverable title: CCAUV Key comparison			
	Start: 1/1/13	**End: 31/12/15**	
Deliverable title: Provision of ultrasonic power facilities achieving 90% availability throughout period.			
5	**Start: 1/1/13**	**End: 31/12/15**	
Deliverable title: Provision of ultrasonic field measurement and characterisation standards achieving 90% availability throughout period.			

Project No.	AIR/2013/A4	**Price to NMO**	£151k
Project Title	Provision of measurement infrastructure for industrial ultrasound	**Co-funding target**	
Lead Scientist	Mark Hodnett	**Stage Start Date**	01/01/2013
Scientist Team	Gianluca Memoli, Pete Theobald, Lian Wang, Bajram Zeqiri, Ian Butterworth	**Stage End Date**	31/12/2015
		Est Final Stage End Date	Ongoing
Sector	7.1 Traceability & Standards 6.2 Process control & efficiency	**Activity**	Provision of Standards & Maintenance of Capabilities

Summary
To provide the UK and Europe with internationally recognised reference facilities, systems and measurement services for acoustic and hydrodynamic cavitation, underpinning new standards; and calibration and characterisation facilities for acoustic emission (AE) applications. This new core area disseminates the unique NMS-developed capability in cavitation generation and detection, and condition monitoring. It underpins the developing metrological requirements of industrial ultrasound for traceable measurements, supporting effective application in advanced manufacturing (food and pharmaceuticals). It will also provide support for further innovation in acoustic cavitation metrology.

The Need
High power ultrasound is applied across a large number of industries, ranging from established practices such as ultrasonic cleaning (a $4bn pa business worldwide, around £75m UK, covering surgical instrument cleaning throughout the NHS; automotive and aerospace components manufacture; and the cleaning of printed circuit boards in the microelectronics industry). Emerging applications such as the novel use of sonocrystallization in food production and preparation of raw materials for pharmaceutical manufacture are also moving beyond research interest (est. $300m worldwide) and are showing rapid development growth towards full-scale industrial processes, through theoretical modelling and engineering design. These applications are all driven by acoustic cavitation - the nucleation, growth, oscillation (and collapse) of gas and vapour bubbles in fluids due to an applied acoustic field. Standardisable methods for cavitation are evolving, and with reference facilities now established, the first NPL measurement services are scheduled to be available for industry take-up during 2013. There is hence a clear need to maintain the systems and sensors which will disseminate acoustic cavitation measurement services to users. The facilities also underpin NPL innovation and peer-reviewed paper output (> 1 paper per year) in the cavitation area, and sustain NPL's worldwide NMI lead in cavitation metrology.
Pumps are key to manufacturing in all applications, with the UK marketplace turning over £900m per annum, and being a net exporter. Cavitation occurs readily in most pumped systems, and this is often attributable to over-cautious system specification and new pumps interfaced to ageing pipework. This causes rapid casing and impeller erosion, and can result in substantially reduced pump lifetimes, in addition to process inefficiencies. Despite widespread concern over the phenomenon, no direct measurement methods are yet available: broadband acoustic emission methods are under development at NPL, using a new reference facility which is in its final stages of validation as a sensor/process test bed, and which will be made available for industrial use. Structural condition monitoring via acoustic emission sensors is also widespread, and NPL's optical methods, providing traceable sensitivity calibrations, are showing increased user demand.

The Solution
Users of cavitation-producing systems are using basic commercial instrumentation to attempt to characterise and understand their novel applications in sonoprocessing and precision cleaning, particularly in the UK, where there is a strong innovation base. Reference metrological infrastructure and the associated capability, resulting from previous NMS funding (AS002AO501 and 2) is hence required for NPL to underpin these industrial measurement methods; initially for comparison with existing reference cavitation fields (utilising current single- and multi-frequency vessels), but once accompanying AIR projects (AIR/2012/A16 and A17) are successfully completed, for subsequent traceable calibrations of cavitation measurement systems.
The industry requirement for pump and flow cavitation measurement methods is beginning to be met by new reference facilities at NPL, providing well-characterised and environmentally-controlled test beds for sensor and signal processing development, and consultancy provision to industry. For acoustic emission sensors, optically-determined displacement methods provide reference calibration and consultancy services for a growing body of industrial users.

Project Description (including summary of technical work)

- Ensuring high power ultrasound and cavitation facilities and services are operational for at least 90% of the time, providing customers with services for cavitation sensor measurements, reference fields and ultimately, calibration, realised through multiple-frequency and single frequency cavitation reference vessels, covering the range 20-140 kHz;

- Provision of characterisation facilities for users' cavitation-producing systems, utilising 'gold standard' sensors and electronics;

- Annual calibrations of in-house gold standard sensors and measurement devices, and maximising performance of critical system hardware and software through traceable pro-active maintenance;

- Supporting the training of new staff, or existing staff who are developing new skills, to ensure the project portfolio is delivered effectively;

- Meeting COSHH, safety and NPL quality system requirements, through risk assessments and the updating of procedures and local instructions.

Impact and Benefits

The project will provide impact through provision of traceable measurement capabilities which will ensure safer and more cost-effective application and measurement of acoustic cavitation for UK industry. Primary beneficiaries of the project are: UK manufacturers and users of cavitation equipment used in industrial processes (cleaning, food, pharmaceutical, waste processing); UK manufacturers and users of AE equipment for structural health and condition monitoring; UK pump and flow system industries driving for improved safety and maintenance programmes and better operating efficiency. Take-up will be measured through the number of Test Reports generated, and ultimate impact via greater competitiveness for UK business.

Support for Programme Challenge, Roadmaps, Government Strategies

Advanced Manufacturing – Process Control and Instrumentation The project is relevant to the NMS AIR Programme Theme Roadmap "**Metrology for industrial applications of ultrasound**", Deliverable "Reference facilities for acoustic and hydrodynamic cavitation". Through providing the tools for improving pumping efficiency, it fits the Measurement Priority: Energy Challenge in the NMO's *2011-2015 Strategy for the National Measurement System*, to "Assist the drive towards greater energy efficiency through measurement research"

Synergies with other projects / programmes

The metrological capability maintained by this project supports current research in Industrial ultrasound (A16, A17), Medical Ultrasound (Dose, and associated EMRP DUTy project) and more widely, in (contracted) EU Framework 7 Research for SME projects: TOPHONEY and AlgaeMax. It will also provide facilities for a further prospective EU FP7 project, and Technology Strategy Board projects.

Risks

Work related to supporting the Measurement Services is typically low risk, as it involves ensuring that the facilities provided to the user community function adequately and with a high uptime. Within this, the technical risk lies in whether manufacturers can continue to support bespoke systems such as the multi-frequency vessel (designed by Sonic Systems, with whom a long-term relationship has been established): this is mitigated by the design, which combines a large proportion of off-the-shelf components, and hence should minimise critical downtime.

Knowledge Transfer and Exploitation

NPL is one of the world's top two NMIs, and is internationally-leading in cavitation metrology research, with patents in cavitation sensor design and cavitation signal detection. The capabilities provided under this project leverage both of these aspects, and will be disseminated via:

- The systems maintained and provided by these project providing data for peer-reviewed papers and presentations on NPL's activities and Services (at least one and two per year respectively, funded under Discretional projects);

- 5-10 customers are expected in the first year, for which Test Reports and Calibration Certificates will be provided. These numbers are expected to grow by at least 5 per year as industry requirements and demands increase.

Co-funding and Collaborators

The chief collaborating partners are Precision Acoustics Ltd and Acoustic Polymers Ltd, who provide expertise and experience in cavitation sensor design, and in material formulations for couplants and absorbers. The 25 kHz and multiple-frequency reference cavitation vessels are designed by Sonic Systems Ltd, and they will contribute their knowledge in reaching the facility uptime targets through hardware support, and system/component loan if required. Cash cofunding is provided through the R4SME projects Tophoney and Algaemax (see above), both of which will improve sensor capability and reference system understanding, hence improving the quality of service to customers.

Deliverables

1	**Start: 1/1/13**	**End: 31/12/15**	

Deliverable title: Provision and dissemination of reference ultrasonic cavitation generation and measurement infrastructure, achieving at least 90% facility uptime throughout the period.

2	**Start: 1/1/13**	**End: 31/12/15**	

Deliverable title: Provision and dissemination of reference hydrodynamic generation and measurement infrastructure, and acoustic emission calibration facilities, achieving at least 90% facility uptime throughout the period

Project No.	AIR/2013/A5	Price to NMO	£265k
Project Title	Development of next generation of acoustical primary standards based on optical methods *(NOTE: EMRP parts have not been funded)*	Co-funding target	
Lead Scientist	Stephen Robinson	Stage Start Date	01-Jul-13
Scientist Team	Acoustics	Stage End Date	31-Jun-16
		Est Final Stage End Date	31-Jun-16
Sector	7.2 Extension of SI; 3.1 Diagnosis 2.2 Pollution & waste reduction	Activity	Methodology for New Capabilities

Summary

This project builds on work funded under the previous and current NMS programmes, and forms the co-funding for a proposal to EMRP which NPL will lead (SI Broader Scope: SRT-s02). The objective is to develop the next generation of primary standards for acoustics that will realise the acoustic pascal using optical techniques. The work represents a paradigm shift away from traditional calibration techniques developed in the mid-twentieth century toward methods capable of meeting the measurement challenges of the twenty-first century. The output of this work will provide modern realisation of primary standards and dissemination of SI units for airborne acoustics using photon correlation spectroscopy, and marine acoustics and high frequency medical ultrasound using optical interferometry.

The Need

Primary standards for acoustics have largely been based on methods derived from the principle of reciprocity, first described by Lord Rayleigh in 1876. The methods derive their traceability through a complicated series of electrical measurements, dimensional measurements, and properties of the medium (air or water). First implemented as a calibration method in the 1940s, and codified in the subsequent two decades, the methods have served the scientific community well in the past. However, the methods suffer from a number of weaknesses. For example, they do not provide a direct realization of the acoustic pascal, and the methods have insufficient uncertainty for the most demanding current and future measurement requirements. Furthermore, the current methods rely on the performance of specific transducers (microphones and hydrophones) and can only achieve the lowest level of measurement uncertainty with specific (so-called “laboratory standard”) configurations of the test device. This means that the primary standards rely on the availability of suitable commercial reference devices, which is not under the control of the NMI community. New transducer types likely to be widely adopted in the next 10 years cannot be calibrated using current methods with the best measurement uncertainty. As the new SI moves away from artefact based standards, so the realisation of the derived units should do likewise, to maintain consistency across all of areas of metrology.
In the light of the above requirements, and particularly to support the emergence of novel microphone measurement technologies, the time is right to establish new primary standards for acoustics that are fit for purpose for the demands of the twenty-first century. Optical techniques offer the most promising candidate methods for improving accuracy and the project vision is to employ these techniques to remove the reliance on commercially available artefacts. Such work requires input from experts in both acoustical and optical metrology, requires a range of test facilities, and is ideally suited to collaboration between NMIs under the auspices of EMRP. Optically-based acoustical primary standards are already established at low megahertz frequencies, and now is the time to establish such primary standards more widely within acoustic metrology.

The Solution

This aim is to establish new primary acoustical standards covering airborne acoustics at audio frequencies, underwater acoustics for marine applications spanning frequencies from a few kHz to 1 MHz, and extending the upper frequency range for medical ultrasound to high megahertz frequencies. The proposed solution builds on the foundations established by previous NMO programmes, enabling NPL to provide an international lead in the area optical techniques applied to acoustical metrology. The work will extend the successful existing NMO-funded work to establish homodyne optical interferometry for primary standards at low megahertz frequencies in the medical ultrasound field, with the method extended to frequencies up to 80 MHz. In underwater acoustics, the research work to develop heterodyne interferometry as a free-field calibration method for hydrophones will be further developed and a primary standard established covering at least the frequency range 100 kHz to 1 MHz, with the limits of the method investigated at lower frequencies. In air acoustics, previous research work on photon correlation spectroscopy for air acoustics will be extended and developed into a primary free-field calibration method for microphones, a task which is the most challenging of the three aims of the project.
The project is also the subject of an EMRP JRP proposal. The successful securing of EMRP funds will significantly enhance the project scope and will enable joint research to be undertaken with other NMIs, namely PTB (Germany), DFM (Denmark), MIKES (Finland), UME (Turkey) and CMI (Czech Republic). The EMRP project also benefits from unrivalled expertise residing at two European universities (Helsinki and Southampton) by inclusion of Researcher Excellence Grants. The EMRP funding will significantly increase the funding for the three activities outlined above, and will allow extra work to investigate any synergies with standards for the measurement of dynamic pressures (EMRP project IND09), and to investigate alternative measurement methodologies provided for airborne sound by use of an optical cantilever microphone and the acousto-optic effect.

Project Description (including summary of technical work)

The proposed work consists of the following (*EMRP only work in italics, NMI leader of work indicated in parentheses*):

1. Review methods for realising the pascal and synergies with standards for the measurement of dynamic pressures (DFM lead); 2. Implement and validate standards for airborne free-field microphone calibration using the technique of photon correlation spectroscopy *(NPL funding increased with EMRP project, NPL lead)*; *3. Investigate alternative optical techniques for realising the acoustic pascal and providing traceability for airborne sound, such as the optical cantilever microphone and optic detection of acoustically-induced refractive index changes (MIKES);* 4. Implement and validate methods for realising the acoustic pascal in water at kilohertz frequencies for marine acoustics, by use of heterodyne interferometry *(NPL funding increased with EMRP project, NPL lead)*; 5. Extend existing homodyne optical interferometry methods for realising the acoustic pascal at frequencies to 80 MHz important for new developments in medical ultrasound *(NPL funding increased with EMRP project, PTB lead)*; *6. A series of knowledge transfer activities such as workshops, web-pages and stakeholder groups will maximise the impact gained from the project (PTB lead).*
Impact and Benefits The new primary standards are needed to underpin a range of industrial sectors with traceable acoustic measurements, including the healthcare, environmental and energy sectors. Acoustic measurements are demanded across a variety of fields: in airborne acoustics, they are vital for determining human hearing response and in support of regulation for human noise exposure and environmental noise; in marine acoustics, they are required for developments in offshore oil and gas and marine renewable energy, oceanography, and in support of incipient regulation of underwater noise pollution; in medical ultrasound, they are required to underpin measurements of acoustic output and patient exposure. This project contains state-of-the-art developments in the field of underwater acoustic measurement, which consolidate NPL's position as an internationally leading NMI in underwater acoustic metrology. They are the continuation of longer term research to provide the next generation of calibration techniques to address the anticipated future requirements. The project will enable NPL to address the more demanding requirements of acoustic metrology into the future.
Support for Programme Challenge, Roadmaps, Government Strategies The project is clearly in direct accord with the EURAMET TC-AUV roadmaps, and accords with the EMRP cornerstones with regard to grand challenges for science and innovation, and capacity building. Once implemented as viable primary standards, the work underpins the same Government strategies and initiatives as the current 'Core' projects to provide standards. Further, the project is fully aligned with the AIR Programme strategy and Acoustic Metrology Theme roadmaps and target for optically based primary standards.
Synergies with other projects / programmes The project combines the work on optical techniques for acoustical metrology (projects NMS/AIR12004 and deliverable 2 of NMS/AIR12006) into one project which will have benefits of creating a critical mass of resource. There are clear synergies with work to establish standards for dynamic pressure.
Risks Whilst the project poses technical challenges, the significant internal expertise and established partnerships with other leading organisations in this area will mitigate the risk in the project.
Knowledge Transfer and Exploitation The project will produce at least 3 peer-reviewed papers (*at least 6 with EMRP funding*) and will produce at least three primary standard methods, which will have been implemented experimentally and validated. This work will feed directly into the activities of international standards committees and into future Key Comparisons organised under the auspices of the Consultative Committee on Acoustics Ultrasound and Vibration (CCAUV), and though EURAMET TC-AUV. *With EMRP,* a *series of knowledge transfer activities such as workshops, web-pages and stakeholder groups will maximise the impact gained from the project.* There is a significant NMI interest in this project, especially from those with limited capacity to carry out research. Opportunities to present at EURAMET and CCAUV, and at higher levels within these metrology organisations (e.g. at EURAMET General Assembly and BIPM JCRB meetings) will therefore be taken to highlight the world-leading nature of this research.
Co-funding and Collaborators This project comprises NPL's input into the EMRP project. The project is led by NPL, with partner NMIs including PTB (Germany), DFM (Denmark), MIKES (Finland), UME (Turkey) and CMI (Czech Republic); two European universities (Helsinki and Southampton) via Researcher Excellence Grants; non-funded NMI partners likely from Japan, Canada and Korea; industrial stakeholders such as sensor and instrument manufacturers.

Deliverables

1	**Start: 01/07/13**	**End: 30/06/16**	
Deliverable title: Implement and validate photon correlation spectroscopy for free-field airborne standards			
2	**Start: 01/09/13**	**End: 30/06/16**	
Deliverable title: Implement and validate heterodyne interferometry for underwater acoustic standards up to 1 MHz			
3	**Start: 01/09/13**	**End: 30/06/16**	
Deliverable title: Extend homodyne optical interferometry up to 80 MHz for medical ultrasound standards			

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Radiation Dosimetry Projects 2013

Project No.	AIR/2013/ DC1	**Price to NMO**	£1150k
Project Title	Provision of therapy and protection level primary standards	**Co-funding target**	
Lead Scientist	Simon Duane	**Stage Start Date**	01/01/13
Scientist Team	H Palmans; P Sharpe; M Bailey; R Thomas; D Shipley; T Sander; G Bass; J Pearce; M Kelly; N Lee.	**Stage End Date**	31/12/15
		Est Final Stage End Date	On-going
Sector	7.1. Traceability & uncertainty; 3.2 Drugs & therapies; 3.3 Health & safety	**Activity**	Provision of Standards & Maintenance of Capabilities

Summary The UK, through the NMS, has a leading presence in the area of radiation dosimetry. This ring-fenced project maintains and provides calorimetric and ionometric primary standards of absorbed dose and air kerma necessary for health and industrial applications. Calorimetric standards will be maintained for electron, photon and proton beams and HDR brachytherapy. Ionometric standards will be maintained in very low, low and medium energy x-ray beams, in therapy and protection level ^{60}Co and ^{137}Cs beams and for HDR Brachytherapy (^{192}Ir) and LDR brachytherapy (^{125}I and ^{192}Ir). NPL's ability to underpin established calibration services at industrial, therapy, diagnostic and protection levels will be maintained. The UK's obligations under the CIPM MRA to link radiation dosimetry measurements in the UK to the international measurement system will be met.

The Need It is expected that these standards be maintained by the UK's National Measurement System for the benefit of use by hospitals, dental practices, nuclear power plants and other industrial and research users of radiation. UK regulations and IPEM and IAEA codes of practice require traceability to these therapy, diagnostic and protection level primary standards via approved NPL calibration services. The standards themselves are comparable with, or exceed, those of other NMIs. The HDR calorimeter is one of only 4 such devices to be developed by NMIs (standards are currently held by NPL, PTB, VSL and ENEA) and will require interaction both with peers and end-users in order to implement a conversion from previous air kerma based protocols to absorbed dose. The 300kV free air chamber is unique in that it is specifically designed to allow for transportation to other NMIs to allow for direct comparison of national standards. High dose industrial calibration services required to meet UK and international regulations are also directly traceable to the therapy level absorbed dose standards.

The Solution In all areas, the project will involve the maintenance, calibration, testing and training to allow capabilities to be continued at current levels. Specifically: Maintenance and provision of the calorimeters, free air chambers and primary standard cavity chambers in line with UKAS and LRQA audit requirements; calibration of reference and transfer standard ionisation chambers for dissemination via approved NPL calibration services; participation in international comparisons via key comparisons with BIPM and other NMIs to ensure international acceptance of NMS capabilities.

Project Description (including summary of technical work)

1. Electron and photon beam calorimetry. The new electron-photon beam calorimeter will have been fully commissioned by the end of 2012 and will be used concurrently with the existing standard prior to its succession. With use of the new calorimeter, better understanding will allow for full optimisation of the system. Results from comparisons with existing primary standard and international comparisons via key comparisons with BIPM will be published in peer reviewed journals. It is expected that the existing electron-photon calorimeter will start to be phased out during 2013.

2. Proton beam calorimetry. The proton beam calorimeter will allow for off-site calibration of ionisation chambers and research activities. This will be maintained at existing and new proton and ion beam centres. With use of the new calorimeter, better understanding will allow for full optimisation of the system. Results from international comparisons undertaken as part of this project will be published in peer reviewed journals.

3. HDR brachytherapy calorimetry. The calorimeter will be maintained for calibration of transfer standard ionisation chambers both at NPL and off-site using a variety of different source types and will be compared with brachytherapy absorbed dose standards of other NMIs. This will allow for re-evaluation of dose rate constants for these different source types. Results of this work will be published in peer-reviewed journals along with results from international comparisons. An addendum to the IPEM/NPL code of practice will be required in order to disseminate an absorbed dose calibration.

4. 50 kV free air chamber. The 50 kV free air chamber to be maintained, and compared as part of international comparisons via key comparisons with the BIPM. Dissemination of the standard will continue through the on-going availability of the therapy and diagnostic level calibration services.

5. 300 kV free air chamber. The 300 kV free air chamber and associated transfer chambers will be maintained and compared as part of international comparisons via key comparisons with the BIPM and bilateral international comparisons with other NMIs via EUROMET project 628. Dissemination of the standard will continue through the on-going availability of the therapy, diagnostic and protection level calibration services.

6. Primary standard cavity chambers. The primary standard cavity chambers will be maintained and compared as part of key comparisons with the BIPM. The old primary standard cavity standards will continue to be maintained for a transition period of approximately one year. Dissemination of the standard will continue through the on-going availability of the therapy and protection level calibration services.

Impact and Benefits This project supports the fundamental infrastructure, facilities and expertise to deliver standards and calibration services for UK stakeholders, including all users of ionising radiation from nuclear power stations, medical device sterilisation plants, to hospital and dental facilities, by enabling compliance with legislation. This project will enable: Accurate delivery of radiation dose to cancer patients and adherence to Codes of Practice; underpin NMS and stakeholder research activities in the development of new and existing radiotherapy techniques by providing the necessary metrology platform to assist innovations in radiation dosimetry; protection level dosimetry and the infrastructure for compliance with current legislation; dosimetry for diagnostic x-rays and the infrastructure for compliance with the IR (Medical Exposure) Regs.

Support for Programme Challenge, Roadmaps, Government Strategies This project aligns with the NMS Strategy 2011-2015 in particular through the provision of the required NMS infrastructure to ensure the safety and efficiency of healthcare diagnosis and therapies. Further, the project links directly onto the AIR Programme strategy and roadmaps for the Radiation Dosimetry theme. In addition, the project supports the Department of Health's Cancer Reform Strategy; Protection of the public and radiation workers from ionising radiation; and supports the Government priority set out by Public Service Agreement Targets (PSAT) 4 'Promote world-class science and innovation in the UK' as well as 18 'Promote better health and wellbeing for all' and 28 'Secure a healthy natural environment for today and the future'.

Synergies with other projects / programmes This project provides direct support to all NMS Radiation Dosimetry projects; all Radiation Dosimetry calibration services; and on-going EMRP Health projects MetrExtRT, BioQuaRT and MetroMRT. Key capability with EUROMET project 628: Direct comparison of primary standards of air kerma for medium energy x-rays (300 kV).

Risks In general, the risks relating to this project are low, given the facilities and expertise are in existence and well established. In addition, given that the project is concerned with solving unanticipated problems with the facilities as they arise, there is an in-built risk mitigation mechanism. Remaining risks include loss of key staff that could affect our ability to maintain our existing capability. Failure of any one standard may be maintained by use of NPL held secondary standard instruments.

Knowledge Transfer and Exploitation Provision of measurement services and advice to end users to ensure the measurements offered meet their needs: each year approximately 90 therapeutic and diagnostic level and 180 industrial level calibrations are provided to end users and 10 protection level calibrations are provided to calibration laboratories and end users; also via key intercomparison reports, NPL provided reference dosimetry training courses (delivered annually to trainee medical physicists) and audit services, that are delivered either as a paid for service or via the NMS.

Co-funding and Collaborators Effectively the customers of the standards and measurement services underpinned by this project play an important role in helping to shape these capabilities. NPL has many regular collaborators in this area, including UK hospitals; overseas proton therapy centres; other NMIs; BIPM; EURAMET partners who provide access to facilities and expertise.

Deliverables

1	**Start: 01/01/13**	**End: 31/12/15**	

Electron and photon beam calorimetry: Maintenance and provision of the electron and photon beam calorimeter in line with UKAS and LRQA audit requirements, minor upgrades to software, international comparisons via key comparisons with BIPM and publication of results.

2	**Start: 01/01/13**	**End: 31/12/15**	

Proton beam calorimetry: Maintenance and provision of the proton beam calorimeter in line with LRQA audit requirements, maintained for off-site calibration of ionisation chambers in proton and ion beams, minor upgrades to software and publications.

3	**Start: 01/01/13**	**End: 31/12/15**	

HDR brachytherapy calorimetry: Maintenance and provision of the HDR brachytherapy calorimeter in line with LRQA audit requirements, maintained for calibration of transfer standard ionisation chambers and re-evaluation of dose rate constants of various source types, minor upgrades to software and publications.

4	**Start: 01/01/13**	**End: 31/12/15**	

50 kV free air chamber: Maintenance and provision of the 50kV free air chamber in line with UKAS and LRQA audit requirements, minor upgrades to software, international comparisons via key comparisons with BIPM and publication of results.

5	**Start: 01/01/13**	**End: 31/12/15**	

300 kV free air chamber: Maintenance and provision of the 300kV free air chamber in line with UKAS and LRQA audit requirements, minor upgrades to software, international comparisons via key comparisons with other NMIs via EUROMET project 628 and publication of results.

6	**Start: 01/01/13**	**End: 31/12/15**	

Primary standard cavity chambers: Maintenance and provision of the primary standard cavity chambers in line with UKAS and LRQA audit requirements, minor upgrades to software, international comparisons via key comparisons with BIPM and publication of results.

Project No.	AIR/2013/DC2	Price to NMO	£2198k
Project Title	Provision of irradiation facilities and mathematical modelling capability	Co-funding target	
Lead Scientist	David Shipley	Stage Start Date	01/01/13
Scientist Team	G Bass, T Sander, D Crossley, J Sephton, S Galer, J Manning, D Maughan, M Kelly, I Billas, M Homer	Stage End Date	31/12/15
		Est Final Stage End Date	On-going
Sector	7.1. Traceability & uncertainty; 3.2 Drugs & therapies; 3.3 Health & safety	Activity	Provision of Standards & Maintenance of Capabilities

Summary This project provides the well characterised electron and photon radiation fields required a) to allow the UK national standards for air kerma and absorbed dose at therapy, protection and industrial dose levels to be maintained and developed; b) to allow the provision of calibration services and training and c) to enable research, thereby maintaining NPL's position as a world-leading centre in the field of Radiation Dosimetry. The project also provides the capability to perform the mathematical modelling that is an integral component of many of the above activities.

The Need

- To provide electron and photon radiation fields in order to enable the rest of the NMS AIR Programme's Radiation Dosimetry Theme activities to be fulfilled and to simulate the radiation fields relevant to the user communities. All the radiations fields need to be well characterised and have a high degree of either inherent stability or beam monitoring. The clinical linac, HDR brachytherapy and high dose ^{60}Co facilities, in particular, are "state of the art".
- To provide the ancillary equipment and facilities for primary standard reference dosimetry, calibration services, research and training.
- To provide the mathematical modelling capabilities and facilities required to support the increasing and diverse modelling needs in the development of standards and facilities in Radiation Dosimetry. For example: to underpin the establishment of new primary standards such as the proton calorimeter; and the extension of NPL's modelling capabilities to support dosimetry for molecular radiotherapy and proton dosimetry in scanned and pulsed beams.

The Solution In all areas, the project will involve the maintenance, calibration, testing and training to allow capabilities to be continued at current levels. Specifically:

- Provide the following characterised irradiation facilities to the standard and availability necessary to enable the NMS Radiation Dosimetry Programme to be undertaken
    - Clinical linac facility
    - X-ray facilities
    - Theratron and Mainance facilities
    - HDR brachytherapy and beta-ray facilities
    - High dose ^{60}Co facility
- Provide the ancillary equipment common to many aspects of the NMS Radiation Dosimetry Programme at the required level of availability, and with traceable calibrations, where appropriate.
- Provide the mathematical modelling capability required by the NMS Radiation Dosimetry Programme.

Project Description (including summary of technical work)

1. **Clinical linac facility.** The NPL clinical linac serviced and maintained to a level to remain representative of a typical hospital linac for primary standard reference dosimetry, calibration services, research and provision of electron and photon radiation fields.
2. **X-ray facilities.** The 50, 300 and 420 kV x-ray facilities serviced and maintained, including necessary tube replacements and minor upgrades to software, covering Half Value Layers in the range from 0.024 – 20 mm Al. New mammographic qualities established.
3. **Theratron and Mainance facilities.** The Theratron and Mainance facilities serviced and maintained to provide a typical therapy ^{60}Co beam (Theratron facility) and ^{60}Co, ^{137}Cs and ^{241}Am sources of varying activities (Mainance facility), including source replacements to maintain required dose rates and minor upgrades to software.
4. **HDR brachytherapy and beta-ray facilities.** The HDR brachytherapy and beta ray facilities serviced and maintained, including regular source replacement and minor upgrades to software.
5. **High dose ^{60}Co facility.** The three self-shielded ^{60}Co irradiators giving dose rates between 0.5 and 200 Gy /min will be serviced and maintained, with dose rates directly traceable to the NPL primary standard therapy level calorimeter. Systems providing controlled irradiation environments to mimic industrial conditions will be maintained and minor upgrades to software carried out.
6. **Maintenance and calibration of ancillary equipment.** Maintenance, servicing and calibration of ancillary equipment used on all the facilities, including secondary standards, voltage standards, current sources, micrometers, barometers, thermistors, thermometers, spectrometers (EPR and UV/VIS) etc.

7. **Mathematical modelling capability.** Modelling capabilities maintained at a level to support existing primary standards and facilities and all other NMS and research projects. New releases (and upgrades) of Monte Carlo radiation transport codes required by other projects will be configured, validated, acceptance tested and enabled for efficient running on NPL Grid.

Impact and Benefits

- The facilities maintained and developed underpin all other NMS Radiation Dosimetry projects and enable involvement in national and international research programmes such as EMRP.
- Vital for UK radiotherapy cancer care with indirect impact on delivery of accurate radiation dose to cancer patients especially on evolving treatment techniques using small fields.
- Indirect impact on improved dosimetry for diagnostic x-rays and on ensuring safe working and living environments for thousands of employees and the general public.
- Enables UK industry to comply with EU Medical Devices Directive and US FDA requirements for radiation sterilization of medical devices.
- Vital for operation of primary standards and calibration services and world standing of NPL radiation dosimetry group.

Support for Programme Challenge, Roadmaps, Government Strategies This project aligns with the NMS Strategy 2011-2015 in particular in addressing some of the needs of various national challenges through the provision of the required NMS infrastructure to: ensure the safety and efficiency of healthcare diagnosis and therapies; in energy generation; defence and security; and growth (radiation processing & radiation hardness testing). Further, the project links directly onto the AIR Programme strategy and roadmaps for the Radiation Dosimetry theme

Synergies with other projects / programmes All NMS projects requiring the use of radiation facilities; all Radiation Dosimetry calibration services and training; On-going EMRP Health projects MetrExtRT, BioQuaRT and MetroMRT.

Risks In general, the risks relating to this project are low, given the facilities and expertise are in existence and well established. In addition, given that the project is concerned with solving unanticipated problems with the facilities as they arise, there is an in-built risk mitigation mechanism. Nevertheless, failure of facilities puts at risk other aspects of the NMS programme and the calibration services required by the user community. This is mitigated by regular planned maintenance and repair / replacement of equipment. Remaining risks include loss of key staff that could affect our ability to maintain our existing capability.

Knowledge Transfer and Exploitation Dissemination via the output of NMS and other research projects, calibration services, on-site training courses and use of facilities by third parties.

Co-funding and Collaborators Effectively the customers of the standards and measurement services underpinned by this project play an important role in helping to shape these capabilities. Indeed, NPL has many regular collaborators in this area, including Hospitals, other NMIs, BIPM, RTTQA, Technical System Limited, Philips Medical Systems, Elekta. In 2012, Elekta has provided in-kind funding through the provision and installation of the new version of the MLCi multileaf collimator.

Deliverables

1	**Start: 01/01/13**	**End: 31/12/15**	
Deliverable title: Provision of the clinical linac: with a target availability of 80%.			
2	**Start: 01/01/13**	**End: 31/12/15**	
Deliverable title: Provision of the x-ray facilities: with a target availability of 80%, including necessary tube replacements and upgrades to carriages.			
3	**Start: 01/01/13**	**End: 31/12/15**	
Deliverable title: Provision of the Theratron and Mainance facilities: with a target availability of 80%, including required replacement of Mainance carriage.			
4	**Start: 01/01/13**	**End: 31/12/15**	
Deliverable title: Provision of the HDR brachytherapy and beta-ray facilities: with a target availability of 90%, including regular source replacements to achieve the required dose rates.			
5	**Start: 01/01/13**	**End: 31/12/15**	
Deliverable title: Provision of the High Dose ^{60}Co facility: with a target availability of 90%.			
6	**Start: 01/01/13**	**End: 31/12/15**	
Deliverable title: Maintenance and calibration of all ancillary equipment shared across facilities; as well as the EPR spectrometers that support the delivery of the alanine calibration and audit services.			
7	**Start: 01/01/13**	**End: 31/12/15**	
Deliverable title: Provision of mathematical modelling capability			

Project No.	AIR/2013/DD1	**Price to NMO**	£147k
Project Title	Provision and development of the small field and IMRT calorimeter	**Co-funding target**	
Lead Scientist	Simon Duane	**Stage Start Date**	01/01/13
Scientist Team	Mark Bailey; Nigel Lee	**Stage End Date**	31/12/14
		Est Final Stage End Date	2014
Sector	3.2 Drugs & therapies; 7.1 Traceability & uncertainty	**Activity**	Development of existing Capabilities

Summary

Enhanced capabilities in calorimetry for small fields and Intensity modulated radiotherapy (IMRT) beams will further develop NPL's ability to underpin innovative radiotherapy techniques strengthening NPL's position as a world-leading centre in this field leading to new, improved therapy and industrial level calibration services.

The Need

Cancer is a major disease accounting for 13% of all deaths worldwide in 2008. The total number of deaths from cancer is projected to rise by 50% over the next 20 years and the demand for all modern radiotherapy modalities will grow accordingly. Growing numbers of patients are treated each year with Intensity Modulated Radiotherapy (IMRT) and other modalities utilising small fields. According to recent estimates[1], 35% of all radiotherapy patients would benefit from the most advanced forms of radiotherapy. This would bring widespread benefit to a significant number of cancer patients, with the likelihood of increased survival rates and improved quality of life. As in all radiotherapy, success is critically dependent on accurate delivery of the specified absorbed dose, yet existing dosimetry standards do not meet the requirements of small field and composite field treatments.

The Solution

The existing prototype calorimeter has demonstrated the possibility of a direct determination of absorbed dose in small and composite fields. However initial measurements in small fields depend on significant corrections for field uniformity. In an IMRT treatment, the relatively long delivery time makes the signal to noise ratio significantly worse than in a measurement under conventional reference conditions. Two developments from the prototype are envisaged, designed to measure different integral quantities based on absorbed dose. For small fields, the integral is defined over a surface perpendicular to and intersecting the whole beam; in composite fields, the integral is defined over a volume of interest. These integral quantities could support reference-level dosimetry for these therapies and the measurements will enable the validation of international dosimetry protocols currently in development.

Project Description (including summary of technical work)

The existing IMRT graphite calorimeter will be developed for the measurement of absorbed dose averaged over a known small volume in small field and composite field treatments. Its performance will be assessed and compared against the level required to support reference-level dosimetry for radiotherapy. A second generation calorimeter will be designed and built for the measurement of an integral dose quantity such as Dose Area Product, and suitable for the calibration of commercial plane parallel ionisation chambers. Compared to absorbed dose at a point, the integral quantity is expected to be better suited to the standardisation of dosimetry in treatments using radiation fields that are significantly smaller, less uniform and/or more complex than normal reference quality fields. A reduced core surface to volume ratio offers the best prospect of improving the signal to noise ratio, and ultimately enabling reference-quality dosimetry in an IMRT treatment. Results of this work will be published in peer-reviewed journals.

Impact and Benefits

NPL calorimeters underpin dosimetry for the delivery and improvement of ~ 200,000 cancer treatments in the UK per year. Of those patients successfully treated, about 40% have radiotherapy as part of their treatment regime. Use of these new absorbed dose standards will potentially reduce the measurement uncertainties in dosimetry for IMRT and other modalities utilising small fields, such as delivered by TomoTherapy and CyberKnife machines, and contribute to an increase in efficacy.

Support for Programme Challenge, Roadmaps, Government Strategies

This project aligns with the NMS Strategy 2011-2015 in particular through the provision of the required NMS infrastructure to ensure the safety and efficiency of healthcare diagnosis and therapies. Further, the project links directly onto the AIR Programme strategy and roadmaps for the Radiation Dosimetry theme and support for new radiotherapy techniques. In addition, the project supports the Department of Health's Cancer Reform Strategy; Protection of the public and radiation workers from ionising radiation; and supports the Government priority set out by Public Service Agreement Targets (PSAT) 4 'Promote world-class science and innovation in the UK' as well as 18 'Promote better health and wellbeing for all'.

Synergies with other projects / programmes

Health II EMRP project: MetrExtRT and on-going NMS project D4 Dosimetry for IMRT and small fields.

Risks Further development of the existing prototype calorimeter from an earlier project may not achieve the required level of performance and an alternative approach may be required.			
Knowledge Transfer and Exploitation Knowledge transfer will be through peer-reviewed publications, NPL-provided reference dosimetry training courses and new and enhanced calibration and audit services.			
Co-funding and Collaborators Several UK hospitals have expressed interest in trial measurements with the prototype calorimeter, enabling measurements in beams and modalities not available at NPL; LNHB and ENEA are the MetrExtRT partners working on integral dose quantities.			
Deliverables			
1	**Start: 01/01/13**	**End: 31/06/13**	
Deliverable title: IMRT calorimeter performance analysed using Monte Carlo and thermal modelling, and the scope for improvement assessed.			
2	**Start: 01/07/13**	**End: 31/12/13**	
Deliverable title: Second generation calorimeter design completed			
3	**Start: 01/01/14**	**End: 31/12/14**	
Deliverable title: Second generation calorimeter ready for measurement and calibration			

[1] Cooper, T., UK Dept. of Health, at BIR meeting on 'Expansion of IMRT in the UK', Feb 2011

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Neutron Projects 2013

Project No.	AIR/2013/N1	**Price to NMO**	£1456k
Project Title	Primary neutron standards	**Co-funding target**	
Lead Scientist	David Thomas	**Stage Start Date**	01/01/13
Scientist Team	Neutron Metrology Group	**Stage End Date**	31/12/15
		Est. Final Stage End Date	On-going
Sector	7.1 Traceability & Uncertainty 3.3 Health & Safety, 1.1 Energy	**Activity**	Provision of Standards (Maintenance of Capabilities; International obligations

Summary The deliverables in this project will provide the UK with continuing access to neutron fluence and dose equivalent standards suitable for its demanding requirements and the ability to measure radionuclide neutron source emission rates to the necessary high precision. These essential capabilities are dependent on two world-class facilities: a manganese bath suite, and a Van de Graaff accelerator with its associated low-scatter experimental area and thermal neutron pile. Both require continued upkeep plus regular validation of the standards, including UKAS accreditation and key international comparisons to maintain CMCs.

The Need Neutron measurements are needed for (*inter alia*) radiation protection for nuclear workers, fusion research, and nuclear reactor control. The level of measurement quality required for this is determined by drivers such as the Ionising Radiations Regulations and the need for safe operation of nuclear plant. To achieve this quality, neutron-measuring devices must be calibrated over energy and intensity ranges spanning several orders of magnitude, and by methods traceable to national standards. NPL is one of only four national metrology laboratories worldwide able to offer these services. Its neutron metrology facilities comprise a manganese bath for measuring neutron source output, plus a Van de Graaff accelerator equipped for fast and thermal neutron production, supported by a range of neutron sources characterised for their emission rates and anisotropies. A programme of maintenance and verification is needed to keep these facilities fully operational. If so maintained they are expected to meet basic UK needs over the period of this project, but continuous development (to be covered in other proposals) is also necessary to keep pace with the evolving needs of those who measure neutrons.

The Solution The exceptional neutron measurement facilities at NPL, unique in the UK and extremely rare elsewhere in the world, will be kept operational and performing to the necessary standards, by means of programmes of maintenance and verification. This will allow NPL to cover the applicable requirements of industry, health care, defence, and academia, and remain one of the top three neutron metrology laboratories in the world.

Project Description (including summary of technical work)

This project will ensure the continued availability and high quality of NPL's major neutron facilities and neutron instrumentation, to provide measurement services and for the Neutron Group's own use in research. Programmes of regular maintenance will be carried out, and schedules will be revised if necessary in the light of experience. Operating practices will be kept under review. Periodic quality checks will demonstrate the continuing reliability of the facilities, key international comparisons will be carried out, and UKAS accreditation of measurement services will be maintained.

The manganese bath (which is the primary standard for source emission rates) and the moderator detector (used for low-output sources) will be kept fully operational, and quality checks will be carried out at least twice a year using manganese sulphate solution activated in the thermal pile. The Neutron Group will maintain precise knowledge of the neutron output characteristics of its own sources by making at least two measurements a year (emission rate and/or anisotropy), so that the sources can be used for irradiations and to calibrate other Group facilities.

The accelerator-driven fluence and dose equivalence standards will be maintained. The calibration of beam current monitors, and the response of the neutron monitors will be verified 2 to 4 times a year. The accelerator's energy selection magnet will be re-calibrated each time the accelerator is reassembled following repair or servicing. The performance of the neutron-producing targets will be monitored, and targets will be replaced when necessary.

The Van de Graaff accelerator will be regularly serviced so as to provide well-characterised beams as required, in continuous or pulsed (time-of-flight) mode, for neutron production or any other application. The quality of these beams underpins the NPL accelerator-based neutron-production capabilities. The maintenance programme will be continually updated in the light of experience, and where spare components are no longer available modern equivalents will be found. The 50 year old Van de Graaff is maintained and developed entirely by NPL staff. **The fast neutron experimental area,** which includes the computerised system for positioning the detector mounts, together with specialised arrangements (lasers, jigs, phantoms, brackets, etc.) for mounting and aligning detectors and dose meters will be maintained to ensure everything is in good order and available for use when needed. New stands etc. will be procured as required. The data acquisition system associated with this experimental area will be kept up-to-date to satisfy data acquisition needs.

NPL's neutron spectrometers will be checked annually for efficiency, resolution, noise levels etc., and deviations from historical behaviour will be investigated and rectified. Obsolete electronic modules will be replaced.

Quality assurance is ensured via UKAS accreditation and participation in key international comparison exercises which underpin the standards. Every 1-2 years the Group will typically participate in a UKAS audit for each service and one international key comparison exercise. Also covered will be formulation and investigations of areas where new standards are required.

Impact and Benefits The Neutron Metrology Group at NPL is globally significant because it operates one of a very small number of neutron metrology labs worldwide, and because UK facilities (e.g. research reactors and accelerators) that could have offered some services have closed down. NPL's verified calibrations enable UK industry to satisfy essential regulatory requirements, and also confer a competitive advantage. The neutron facilities and expertise at NPL allow instrument manufacturers to demonstrate the efficacy of novel designs. In the UK roughly 16,000 radiation workers are routinely monitored for neutron dose, and the secondary standards on which the monitoring services are based are provided by NPL. Certified NPL sources are used for performance tests of these dose-monitoring services. The thermal pile is now a unique facility in the UK for mandatory testing of reactor instrumentation. The NPL neutron facilities are used for approximately 30 different calibrations, performance test, or type test exercises per year for external customers, and each exercise may involve irradiating numerous different devices, sometimes hundreds of personal dosemeters. Internal NMS research work is also carried out with these facilities.

Support for Programme Challenge, Roadmaps, Government Strategies This project underpin all the goals set out in the Neutron Metrology Theme Roadmap, and are the basis for all neutron dose monitoring in the UK. Reliable neutron instrumentation and dose measurement, as facilitated by this project, is required for the Government programmes for reactor decommissioning, homeland security, and new and existing nuclear power generation.

Synergies with other projects / programmes These facilities are essential for neutron work at NPL (NMS projects, measurement services, third party contracts and consultancies).

Risks Many of the experimental neutron facilities at NPL require the Van de Graaff accelerator for some part of their operation, and its continued reliability is the main technical risk. The accelerator is now 50 years old, spare parts are becoming hard to find, and systemic problems (such as degraded insulation on top terminal wiring) are becoming noticeable. To mitigate this risk, a programme of preventative maintenance will be followed, and opportunities will be sought to acquire critical spare parts from any suitable source, such as the closure or replacement of a similar machine elsewhere in the UK or abroad.

Knowledge Transfer and Exploitation Project outputs will be exploited via the continuing availability of the NPL neutron facilities. Awareness of NPL's facilities will be promoted through research papers produced as a part of NMS and other research projects. Papers are typically presented at specialist meetings, such as the Neutron Users' Club or the NEUDOS series of international conferences, and/or published in peer-reviewed journals such as Metrologia, Nuclear Instruments and Methods or Radiation Measurements. Advice on neutron metrology problems will also be available to end-users directly. Continued take-up of neutron services is expected from the Energy, Health, and Defence sectors. Requirements range from routine calibrations to the type testing of novel instruments.

Co-funding and Collaborators The provision and maintenance of these enabling facilities does not lend itself to collaborations, as potential partners usually have less metrology expertise than NPL, and technical goals that are more applied and less fundamental than those of this project. (International key comparisons are one important form of collaboration involving effort from NMIs worldwide.)

Deliverables (brief descriptions)

1	**Start: 01/01/13**	**End: 31/12/15**	
Radionuclide neutron source emission rate measurements: Maintenance of the manganese bath facility, and regular measurement of the neutron output of the Neutron Group's sources.			
2	**Start: 01/01/13**	**End: 31/12/15**	
Accelerator-based standards (including time of flight): Maintenance of fluence and dose equivalent standards for monoenergetic, broad spectrum and thermal neutrons fields.			
3	**Start: 01/01/13**	**End: 31/12/15**	
Maintenance of the 3.5 MV Van de Graaff, low-scatter area, and data acquisition systems: Continued provision of good-quality charged particle beams for the neutron production facilities and related purposes.			
4	**Start: 01/01/13**	**End: 31/12/15**	
Maintenance and regular checks of spectrometers: Regular spectrometer checks and maintenance of the signal processing electronics.			
5	**Start: 01/01/13**	**End: 31/12/15**	
Accreditation, quality assurance and international demonstrations of equivalence: Participation in international key comparisons, and UKAS accreditation for NPL neutron measurement services.			

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Radioactivity Projects 2013

Project No.	AIR/2013/R1	Price to NMO	£1056k
Project Title	Maintenance of primary standards	Co-funding target	
Lead Scientist	Lena Johansson	Stage Start Date	01/01/13
Scientist Team	John Keightley, Hilary Phillips, Julian Dean, Andy Pearce, Arzu Arinc, Eleanor Bakhshandeiar	Stage End Date	31/12/15
		Est Final Stage End Date	On-going
Sector	7. Underpinning metrology	Activity	Provision of Standards and Maintenance of Capabilities; International Obligations

Summary

This project maintains primary measurement techniques for radioactivity in solution and gas, in order to provide the UK's capability for realizing primary standards of radioactivity for more than 100 radionuclides. These primary standards underpin the UK measurement infrastructure for radioactivity measurement, which aims to enable the UK to use radioactive materials in healthcare and nuclear power sectors while keeping the harmful effects at an acceptable level. The capability is demonstrated by meeting the obligations of the CIPM Mutual Recognition Arrangement.

The Need

The main requirements for accurate radioactivity metrology are:

1) In nuclear medicine (hospitals and radiopharmaceutical manufacturers), for the protection of patients to ensure that they receive the minimum quantity of radioactivity consistent with effective imaging or therapy (Ionising Radiation (Medical Exposure) Regulations 2000 (IR(ME)R 2000)).
2) For the nuclear industry and regulatory agencies, to determine the radioactivity content of gaseous and aqueous discharges into the environment for regulatory compliance (Environmental Permitting Regulations 2010).
3) For decommissioning legacy nuclear sites and the Low Level Waste Repository, to characterise solid waste materials (building, plant etc.) to consign the waste to the correct waste stream for regulatory compliance and cost savings (Environmental Permitting Regulations 2010).
4) For all organisations that use radioactive materials, for the protection of the workforce and regulatory compliance (Ionising Radiations Regulations 1999).
5) In the defence sector, the emerging discipline of nuclear forensics demands very high accuracy standards to address the increased risk to national security as identified by the UK's Strategy for Countering Chemical, Biological, Radiological and Nuclear Terrorism.

All of these measurements depend ultimately on the maintenance of independent, internationally-accepted, primary standards of radioactivity. These standards underpin all the other research projects and associated measurement services / proficiency test exercises that disseminate the standards to organisations in the UK. The challenges in radionuclide metrology are the large number of primary standards needed (approximately 100 radionuclides) and that the standards decay away naturally over time.

The Solution

The solution is to maintain the bespoke equipment, procedures and skills needed for realising the primary standards (in liquid and gaseous form), and to demonstrate this internationally through compliance with the Mutual Recognition Arrangement. In the radioactivity field, this means participating in the Consultative Committee's rolling programme of Key Comparisons (at least one per year), ensuring NPL's entries in the BIPM reference system are maintained and sustaining the procedures and skills needed for accreditation to ISO17025. This approach is taken by all the leading NMIs in this field, including NIST, PTB and LNHB.

Project Description (including summary of technical work)

1. Maintenance of the bespoke primary standards systems, including like-for-like replacement and commissioning of obsolete electronic components, fault-finding and repairs, replacement of gas valves and transfer systems and ensuring software is maintained (for example, when compilers are updated).
2. Primary standardisations of radionuclides for Key Comparisons. This includes obtaining the raw materials, checking purity, preparing samples for analysis, measurement by primary techniques, data collection and analysis, and reporting.
3. Primary standardisations of radionuclides for submission to the BIPM SIR system to ensure that NPL's entries in different categories of radionuclides do not expire.
4. Reviewing and maintaining written operating procedures.

Impact and Benefits

The primary standards (via the dissemination mechanisms) aim to deliver the following benefits to end-users and stakeholders:

1) Patient safety: Compliance with the IPEM / NPL Good Practice Guide on the quality control of radiopharmaceuticals in the clinic (approximately 700,000 diagnostic procedures and 30,000 therapeutic administrations using radioisotopes are carried out annually in the UK).

2) Environmental monitoring (approx. 30 UK labs): Compliance with the Environmental Permitting Regulations 2010 and the associated nuclear site licences (daily measurements at all the UK nuclear sites and the associated environmental monitoring programmes (EA/SEPA programme).

3) Site decommissioning: Compliance with waste repository acceptance criteria and the Nuclear Industry Code of Practice. The latest estimate of the current and future inventory of Low Level radioactive Waste (LLW) is around 3 million cubic metres, however the LLW repository at Drigg has space for only 0.7 million cubic metres. The disposal bill for LLW in the UK is expected to reach almost £10bn. Therefore, the metrology infrastructure needs to be maintained to ensure that waste streams are consigned cost-effectively for appropriate storage and disposal.

4) Compliance with the Ionising Radiations Regulations 1999 for exposure to airborne radioactivity and surface contamination (all organisations that are potentially exposed to anthropomorphic or natural radioactivity – nuclear industry, defence, oil & gas, mining, etc.).

Support for Programme Challenge, Roadmaps, Government Strategies

This work links to the NMS Strategy 2011-2015, in particular addressing the underpinning science for sectors that interact with the NMS, such as instrumentation, healthcare and nuclear and the national challenges Health, Energy and Sustainability. As this project provides the basic capabilities for radioactivity measurement it supports all the major challenges addressed by the AIR Programme's Radioactivity Theme, forms the basis of the Radioactivity Primary and Secondary Standards Theme Roadmap and underpins all activity within the Radioactivity Environmental, Energy and Radiation Protection and Health-related Theme roadmaps.

Synergies with other projects / programmes

All other projects in the Radioactivity theme including on-going EMRP projects (MetroFission, MetroRWM and MetroMRT) are founded on the availability of the primary standards. This project also relies on the maintenance of the associated secondary measurement systems (see Project AIR/2013/R2).

Risks

The technical risk of this project is low given the facilities and expertise are in existence. In addition, the project is designed with an in-built risk mitigation mechanism to solve problems with the facilities as they arise.

Knowledge Transfer and Exploitation

KT and exploitation of the results of this project will be through the provision of measurement services to industry and the advice provided to end users to ensure the measurements offered meet their needs (including reference materials and proficiency test exercises or via research projects aimed at specific user groups). The scientific knowledge transfer is two-way with other NMIs, through participation in CCRI meetings, workshops and associated publications in the scientific literature.

Co-funding and Collaborators

Effectively the customers of the measurement services underpinned by this project are collaborators. Collaboration with other NMIs worldwide is expected in this project, as well as with international organisations such as the IAEA and BIPM, universities and other national laboratories. Direct cash co-funding is unlikely. However, this capability enables bidding into other (mostly European) projects and funded networking activities related to radioactive standards.

Deliverables

1	**Start: 01/01/13**	**End: 31/12/15**	

Compliance with the Mutual Recognition Arrangement : Submission of results from Key Comparison exercises (one per year) for radioactive solutions, gases or solids; submission of primary standards to the International Reference System (at least one per year) to maintain NPL's entries; maintenance of operating procedures and meeting requirements to maintain ISO17025 accreditation.

2	**Start: 01/01/13**	**End: 31/12/15**	

Maintenance and validation of primary systems: Replacing obsolete sensors, electronics and sample / gas handling systems, commissioning and validating to ISO17025 standard as required, for the bespoke primary standards including coincidence counters, TDCR systems, gas counting and large area reference source counters. Maintaining software to ensure compatibility with modern hardware and software compilers.

Project No.	AIR/2013/R2	Price to NMO	£832k
Project Title	Secondary Measurement: Standards and Systems	Co-funding target	
Lead Scientist	Simon Jerome	Stage Start Date	1 Jan 2013
Scientist Team	John Keightley, Sean Collins, Andy Pearce, Arzu Arinc, Andrew Fenwick, Michaela Baker, Chris Gilligan	Stage End Date	31 Dec 2015
		Est Final Stage End Date	Ongoing
Sector	7. Underpinning metrology	Activity	Provision of Standards and Maintenance of Capabilities

Summary

The secondary measurement systems comprise a set of radioactivity measurement equipment (generally commercially available instruments with minor modifications) plus support services and equipment. These have two main functions: (1) Preparing and checking samples of radionuclides prior to standardisation; (2) Acting as stable transfer instruments so that primary standards may be reproduced. The systems and facilities are also essential for preparing reference materials for the commercial services, including the provision of laboratory proficiency test exercises. This project covers the maintenance activities associated with these systems: regular calibration, daily quality control checks, maintenance of procedures, the replacement of obsolete or broken equipment and software updates.

The Need

The production of primary standards cannot alone satisfy the user community with its heavy demands for radionuclide standards. Primary standards are very costly and the industries (such as medical, energy, waste management, decommissioning and environmental monitoring) require a more cost-effective and flexible way of disseminating standards and produce results for investigative projects faster and at lower costs. At the moment, the six NPL gamma-ray spectrometers are heavily scheduled with internal and external work requests. The ionisation chambers providing essential calibrations for nuclear medicine departments in the UK are also utilised for standardisation of solutions used in other areas due to the method's excellent stability, low uncertainty and historical reliability. The same goes for the other secondary methods held.

Approximately 50 UK hospitals have their Radionuclide calibrators calibrated yearly by NPL's secondary methods. An estimated 100 000 UK patients yearly are expected to have a PET camera investigation where NPL secondary measurements have played a significant role in delivering Quality Assurance and calibrations. The nuclear waste and decommissioning industry are benefiting from alpha-particle analysis of samples and large-area samples, mostly related to nuclear waste sentencing. In 2011, approximately 50 large-area samples were measured and many more alpha sources. The need for secondary measurements can be summarised as providing:

1) Ultra-stable transfer instruments (<0.1% over decades) to reduce significantly the cost of reproducing primary standardisations;

2) Instrumentation to check the purity of the materials used in primary standardisations and to check dilution factors; and

3) Facilities to prepare the materials into a form suitable for measurement by primary standards (and for associated measurement services and reference materials).

The Solution

The solution is to maintain a set of commercial radioactivity measurement instruments (including gamma and alpha spectrometers and liquid scintillation counters), plus a set of re-entrant ionisation chambers as stable transfer instruments for gamma / high energy beta emitters (the same approach is used at other NMIs). All of this work requires facilities for handling open radioactive sources, preparing carrier solutions, high accuracy balances for source preparations and conducting radiochemical separations to isolate the element for standardisations. To comply with ISO17025, the instruments must be calibrated regularly and their fitness for purpose checked before each use.

Project Description (including summary of technical work)

1. Calibrating and conducting quality control checks of secondary standards of radioactivity (including gamma spectrometers, ionisation chambers, liquid scintillation counters, large-area proportional counters, alpha spectrometers and associated support equipment). This includes re-calibration of the ultra-stable ionisation chambers (these instruments have been proved to be very stable [<0.1% variation over 30 years] but are sensitive to minor changes in the type of ampoule used for the radioactive solutions).

2. Calibrating and conducting quality control checks on ancillary equipment (balances, pipettes, electrometers etc.).

3. Replacing obsolete instruments and components (in particular, replacing, recalibrating and revalidating obsolete high resolution gamma spectrometers with like-for-like equipment).

4. Maintaining commercial analysis software, updating to current standards and revalidating as required.

5. Maintaining stocks of carrier solutions, reagents and separation equipment.

Impact and Benefits

The benefits of providing these secondary standards and systems include:

- Patient safety: Compliance with the IPEM / NPL Good Practice Guide on the quality control of radiopharmaceuticals in the clinic (approximately 700,000 diagnostic procedures annually in the UK, and 30,000 therapeutic administrations).

- Environmental monitoring (approx. 30 UK labs): Compliance with the Environmental Permitting Regulations 2010 and the associated nuclear site licences (daily measurements at all the UK nuclear sites and the associated environmental monitoring programmes (EA/SEPA programme).
  3) Site decommissioning: Compliance with waste repository acceptance criteria and the Nuclear Industry Code of Practice. The latest estimate of the current and future inventory of Low Level radioactive Waste (LLW) is around 3 million cubic metres, however the LLW repository at Drigg has space for only 0.7 million cubic metres. The disposal bill for LLW in the UK is expected to reach almost £10bn.

- 4) Compliance with the Ionising Radiations Regulations 1999 for exposure to airborne radioactivity and surface contamination (all organisations that are potentially exposed to anthropomorphic or natural radioactivity – nuclear industry, defence, oil & gas, mining, etc.).

Support for Programme Challenge, Roadmaps, Government Strategies

As this project provides basic capabilities for radioactivity measurement it supports all the major challenges addressed by the AIR programme, and in particular, it provides capability to address the National Challenges: Energy and Sustainability as mentioned in the NMS Strategy 2011-2015. This work links to the Radioactivity Theme roadmap on Primary and Secondary Systems mostly as enabling science.

Synergies with other projects / programmes

This project provides essential support for all other projects in the radioactivity theme and relies on the output from the Primary Standards project AIR/2013/R1.

Risks

The technical risk of this project is low, as it aims only to maintain current capability.

Knowledge Transfer and Exploitation

Knowledge acquired during this project is typically disseminated through the user meetings (NM3, LSUF, NSUF etc.) and metrology clubs. Further dissemination is via on-going sales of radioactivity standards, calibrations and measurement services to our stakeholders.

Co-funding and Collaborators

Collaboration with other NMIs and standards institutes such as CIEMAT/NIST, PTB, LNHB and the IAEA

Deliverables

1	**Start: 01/01/13**	**End: 31/12/15**	

Deliverable title: Maintenance and validation of secondary standards. Update calibrations for secondary instruments to schedule, including re-calibrating the ionisation chambers for the new ampoule type (a long term, rolling programme). Conduct daily quality control checks on liquid scintillation counters, gamma spectrometers etc., record the results on Shewart charts and take corrective actions as necessary.

2	**Start: 01/01/13**	**End: 31/12/15**	

Deliverable title: Replacing obsolete instruments and commercial software (like-for-like).
Replace at least one high resolution gamma spectrometer, validate and calibrate to ISO17025. Trouble-shoot problems with other detector systems as required and replace electronic units and instruments as needed.

3	**Start: 01/01/13**	**End: 31/12/15**	

Deliverable title: Provision of radiochemical support.
Prepare targets, arrange irradiations and conduct radiochemical separations needed to maintain the primary standards and to calibrate the secondary instruments. This includes maintaining stocks of carrier solutions and ordering laboratory consumables.

Project No.	AIR/2013/R3	Price to NMO	£207k
Project Title	New Primary Standards for Radiopharmaceuticals (including alpha emitters)	Co-funding target	
Lead Scientist	Lena Johansson	Stage Start Date	01/01/13
Scientist Team	Andy Pearce, Andy Fenwick	Stage End Date	31/12/14
		Est Final Stage End Date	2018
Sector	Health (3.2 Drugs & therapies)	Activity	Development of Existing Capability

Summary

This project concerns the provision of a measurement infrastructure for new radionuclides being used in nuclear medicine, for regulatory compliance and patient safety. There are two elements to the project:

- Providing new primary standards to meet customer needs.
- Commissioning a new instrument for standardising alpha emitting radionuclides to meet the expected growth in the use of alpha emitters for cancer therapy.

The Need

Developments in biotechnology are driving the development of new drugs based on radionuclides that have not been used before. For example, a detailed study of the future needs in nuclear medicine in the USA has identified 'tremendous potential' in using alpha emitters for cancer therapy, as they have significant advantages over other types of radionuclides. A recent clinical trial of Ra-223 for use in treating castration-resistant prostate cancer showed exceptional results; proven to almost double the life expectancy after therapy and significantly improve patient quality of life. Cancer metastases are difficult to treat and this kind of treatment (with Ra-223) is practical and successful as the radium will naturally go to the bone (metastases). Alpha treatments are evidently in a strong competitive position with chemotherapy as the only other treatment alternative.

Traceability to national standards of the radioactivity content of such radiopharmaceuticals is required by the regulators under Good Manufacturing Practice – Manufacture of radiopharmaceuticals, a directive by the EC, and by hospitals for patient safety (The Ionising Radiation (Medical Exposure) Regulations 2000). This is needed both for current alpha-emitting radiopharmaceuticals as well as for new products that are involved in clinical trials. The required accuracy of the activity in the final stage of a clinical trial or the use of a radiopharmaceutical is ±10%. Therefore, for future clinical trials there is a need for the provision of such primary standards, especially as individual manufacturers or hospitals do not have the infrastructure or expertise in place as in a NMI.

The Solution

The provision of new primary standards for priority radionuclides, which leads in turn to associated measurement services. To address the potentially growing field of alpha emitters, a new instrument for standardising alpha emitting radionuclides is proposed using solid angle alpha counting based on a study conducted in a previous AIR Programme project (RR1.1) around the refurbishment and upgrading of the alpha spectrometer. This instrument addresses the problem that alpha emitters are often in equilibrium with daughter radionuclides that perturb coincidence counting techniques.

Project Description (including summary of technical work)

This project will develop two new primary standards for alpha-emitting radiopharmaceuticals and construct a solid angle alpha counter instrument. The main steps in the primary standardisations are:

- Consulting with the user communities
- Reviewing the scientific literature
- Devising the primary standardisation techniques
- Realising the standards and establishing traceability to international standards
- Publishing in the scientific literature
- Calibrating transfer instruments to disseminate the standards to the hospitals / industry

Development of the new instrument will involve preparation of very detailed user requirements specification and functional specification, arranging construction and commissioning, validating to cGMP including comparison studies with other techniques.

Impact and Benefits

The main impact is that successful clinical trials can lead to start of treatments when traceability of the administered activity can be proven. From a patient's point of view this means prolonged life expectancy and significantly improved quality of life. In order to achieve this, the metrology for radiation protection and regulatory compliance must be in place. This will enable EU directives on dose planning for treatments by radiopharmaceuticals and the Ionising Radiation (Medical Exposure) Regulations 2000 to be fulfilled as well as aspects concerning patient safety; compliance with the IPEM / NPL Good Practice Guide on the quality control of radiopharmaceuticals in the clinic and regulatory compliance (cGMP) for manufacturers of radiopharmaceuticals.

Support for Programme Challenge, Roadmaps, Government Strategies

This project aligns with the NMS Strategy Document 2011-2015 in particular ensuring the safety and efficiency of healthcare diagnosis and therapies. The project also aligns with the AIR Programme Strategy and Health-related Radioactivity Metrology Theme roadmap in developing facilities to provide nuclear medicine support.

Synergies with other projects / programmes

This project uses the instrumentation and techniques maintained in projects AIR/2013/R1 and R2 and builds on previous work in project RR1.1 Refurbishment and upgraded alpha spectrometer.

Risks

The technical and scheduling risks to this project are medium; previous experience has shown that new primary standards can require additional work due to unexpected impurities in the raw material or difficulties with source preparation. The radionuclides are also short-lived, so there can be delays in obtaining raw material to repeat work. The main risk is the very high accuracy needed in machining the collimators needed for the solid angle alpha counter.

Knowledge Transfer and Exploitation

The new standard will be disseminated in collaboration with radiopharmaceutical manufacturers and hospitals, including increasing the scope of the measurement services (e.g. traceable calibrations and sale of certificates to hospitals) and running proficiency test exercises. Furthermore, this might lead to development of a transfer instrument that would provide traceable measurements of alpha-emitting radiopharmaceuticals on-site.

Co-funding and Collaborators

Collaboration with other NMIs and standards institutes such as NIST, PTB, LNHB and the IAEA and directly with specific radiopharmaceutical manufacturers, hospitals (e.g. Royal Surrey County Hospital), the NHS and MHRA (Medicines and Healthcare products Regulatory Agency).

Deliverables

1	**Start: 01/01/13**	**End: 31/12/13**	

Deliverable title: New primary standard of alpha-emitting radiopharmaceutical

Reviewing previous scientific literature, devising and implementing a standardisation method, calibrating a transfer instrument, publishing a scientific paper on the technique for peer review, submitting a sample to the BIPM SIR system, determining nuclear decay data (e.g. half-life, emission probabilities) needed for the standardisation. Publicising availability of new calibration service to hospitals and manufacturer.

2	**Start: 01/01/13**	**End: 30/09/13**	

Deliverable title: Solid angle alpha counter

Construction of solid angle alpha counter to NPL design and validation to GMP standards.

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

Deliverable title: New primary standard of alpha-emitting radiopharmaceutical

Reviewing previous scientific literature, devising and implementing a standardisation method, calibrating a transfer instrument, publishing a scientific paper on the technique for peer review, submitting a sample to the BIPM SIR system, determining nuclear decay data (e.g. half-life, emission probabilities) needed for the standardisation. Publicising availability of new calibration service to hospitals and manufacturer.

Project No.	AIR/2013/R4	**Price to NMO**	£100k
Project Title	New Reference Materials for Nuclear Decommissioning	**Co-funding target**	
Lead Scientist	Julian Dean	**Stage Start Date**	01/01/13
Scientist Team	Andy Pearce, Chris Gilligan, Sean Collins	**Stage End Date**	31/12/14
		Est Final Stage End Date	Ongoing
Sector	2.2 Pollution and waste reduction 7.1 Traceability and uncertainty	**Activity**	Development of existing capabilities

Summary

This project aims to develop new reference materials, based on concrete and oil, to validate radioanalytical procedures used in environmental radioactivity monitoring and nuclear decommissioning applications.

The Need

The decommissioning of UK nuclear sites under the Nuclear Decommissioning Authority continues to generate a very large inventory of potentially radioactive wastes (e.g. building materials and laboratory wastes), all of which require assay to classify them in order that the correct disposal route can be used, such as consignment to a Low-Level Waste (LLW) site. Accurate measurement is vital; underestimates of activity can lead to increased radiation doses to the public (e.g. due to disposal of LLW at a non-LLW site), whereas overestimates can result in clean material being consigned to the UK's LLW Repository, incurring unnecessary disposal costs and utilising dwindling repository capacity.

Recent changes to UK legislation (e.g. the LLW strategy 2010 and the Environmental Permitting Regulations 2011) have introduced more stringent requirements for the treatment and measurement of these potential wastes. The former requires the application of the 'waste hierarchy' (i.e. minimise or recycle rather than dispose) whereas the latter requires many radionuclides to be assayed at lower activity concentrations than before.

Therefore, there is a need to develop Certified Reference Materials (CRMs) specifically to validate radioanalytical procedures used in the environmental radioactivity and nuclear decommissioning sectors so that measurement accuracy can be optimised. The CRMs are also needed to enable UKAS accreditations for radioanalytical laboratories in these sectors. This need was highlighted by delegates at a NPL held 'Metrology for Decommissioning' Workshop (January 2012) who proposed setting up a working group to identify the priority materials to be certified. This 'CRM Working Group' (including representatives from Sellafield Ltd., LLW Repository Ltd., Magnox Ltd., NNL, AMEC, Nuvia and LGC) identified the priorities as concrete, oil, metal and soil. The conclusions of the NPL CRM Working Group were endorsed by the Characterisation Working Group of the NDA's Nuclear Waste Research Forum in July 2012 (including delegates from the NDA and the EA). Currently, there are no IAEA Reference Materials available that meet the specifications defined by the NPL CRM Working Group.

The Solution

The development of two new reference materials (concrete and oil) with individual radionuclide concentrations in the approximate range 0.1 – 10 Bq/g. The materials will preferably be 'real' (i.e. made from contaminated materials from nuclear sites), although practical considerations such as stability may mean that 'spiked' materials must be made instead. The materials should ideally contain a combination of U, Pu and Am nuclides, ^{90}Sr, ^{14}C and gamma-emitting radionuclides.

Project Description (including summary of technical work)

The project will consist of two deliverables.

1. Development of a concrete-based CRM. NPL will have access to a batch of homogenised contaminated concrete. The work will consist of (i) working with external radioanalytical laboratories to set up data reporting arrangements, (ii) dispatching subsamples to laboratories for assay and (iii) collating and analysing the data at NPL and certificating activity concentrations by consensus.

2. Development of an oil-based CRM. The CRM is to consist of a typical nuclear industry oil type containing activity probably in particulate form and rendered stable and homogenous. The exact specification will be defined by user consultation. Details of the work include (i) liaising with a group within or outside NPL with expertise in oil stability, (ii) preparing a radioactively-loaded dust using standardised material, (iii) incorporating it into an oil, (iv) homogenising and stabilising the oil with a suitable additive, (v) testing the stability by gamma spectrometry, (vi) dispatching subsamples to external radioanalytical laboratories, and (vii) collating and analysing the data at NPL and certificating activity concentrations by consensus.

Impact and Benefits

More accurate measurement of 'borderline' radioactive wastes (e.g. at the limit between 'Exempt waste' and LLW) would enable more waste to be consigned to the lower category. Given that the disposal cost per m^3 of Exempt waste is typically a factor of 50 lower than that for LLW, and the forecast LLW inventory for the UK for the period 2010 – 2020 is 4.4million m^3 (LLWR estimate), substantial savings are possible if even a fraction of the 'overclassified' waste is correctly measured. This work will benefit the Site Licensed Companies and the NDA. In addition to the disposal cost issue, according to the Environment Agency's LLW webpage, the UK LLW repository 'does not have the capacity to meet future national LLW needs'. Another impact is therefore to reduce unnecessary usage of this facility, benefitting LLW Repository Ltd. UKAS accreditations of radioanalytical laboratories will reduce the need for repeat analysis of materials, potentially reducing analysis costs. Again, this will benefit the SLCs and NDA.

Support for Programme Challenge, Roadmaps, Government Strategies

This project supports the National Measurement System Strategy 2011 – 2015, specifically:

Section 3.1.3 (Sustainability challenge) - 'the NMO will, through the NMS programmes…Enable characterisation of wastes, to allow safe and secure disposal within legal limits.'

Section 4.3.4 (United Kingdom Accreditation Service) – 'the NMO will…Ensure calibration and testing laboratories are adequately supported by the NMS infrastructure through the provision of traceable measurement standards.'

This project also supports the UK's Nuclear Decommissioning Authority's 2011 Strategy, which states that 'the UK's civil nuclear legacy is a major public liability, and represents the largest, most important environmental restoration programme in Europe.' The project would also support the UK LLW strategy 2011. Finally, certified reference materials are a deliverable on the AIR Programme Theme Roadmap for Radioactivity Measurements for Environmental, Energy and Radiation Protection.

Synergies with other projects / programmes

The project will build on expertise and procedures developed during NPL's Environmental Proficiency Test Exercises (e.g. the preparation and consensus certification of materials) as in AIR Programme project RE4 - Infrastructure for Environmental Radioactivity Standards. In addition, the project has synergies with AIR/2013/R1 and AIR 2013/R2 'Maintenance of primary standards' and 'Secondary Measurement: Standards and Systems', respectively, as they will provide the necessary techniques and infrastructure for producing traceable starting materials.

Risks

The technical and scheduling risks to this project are medium. The main risk is that no (or insufficient) expert analytical laboratories will participate in the analysis of sub-samples, so candidate laboratories will be contacted as early as possible to optimise choice of laboratories and to give those laboratories as much notice as possible. Reference materials can require additional work due to difficulties with source preparation or non-homogeneity of the processed material and also procurement of a suitable starting raw material can be problematic. However, our previous expertise in this area will mitigate against these risks.

Knowledge Transfer and Exploitation

The new Reference Material will be disseminated to the end-user base via the NPL website, technical meetings, conferences and exhibitions. In particular, their availability will be exploited via UKAS, the Environment Agency, the NDA and its SLCs (including LLW Repository Ltd.) as stated beneficiaries.

Co-funding and Collaborators

Collaboration with expert radioanalytical laboratories is envisaged. Their data will enable consensus values for the activity concentrations to be derived. Support from the NDA will also be sought.

Deliverables

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

Deliverable title: Prepare a new Certified Reference Material for contaminated concrete

Contacting external laboratories and establishing data reporting procedures; dispatching subsamples of homogenised material to external laboratories for assay; collating and analysing data at NPL; certificating activity concentrations by consensus.

2	**Start: 1/07/13**	**End: 31/12/14**	

Deliverable title: Prepare a new Certified Reference Material for contaminated oil

Canvassing expert users on final specification; liaising with expert group within or outside NPL on oil stabilisation; preparing radioactively-loaded dust using standardised material; incorporating into oil; homogenising and stabilising oil; testing stability by gamma spectrometry; contacting external laboratories and establishing data reporting procedures; dispatching subsamples of homogenised material to external laboratories for assay; collating and analysing data at NPL; certificating activity concentrations by consensus.

Project No.	AIR/2013/R5	Price to NMO	£316k
Project Title	EMRP Metrology for processing materials with high natural radioactivity (MetroNORM)	Co-funding target	EMRP MetroNORM
Lead Scientist	Lena Johansson	Stage Start Date	01/06/13
Scientist Team	Julian Dean, Simon Jerome, Andy Pearce, Hilary Phillips, Maria Garcia-Miranda, Sean Collins, Chris Gilligan	Stage End Date	30/08/16
		Est Final Stage End Date	2016
Sector	2.2 Pollution & waste reduction	Activity	Methodology for New Capabilities; Statutory and Policy Obligations

Summary

The work proposed contributes to a wider body of research in the European Metrology Research Programme (EMRP) Industry 2012 joint research proposal "Metrology for processing materials with high natural radioactivity". The project aims to lead to improvements in metrology for NORM containing matrices, and the production of reference standards for in-situ use in industry and laboratory settings. Innovative measurement techniques will be evaluated and developed into measurement systems suitable for the non-expert user on site. Industrial cost savings will result from the removal of the requirement to store uncharacterised radioactive waste at industrial sites whilst results are generated by remote expert labs performing sample analysis.

The Need

The EU directive 96/29/EURATOM is being revised to include naturally occurring radioactive materials (NORM). Revision of the European Construction Products Regulation 2011 will introduce requirements for the building industry to measure gamma emissions from products. Both updates to this legislation will come in to force by 2014 and NORM containing raw materials, industrial wastes and by-products will require accurate radionuclide activity characterisation prior to use or disposal. The activity level in NORM material is in the range between Bq/g and kBq/g. Today, large quantities of raw materials are consumed by NORM industrial processes and the waste volumes produced are significant. These waste materials constitute a huge economic and ecological burden. Some industries e.g. oil and gas industry and the steel industry generate residues and scales with significant radioactive content. These may be used as a feedstock in subsequent industrial applications (e.g. the use of slag from the steel industry as aggregate in road construction) or may require consignment as characterised radioactive waste. To avoid environmental contamination and increased radioactive dose to the public, traceable, accurate, and standardised measurement methods and systems are required, particularly for in-situ applications.

The Solution

The project will address the needs of diverse industries that use NORM in their processes through:

- Development of reference standards to address the traceability needs of industries using NORM materials.
- Development of innovative techniques and methodologies for use in laboratory analysis and for in-situ measurements of samples from NORM industries (both raw materials and waste streams) based on sound metrological practices.
- Dissemination of best practice via input to CEN/CENLEC standards and research papers in relevant industrial journals and the holding of workshops.

Project Description (including summary of technical work)

This project focuses on:

- The development of in-situ / on site measurement systems, methods and techniques to support innovative industrial processing of NORM resources.
- The development and establishment of traceable metrological reference standards and calibration sources for NORM measurements.
- The testing of systems, standards and reference materials developed for industrial processing situations.
- The drafting of traceable measurement procedures as input to CEN/CENELEC standards for NORM industry raw materials, products, by-products, residues and waste.
- Improvements to decay data for selected natural radionuclides, focusing on decay chains description and gamma-ray intensities and half-life improvement.

Impact and Benefits

One of the main benefits of this project is the cost reduction for industries that is achieved by on-site instrumentation and methodologies for routine monitoring of materials. The project will also deliver a faster sample preparation method to be applied according to requirements with traceability to national standards of radioactivity. The NORM industries can, by implementing the developed metrology, demonstrate compliance with the new European Construction Products Directive prior to export and accurate product and waste characterisation leading to cost reductions in waste consignment. If this project is successful, the benefits will be across industries and sectors, that all use NORM in their processes.

Support for Programme Challenge, Roadmaps, Government Strategies

This project aligns with the NMS Strategy 2011-2015 document with the aim of lowering of waste in industrial processes and in-situ monitoring for efficient processing and production. It is also part of the AIR programme strategy and Radioactivity Measurement for Environmental, Energy and Radiation Protection roadmap and the roadmap for EURAMET TC-IR that was presented to the EURAMET GA in June 2012.

Synergies with other projects / programmes

This project will build on Radioactivity Group's existing capability to generate reference standards and lead to enhanced expertise in this area. By addressing the measurement challenges encountered in NORM industries transferable skills will be developed for future use in the nuclear and environmental sectors. The contamination of ground waters by NORM from mine spoils is an area of increasing environmental concern and may be proposed as a continuing area for research in the EMRP Environmental call.

Risks

Technical risks in this project centre on the production of well characterised reference standards and calibration materials for use in diverse NORM industries. Different industries may require different material matrices making it impossible to formulate a generic standard to suit all users. This will be mitigated by the generation of at least three calibration standards for different NORM industry branches using supplied materials for accurate characterisation or by the synthetic manufacture of suitable surrogates. Testing will be performed by all the consortia NMI to ensure a metrologically sound reference standard is produced.

Knowledge Transfer and Exploitation

Dissemination of the work will be ensured by presentation of the results at scientific conferences and publication in peer-reviewed journals, coupled with the holding of workshops and attendance of other events organised by industrial stakeholders. A website for the project will be established and training on in-situ measurement techniques will be delivered by web based material and a short demonstration video/film. PTE schemes will be provided within the project for the NORM industries. By participating, NPL will strengthen its relationships with academia, industry and instrument makers and exploit routes for dissemination of new standards, reference materials, PTE schemes and training courses. The metrology developed for in-situ measurement may lead to a possible income from licencing.

Co-funding and Collaborators

This project comprises NPL's input into the EMRP MetroNORM joint research proposal . The project is led by BEV (Austria) with funded partners including CEA, CIEMAT, CMI, ENEA, IJS, NRPA, SMU, STUK, and a number of collaborators representative of Academia (IST/ITN, Univ of Natural Resources, Vienna, etc.). A wide range of NORM Industries are supportive of the project (oil and gas operators and service companies, steel producers, suppliers of by-products to the building industries, mineral refiners).

Deliverables

1	**Start: 01/06/13**	**End: 30/08/16**	
Deliverable title: Co-funding for EMRP MetroNORM			
	Start: 01/06/13	**End: 31/05/15**	
Development of reference materials and sources Selection and evaluation of NORM key-materials; Development of Reference materials and sources for laboratory use; Development of Reference materials and sources for in-situ measurement instruments; Standardisation of the reference material and standard sources			
	Start: 01/01/14	**End: 31/05/16**	
Development of measurement systems Development of an in-situ measurement system; Development of a sampling device for laboratory analysis; Creation of a standard for ^{220}Rn activity in order to assure the traceability of the measurement chain			
	Start: 01/06/14	**End: 31/05/16**	
On-site testing Specification of verification criteria and procedures; On-site / in-situ verification of measurement systems and procedures			
	Start: 01/06/13	**End: 31/08/16**	
Initial studies, Impact and Management Study of particular problems appearing in NORM key-materials (Ra-226/228 measurements); Design of measurement procedures for in-situ measurements on industrial sites; Creating Impact; Management			

Project No.	AIR/2013/R7	Price to NMO	£210k
Project Title	Development of a mobile radiochemistry laboratory (Update: TSB funding was not won)	Co-funding target	
Lead Scientist	(New appointment)	Stage Start Date	01/04/13
Scientist Team	Simon Jerome, Julian Dean, Cyrus Larijani, Maria Garcia-Miranda, Selina Woods	Stage End Date	31/12/14
		Est Final Stage End Date	2016
Sector	2.2 Pollution and waste reduction	Activity	Methodology for new capabilities

Summary

This project has been developed in response to the TSB's call for proposals to develop the civil nuclear power supply chain. The project aims to develop novel UK capabilities to provide mobile radiochemical technologies able to address requirements to quantify and report on radioactive waste materials. Parts of the TSB's call concerns developing new technology to help address 'the largest, most important, environmental restoration project in Europe' (Nuclear Decommissioning Authority 2011). Accurate measurement of radioactivity in waste materials has an important role to play in this restoration, as it enables site operators to dispose of waste in compliance with the regulations.

The Need

The UK is starting to decommission legacy nuclear sites with 'a greater sense of urgency' (NDA Strategy 2012-2015), a process that will generate vast quantities of potentially radioactive waste. Site operators are required by the Environment Agency to measure the radioactivity content of such wastes to determine appropriate disposal routes to meet the Environmental Permitting Regulations (2010) and the Low Level Waste Repository waste acceptance criteria. At present, this requires sampling, packaging and transport to specialised laboratories located off site. From the experience of the project partners and stakeholders, this is time consuming and very expensive, acting as a bottleneck to remediation programmes. Two of the major consultancy companies in the field (Nuvia and Serco Nuclear Technical Services [now part of Amec]) conducted a detailed study of the options to improve turnaround times for radioactivity measurements and concluded that part of the solution is a mobile radiochemistry laboratory. There are two significant barriers to overcome that have prevented progress: the capital investment needed (£0.5-1m) and the metrological challenge of conducting rapid, accurate, traceable measurements in a limited space.

The Solution

The proposed solution to this problem is the development of a state-of-the-art mobile laboratory for characterising environmental and construction materials on site, upgraded to incorporate novel developments in radiometrics. Not only will this significantly improve analytical turnaround, it will avoid the need to transport large quantities of radioactive material by road and rail. Specifically, Loughborough University has a mobile laboratory which can be adapted for radiochemical assays and be used as a demonstration unit. NPL will build on its existing expertise (for example, through work with various European partners on an EMRP project (Metro RWM) to automate radiochemical analyses/measurements and to develop portable 'calibration-free' instrumentation. As a result, this project brings these complementary capabilities together, developing and validating measurement methods for typical materials found on a nuclear site, and transferring these to a mobile laboratory, ultimately culminating in a new measurement service for the UK.

Project Description (including summary of technical work)

The project has six phases:

- Phase 1: Consultation with site operators and the EA/SEPA to confirm specifications for the measurements.
- Phase 2: Specification and purchasing of any additional instrumentation needed (the consortium already owns much of the equipment e.g. mobile laboratory, automatic radiochemistry system, liquid scintillation counters, sampling and sample preparation equipment).
- Phase 3: Development and testing of analytical procedures in the laboratory setting – this will include developing novel sample preparation and analysis techniques.
- Phase 4: Transfer of instruments and testing of procedures in the mobile laboratory.
- Phase 5: Testing of mobile system on a nuclear or NORM site.
- Phase 6: Reporting of results, documentation of procedures in preparation for ISO17025 accreditation.

Impact and Benefits

- The project has the potential to revolutionise the approach to characterising radioactive waste on nuclear sites, reducing turnaround times for measurements from 6 weeks to 1-2 days and avoid the need to transport samples for measurement at off-site facilities, addressing a known bottleneck in nuclear decommissioning projects.
- The total market size for radioactivity measurements in the UK for decommissioning alone is estimated at around £10 million per annum, served currently by USA and UK radioanalytical laboratories.
- The project's outputs would also have application in environmental research (e.g. investigating transport mechanisms for radioactivity in the environment).

Support for Programme Challenge, Roadmaps, Government Strategies

The main driver for this project is the Nuclear Decommissioning Authority's 2011 strategy, which states that the "the UK's civil nuclear legacy is a major public liability, and represents the largest, most important environmental restoration programme in Europe". The NDA (along with DECC and the EPSRC) has supported the recent TSB competition for research proposals aimed at developing the civil nuclear supply chain, in particular to support the development of innovative technologies for waste management (the TSB estimates the global market to be £250bn in this field over the next 20 years).The alignment of this project with government strategy is also supported by the NMS Strategy 2011-2015, which identifies the need to 'underpin remediation and ensure the safe disposal of hazardous materials'. Finally, the project aligns with the AIR Programme's strategy and Radioactivity Environmental, Energy and Radiation Protection Theme roadmap in delivering: new enabling science (in-situ assay techniques); new technologies (in-situ measurement technologies and instrumentation); and targets (in-situ, cost-effective and safe analyses to support radioactive waste management).

Synergies with other projects / programmes

The project complements and builds on the advances made in this field in the EMRP MetroRWM project.

Risks

The nuclear industry is conservative: the main risk to the project is that a novel approach to radioactivity measurement would not be adopted. These factors can be mitigated by support from the TSB, consulting the EA & SEPA throughout the project and setting up demonstrations on nuclear/non-nuclear sites. The main technical risk is the use of the novel automatic radiochemical separator. However, the partners are experienced in developing radioactivity measurement methods. To mitigate this risk further, NPL has strong links with colleagues at PTB who have also invested in the equipment.

Knowledge Transfer and Exploitation

Where appropriate, the measurement methods and new scientific capability will be disseminated through technical reports, in peer-reviewed publications or patents. NPL already maintains relationships with key stakeholders in the area of radiochemical analyses and instrumentation, which will greatly facilitate knowledge transfer. Exploitation will be through the launch of a new mobile radiochemistry measurement service.

Co-funding and Collaborators

Update: TSB funding was not won

Co-funding is being sought through the TSB Call 'Developing the civil nuclear power supply chain'. *This cofunding will provide critical mass to enable acceleration of the deliverables within 2 years; without the cofunding the project delivery will be slower, reverting to a 3 year timescale.* Collaborators are Loughborough University, the British Geological Survey and Enviras Ltd. Sellafield Ltd. and Magnox Ltd. have expressed their support for the project. In addition, we will work closely with the Environment Agency and SEPA.

Deliverables

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

User Requirements Specification

Development of a written user requirements specification, based on consultation with site operators and the EA/SEPA to confirm specifications for the measurements**.** Specification and purchasing of any additional instrumentation needed.

2	**Start: 1/07/13**	**End: 31/03/14**	

Development of new methods (laboratory based)

Development, testing, validating and documenting new analytical procedures in the laboratory setting – this will include developing novel sample preparation and analysis techniques using the automated radiochemistry system.

3	**Start: 1/04/14**	**End: 30/09/14**	

Transfer of new methods to mobile laboratory and on-site testing

Transfer equipment to mobile laboratory, devise quality control tests, and conduct on-site validation.

4	**Start: 1/10/14**	**End: 31/12/14**	

Reporting

Papers, presentations on the outcome of the project.

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Acoustics metrology projects 2014

Project No.	AIR/2014/U1	Price to NMO	£262k
Project Title	Novel detectors for enhanced ultrasound computed tomography – TSB Cofunding	Co-funding target	TSB
Lead Scientist	Bajram Zeqiri, Peter Sharpe	Stage Start Date	1 January 2014
Scientist Team	Christian Baker	Stage End Date	31 December 2016
		Est Final Stage End Date	31 December 2017
Sector	3.1 Diagnosis	Activity	Methodology for New Capabilities

Summary

Through previous work, we have demonstrated the utility of a novel NPL-conceived detection technology for Ultrasound Computed Tomography (UCT) applications, with particular reference to whole breast imaging. This project co-funds a successful Technology Strategy Board (TSB) funding application made in response to the "***Advancing in-vivo imaging for stratified medicine"*** Call. The NMO component of the project will target metrological aspects of quantitative UCT. The parallel TSB project will exploit this knowledge to build a well-characterised UCT demonstrator, undertaking a limited clinical evaluation. The three-year TSB project will start on 1 January 2014.

The Need

Reliable imaging is crucial to a range of clinical diagnostic techniques, providing essential information informing patient management and targeting therapeutic procedures. Irrespective of the applied modality (MRI, x-ray or ultrasound) there is a strong move towards **Quantitative Imaging**, where images relate to intrinsic tissue properties which may correlate with particular pathologies. This approach will assist improved identification of the onset or progression of diseases such as cancer but it crucially demands that the image is free of instrumentation-related artefacts. For ultrasound, there is significant motivation to develop UCT techniques for non-ionising whole-breast imaging, potentially replacing (x-ray) mammography. Unfortunately, ultrasound images are strongly affected by artefacts caused by differences in the acoustic properties of the various tissue components and the disruptive effect this has on the propagating ultrasonic wave. Image artefacts, leading to false positive diagnoses, fundamentally arise from the type of detectors employed within conventional ultrasound imaging systems and, in particular, the fact they are ***phase-sensitive***. There is therefore a need for a fundamentally new detection scheme, coupled with a detailed study of the measurement uncertainties involved with quantitative UCT imaging: that is, the ability to reliably associate a region of any specimen or patient with an intrinsic acoustic property, either sound speed or ultrasound attenuation.

The Solution

Through co-funding provided by NPL Strategic Research (SR) and a NIHR Invention for Innovation (i4i) Proof-of-concept Project (II-FS-0909-13081), NPL has pioneered novel ***phase-insensitive*** detectors for UCT application. The ability of these detectors to remove many of the imaging artefacts associated with conventional detectors has been proven and an early study carried out using stable polyurethane-based test objects has recently been published in *Phys. Med. Biol*. To exploit its full potential, the technique must be developed further, in terms of optimising sensor designs for response time, detection sensitivity and spatial-resolution, as well as developing a detailed ***metrological understanding*** of key factors affecting ***quantitative*** reconstruction of the acoustic properties of an object. This project will carry out this optimisation and rigorously test achievable UCT imaging performance. It involves collaboration between the Acoustics and Radiation Dosimetry Groups of AIR, and, as an example application, will address the potential of the ultrasound detectors to further develop 3D gel-based radiation dosimetric methods. The optical, acoustic and mechanical properties of these gels are sensitive to exposure to radiotherapy beams and the ability to determine the spatial variation of these modified properties could provide a means of quantitative 3D imaging of applied radiotherapy doses. Whilst optical and acoustical "readers" of dose distributions have been investigated, these have not been of acceptable performance. The need for such dosimeters has accelerated in line with the increasing complexity of radiotherapy treatments, particularly through techniques such as Intensity Modulated Radiation Therapy (IMRT). It should be noted that this radiotherapy gel application has been chosen as a **test system** providing a particularly stringent challenge for the new UCT imaging capability as there will be a need to characterise relatively small changes in gel-matrix sound speed and ultrasonic attenuation induced by exposure to radiotherapy beams. Potentially important clinical ultrasound imaging applications are also envisaged, such as the one targeted by the TSB application (whole breast imaging).

Project Description (including summary of technical work)

The project will be delivered in three Deliverables. **D1** will involve optimising the response of the pyroelectric detectors for UCT application. The detectors, which will be large-area to mitigate the effects of acoustic refraction, will be manufactured from thin films of polyvinylidene flouride (*pvdf*), backed with a material which is highly absorbing to ultrasound. In order to achieve higher acoustic frequencies than the current 2 MHz, due to the increasing attenuation of material with frequency, there will be a need to increase the detection sensitivity of the method. Currently, this is limited by the low frequency piezoelectric response of the *pvdf*, which means that detection is significantly compromised by the effects of background environmental vibrations. Mitigation strategies will be developed to reduce these effects. Enhanced detection electronics will also be developed in order to boost sensitivity, which will be pivotal in achieving the objective of **D1** which is to significantly increase the speed of UCT scanning. Developed phase-insensitive detector configurations will be tested using existing facilities and capabilities. **D2** will involve designing, building and commissioning a UCT scanning platform. This will involve a central platform positioning the object to be scanned, around which an ultrasound transmitter and single or multiple pyroelectric detectors are deployed. Automatic scanning capability will enable the transducer and pyroelectric detectors to be rotated and appropriately translated around the interrogated object; through-transmitted data being acquired under PC control. The developed platform will be fully tested as a part of **D3** through measurements on a range of test objects: from the simple polyurethane phantoms developed under previous projects (NIHR i4i; Project II-FS-0909-13081); commercially available breast phantoms and the irradiated radiotherapy gels. For the latter, the Acoustics and Radiotherapy Groups within AIR will collaborate to identify suitable gel materials, irradiation levels and protocols. A number of reference test plaques will be irradiated and tested using NPL facilities for determining speed of sound and ultrasound attenuation in order to establish detection limits.

Impact and Benefits

The project, in terms of the development of phase-insensitive sensors, will support the application of ultrasonic imaging in clinical and industrial sectors. This will result in improved potentially operator independent diagnosis, lower false positives, and savings to the health service from fewer biopsies, as well as reduced patient trauma. There are also a number of benefits of the project in terms of the development of new instrumentation targeted at verifying 3D dosimetry distributions, the development of new gels and the establishment of optimised UCT methodologies. This should result in better targeting of radiotherapy doses and enhanced confidence in treatment planning.

Support for Programme Challenge, Roadmaps, Government Strategies

The proposed project is very well aligned with the respective Roadmaps for the Medical Ultrasound area (through Quantitative Imaging Techniques) and Radiation Dosimetry area (Complex fields). It is also consistent with National Measurement Strategy (2011-15), in particular the *"…. need to introduce more efficient clinical practices, and (early) prognostic and diagnostic techniques, therapies and assistive technologies for deployment in the hospital, surgery and home environment, both to meet patient needs and to improve value for money*". The NMS Strategy also states that *"These new practices and technologies must be validated as safe and effective"*, which involves developing confidence in 3D distributions of radiation in complex treatments. The project will also *"Support the optimisation of … technologies in clinical practice"* and, longer term, *"Develop measurement protocols and standards to enable infectious disease detection technologies to be deployed and utilised with confidence"*.

Synergies with other projects / programmes

The project augments current research within the AIR programme exploiting NPL's novel pyroelectric detection capability (AIR/2012/A14 and NMS/AIR13006). It also builds on previous proof-of-concept UCT work funded by NPL SR and NIHR i4i.

Risks

Previous funding through NPL SR and NIHR i4i established proof-of-concept for the application of the new detectors to UCT, so the risks reside in whether the detectors can be made sensitive enough, and the UCT capability fast enough and of sufficient spatial resolution, to enable the contrast in the acoustic properties of materials within a test object to be differentiated. Risks are considered to have a medium impact and will be mitigated through careful detector design, underpinned by modelling. For the TSB project, where the aim is to scan volunteers, the technical risks for imaging are considered to be high, hence the need for TSB funding. Ethical issues for the TSB project will be addressed by the clinical partner, University Hospitals Bristol.

Knowledge Transfer and Exploitation

Primary routes for dissemination of the science outputs will be through peer-reviewed publications and presentations at scientific conferences. A whole range of exploitable products are possible. IP, related to implementing UCT techniques using phase-sensitive pyroelectric detectors, of both hardware and software, in terms of the algorithms used, should be developed. If the TSB funding application is successful, it will be a key development in moving the technology towards a clinical device, and we will seek to secure manufacturer interest. Quantitative aspects of the imaging could promote spin-off developments such as anthropomorphic phantoms of well-specified properties. Industrial applications of the new imaging capability are also likely.

Co-funding and Collaborators

The three-year TSB project involves collaboration with Precision Acoustics and University Hospitals Bristol. In the TSB project, a UCT-based system will be developed and tested, and used for a limited number of whole breast scans on patients or volunteers. It is envisaged that this will open up further co-funding opportunities to develop prototypes leading to more extensive clinical trialling, potentially NIHR funded.

Deliverables

1	**Start: 1/1/2014**	**End: 31/12/2014**	
Deliverable title: Optimised phase-insensitive detector scheme designed; detectors fabricated.			
2	**Start: 1/1/2015**	**End: 31/12/2015**	
Deliverable title: Designed and commissioned phase-insensitive Ultrasonic Computed Tomography (UCT) scanning platform, employing transmit transducer and pyroelectric detector arrays.			
3	**Start: 1/10/2015**	**End: 31/12/2016**	
Deliverable title: Evaluation of phase-insensitive UCT performance through imaging of various standard Test Objects, including polymer gels and clinically relevant phantoms, as evidenced by at least one scientific paper submitted to peer-reviewed journal.			

Project No.	AIR/2014/U2	Price to NMO	£132k
Project Title	Exploiting photoacoustic (PA) techniques	Co-funding target	
Lead Scientist	Bajram Zeqiri	Stage Start Date	1 July 2014
Scientist Team	Srinath Rajagopal	Stage End Date	31 December 2015
		Est Final Stage End Date	31 December 2018
Sector	3.1 Diagnosis	Activity	Methodology for New Capabilities

Summary

Photoacoustic Imaging is a rapidly accelerating biomedical technology providing high resolution optical absorption-based images of tissue. It involves the absorption of modulated high-intensity optical (laser) radiation within tissue and detecting the *acoustic radiation* generated by the rapid expansion of the heated region. Although the degree of heating is calculated to be very small (0.01ºC – 0.05ºC), subsequent thermal expansion occurs so quickly that broadband high frequency acoustic signals are generated. Detecting the spatial and temporal distribution of these signals provides the basis of PAI. The proposed research will establish an exploratory capability having two specific themes. The first of these will investigate applying Photoacoustic (PA) generation to ultrasound metrology. Of particular interest is the ability of PA to generate broadband acoustic signals which might be applied to high frequency hydrophone calibration and also to determining material properties: measurements that are extremely difficult to make using conventional piezoelectrically generated acoustic signals. The second, longer-term aim is to develop expertise within the emerging PA area, scoping the metrological requirements needed to support development of these techniques, which have applications over a range of areas: intravascular, microscopic, functional and molecular imaging, as well as therapy.

The Need

There is increasing use of high frequency ultrasound (> 50 MHz) tissue imaging techniques, driven by the greatly enhanced spatial resolution they provide. Characterising the applied acoustic fields requires measurements made using detectors which have been calibrated at the frequencies of interest. Generating suitable broadband plane-wave acoustic calibration fields of sufficient acoustic pressure amplitude is very challenging above 50 MHz, and alternative approaches are required. One possibility is to harness Photoacoustic (PA) generation techniques. PA involves the absorption of modulated high-intensity optical (laser) radiation within a material and detecting the *acoustic radiation* generated by the expansion of the heated region, which occurs so rapidly that broadband high frequency acoustic signals are generated. Although the PA effect has been known for over 130 years, advances in technology have meant that its application for clinical imaging have only recently emerged, particularly over the last decade. Photoacoustic Imaging (PAI) is a hybrid modality, powerfully combining the ***enhanced contrast*** and ***spectroscopic-based specificity*** of optical imaging with the ***high spatial resolution*** of ultrasound imaging. In essence, a PA image can be regarded as an ultrasound image in which the tissue contrast depends on the optical absorption properties of the material. The quality of the image, and therefore the quantitative information which it may yield regarding the specimen under test, depends critically on the broadband nature of the acoustic detection system. Commercial systems used for pre-clinical imaging, and scanning of the breast to tissue depths of a few centimetres, are already commercially available and the potential for further developments is significant. Metrology can play a key role in the technology pull-through.

The Solution

This proposal aims to start NMO-funded activity in this area and has two objectives: (i) to exploit PA technology for establishing and disseminating hydrophone calibrations at high acoustic frequencies and (ii) to scope the role of metrology in supporting the development of clinical PA techniques. Relevant to the AIR programme, the high-frequencies of the acoustic signals generated by the photo-acoustic conversion process will provide opportunities for high frequency hydrophone calibration and materials characterisation, as well as quantitative imaging of properties. The aim will be to construct an experimental measurement facility, undertaking a range of studies to assess the most effective means of generating appropriate broadband, high amplitude acoustic signals required for hydrophone calibration and for tissue-mimicking material property assessment (attenuation and speed of sound). This research will lay the foundation for potential future Discretionary projects whose aim will be to disseminate developed capabilities.

Project Description (including summary of technical work)

The project will be delivered through two Deliverables. The first (**D1**) will undertake an extensive review of the technical field. This will be done through a wide-ranging literature search, visits to key centres, and attending appropriate scientific conferences. The review will (a) assess the way in which PA techniques can be exploited to address current ultrasound metrology issues and (b) establish how the developing capability might be applied in other areas metrology, for example, molecular and functional imaging. **D1** will culminate in an NPL Report summarising the major review findings and identifying a strategy for developing the area, if appropriate. **D2** will establish an experimental test bed, whose specification has been formulated from the **D1** review and optimised in terms of the ability to generate appropriate acoustic signals. This will involve the irradiation of identified, primarily homogeneous materials, with an appropriate optical source, and detecting emitted acoustic radiation using broadband detectors. PA sources may be as simple as a small region of optical absorber supported on a thin membrane. Theoretical treatments of the PA process will be reviewed to enable the acoustic pressure waveforms to be predicted, and tested through measurement. With NPL's range of hydrophones, and calibration capability up to 50 MHz, we are well positioned to record the acoustic pulses in absolute terms, and test how they vary with sample properties, propagation distance and laser properties. Research activities will be heavily guided by modelling, coupled with materials property measurements.

Impact and Benefits

The project will underpin the development enhanced calibration services for hydrophone calibration and materials properties above the current 50 MHz limit. Beyond this, subject to the findings of the scoping Review (D1), the project may be the first step to developing an important new work area within the AIR Programme enabling the capability of photoacoustics to generate high frequency acoustic radiation to be exploited. More widely, applications of PA are growing rapidly with clinical instruments starting to appear. Despite the potential for improved diagnosis and monitoring of patient disease, there remain major science questions to address to convert the spectacular high-resolution images reported in the literature to ***quantitative evaluation*** of tissue properties and through this, improve clinical diagnostics. The research described constitutes the first step in underpinning better diagnostic and therapeutic applications of PA technology, through establishing appropriate metrology.

Support for Programme Challenge, Roadmaps, Government Strategies

The project is very well aligned with the Roadmap for Medical Ultrasound (through Quantitative Imaging Techniques). It is also consistent with National Measurement Strategy (2011-2015), in particular the *"… need to introduce more efficient clinical practices, and (early) prognostic and diagnostic techniques, therapies and assistive technologies for deployment in the hospital, surgery and home environment, both to meet patient needs and to improve value for money"*. The project will *"Support the optimisation of … technologies in clinical practice"* and, longer term regarding the development of potential clinical imaging systems *"Develop measurement protocols and standards to enable infectious disease detection technologies to be deployed and utilised with confidence"*. It will also support the development of new clinical techniques. The work aligns well with the Metrology 2020s Vision for *"A Healthy population"*, especially the reference to quantitative differential diagnostics and imaging, and with NPL's strategy on *"Measurements and modelling to characterise atoms, molecules, bio-systems and materials"*.

Synergies with other projects / programmes

It is anticipated that establishing a PA capability will be important in developing applications relevant to a range of areas of the NMO Programme portfolio particularly within the biomaterials areas, e.g. for applications such as molecular imaging and the characterisation of soft, tissue-like materials. Capability established through this project will be exploited through submissions to the Innovation R&D NMO Programme. NPL recently won an EPSRC CASE Studentship with UCL which will address quantitative PA imaging and this proposal will provide a modest platform for NPL's first involvement in the area. UCL have been pioneers in the area of PA. The objective of the UCL project is to demonstrate that accurate 3D quantitative PAI can be achieved, thereby vastly widening its potential range of applications. This project will support the greater integration of NPL staff into the UCL project and access to their expertise. TSB has declared an interest in supporting work related to medical imaging, specifically citing PA.

Risks

Although this is strongly exploratory work, risks are considered to be small. D2 will establish the experimental platform which allows samples to be subjected to optical irradiation and the generated acoustic emissions to be detected, and there is a slight risk that an inappropriate system will be developed for study of the phenomena in terms of materials and laser properties, but this will be readily mitigated through the literature review, the scoping part of the review and discussions with UCL (D1).

Knowledge Transfer and Exploitation

It is likely that the research, beyond the time-frame of the current project, will meet customer requests for enhanced hydrophone calibration Measurement Services, extending up to at least 80 MHz. An important dissemination route will be through presentations and peer-reviewed publications. The aim will be to present the results of the work at a major international conference during the second year of the project. Longer-term, in parallel to this project, we will look to exploit the new capability across the NMO Programmes. This will demand a genuine multidisciplinary approach: acoustic, optical & bio-materials. Within this new area of research, there will be ample opportunities to generate traditional scientific outputs, such as collaborative publications and presentations, along with longer-term potential to develop IP within a rapidly developing field.

Co-funding and Collaborators

The primary collaborator within the project will be UCL, and this project will increase the level of interaction between NPL and UCL staff which is anticipated as part of the EPSRC CASE. Although the topic areas of the CASE PhD and the proposed project are complementary with a small overlap, it is envisaged that the Student would spend between and 3 to 6 months at NPL to assist in setting up and evaluating the performance of the new test platform developed through D2, providing in-kind co-funding. During D1, it is anticipated that the detailed review process will expedite interaction with other key research groups.

Deliverables

1	**Start: 01/07/2014**	**End: 28/02/2015**	
Deliverable title: Review of emerging Photoacoustics field completed and strategy for exploiting metrological capability identified and summarised in an NPL Report			
2	**Start: 01/02/2015**	**End: 31/12/2015**	
Deliverable title: Photoacoustic generation and detection platform commissioned, broadband acoustic emission measurements undertaken as evidenced through a submitted peer-reviewed publication			

Project No.	AIR/2014/U4	**Price to NMO**	£75k
Project Title	New measurement methods for kHz frequency ultrasonic cleaning systems (Note: Deliverable 2 not contracted)	**Co-funding target**	
Lead Scientist	Bajram Zeqiri	**Stage Start Date**	1 January 2014
Scientist Team	Mark Hodnett, Lian Wang	**Stage End Date**	30 June 2015
		Est Final Stage End Date	30 June 2015
Sector	6.3 Advanced instrumentation & sensors 3.3 Health & safety	**Activity**	Methodology for New Capabilities

Summary

The project meets the measurement/QA needs of the UK user base in established, yet empirical, ultrasonic cleaning processes (healthcare, automotive) with an objective assessment of candidate sensor technologies, underpinned by NPL's unique cavitation capabilities. The project builds on an NMO-supported platform, which has been pivotal in developing unique reference cavitating facilities, novel measurement devices, and providing support for dissemination of the cavitation research results through standardisation routes (IEC). These measurement findings for established low-frequency cleaning systems will be disseminated through highly-accessible routes, ensuring rapid and widespread take-up. The project then applies the outcomes to design and build new measurement methods to address the rapidly-emerging need for QA devices in MHz-frequency cleaning systems, applied in advanced manufacturing industries (optics, high value manufacture, microelectronics).

The Need

Ultrasonic cleaning is a £2.7bn pa business worldwide, and around £80m in the UK, covering surgical instrument cleaning throughout the NHS and in areas such as automotive and aerospace components manufacture. Its numerous users and manufacturers require repeatable, reliable and traceable real-time measurement methods and tools to acoustically characterise their ultrasonic cleaning systems. Several commercial solutions claiming to offer this capability are available but, as there is a deficit of specification standards, these differ greatly in performance, with considerable variation seen in ultrasound-generated field maps, and no consensus on what parameters to measure. Existing devices are generally applicable to vessels operating up to 150 kHz, whereas precision cleaning applications (for fine wire printed circuit boards (PCB's, a £7.5bn industry in Europe alone), optical components and microelectronics wafers) are developing rapidly towards MHz frequencies. MHz cleaning is believed to operate differently from kHz systems: collapsing cavitation bubbles are accompanied by streaming effects, and hence this presents a significant metrological challenge for acoustic measurements, with downstream effectiveness then assessed by particle removal efficiency (PRE). PRE is critical to the in-service performance of the resulting microelectronics devices. This project will address both the lack of consensus in commercially-available devices and the deficit of acoustical measurement (for QA & device development) methods for MHz cleaning systems, by applying NPL's multi-frequency reference vessel and cavitation sensors to compare candidate measurement devices, and to design, build and test new measurement methods, potentially correlated with PRE, specifically addressing so-called Megasonic cleaning.

The Solution

Following protocol development, commercially-available ultrasonic cleaning system probes, NPL's cavitation sensor and additional measurement methods (e.g. sonochemical yield) will each be tested in spatially-variant cavitation fields up to 140 kHz using NPL's reference vessel facilities. In consultation with IEC TC87 WG3, the findings will be used to propose standard definitions for cleaning system characterisation, and the sensor performances compared against the developed criteria.

An experimental scoping study will then be carried out of the measurement requirements for MHz-frequency (Megasonic) cleaning systems and from this, a specification drawn up and sensing techniques developed. This is likely to require new materials development, and will draw on experiences and progress in the medical ultrasound area. The resulting concept will be tested in reference fields and commercial MHz cleaning systems, and trialled with industrial users in the PCB sector.

This project will be carried out through extensive collaboration with vessel and sensor manufacturers (and trade associations, such as in the PCB industry), providing a thorough review and objective assessment of the state of the art, and the development of a new measurement capability for Megasonic cleaning systems. Collaboration within NPL is likely on PRE and surface damage.

Project Description (including summary of technical work)

- Existing contacts (Ultrawave, Waters Corporation) will be leveraged to supply typical benchtop ultrasonic cleaners (kHz and MHz), providing 'real' systems alongside NPL's unique reference cavitation vessels. Representative commercial cleaning system probes (Onda MCT/HCT, ppb, Elma etc.) will be purchased or, loaned, and a testing protocol generated;
- The procured probes (and a 'user-level' method, e.g. Sonocheck vials) will be characterised in at least four frequency cavitation fields up to 140 kHz, alongside measurements made with NPL's new generation cavitation sensor (115682/A17). The results will then be used to produce draft definitions for an IEC TC87 WG3 document, and the data critically analysed against the draft parameters, and a Good Practice Guide produced, comparing their findings;
- Existing sensors will then be used to test the MHz-frequency cleaning fields, and their performance evaluated against the IEC criteria drafted above: this will generate the specification for new sensors and methods;

- Prototype new sensors will be developed in collaboration with Precision Acoustics/Onda, calibrated using NPL's secondary standard facilities, and then tested in the MHz-frequency cleaning fields;
- Collaborations with the electronics manufacturing industry / user base will then enable the sensors to be tested in real world environments (at least two prototype systems will be manufactured for trial); and NPL's Materials team will evaluate, for the first time, correlations between cavitation dose and particle removal efficiency (PRE).

Impact and Benefits

Successfully completing the project will provide an objective assessment of commercially available ultrasonic cleaning devices, underpinned by identification of standardisable and eventually potentially traceable parameters. The findings will be promoted to the user community as Good Practice (from Deliverable 1), enhancing cleaning vessels and system performance and consequently improving, for example, patient safety. Devices and methods for characterising megasonic cleaning applications will develop new science, and advanced new measurement capability for NPL, extending the scope of the present measurement device and service portfolio, providing cavitation detection capability at much higher frequencies for the megasonic user base. Research will support the establishment of enhanced Consultancy Services and Measurement Services related to the use of the developed sensors and facilities. NPL's internationally-leading position in cavitation metrology will be further enhanced by the MHz-frequency cavitation sensing capability, and the trial phase will provide UK equipment manufacturers and users with access to objective assessment tools for the application of cavitation, primarily for the manufacturing sector.

Support for Programme Challenge, Roadmaps, Government Strategies

Advanced Manufacturing – Process Control and Instrumentation. The project is strongly aligned to the NMO Roadmap "*Metrology for industrial applications of ultrasound*", with particular relevance to the Deliverables "*Reference sensors and methods for measuring acoustic cavitation*", "*Robust methods of quantifying cleaning ability appropriate at the industrial level*" and the Technology "*Novel robust sensors for cavitation detection*". Through supporting high value, traceable manufacturing of nano-scale structures in PCB's, it fits the Measurement Priority: Growth Challenge in the NMO's *2011-2015 Strategy for the NMS*.

Synergies with other projects / programmes

The project directly builds upon existing NMO Projects NMS/AIR1201101 (A16) and NMS/AIR1201201 (A17), which are developing facilities for researching cavitation measurement units, and new reference and user-focused (semi-quantitative) methods for cavitation fields (at low frequencies) respectively. AIR1201101 (A16) also offers early testing of the protocol through the bilateral EURAMET intercomparison with PTB. The project will use existing reference facilities maintained under NMS/AIR1300402 (A4). It will benefit from the MHz-frequency cavitation threshold research ongoing in the fully-funded EU R4SME project AlgaeMax, and the cavitation dose (Work Package 2) in the EMRP DUTy project.

Risks

The assessment of kHz-frequency measurement devices against defined protocols is low risk, because of the established reference cavitating systems used as the test bed: the objective comparison should also rapidly lead to consensus within IEC TC87. Developing new sensors and methods for MHz- frequency cleaning systems is of medium risk, mitigated by the unique experience NPL has in developing gold-standard hydrophones and cavitation sensors, the calibration facilities to understand their performance, and the partnerships with Precision Acoustics and Acoustic Polymers Ltd. Take up of the developed protocols and Good Practice findings will be maximised through IEC TC87 WG3 (NPL holds the WG convenorship), through the Ultrasonic Industry Association, and through strategic conferences, Open Access journals and trade publications.

Knowledge Transfer and Exploitation: The first stage will, uniquely, provide extremely valuable objective data from commercially-available characterisation devices, and this will be disseminated to the user base, with access maximised through an NPL Good Practice Guide for kHz cleaning system characterisation (online), a peer-reviewed paper submitted to an Open Access Journal, and a webinar, targeting contacts through the KTN's, Ultrasonic Industry Association and IEC TC87 WG3. Take up will be measured through GPG downloads, paper accesses and webinar attendees, as well the take-up of new Consultancy and Measurement Services. The development of new sensor methods for MHz systems will primarily be disseminated through peer-reviewed publication and an international conference presentation or poster, and a targeted trade press article. It is highly likely that sideground and foreground IP will be generated in the MHz frequency development, and this will be protected as required, with license opportunities established through current and new routes-to-market.

Co-funding and Collaborators: Co-funding will be actively sought. Ultrawave and Waters Corporation will be collaborators, contributing expertise, cleaning vessels and access to characterisation devices. Current user base contacts in the electronics and high value manufacturing industry (STI, Cooknell) will form part of the trialling phase. Precision Acoustics and Acoustic Polymers Ltd will provide in-kind support in sensor design and manufacture.

Deliverables

1	**Start: 01/01/2014**	**End: 30/06/2015**	

Deliverable title: Submitted peer-reviewed paper, Good Practice Guide, and webinar on kHz cleaning system characterisation.

2	**Start: n/a**	**End: n/a**	

DELIVERABLE 2 NOT CONTRACTED: - Submitted peer reviewed paper, conference presentation and trade press article describing megasonic cleaning system characterisation and completed industrial trial.

Project No.	AIR/2014/U5	**Price to NMO**	£125k
Project Title	Correlated flow cavitation sensors	**Co-funding target**	
Lead Scientist	Mark Hodnett	**Stage Start Date**	1 October 2014
Scientist Team	Bajram Zeqiri, Graham Beamiss	**Stage End Date**	30 September 2016
		Est Final Stage End Date	30 September 2016
Sector	6 Advanced Manufacturing and Services	**Activity**	Methodology for New Capabilities

Summary

Although cavitation in pumps is commonplace, causing damage and wasting electricity, methods applied by industry to detect it are based on shaft condition monitoring or vibration, or its consequences are simply ignored, and the pump periodically replaced. This project, building on previous NMO-funded research (AS002AO506), will apply multiple sensors to the developed pump rig, and begin to correlate their outputs with optical observations of within-pump cavitation, subsequent generated cavitation-induced erosion and the impact cavitation has on energy efficiency. The project harnesses and refocuses expertise in the acoustic cavitation area (NMS/AIR12012 (A17)) to apply broadband acquisition and signal analysis and, in a novel dissemination approach, generate an interactive online Good Practice Guide to demonstrate the significant effects of cavitation in flow systems.

The Need

The UK pump manufacturing industry is estimated by the British Pump Manufacturer's Association (BPMA) to generate £900m per annum, and the UK is a net exporter of pumps. It is a widely-acknowledged problem that cavitation occurs readily in most pumped systems, often due to new pumps being interfaced to ageing pipework, or over-cautious system specification. Cavitation causes casing and impeller erosion, and can result in pump lifetimes of 3 months or less. In many applications, cavitation damage to pumps is just accepted, and 'engineered around', and frequently this involves replacement of expensive capital equipment on a yearly basis, increasing significantly the lifetime costs of a flow system. The energy usage figures for pumps are staggering - BPMA estimates that 12%-20% of the UK's electricity is consumed by pumps. Cavitating pumps clearly run inefficiently, and so the application of validated metrology would improve design, installation and longevity, and potentially provide significant energy and cost savings. Cavitation is presently detected by changes in Net Positive Suction Head or by indirect techniques such as shaft and bearing vibration monitoring, but these frequently indicate a fault condition well after establishment.

Specifically, there is a clear requirement to provide spatially-sensitive cavitation detection methods that will pinpoint the location of cavitation, so improving assessment and ultimately supporting prediction and management of damage. This will also enable users to correlate the operating flow conditions with cavitation inception, and to monitor its subsequent extent. These detection methods should be developed such that they may be retro-fitted to existing systems, used as diagnosis tools, and applied to new installations.

The Solution

The project will build on previous NMO work (which developed and characterised remotely-coupled pump cavitation detection methods, and commissioned a reference flow cavitation system) and incorporate recent proof-of-concept work in sensor, coupling and instrumentation development, to deploy multiple acoustic sensors around the pump and valves in the existing pump loop. Using newly-developed PC-based multi-channel sensing electronics, and NPL's 330Mfps high speed camera, systematic tests will be carried out to determine the development and extent of cavitation within the pump loop, and to directly correlate this with throughput measures of energy efficiency and damage assessments (mass loss, visible inspection). Through previous research, NPL has demonstrated that occurrence of damaging cavitation shows a strong correlation with the emission of acoustic shock-waves whose frequency content contains components significantly beyond 1 MHz. A Patent has been filed covering the detection of these high frequency signatures of damaging cavitation. It should be noted that the current project proposal is targeted at demonstrating the potential of the detection method against alternative measures, including erosion. A logical, strongly collaborative second stage, which lies beyond the scope of the current project (potentially a TSB project, with NMO co-funding) is envisaged, to trial the technique directly with industrial partners (e.g. from the aerospace, water and power-generation industries), culminating in dissemination to a wider audience. The feasibility of a wireless network approach to sensor integration will be considered.

Project Description (including summary of technical work)

- Modify existing/procure new pump to provide transparent window adjacent to impeller, enabling illumination and optical bubble detection using conventional and high speed (330Mfps) cameras, to investigate cloud collapse locations and assess surface events with high time resolution. The pump impeller mounting will also be modified to allow simple removal and replacement
- The CaviSuite software and capture hardware developed under NPL Proof of Concept funding will be upgraded, to facilitate correlated multi-channel cavitation detection around pump and flow rig hardware
- In collaboration with Acoustic Polymers Ltd, novel injectable couplant materials will be developed, and existing piezo

sensors and transducers modified to incorporate the couplant deployment method

- Implement volume flow metering and incorporate energy consumption hardware
- Generate a test protocol, and execute energy efficiency studies for water pumping, for a range of flow conditions, under continuous monitoring
- Assessment of candidate techniques of monitoring degree of erosion, implementing most appropriate technique within the pump cavitation detection facility and correlating results with secondary methods such as acoustic emission;
- Develop concept for wireless sensor cavitation monitoring approaches, to proof-of-concept stage

Impact and Benefits

The project will develop a detection method for assessing the inception, establishment and impact of cavitation in pumps and, through peer-reviewed publication and collaboration, will disseminate NPL's flow cavitation measurement capabilities to the user community. This will ultimately provide users with reliable methods for use with new and existing pump installations for initial diagnosis, monitoring and efficiency assessment, where it is estimated that 10%-15% energy savings may be made through detection of cavitation and consequent reduction in operating conditions. Take-up of the methods, facilitated by the provision of a Good Practice Guide, should lead to improvements in pump specification with consequent financial benefits to industry.

Support for Programme Challenge, Roadmaps, Government Strategies

Advanced Manufacturing – Process Control and Instrumentation. Here, it is strongly relevant to the NMO Roadmap "*Metrology for industrial applications of ultrasound*", Target "*Validated sensors for acoustic and hydrodynamic cavitation monitoring*" and the Deliverable "*Reference facilities for acoustic and hydrodynamic cavitation*". Through providing the tools for improving efficiency, it fits the Measurement Priority: Energy Challenge in the NMO's *2011-2015 Strategy for the National Measurement System*, to "*Assist the drive towards greater energy efficiency through measurement research*"

Synergies with other projects / programmes

The measurement hardware and software will benefit from developments in the acoustic cavitation area: specifically the proposed project U4, and existing projects NMS/AIR1201101 (A16), NMS/AIR1201201 (A17) and NMS/AIR1300402 (A4), the latter of which specifically ensures that the pump rig is available for use.

Risks

The most significant risk, assessed as medium likelihood and impact, is the availability and longevity of a bespoke/modified pump with optical access. Transparent volutes have been manufactured and used successfully by researchers in particle image velocimetry (PIV) flow assessment (http://www.lfm.polimi.it/research/unsteady.php), and pump health monitoring demonstrations, and so collaborations will be investigated to maximise the chances of success. Optical access to the pump interior may also be achieved obliquely through the inlet and outlet flows.

Knowledge Transfer and Exploitation

Early in the project, contact will be made with the Pump Centre (UK), to identify dissemination and exploitation routes to their membership (likely to be via conference presentation and a newsletter article). The multi sensor approach will be exploited to generate an interactive web guide, which could potentially be configured to update and display data in real time, so giving interested users the opportunity to view energy efficiency data and cavitation detection results directly (providing targeted statistics on knowledge transfer, through monitored page accesses). The collated data will be used to generate a Good Practice Guide, and a peer-reviewed paper for journal submission (potentially to Wear). Any new IP generated will be reviewed for any protection needed, and then exploited with collaboration partners.

Co-funding and Collaborators

Opportunities for co-funding will be actively sought. The Pump Centre, IDEAS Ltd, Eaton Aerospace and a UK pump manufacturer are potential collaborators, providing expertise on industrial applications and helping to maintain a user focus. Acoustic Polymers Ltd will provide in-kind support and development in the couplants work, building on previous collaborations with NPL in the acoustic emission area. A validated detection methodology would provide the basis for a future TSB project built around industrial trialling. A number of implementations of the acoustic emission detection methods are envisaged, from direct in-line, to an externally applied "cavitation" stethoscope which can be pushed against a relevant fixture. The most appropriate route for disseminating the generated instrumentation would be through Licence arrangement with appropriate equipment suppliers.

Deliverables

1	**Start: 1/10/2014**	**End: 30/9/2016**	

Deliverable title:

Submitted peer reviewed paper and conference presentation describing systematic studies of correlated sensors and methods. Interactive web guide, demonstrating to users in real time the effects of cavitation.

Project No.	AIR/2014/SA2	Price to NMO	£280k
Project Title	In-situ acoustic measurement and calibration	Co-funding target	
Lead Scientist	Richard Barham	Stage Start Date	1 January 2014
Scientist Team	Richard Barham, Richard Jackett, Ben Piper	Stage End Date	31 December 2016
		Est Final Stage End Date	31 December 2016
Sector	2 Environmental sustainability 6.3 Advanced instrumentation & sensors	Activity	Methodology for New Capabilities

Summary

Permanently deployed noise measurement systems including full integration into its surroundings where appropriate, is part of noise futures scenarios being considered in government (DEFRA) and industry. This proposal is to develop and trial an in-situ calibration capability for maintaining traceability of embedded noise measurement systems, as traditional return-to-base calibration is not possible. In-situ calibration will be evaluated by developing and deploying a demonstrator system in collaboration with industrial partners, in an application chosen for the quality of the impact and benefits that can be yielded.

The Need

The current approach to acoustic measurement, of having a skilled operative calibrate and then conduct measurements with a sophisticated hand held analyser, and then provide an interpretation of the results, is becoming increasingly uneconomical, and modern disruptive approaches are under consideration. The vision for the future sees the use of permanently installed systems of sensors (microphones and other types of sensor) continually providing data to a generic data repository (such as the cloud) where it is automatically analysed and interpreted to provide the user with resulting implications or actions, rather than simply reporting the measurements themselves. The hardware building blocks for such systems already exist, but a **new approach to calibration and traceability is a vital requirement** for the effective realisation of this vision and the UK NMS needs to respond with new solutions founded on robust metrology. Low cost sensors provide significant scope for permanently installed or even fully embedded noise monitoring systems. Inherent in this vision are intelligent sensor networks that are self-configuring and autonomous in their operation, providing a 'deploy-and-leave' solution. In-situ calibration is therefore essential to fully realise the economic benefits and usability. Whether systems in the future are fully integrated into their environment or remain stand-alone, overcoming the need for regular human intervention to facilitate traceability removes significant operational costs.

The Solution

NPL has developed a lab-based system demonstrating the concept of true acoustic in-situ verification of traceability, using multi-element transducers. As the next step towards the long-term vision of permanently installed noise measurement systems, the concept is now ready for further development as a practical system suitable for widespread deployment indoors or outdoors and remote operation. So far the solution has been based on closely spaced clusters of transducer elements operating as a single sensor. However, using recent developments in understanding the performance of miniature acoustic transducers in the ultrasound region and as transmitters, there is now scope to extend functionality to short-range mutual calibration across locations. An embedded system demonstrator will therefore be developed, and in collaboration with key users, deployed in selected real-life measurement applications chosen for the scale of impact and benefits that can be demonstrated. This demonstrator system will illustrate the in-situ calibration concept and the potential for the system to maintain its traceability over extended periods limited only by the ability of the sensors to continue to function effectively. There is likely to be many aspects of the work concerning the handling and management of the 'big data; sets generated by such networks, such as exploiting redundancy to monitor long term changes in the sensors. These aspects are covered by a separate project in the NMO IRD Programme (see **Synergies** below) which is highly likely to be funded, and in which acoustic systems feature as case studies.

Project Description (including summary of technical work)

Delivery will be by applied research and field trial of a demonstrator system, involving the following activities:

- Transform lab-based self-calibration techniques for use in-situ
- Develop electronics to implement 'on-board' self-calibration
- Consult with user communities to identify application offering potential for high impact
- Select measurement location and evaluate integration requirements, and associated measurement requirement
- Specify system (from above), and produce laboratory mock-up to optimise performance
- Install and operation of the system at the chosen location
- On-going evaluation of system performance and generated data

Impact and Benefits

The need for daily calibration of the equipment that must be carried out by the user, and regular return-to-base calibration, places considerable constraints on the deployment of instrumentation and the number of sensors that can be considered in building measurement systems. A means of self-calibration in-situ overcomes these constraints and releases the potential for innovation in environmental noise management, urban and transport infrastructure planning, management of built environments, residential and commercial construction, acoustic design of product and machinery, and other routine noise measurement applications. Making such systems accessible to non-specialists by taking an *expert systems* approach (in which self-calibration is a vital part) also leads to wider exploitation of acoustic measurement in applications that have yet to consider the related benefits, or where the cost-to-benefit ratio has previously not been favourable. These benefits include availability of rich data sets on noise, in real-time if required, addressing growing public expectation for the general availability of data affecting aspects of daily life, of which exposure to noise is widely recognised. As a result of autonomous permanently deployed systems, noise measurement becomes both affordable and available to non-specialists users. Knowledge extracted from the data may be used for many purposes, but is generally aimed at noise mitigation. Ultimately, a proliferation in noise measurement informs and improves action planning which in turn leads to a more favourable environment for the population.

Support for Programme Challenge, Roadmaps, Government Strategies

The project will support the NMO's developing roadmap on *Sound-in-air metrology* in the areas of **novel measurement systems addressing emerging requirements**, and **driving innovation in exploitation noise measurement**. It also aligns with the EURAMET TC-AUV roadmaps. Two of the four Metrology2020 themes, namely, **smart and interconnected world** and **embedded and ubiquitous measurement,** and two of the application areas, namely, **a healthy population** and **managing key resources and infrastructure** will benefit from the embedded system approach to noise measurement. In-situ calibration is also highlighted as a priority in this NMO strategy. Noise, and particularly the health effects and associated economic impact, is a particular concern of DEFRA, whose Noise Policy Statement for England has a vision to promote good health and quality of life through the management of noise. A recent DEFRA meeting on Noise Futures identified scenarios featuring the vision for noise measurement indicated in **The Need** above. The Health Protection Agency has also recently added noise to its remit and is actively developing strategies to better understand and quantify noise related health effects. Permanently installed systems gathering noise data provides support for their activity. The Technology Strategy Board is exploring the challenges associated with shaping the urban environment for future generations in cities, in which noise management is clearly a key part.

Synergies with other projects / programmes

The project builds on past projects developing MEMS microphones, culminating with *DREAMSys* and *Minim* demonstrators. It also applies the output from a current NMO project developing self-calibration methods in practical measurement situations. The project is strongly connected to a proposal in the Innovation R&D Programme developing mathematical algorithms for analysis of large data sets and data fusion from multi-parameter sensor systems. Capabilities developed in the IRD project and in this proposal will together facilitate the operation of distributed noise measurement networks of any scale. Externally there are emerging industrial projects creating requirements for large distributed noise measurement sensor system, for construction of London's cross-rail system for example, that is a candidate application for this proposed NMO project.

Risks

Collaboration in this project is essential, so securing suitable partnerships to provide access to the built infrastructure presents some risk. However, NPL already has contacts with major consultancies capable of facilitating such access. There is technical risk in achieving the desired embedded system functionality, which is offset by significant past experience in solving such problems.

Knowledge Transfer and Exploitation

The demonstrator system and its web-based data portal provide direct dissemination opportunities. There is also prospect of further patentable technology around the optimisation of *embedded* system performance and new product development opportunities. Noise topics always solicits significant media and society interest and the usual dissemination routes will be exploited (trade press and media articles/interviews, website features, conference presentations). Industrial collaborators will facilitate direct communication with authorities and project managers for take-up in further infrastructure projects (construction, transportation, urban planning etc.). Scientific dissemination will be by at least two peer reviewed papers (see Deliverables).

Co-funding and Collaborators

Smart Cities and Sensor networks are key technologies identified by the **Technology Strategy Board** and opportunities are being explored, (e.g. current Technology-inspired innovation call). NMO **Innovation R&D programme** (IRD/2013: Sensor networks: data to knowledge) and associated **EMRP** proposals feature case studies involving acoustic systems to generate data sets to test new data fusion algorithms. (IRD value £1M with £200k for case studies on urban noise networks. 95% likelihood. A successful EMRP proposal will double this value – NB. not incl. as co-funding). Arup and Aitkins are two major engineering consultancies that have interest in environmental monitoring from construction activities associated with London crossrail project. Their experience with distributed noise monitoring is limited and co-funding/collaboration opportunities are being explored.

Deliverables

1	**Start: 01/01/2014**	**End: 31/12/2014**	
Deliverable title: Practical implementation of in-situ microphone calibration developed			
2	**Start: 01/01/2015**	**End: 30/06/2016**	
Deliverable title: Development of an embedded noise measurement demonstrator system featuring self-calibration functionality documented in a scientific paper submitted to a peer reviewed journal			
3	**Start: 01/01/2016**	**End: 31/12/2016**	
Deliverable title: Operation of an embedded noise measurement demonstrator system in a long-term measurement trial documented in a scientific paper submitted to a peer reviewed journal			

Project No.	AIR/2014/UA1	Price to NMO	£151k
Project Title	Extension of free-field standards for transducers and materials to lower frequencies	**Co-funding target**	
Lead Scientist	Stephen Robinson	**Stage Start Date**	1 January 2014
Scientist Team	Justin Ablitt, Graham Beamiss, Gary Hayman, Nick Lucas	**Stage End Date**	31 December 2016
		Est Final Stage End Date	31 December 2016
Sector	7. Underpinning metrology, 2. Environmental sustainability	**Activity**	Development of Existing Capabilities

Summary

The theme of this project is the extension of the existing free-field standards for transducer calibration down in frequency. The project will extend the frequency range of *free-field* primary calibrations, currently provided using the NPL laboratory tank facilities, down from the current frequency limit of 1 kHz to at least 250 Hz by the use of the Open Water Test Facility (OWTF). This will also substantially increase the *range of devices* that can undergo primary calibration. In addition, novel calibration techniques will be used to extend the low frequency free-field limit of the NPL acoustic pressure vessel (APV) and the open-water test facility test facilities, to maximise the usable frequency range.

The Need

Recent years have seen an increased need for absolute measurements of sound in the ocean. This has been driven in part by the needs of industry and oceanographic science, but the main driver has been the need to make absolute measurements of underwater anthropogenic noise due to concerns about environmental impact. The noise sources of greatest concern are the high amplitude, low frequency sources such as airgun arrays for geophysical surveying, marine impact piling for offshore construction, explosive decommissioning and noise from shipping traffic. All these sources radiate most of their sound energy in the frequency range 20 Hz to 1 kHz. Traceability for the measurements is required to underpin regulation where absolute acoustic measurements are made in support of environmental impact assessments for anthropogenic noise, and in support of EU Directives such as the Marine Strategy Directive. In support of in-situ measurement applications, traceability is also required for low-frequency calibration at simulated ocean conditions. Current *primary free-field* standards are limited to frequencies above 1 kHz in the NPL test tanks due to the finite size of the tank. The current primary coupler reciprocity facility which is capable of providing a pressure calibration of a hydrophone at frequencies below 1 kHz is very limited in scope and can only be used for very specific hydrophones types (small insensitive devices that are not best suited as secondary standards at frequencies below 1 kHz). In addition, the coupler facility cannot be used *at all* for calibration of source transducers. NPL currently provides a service for *free-field* calibrations with traceability provided only indirectly by comparison calibrations using the NPL Open Water Test Facility (OWTF) based at Wraysbury reservoir. However, the capability for undertaking absolute primary calibrations at the OWTF at frequencies less than 1 kHz is limited in accuracy, suffers from lack of environmental control, and offers an unacceptably degraded uncertainty (> 1 dB).

The Solution

The solution falls into two parts: extending the frequency range of *free-field* standards to lower frequencies in a larger water volume using traditional free-field reciprocity methods; and using novel calibration techniques to break through the free-field limit of the facilities and maximise the useful frequency range. Firstly, the capability for absolute primary calibration at the NPL Open Water Test Facility will be enhanced and extended for the frequency range below 1 kHz (down to *at least* 250 Hz) providing a new extended capability for free-field primary calibration. This will require substantial improvements to the capability of the facility in order to achieve the desired uncertainties of 0.5 – 0.7 dB. Once achieved, this will allow the calibration of a much wider range of hydrophones *and* source transducers for use in customer calibrations to disseminate standards. Secondly, novel techniques will be investigated to extend the capability of the facilities beyond the low frequency free-field limit. This will involve use of techniques such as Complex Moving Weighted Averaging Method (CMWA), pioneered at VNIIFTRI, and signal modelling already pioneered at NPL. Techniques will be applied to the NPL Acoustic Pressure Vessel (APV) and to the OWTF where the most challenging calibrations are at low frequencies (40 Hz to 1 kHz).

Project Description (including summary of technical work)

The project is formed of two parts:

1. <u>Extension of *free-field* primary calibrations down from 1 kHz to 250 Hz</u>

Extend free-field primary calibrations down from 1 kHz to at least 250 Hz by use of the open-water test facility (OWTF), extending the range of free-field primary standards currently provided (and substantially increasing the range of devices that can undergo primary calibration). This will require improved mounting and stability, new software and source transducers, and improved rejection of noise, vibration and station movement. This will also require accurate characterisation of transducers for variation in performance with temperature and correcting for the effect using an appropriate model, extending work already undertaken with the NPL Mathematics and Modelling Group.

2. Develop novel techniques to extend free-field limits
Novel techniques will be used to extend the low frequency free-field limit of the NPL acoustic pressure vessel (APV) and the OWTF test facility with techniques such as CMWA method and signal modelling. The accuracy and limitations of the techniques will be evaluated, and results published in a scientific journal.

Impact and Benefits

The traceable standards provided by NPL directly support the UK industry, the UK being one of the most active European countries in underwater acoustics with at least 30 companies involved in manufacturing transducers, hydrophones and systems for sonar, positioning, navigation, surveying, communication and monitoring marine life. These support industries such as the oil & gas, defence, and ocean surveying, with business worth hundreds of millions of pounds per annum. Many of these companies require rigorous calibration and testing to internationally-recognised standards, especially when accessing overseas markets. NPL is the leading NMI in underwater acoustics. The ability of industry, academia and OGDs to use the world-class national facilities maintained by NPL provides cost savings to industry (as opposed to maintaining their own facilities or conducting expensive sea-trials), an example being the APV which is approximately a factor of 10 lower in cost than undertaking equivalent sea-trials with considerably more environmental control. Most of the NPL facilities are unique in the UK (and in Europe for the APV) and are enablers of research. Extending the useable frequency range would significantly enhance their utility, and would further underpin measurements relating to anthropogenic noise where many of the sources have a substantial proportion of their energy below 1 kHz. Underwater acoustics is a crucial underpinning technology in the offshore oil and gas industry, in maritime defence and in oceanographic exploration, with applications such as sonar, positioning, navigation, surveying, communication and monitoring marine life. NPL standards underpin marine environmental regulation with regard to the absolute acoustic measurements required to support environmental impact assessments of the influence of anthropogenic noise (e.g. EU Habitats Directive). Recent EU Directives (MSFD) mandate member states to monitor ocean noise in their waters to demonstrate achievement of Good Environmental Status; both the current indicators relate to low frequency noise where most of the energy is at frequencies less than 1 kHz. With incipient legislation in this field, it is vital that decisions are made based on robust metrology, and traceability is supplied in an effective way for all relevant frequencies.

Support for Programme Challenge, Roadmaps, Government Strategies

The work is in direct accord with the NMS Strategy and NMS Strategy Roadmap, and with the NMS roadmap for underwater acoustics. It is also directly aligned with the EURAMET TC-AUV roadmap. The work underpins the requirements of the DEFRA Marine Bill (marine environment strategy), the UK Renewable Energy Strategy, and the EU Marine Strategy Framework Directive. The work is relevant to the following sectors: Environment; Instrumentation and Test Laboratories, Defence & Security; Advanced Manufacturing, Energy.

Synergies with other projects / programmes

The work to further develop the capability will enhance the metrology infrastructure underpinning the rest of the underwater acoustic metrology projects in the NMS programme. The facilities are an enabler of research, without which much of the benefits of that research could not be realised, and this project will extend traceability for a vital frequency range available in a much more robust and practicable manner. Externally, there are synergies with the work of EURAMET and CCAUV member NMIs, with the work programme of DEFRA, and with the research programmes of academia. Other NMIs share the same need to ensure international consistency of measurement standards and benefit from the data made available under the MRA. Internally, the project will benefit from the work of the Mathematical Modelling Group for modelling transducer performance and with signal processing for some of the novel calibration techniques.

Risks

Whilst the project poses some significant technical challenges, NPL have over recent years built up significant expertise and established partnerships with other leading organisations in this area. This will mitigate the risk in the project.

Knowledge Transfer and Exploitation

The main knowledge transfer in this project comes from enhanced services to customers (providing calibration services and certificates), and improved *free-field* primary standards, which will enable the calibration of a much wider range of hydrophone and transducer types. The new primary standards will also enable NPL to cover a wider frequency range in the upcoming CCAUV Key Comparison, underpinning UK CMCs within the MRA. The project will result in significantly improved uncertainties for customer calibrations (by up to a factor of two). Two peer review papers will be submitted from work undertaken in the project.

Co-funding and Collaborators

This project will be delivered through a collaborative effort including VNIIFTRI and NUWC-USRD.

Deliverables

1	**Start: 01/01/2014**	**End: 31/12/2016**	
Deliverable title: Extended primary calibrations for the NPL OWTF at frequencies down to 250 Hz established with target uncertainties of better than 0.7 dB			
2	**Start: 01/01/2015**	**End: 31/12/2016**	
Deliverable title: Novel techniques to extend the low frequency free-field limit of the test facilities (OWTF and APV) established and evaluated, and paper submitted to scientific journal			

Project No.	AIR/2014/UA2	Price to NMO	£150k
Project Title	Establish metrology for underwater noise measurement for marine renewables including wave and tidal	Co-funding target	
Lead Scientist	Stephen Robinson / Pete Theobald	Stage Start Date	1 October 2014
Scientist Team	Gary Hayman, Tanja Pangerc, Lian Wang	Stage End Date	31 December 2016
		Est Final Stage End Date	31 December 2016
Sector	2.2 Pollution reduction, 1.3 Low carbon energy;	Activity	Methodology for New Capabilities

Summary

This project aims to develop techniques for measurement of the noise radiated by marine renewable energy devices (MREDs), specifically, wave and tidal stream energy devices. Measurements pose significant challenges due to the hostile environments such as high flow rates and wave action in the vicinity, and new techniques will be required to overcome these issues. Specific techniques such as drifting and static systems must be assessed, and methods to reduce parasitic signals from cable strum and flow noise will be evaluated. The results will feed into international standards within ISO and IEC, and scientific journal publications. They will also feed into protocols and test methods to be used by the European Marine Energy Centre (EMEC).

The Need

Marine renewable energy forms a major pillar of the UK's plan to meet its renewable energy commitments over the next 5-10 years. Since 2008, the UK has been a world leader in offshore wind with more installed capacity than the remainder of the world combined. What is sometimes less appreciated is that the UK is also a leader in the development of wave and tidal energy devices. This is true for the design of novel devices, and now also in their deployment, with plans for extensive arrays of such devices around the UK (around the Pentland Firth and Orkney alone there are 1.6 GW currently planned by 2020). The environmental impact of these developments is recognised as one of the major barriers to future exploitation, and realising the ambitious future targets for renewable energy supply. The increasing concern about underwater anthropogenic noise affecting marine life has led to legislation at both national and European level (e.g. EU Habitats Directive 92/43/EC, EC Directive 2001/42/EC, Food and Environment Protection Act 1985). Environmental Impact Assessments are routinely required, but standard methodologies to measure such noise sources in-situ have not yet been developed. So far, the focus has been on construction noise from offshore wind developments, where marine piling is a major source of noise. However, some noise sources have been poorly studied such as wave and tidal devices, and it is a particular problem for large arrays of devices. An improved understanding of the nature of these noise sources and likely environmental consequences of the associated changes in the underwater noise is needed. Accurate data for radiated noise is important for assessing behavioural response in the vicinity of individual devices (influencing risk of collisions and barrier effects) and for scaling up to large scale commercial arrays. Such data as are available currently show a wide variety of measurement methodologies and acoustic metrics used. This reflects the extremely challenging nature of the measurements in the harsh environments (rapid flow rates, high wave action) experienced. Agreed standards are required for the measurement of the radiated noise during operation and construction in order for results to be comparable, and for planning and licensing decisions to be made on well-founded science. This project will build on early work undertaken by NPL to review this need [Crown Estate, 2013], and joint work with Loughborough University and EMEC (funded by the Scottish Government and published as a chapter in a recent book on wave and tidal energy).

The Solution

Accepted standard methodologies for the measurement and characterisation of noise sources must be provided, establishing in-situ methods for underwater noise measurement of sources in harsh environments. Wave energy devices and tidal turbines pose significant challenges due to the high flow rates and wave action in the vicinity, and new techniques will be required to overcome these issues. For example, the advantages and disadvantages of drifting systems compared with static systems must be evaluated. Techniques to reduce parasitic signals from cable strum and flow noise must be evaluated. The feasibility of measuring other important field parameters such as particle velocity must be assessed. The influence of noise on spatial planning of arrays must be considered because this influences other risks such as that from collisions and barrier effects. It was always envisaged that the work on noise is a likely feature in the NMS programme for a number of years – extending beyond the three-year horizon. The work here will be carried out in collaboration with partners such as the European Marine Energy Centre (EMEC) and Southampton and Loughborough Universities, and the Scottish association for Marine Science (SAMS).

Project Description (including summary of technical work)

1. Establish methodology for measuring radiated noise from wave energy developments

Methodologies will be developed for measuring radiated noise from wave energy developments during operation and construction, including for different device designs such as surface attenuators, point attenuators and overtopping devices. Techniques will deal with high background noise and severe wave action, and distributed sources on large devices.

2. Establish methodology for measuring radiated noise from tidal stream energy developments

Methodologies will be developed for measuring radiated noise from tidal stream energy developments during operation and construction, including tidal turbines in high tidal flow areas using techniques which mitigate the effects of harsh environments (flow noise, sediment noise, turbulence, and severe tides).

Impact and Benefits

The environmental effect of the underwater noise generated by marine renewable developments is recognised as one of the major barriers to development, putting some developments at significant risk. Marine renewable energy forms a major pillar of the UK's plan to meet its renewable energy commitments over the next 5-10 years, and the industry has been a stimulator of innovation. Since 2008 the UK has been a world leader in offshore wind with more installed capacity than the remainder of the world combined (almost 800 turbines, total capacity of 2.6 GW, generating 8 TWh – enough to power approximately two million homes). The UK is also a leader in the design and development of wave and tidal stream energy devices, with the industry benefiting from innovation. The deployment of these devices is now taking off; the Pentland Firth and Orkney Waters wave and tidal projects alone will generate 1.6 GW by 2020, with current plans for 1600 devices requiring a total investment of nearly £6bn [The Crown Estate 2013]. UK policy is to drive delivery and clear away barriers whilst protecting the environment and natural heritage through the application of relevant controls. This project may be seen as an enabler to achieving the UK's renewable energy and CO_2 reduction commitments by ensuring that decision-making about anthropogenic noise and environmental impact assessments are based on sound metrology. Beneficiaries of the work include offshore renewable energy developers, UK regulators and licensing authorities, and those undertaking measurements of noise radiated from renewable energy devices.

Support for Programme Challenge, Roadmaps, Government Strategies

The project aligns with the European Strategic Energy Technology Plan that has established an energy technology policy for Europe which encourages and accelerates the development and deployment of cost-effective low carbon technologies. The project addresses the programme challenges in the BIS NMS strategy 2011-2015, specifically *science to support low-carbon technologies and sustainability (e.g. metrology to support the introduction and deployment of renewable energy technologies, provide measurement and characterisation methods to support the development of marine energy)* and aligns with the Department of Energy and Climate Change Roadmap and its goal to "drive delivery for marine renewable energy and clear away barriers whilst protecting the environment and natural heritage through the application of relevant controls". It addresses one of the key challenges in the NPL Metrology 2020 strategy for achieving a *sustainable low-carbon economy,* and aligns with the AIR NMO road map and EURAMET TC-AUV road maps.

Synergies with other projects / programmes

To address the enormous challenges within marine environmental acoustics, collaboration is essential and the intention is to explore funding for complementary projects from UK OGD (e.g. The Crown Estate, Marine Scotland), as well as Research Councils and EU FP7. The work here is in accord with the research priorities of DEFRA, DECC and Marine Scotland. The project aligns well with several existing NERC funded projects (e.g. RESPONSE, FLOWBEC and EBAO), and projects currently funded by EU, ETI and the Scottish Government. The work will be complementary, learning from these projects and sharing data where appropriate.

Risks

There is inevitably some technical risk, especially that associated with the extreme environments in which measurements must be made. However, the risk is strongly mitigated by the choice of collaborative partners that are experts in their field. In particular, the existing partnerships with Loughborough and Southampton Universities will be important, and the partnership with EMEC is seen as key to the success of the project.

Knowledge Transfer and Exploitation

The results will feed into future international standards within ISO TC43 SC3 and IEC TC114, and will be the subject of at least two scientific journal publications. The work will also be publicised at workshops run by the Marine Science Coordination Committee, and will be presented to UK regulators and licensing authorities, and to renewable energy developers at workshops hosted by NPL and by EMEC.

Co-funding and Collaborators

The work will be carried out in collaboration with partners such as the European Marine Energy Centre and Southampton and Loughborough Universities, and the Scottish Association for Marine Science (SAMS). Other potential partners with relevant expertise will also be approached (e.g. Ultra Electronics, Chickerell Bioacoustics). To address the enormous challenges within marine environmental acoustics, collaboration is essential and the intention is to apply for funding for complementary projects. Specific proposal are currently being developed for consideration by UK OGD, in particular DEFRA, DECC, The Crown Estate and Marine Scotland. There will be opportunities provided by EU FP7 calls (initial review studies are already being commissioned in this area).

Deliverables

1	**Start: 01/10/2014**	**End: 31/12/2016**	
Deliverable: Methodology for measuring radiated noise from wave energy devices established and journal publication submitted			
2	**Start: 01/10/2014**	**End: 31/12/2016**	
Deliverable: Methodology for measuring radiated noise from tidal stream energy devices established and publication submitted			

Project No.	AIR/2014/UA5	Price to NMO	£50k
Project Title	Feasibility of measurement methodologies for vector field quantities and calibration standards for vector sensors	Co-funding target	
Lead Scientist	Pete Theobald	Stage Start Date	1 January 2014
Scientist Team	Stephen Robinson	Stage End Date	31 June 2015
		Est Final Stage End Date	31 December 2018
Sector	2.2 Pollution reduction, 1.3 Low carbon energy;	Activity	Methodology for New Capabilities

Summary

This project investigates the feasibility of measuring acoustic particle velocity in the water column and vibration of the seabed, and the requirement for standards relating to these parameters. The requirements of the sensing modalities will be identified for particle motion, including the sensitivity and the frequency range. These requirements will also inform the accuracy requirements of the calibration methods to be established. A number of possible methodologies for providing primary standards will be considered including pressure gradient, interferometric methods and travelling wave tubes. There already exist standards relating to the calibration of vibration measurement instrumentation (ISO 16063) but the applicability of these to seabed instrumentation needs to be established. Establishing measurement methods for both seabed vibration and particle velocity in the water column is essential to obtaining measurements of these parameters for establishing exposure to fish and other sensitive marine fauna such as crustaceans, especially with regard to marine renewable energy developments.

The Need

Marine renewable energy forms a major pillar of the UK's plan to meet its renewable energy commitments over the next 5-10 years. Anthropogenic noise is recognised as a major barrier to offshore renewable energy development. The increasing concern about underwater anthropogenic noise affecting marine life has led to legislation at both national and European level (e.g. EU Habitats' Directive 92/43/EC, EC Directive 2001/42/EC, Food and Environment Protection Act 1985). As part of the consents application process Environmental Impact Assessments are routinely required, most of which require the assessment of the potential effect of vibration and/or particle motion on marine receptors (particularly fish species which are sensitive to motion as well as pressure). Whilst vibration and particle velocity (in the water column or along seabed) are not currently measured, the demand for measurement of these parameters has increased rapidly by the requirements of the Environmental Impact Assessment process for new developments. Sensors are now beginning to be made available although measurements techniques are in their infancy. Agreed methodologies are needed to enable meaningful and comparable measurements of vibration and particle velocity, and the calibration of the sensors is essential to this.

The Solution

The feasibility of measuring acoustic particle velocity in the water column and vibration of the seabed for assessing the contribution of offshore renewable installations must be established. Furthermore, the performance requirements of the sensors need to be identified for the spatial degrees of particle motion, the sensitivity required and the frequency range. These requirements will also inform the calibration requirements of the methods to be established. At present a number of options exist, pressure gradient, interferometric methods and travelling wave tubes, although the pressure gradient method is likely to be limited to higher frequencies due to dimensional requirements of the test facility. There already exist standards relating to the calibration of vibration measurement instrumentation (ISO 16063) but the applicability of these to seabed instrumentation needs to be established. Establishing measurement methods for both seabed vibration and particle velocity in the water column is essential to obtaining meaningful and comparable measurements of these parameters for the offshore renewable energy sector, but also for establishing exposure to fish and other particle motion-sensitive marine fauna such as crustaceans.

Project Description (including summary of technical work)

The study is in two parts:

1. <u>Feasibility of methodologies for measuring seabed vibration from sources such as construction noise and for particle velocity measurement using vector sensors and their application to real world field measurements</u>

The feasibility of measuring acoustic particle velocity in the water column and vibration of the seabed for assessing the contribution of offshore renewable installations will be established in terms of existing and (potentially) future technologies with regard to the performance requirements of the sensors (dynamic range, frequency response, etc).

2. <u>Options for calibration methodologies for vector sensors such as particle velocity sensors reviewed and appraised</u>

Options for provision of primary and secondary standards for particle velocity sensors will be reviewed including pressure gradient, interferometric methods and travelling wave tubes. Standards relating to the calibration of vibration measurement instrumentation will be reviewed for applicability and recommendations made.

Impact and Benefits

The environmental effect of the noise generated by marine renewable developments is recognised as one of the major barriers to development, putting some developments at significant risk. One of the consenting uncertainties, and thus risks, relating to underwater noise is the level of particle motion produced in the water column and the seabed, which is of particular concern for fish and shellfish ecology. Improving the ability to quantify and therefore predict particle motion resulting from either the construction or operation (typically for a planned operational period of 25 years) phases of offshore energy developments and to assess the potential for impact on sensitive marine fauna will remove potential planning and consenting barriers to offshore developments and will ultimately lead to reductions in the economic impact of offshore developments on the UK fishing industry.

Support for Programme Challenge, Roadmaps, Government Strategies

The work on particle motion field parameters extends the work already started in the previous NMO programmes which have been primarily focussed on acoustic pressure as a 'noise' parameter. The requirement for this project stems from recent concern regarding effect of particle motion on key environmental and economic species. The breadth of this issue demands collaboration and the intention is to seek support from UK OGD (DEFRA, DECC, The Crown Estate, Marine Scotland) and offshore energy developers, in addition to collaboration with universities.

The project addresses the programme challenges in the BIS NMS strategy 2011-2015, specifically science to support low-carbon technologies and sustainability (e.g. metrology to support the introduction and deployment of renewable energy technologies) and it aligns with the Department of Energy and Climate Change Roadmap and its goal to drive delivery for marine renewable energy and clear away barriers whilst protecting the environment and natural heritage through the application of relevant controls. It also addresses one of the key challenges in the NPL Metrology 2020 strategy for achieving a sustainable low-carbon economy. It also aligns with the AIR NMO road map and EURAMET TC-AUV road maps.

Synergies with other projects / programmes

The project has synergies with current proposals with NERC with regard to the development of major facilities for large-scale testing of exposure of marine life to anthropogenic noise (part of which will be in the area of particle motion and seabed vibration). The issue is recognised by the EU as demonstrated by a recent call for proposals on the effect of marine renewables which explicitly covers this topic as part of the scope (study about to be commissioned).

Risks

There is little effective risk of delivery for a scoping study / feasibility study.

Knowledge Transfer and Exploitation

The principle project output will be a technical report, and possibly a presentation at a scientific conference.

The project will feed into future NMO programme formulation, and considerations within international standards bodies about future standards (e.g. ISO TC43 SC3).

Co-funding and Collaborators

The intention is to seek support and advice from key stakeholders such as UK OGD (DEFRA, DECC, The Crown Estate, Marine Scotland) and offshore energy developers, in addition to collaboration with universities. Advice will be sought from key experts in the field with prior experience of measuring particle motion and seabed vibration such as Dr R Hazelwood and Prof A Hawkins as well as staff of the National Oceanography Centre in the UK, Dr Peter Sigray in Sweden, and researchers and suppliers in the USA.

Deliverables

1	**Start: 01/01/2014**	**End: 30/6/2015**	

Deliverable title: Feasibility of methodologies for measuring seabed vibration and for particle velocity measurement using vector sensors established, and options for calibration methodologies for vector sensors reviewed and appraised. Published in NPL report

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Dosimetry projects 2014

Project No.	AIR/2014/DS1	**Price to NMO**	£182k
Project Title	Development of specialised phantoms for audit	**Co-funding target**	
Lead Scientist	Catharine Clark	**Stage Start Date**	1 January 2014
Scientist Team	Simon Duane, Russell Thomas; Ileana Silvestre Patallo; Hugo Palmans	**Stage End Date**	31 December 2015
		Est Final Stage End Date	31 December 2015
Sector	3. Health	**Activity**	Methodology for New Capabilities

Summary

Advanced radiotherapy is increasingly reliant on the use of very small and complex composite fields. Evidence suggests that at least half of all cancer patients would benefit from receiving radiotherapy as part of their treatment regime and, according to recent estimates[1], 35% of all radiotherapy patients would benefit from the most advanced forms of radiotherapy. This would bring widespread benefit to a significant number of cancer patients, with the likelihood of increased survival rates and improved quality of life. As in all radiotherapy, success is critically dependent on accurate delivery of the specified absorbed dose. This research will develop bespoke phantoms that will support end-to-end audit using appropriate anthropomorphic geometries, thus enabling validation of advanced radiotherapy techniques.

Cooper, T., UK Dept. of Health, at BIR meeting on 'Expansion of IMRT in the UK', Feb 2011

The Need

Radiotherapy remains a rapidly developing field with numerous new technologies on the horizon. In the UK new technologies that are starting, or will soon start to be used clinically, include pulsed dose rate brachytherapy, electronic brachytherapy, radiosurgery and protons; external audits will be vital to ensure accurate implementation. For example, a recent UK national audit of rotational radiotherapy, led by NPL and the National Cancer Research Institute Radiotherapy Trials Quality Assurance group (NCRI RTTQA), enabled independent verification of this new technology. The audit was very well supported by clinical radiotherapy centres (with a very high level of participation) and has resulted, for example, in increased confidence in patient treatment. However, this national audit necessarily made use of a commercial detector array and phantom; this meant that audits carried out for centres that use the same commercial equipment for their verification were not strictly as independent as for centres using other systems. For many new modalities, appropriate phantoms either do not exist or are not suitable for audit purposes, due to issues such as tissue equivalence (for protons), organ motion, positioning of detectors within heterogeneous tissues (such as lung and bone) and design of the shape and form of the phantom, in particular in the ability to position detector(s) where needed.

In addition, a number of clinical trials need to be designed to test the delivery of these new radiotherapy techniques. Quality assurance is required which is specific to the needs of the trial, and appropriate phantoms are required to fulfil these requirements. These trials may also include international recruitment where postal phantoms would be required. Furthermore, proton facilities will be available in the UK within the next 5 years and currently no phantom materials exist to adequately represent either water or other tissue equivalent materials. Once these materials are developed, reference and anthropomorphic phantoms will need to be designed and made.

The Solution

A review of currently commercially available anthropomorphic phantoms will be carried out to determine their suitability for adaptation for independent external audit of new therapies, investigating factors such as appropriate material selection for different therapies (e.g. tissue equivalence for protons), suitability for imaging and versatility for the different aspects required in an end-to-end audit. Bespoke anthropomorphic phantoms will then be developed and built for use in end-to-end postal and on-site audit of advanced radiotherapy techniques. These will be able to accommodate a number of different detectors (including alanine) in an extensive number of well-defined positions. Appropriate audit protocols will be developed for use with the phantoms. Initially, this project would consider a single anatomical site. However, it is anticipated that, if successful, this work would be continued in a future project to develop phantoms and audit protocols for further anatomical sites and technologies.

Project Description (including summary of technical work)

- Identify UK requirements in collaboration with RTTQA, IPEM, CTRad and users
- Carry out survey of what is currently available, and ascertain possibilities to adapt for need
- Or alternatively, design new phantom in collaboration with a hospital group (e.g. Christie)
- Develop suitable audit protocols

Impact and Benefits

Facilitate the effective and efficient application of innovation to improve quality, reliability and comparability of individually optimised radiotherapy for patients undergoing new treatment techniques leading to increased cancer survival rates and improved quality of life for cancer survivors.

Integration of protocols and procedures for audit with advanced phantoms with national and International groups such as National Cancer Research Institute Radiotherapy Trials Quality Assurance group (NCRI RTTQA), National Cancer Research Institute Clinical and Translational Radiotherapy (CTRad), European Organisation for Research and Treatment of Cancer (EORTC) and Radiological Physics Centre (RPC, USA)

Support for Programme Challenge, Roadmaps, Government Strategies

The project is in line with the long-term strategic aims of NPL's Dosimetry Group and road maps in supporting research, development and application of advanced and novel radiotherapy modalities and more specifically in terms of developing audit processes to support the implementation of advanced radiotherapy techniques. The Department of Health Cancer Reform Strategy states that the use of radiotherapy machines varies over twofold per year, per machine, by centre, and identified the potential for existing capacity to be used much more productively. This work supports the implementation of the most up to date and efficient treatment strategies, such as rotational IMRT.

Supports the Government priority set out by Public Service Agreement Targets (PSAT) 4 '*Promote world-class science and innovation in the UK*' as well as 18 '*Promote better health and well-being for all*' and aligns with NMO roadmap on Dosimetry – Radiotherapy. Longer term would support the new proton facilities which are a government priority, in particular for paediatrics.

Synergies with other projects / programmes

This project builds on extensive experience gained in Intensity Modulated Radiotherapy (IMRT) and national rotational audit for auditing advanced techniques (but in homogeneous phantoms). It would extend the use of the NPL Alanine service, recommended in a recent National Radiotherapy Implementation Group (NRIG) report on Stereotactic Ablative Radiotherapy (SABR), as the small size, near tissue equivalence and stable chemical changes mean that alanine is ideal for complex high dose radiotherapy.

Risks

This project requires collaboration with end users, e.g. IPEM and RTTQA. However, links with these groups are already well established.

Knowledge Transfer and Exploitation

The outputs of this project will be disseminated via audit (extension of existing measurement services), publications in peer reviewed journals and presentations at national and international conferences. RTTQA are actively expanding their portfolio of clinical trials and will need more and more complex phantoms with which to make measurements to support the credentialing of radiotherapy centres joining those trials. IPEM audit groups are also expanding the audit work they do to more complex radiotherapy techniques and have a need for appropriate phantoms as evidenced by a recent survey of phantom existence and availability. This could lead to potential national audits with RTTQA and IPEM.

Co-funding and Collaborators

Collaboration with the National Cancer Research Institute Radiotherapy Trials Quality Assurance group (NCRI RTTQA), Royal Surrey County Hospital and IPEM RTSIG Interdepartmental Audit Group.

It is anticipated that as part of any follow on project an application would be made for NIHR i4i funding in collaboration with one or more end users.

Deliverables

1	**Start: 01/01/2014**	**End: 30/06/2014**	

Deliverable title:
Report on survey of currently available anthropomorphic phantoms.

2	**Start: 01/07/2014**	**End: 31/12/2015**	

Deliverable title:
Phantom development and construction. Written audit protocols.

Project No.	AIR/2014/DS2	Price to NMO	£20k
Project Title	Development of a primary standard for electronic brachytherapy (Note: deliverables 2 and 3 not contracted)	Co-funding target	
Lead Scientist	Thorsten Sander	Stage Start Date	1 January 2014
Scientist Team	David Maughan, Ilias Billas, Martin Kelly, David Shipley	Stage End Date	31 December 2014
		Est Final Stage End Date	31 December 2017
Sector	3. Health	Activity	Methodology for New Capabilities
Project Champion	Philip Mayles		

Summary

Recent studies claim that one in three people living in the industrialised countries will develop cancer in their lifetime and one in four will die from it (Walter & Miller's Textbook of Radiotherapy, Elsevier, Seventh Edition 2012). Cancer remains one of the most important public health problems in Europe and the USA. As the population in many countries ages, it is expected that the number of cancer incidents will increase in the future.

Brachytherapy (BT) is a special form of radiotherapy where the radiation source is in close proximity to the target volume and the absorbed dose due to the ionising radiation is mainly imparted in the tumour. The American Association of Physicists in Medicine (AAPM) and the European Society for Radiotherapy and Oncology (ESTRO) recommend that BT centres should independently verify the source strength provided by the manufacturer and to ensure traceability to internationally accepted standards.

Traditionally, brachytherapy has been delivered with encapsulated radionuclide seeds. Primary standards for these sources are already in use. With the recent development of new electronic BT sources (miniature X-ray sources), which are sufficiently different from low-energy photon-emitting brachytherapy seeds, dedicated primary standards need to be developed in order to measure the source strength of these new X-ray sources and to comply with current recommendations.

The Need

Brachytherapy (BT) is a type of internal radiotherapy, which involves putting the radiation source close to, or directly within the volume of interest to be treated. BT sources are designed to deliver a high radiation dose to the tumour, while sparing the healthy tissue around it. Traditional BT is based on the use of radionuclide-based sources and the Dosimetry Group at NPL has already developed and commissioned suitable standards for traceable calibration of high dose rate (HDR) ^{192}Ir sealed sources and low dose rate (LDR) ^{125}I seeds in terms of reference air kerma rate. The calibrated sources are then used to calibrate suitable secondary standards, e.g. well-type ionisation chambers, which are used in radiotherapy centres for the dosimetry of BT sources.

Electronic BT utilises X-rays which are produced by miniaturised X-ray tubes which can be placed inside the treatment volume. For electronic BT there are no radionuclide regulatory, handling and safety issues, which is advantageous. The use of electronic BT has increased worldwide over recent years and at least ten UK brachytherapy centres have now installed electronic BT systems (May 2013). Dosimetry of electronic BT sources in the UK is currently based on soft X-ray parallel plate ionisation chambers, which have originally been developed for measurements in external radiation fields (very-low energy therapy level X-rays, tube potentials: 8.5 kV – 50 kV). The steep dose gradient close to electronic BT sources makes measurements at 10 mm distance (the prescription is usually defined at 10 mm depth in water) very sensitive to positioning errors. Both a dedicated primary standard and a suitable secondary standard for electronic BT are needed. Only NIST and PTB are currently developing primary standards for electronic BT and there is growing need for international comparisons against other standards. There is also need to provide guidance on a calibration procedure for electronic BT as the current Institute of Physics and Engineering in Medicine and Biology (IPEMB) code of practice for kV X-rays (Klevenhagen *et al*, Phys. Med. Biol., 1996) was written for applications in external radiation fields and before electronic BT was developed.

The Solution

In order to improve the relative measurement uncertainty for electronic BT sources to a level currently achievable for radionuclide-based BT sources, a dedicated primary standard will be developed at NPL. This project will extend NPL's established capability for provision of primary standards for radionuclide-based BT to electronic BT. The device could possibly be based on the existing 50 kV free air chamber (originally developed for the measurement of therapy level very-low energy X-rays (8.5 kV – 50 kV, HVL: 0.024 mm Al – 1.0 mm Al). The challenge will be to develop a primary standard that can be used for measuring a range of miniature x-ray sources (at least three different types of electronic BT sources are already commercially available) having differences in their physical and field geometries and their spectra. A calibration setup will be developed and primary standard correction factors for typical electronic BT beam qualities will be either measured or calculated using Monte Carlo techniques.

This project also aims to find a suitable transfer method for disseminating the new NPL primary standard, for instance by calibrating well-type ionisation chambers modified for electronic BT sources. Discussions will be held with hospital physicists to get their early input for selecting a secondary standard of choice. Well chambers are already used in hospitals for measuring LDR,

PDR (pulsed dose rate) and HDR sources. Such chambers could potentially be used for electronic BT sources.
A dedicated primary standard and a secondary standard, more suitable than the ones designed for external radiation fields, would possibly reduce the relative measurement uncertainty for electronic BT.
NPL will collaborate with IPEM and end-users in order to draft guidelines on the calibration of electronic BT sources.

Project Description (including summary of technical work)

The first stage of this project will include a literature review on possible designs of a reference air kerma rate or absorbed dose rate primary standard for measuring the source strength of typical electronic BT sources and an evaluation of the most appropriate route for dissemination. A decision on whether or not to continue with this project will be made after completing deliverable 1. Stage two of this project will be concerned with the actual development of a primary standard for electronic BT (design and build). Parallel to stage two, it is anticipated that work on the third deliverable of this project will be started. This final stage will be concerned with the development of a suitable transfer method via secondary standard ionisation chambers. This will also involve writing new guidelines on electronic BT dosimetry in collaboration with IPEM.

Impact and Benefits

Miniature X-ray devices for electronic BT have the potential for rapid uptake when randomised trial results from the INTRABEAM trial in the UK (Eaton and Duck, Phys. Med. Biol., 2010) will be published. Improved dosimetry for electronic BT sources and direct traceability to a new NPL primary standard will potentially reduce the relative measurement uncertainties and this will result in better treatment outcomes for cancer survivors.
This project will broaden NPL's range of brachytherapy calibration services which are already offered to UK and overseas radiotherapy centres and it will enable NPL to remain a world-leading NMI in the area of brachytherapy dosimetry.

Support for Programme Challenge, Roadmaps, Government Strategies

This project is in line with long-term strategic aims of NPL in supporting research, development and application of improved dosimetry techniques for new radiotherapy modalities. This work also supports the DoH – Cancer Reform Strategy, and it aligns with the NMO roadmap Dosimetry – Radiotherapy 2012 – 2020.

Synergies with other projects / programmes

This project will build on experience gained through the recent development of NPL's air kerma and absorbed dose standards for HDR Ir-192 BT sources and the use of the established 50 kV free-air chamber for very low energy X-rays.

Risks

Deliverable 1 of this project will be concerned with a general evaluation of a suitable dissemination route for electronic brachytherapy (stage gate). Based on the initial findings and discussions with the NPL Radiation Dosimetry Steering Group, a decision on whether or not to continue with this project will be made after completing deliverable 1.
NPL does not currently own a commercial electronic BT X-ray unit. In order to carry out test measurements, NPL would either have to install an electronic BT source or gain access to one of the hospitals which have already installed and commissioned an electronic BT source. NPL could potentially collaborate with one of three local hospitals (Royal Free Hospital (London), Guy's and St Thomas' Hospital (London), Royal Surrey County Hospital (Guildford)), or with the Clatterbridge Cancer Centre. NPL will have to rely on manufacturers of secondary standard ionisation chambers to develop and supply suitable source holders for electronic BT sources.

Knowledge Transfer and Exploitation

The results of this project will be disseminated through publication in peer reviewed journals and NPL contributions to new IPEM guidelines on dosimetry for electronic BT. The new primary standard will be used for a new calibration service for hospitals which have adopted electronic BT. Throughout this project, NPL will be liaising with end-users and consult hospital physicists on how best to implement the new primary standard and the new calibration service.
This project will extend NPL's calibration and measurement capabilities in an area of growing importance.

Co-funding and Collaborators

Possible collaboration with users of the 'Papillon 50' electronic BT X-ray unit (e.g. Royal Surrey County Hospital, Clatterbridge Cancer Centre) or with users of the 'Carl Zeiss INTRABEAM' X-ray unit (e.g. Royal Free Hospital, Guy's and St Thomas' Hospital).
This project will be in collaboration with IPEM.

Deliverables

1	**Start: 01/01/14**	**End: 31/12/14**	
Deliverable title: Results of initial literature review on primary standards for electronic brachytherapy and evaluation of most appropriate route for dissemination reported to the NPL Radiation Dosimetry Steering Group: stage gate.			
2	**Start: n/a**	**End: n/a**	
DELIVERABLE 2 NOT CONTRACTED: Development and commissioning of a new primary standard for electronic brachytherapy presented at national and/or international conference			
3	**Start: n/a**	**End: n/a**	
DELIVERABLE 3 NOT CONTRACTED: Development of a new calibration service and guidelines on electronic brachytherapy drafted in collaboration with IPEM			

Project No.	AIR/2014/DS4	Price to NMO	£396k
Project Title	Dosimetry and radiobiology for new MRI-radiotherapy facilities (Note: Deliverable 3 not contracted)	Co-funding target	
Lead Scientist	Giuseppe Schettino	Stage Start Date	1 January 2014
Scientist Team	Hugo Palmans, Peter Sharpe, David Shipley, Graham Bass, Alex Knight	Stage End Date	31 December 2016
		Est Final Stage End Date	31 December 2018
Sector	3. Health	Activity	Methodology for new capabilities
Project Champion	Stuart Green		

Summary

The combined simultaneous use of MRI (Magnetic Resonance Imaging, with its strong magnetic fields) and megavoltage photon irradiators (^{60}Co sources and Linac accelerators) is one of the most promising innovations for cancer radiotherapy as it offers the capability of using non-ionizing radiation for high quality imaging with tissue selectivity to drive the delivery of lethal doses of ionizing radiation to tumour volumes. Clinical application of such facilities however presents new dosimetric and radiobiological challenges. This project aims to develop dosimetry procedures, defining standards in MRI-related facilities and validate the biological effectiveness of ionizing radiation in combination with magnetic fields. Combined with dosimetry and radiobiology models, output from this project will be critical in estimating biologic effective dose distributions for treatment plans.

The Need

MRI radiotherapy prototypes are already available (Elekta/Philips, ViewRay) and currently being evaluated for therapeutic use, attracting worldwide interest including at leading UK centres. Contrary to conventional radiotherapy treatments, electrons produced by megavoltage photons within the patient will travel in a spiral path around the lines of magnetic flux.

Detectors currently used in dosimetry will be affected by the magnetic field by two main mechanisms. Firstly, corrections for electron fluence perturbations are determined by the range electrons travel within the detector medium, which is modified by the curved paths the electrons follow in the magnetic field. This will most drastically affect the response of ionisation chambers, and also any other detector that has a non-water equivalent sensitive medium, as well as the gap corrections in calorimeters - the primary instruments for ionising radiation dosimetry. Secondly, in chemical and solid state dosimeters, the yield of physical and chemical reaction sites can be affected by the presence of the magnetic field.

To date, there is basically no literature of radiobiological investigation in strong magnetic fields (>1 T). Studies are paramount as biological effectiveness is determined by the ionization pattern caused by the tracks of secondary electrons and the yield/type of reactive radical species produced. These are expected to be severely affected by the strong magnetic field of the MRI with significant consequences for the volume across which the dose is deposited, the clustering of DNA lesions and the radical recombination which ultimately determines the biological effectives per unit dose absorbed. Moreover, tissue heating by absorbed RF power of the MRI system is an established health risk for patients which could also affect the repair rate and repair efficiency of DNA damage caused by the ionizing radiation in both healthy tissue and cancer cells.

The Solution

The main aim of the project is the characterization of existing dosimetry technology in strong magnetic fields. This will lead to definition of standards and traceable measurement procedures for establishing dosimetry protocols for MRI-related radiotherapy facilities. It will also include Monte Carlo and prediction modelling of dose response as a function of key MRI and Linac parameters. The project also aims to establish a methodology for assessment, quantification and quality control of key parameters (magnetic field, dose rate, radiation quality, reactive radical species, temperature) regulating the radio-biological response in strong magnetic fields. Such methodology will be used to establish standards and traceable and comparable measurement methods providing recommendations for clinical applications (as for biological optimized radiotherapy treatment planning), and optimise the development of future MRI-based radiotherapy facilities and treatment planning systems.

Project Description (including summary of technical work)

The first phase of the dosimetry aspect, building on NPL's expertise in dosimetry, will be on building a magnet system at a ^{60}Co-irradiator to investigate the dose response of ionization chambers as a function of size, orientation and magnetic field strength and compare this with the response of chemical dosimeters such as alanine and radiochromic film. Monte Carlo simulations of radiation transport will provide in-depth understanding of the mechanisms that underlie the modified response of detectors in a strong magnetic field. In the second phase, in a more clinically relevant effort in collaboration with Elekta and with one or more UK centres that will host a prototype MRI-Linac facility, the dose response of calorimeters, ionisation chambers and chemical dosimeters will be characterized.

The radiobiological work will be performed in parallel with the dosimetry measurements using the developed magnetic-irradiation set up. Variation in the yield and spectrum of radiation induced reactive radical species will be initially investigated as a function of the magnetic field strength in biologically relevant bulk solutions using a range of specific probes. Cell work will be performed both at NPL in collaboration with NPL's Biotechnology group and building on previous research of the project leader and at collaborator sites (Queen's University Belfast) and concentrate on cell survival, DNA repair and sub-lethal effects (i.e. micronuclei, chromosomal aberrations) as a function of dose, dose rate and magnetic field. Temperature increase due to the magnetic field will also be considered. These experiments will be performed in appropriate cell based models (normal and cancer cell line) with the aim to quantify relative biological effectiveness and define key parameters regulating radio-biological response in strong magnetic fields. This work will initially be performed on the developed magnetic-irradiation setup at NPL and then validated in more clinical settings using the MRI-Linac prototype.

Impact and Benefits

The data, knowledge and expertise developed will promote safe use of revolutionary cancer treatment MRI-based facilities in the UK by providing metrological support for standards and regulations. Outcome from this project will support the translation to market of recent technological MRI developments which haven't yet made it into the market due to unresolved safety issues for patients and staff. This work will reinforce NPL's world leadership role in radiation dosimetry for advanced radiotherapy and initiate complementary radiobiological activities, strengthening existing collaborations (i.e. Elekta, specific calibration projects currently being finalized) and fostering new ones (UCL and Belfast radiotherapy centres). This project will provide NPL with the capability for defining dosimetric and radiobiological standards and performing traceable measurements in strong magnetic field necessary for the clinical application of MRI-based radiotherapy facilities and the validation of future related technologies.

Support for Programme Challenge, Roadmaps, Government Strategies

The project aligns with the long-term strategic aims of NPL in supporting research, development and application of advanced and novel radiotherapy modalities and characterizing key quantities which regulate biological response to ionizing radiation exposure. Metrology for MRI-Linac systems is a key point on the roadmap for the AIR dosimetry group and the work proposed addresses objectives of the NPL Science Strategy. The proposal also addresses aspects of The Health Challenge of The Strategy for the National Measurement System: 2011-2015 as well as Societal Challenges in the Horizon 2020 programme of the EU.

Synergies with other projects / programmes

Synergy with AIR Dosimetry long-term strategy for the definition of biological weighted quantities for radiotherapy. In particular, the work proposed will add value to existing projects on the development and characterization of dosimeters for new radiotherapy modalities (i.e. hadron therapy) and role of reactive radical species. The radiobiological output will represent a significant step forward towards future projects aimed to develop biological optimized radiotherapy approaches by combining physics (microscopic dosimetry information) and biological (damage quality and dose effectiveness) parameters.

Risks

Risks related to dosimetry are considerably low considering the expertise available and support from MRI-Linac manufacturers (i.e. Elekta). Radiobiological validation is a new area of work for NPL. However, risks are mitigated by collaboration with NPL Biotechnology group and established radiobiological UK laboratories, both with considerable cell biology expertise. Modelling and simulations in strong magnetic fields will also be implemented on the base of existing NPL expertise.

Knowledge Transfer and Exploitation

Elekta-Philips is very interested in the dosimetric and radiobiological characterization of the MRI-Linac prototype they are developing for selected worldwide centres. Output from the project will provide radiotherapy manufacturers with critical information for further optimization and development of new MRI-based products for radiotherapy. Methodology and traceable measurements will help in defining UK standards for employment of MRI-Linac in clinical settings. Moreover, the complementary dosimetric and radiobiological characterization approach will be very beneficial for the development of biological optimized treatment planning in radiotherapy and it could be adapted to more conventional modalities (i.e. IMRT, hadron therapy).

Co-funding and Collaborators

The developed radiobiological metrology will favour collaboration with academic research institutions (i.e. Gray Cancer Institute, Queen's University Belfast and potentially University of Surrey) opening opportunities for further research projects and driving forward the implementation of biological optimized treatment planning for cancer radiotherapy. The project will also strengthen the collaboration with Elekta which are very interested in commissioning dosimetry validation/characterization projects.

Deliverables

1	**Start: 01/01/2014**	**End: 30/6/2015**	
Deliverable title: Magnetic - 60Co irradiator facility allowing inserts for ion chambers, alanine, film, chemical and biological samples. Facility developed.			
2	**Start: 01/10/2014**	**End: 31/12/2016**	
Deliverable title: Characterization of ion chambers and chemical detectors in magnetic fields. This will include measurements, Monte Carlo simulation and models of dose response as a function of size, orientation and magnetic field strength. Peer reviewed publication submitted.			
3	**Start: n/a**	**End: n/a**	
DELIVERABLE 3 NOT CONTRACTED: Definition of traceable standards and parameters of interest for radio-biological effects in strong magnetic fields. This will include quantification of yield/spectra of reactive radical species and relative biological effectiveness as a function of magnetic field characteristics. Report, peer reviewed publication submitted.			

Project No.	AIR/2014/DS5	Price to NMO	£196k
Project Title	Dosimetry for novel radiation processing applications	Co-funding target	
Lead Scientist	Peter Sharpe	Stage Start Date	1 January 2014
Scientist Team	Mark Bailey, David Crossley, Sebastian Galer	Stage End Date	31 December 2016
		Est Final Stage End Date	31 December 2016
Sector	3. Health; 6. Advanced Manufacturing & Services	Activity	Methodology for New Capabilities
Project Champion	John Woolston		

Summary

Dosimetry traceable to national standards and having a known level of uncertainty is a regulatory requirement for the sterilization of medical devices under both EU and US FDA regulations (e.g. EU MDD and standard EN/ISO 11137). In order to meet the needs of the medical device industry both in terms of new product development and regulatory compliance, it is necessary to enhance the existing standards and services provided by NPL in a number of areas. This project addresses the need for the development of accepted protocols for dosimetry at low temperatures and for determination of beam energy (quality) in high dose industrial mega-voltage x-ray beams. An experimental study to characterise a new primary standard for low energy electron beams will also be undertaken and correction factors will be established for reference dosimetry in high dose mega-voltage x-rays.

The Need

Accurate dosimetry traceable to national standards and having a known level of uncertainty is a regulatory requirement for the sterilization of medical devices under both EU and US FDA regulations (e.g. EU MDD and standard EN/ISO 11137). The EN ISO standards covering radiation sterilization of medical devices are presently undergoing revision and this has highlighted a number of areas where the current availability of measurement standards and validated methods is not adequate to enable straightforward compliance by the medical device industry with regulatory requirements. This is particularly apparent in the areas of low temperature irradiation, where accurate correction factors for dosimeters are not available; low energy electron beams, where overall uncertainty is dominated by the unacceptable uncertainty (10-15%) of the primary standards and high dose megavoltage x-ray irradiation, where there is a need for a standardised method to determine x-ray beam energy.

Over 50% of single use medical devices are sterilised by radiation and the fraction continues to increase. The proportion of medical devices processed by machine sources of radiation (electrons and x-rays) is increasing, resulting in a number of new requirements for standards for low energy electron beams and both kilo-voltage and mega-voltage x-ray beams. Recent microbiological studies in high dose rate x-ray beams have shown unexpected results, which may be due to errors in dosimetry system calibrations based on extrapolations from low dose rate behaviour.

Innovation in the medical device industry is being driven by the development of drug/device combination products, which require specialised irradiation techniques to sterilise the device whilst maintaining pharmacological or biological effectiveness of the active agent. Foremost amongst these techniques are sterilization at low temperatures and within tightly restricted dose ranges. Current dosimetry standards and calibration methods often do not have the required accuracy or traceability requirements needed by industry to efficiently utilise these new techniques, with resultant problems in gaining regulatory approval for novel products.

The Solution

In order to meet the needs of the medical device industry both in terms of new product development and regulatory compliance, it is necessary both to enhance the existing standards and services provided by NPL, for example in low temperature irradiation, and also to develop new techniques, such as a method for determining x-ray beam quality in mega-voltage industrial x-ray facilities. The formalization of newly developed techniques into accepted CEN/ISO standards, or other industry documents, is also an essential aspect in terms of regulatory approval. The project outlined below addresses these needs in the areas of low temperature dosimetry, standards for low energy electron beams and high dose mega-voltage x-ray dosimetry.

Project Description (including summary of technical work)

- Cryogenic Irradiation - Development of industry guidelines on dosimetry for cryogenic irradiation based on data obtained during the 2012+ programme.
- Low energy electron beam irradiation - Experimental study to characterise the new primary standard developed in 2012+ programme (collaboration with Risø, DTU, Denmark).
- High dose / dose rate mega-voltage x-ray irradiation – Development of a practical protocol for the determination of x-ray energy in industrial mega-voltage x-ray irradiators to allow compliance with regulatory standards.
- High dose / dose rate mega-voltage x-ray irradiation – Validation of correction factors for chemical dosimetry systems using calorimetric dose measurements in industrial mega-voltage x-ray beams.

Impact and Benefits

Enable UK industry to comply with EU Medical Devices Directive and US FDA requirements for radiation sterilization of medical devices through the development of dosimetry standards and techniques, industry guidelines and associated calibration services. Facilitate innovation by the development of new dosimetric techniques required for the radiation sterilization of novel drug/device products, pharmaceuticals and vaccines. The global market for combination products was estimated to be US$ 14 billion in 2009, with growth forecast at 15% per year.

Support for Programme Challenge, Roadmaps, Government Strategies

This project supports strategic initiatives in the Healthcare and Advanced Manufacturing sectors (e.g. regulatory compliance and development of innovative active medical devices, pharmaceuticals, vaccines etc., radiation hardness testing) as outlined in documents such as the BERR UK Life Sciences Marketing Strategy, the BERR Healthcare Industry Task Group Report and the document "Radiation Processing: Current Initiatives And 'Industry Needs' Summary" of the Panel on Gamma and Electron Irradiation published in 2011. The project aligns with the NMS Industrial Dosimetry Roadmap, 2013.

Synergies with other projects / programmes

There are strong synergies with other NMS IR projects, for example those concerned with high dose irradiation facilities, the development of primary standard calorimeters and mathematical modelling of radiation transport and heat flow.

Risks

Overall, the project is classed as low to medium risk, the highest risks being associated with the experimental studies to characterise the low energy electron standard and the development of a protocol for the determination of x-ray beam quality in an industrial environment. The risks are mitigated by previous experience in the development of low energy electron beam standards and by the involvement in the project of x-ray irradiator manufacturers.

Knowledge Transfer and Exploitation

Knowledge transfer will mainly be through publication in the open literature, the development of ISO/ASTM and CEN/ISO standards and the development of industry guidelines in collaboration with organisations such as the Panel on Gamma and Electron Irradiation. New and enhanced services will be introduced for calibration irradiation and reference dosimetry at low temperatures and reference dosimetry for mega-voltage x-rays.

Co-funding and Collaborators

Characterisation of the low energy electron beam calorimeter will be carried out as a collaborative project using the irradiation facility at Risø that was partially funded by the NMS in an earlier project. The high dose mega-voltage x-ray studies will be carried out in collaboration with IBA, the principle European manufacturer of these facilities, and Synergy Health, a facility operator.

Deliverables

1	**Start: 01/01/2014**	**End: 31/12/2014**	
Deliverable title: Industry guidelines on dosimetry for cryogenic irradiation.			
2	**Start: 01/01/2015**	**End: 31/12/2015**	
Deliverable title: Evaluation of new primary standard for low energy electron beam irradiation: scientific paper submitted to peer reviewed journal.			
3	**Start: 01/01/2016**	**End:31/12/2016**	
Deliverable title: Protocol for the determination of x-ray energy in industrial mega-voltage x-ray irradiators submitted for publication in industry standards (e.g. ASTM), including the development of associated calibration services.			

Project No.	AIR/2014/DS7	Price to NMO	£311k
Project Title	A new code of practice for MV x-ray therapy dosimetry	Co-funding target	
Lead Scientist	Simon Duane	Stage Start Date	1 July 2014
Scientist Team	Hugo Palmans, Rebecca Nutbrown, Russell Thomas, David Shipley, Graham Bass, Florian Graber	Stage End Date	30 June 2017
		Est Final Stage End Date	30 June 2017
Sector	3. Health	Activity	Methodology for New Capabilities

Summary

Since the publication in 1990 of the IPEM-recommended Code of Practice (CoP) for MV photon dosimetry, there have been very significant developments in the treatments routinely planned and delivered to radiotherapy patients. Highly conformal treatments can be quickly delivered by the dynamic modulation and shaping of beams used, supported by high resolution image guidance. This, and the increasing use of sometimes very small fields, means that users of the 1990 code must make dosimetric measurements under conditions which are often quite far from those specified in the 1990 code. The suitability of existing detectors for reference class measurements in this context will be assessed and, if needed, the feasibility of a new reference standard instrument for small field dosimetry will be determined. A new Code of Practice will be developed to meet UK needs, in collaboration between NPL and IPEM experts. The Code of Practice would build on the emerging international consensus on how best to measure absorbed dose in small and composite fields. The project proposed here will position NPL to disseminate absorbed dose in accordance with the new code.

The Need

Since the publication in 1990 of the IPEM-recommended Code of Practice for MV photon dosimetry, there have been very significant developments in the treatments routinely planned and delivered to radiotherapy patients. Highly conformal treatments can be quickly delivered by the dynamic modulation and shaping of beams used, supported by high resolution image guidance. This, and the increasing use of sometimes very small fields, means that users of the 1990 code must make dosimetric measurements under conditions which are often quite far from the standard reference conditions of the 1990 code. This results in greater uncertainty and an increased risk of measurement error through the use of inappropriate detectors and techniques. It is anticipated that IPEM will decide, possibly late in 2013, to replace the 1990 code: significant work would be required in order for NPL to provide the necessary support for a new Code of Practice.

The Solution

The capability for reference class dosimetry in small and composite fields will be developed, including the specification of a new secondary standard ionisation chamber for use in small photon fields. A new Code of Practice will be developed to meet UK needs, in collaboration between NPL and IPEM experts. The Code of Practice would build on the emerging international consensus on how best to measure absorbed dose in small and composite fields. The project proposed here will position NPL to disseminate absorbed dose in accordance with the code.

In the first year the scope of a new Code of Practice, and a schedule for its development, will be determined in collaboration with IPEM. This should take account of recent and forthcoming protocols but be adapted, for example in the selection and recommendation of appropriate type(s) of reference ionisation chamber, and in the identification of reference beam types and measurement conditions. The possible need to design a new secondary standard ionisation chamber will be determined.

In the following period, the absorbed dose standard will be commissioned in a range of high energy photon beams which are relevant to advanced radiotherapy techniques. If needed, the design for a new reference chamber will be developed, more suitable than the 2611, for use in small fields. Depending on the outcome of the EMRP project MetrExtRT in 2016, this could also include the use of integral quantities for dosimetry in very small and irregular fields.

Project Description (including summary of technical work)

High energy photon beams relevant to advanced radiotherapy techniques will be specified, in which the absorbed dose primary standard can be commissioned and which would allow dissemination under a new calibration protocol. This is likely to include a range of Flattening Filter Free (FFF) beams, fields smaller than 10 cm x 10 cm and, potentially, composite/dynamic/rotational fields. These are all beyond the reach of existing reference dosimetry standards and protocols. The need for a new secondary standard ionisation chamber suitable for use under these conditions will be determined and design options developed. The scope and timing for a new dosimetry Code of Practice for MV x-ray therapy in the UK would be agreed in collaboration with the IPEM. Subsequently a new dosimetry Code of Practice would be published; as well as a protocol for the use of integral quantities in very small and irregular fields dependent on the outcome of the EMRP project MetrExtRT. Training would be provided via the NPL practical course in reference dosimetry.

- Calibration beams specified: a range of FFF beam qualities, field sizes and measurement depths, including possible calibration procedures

- Reference class ionisation chamber options evaluated, including the possible development of a new secondary standard
- Absorbed dose standard commissioned in the newly specified calibration beams.
- Calibration procedures developed and piloted, with recommendations for choice of secondary standard ion chamber
- A new dosimetry Code of Practice for MV x-ray therapy in the UK, in collaboration with IPEM
- A protocol for the use of integral quantities in very small and irregular fields
- Training in the use of the new dosimetry Code of Practice for MV x-ray therapy

Impact and Benefits

Accurate dosimetry is fundamental to successful radiotherapy, which is used to treat 250,000 new cancer patients annually in the UK. As treatment techniques evolve, increasing uncertainty is associated with the difference between standard reference conditions and the fields used in patient treatments. A revised Code of Practice for radiotherapy dosimetry, written to address UK needs, will provide a secure foundation for optimisation of current treatment practice with benefits to patients.

Support for Programme Challenge, Roadmaps, Government Strategies

The project is in line with the long-term strategic aims of NPL in supporting research, development and application of advanced and novel radiotherapy modalities, and aligns with the NMO roadmap for Radiotherapy Dosimetry. The proposal addresses also aspects of The Health Challenge of The Strategy for the National Measurement System: 2011-2015 as well as Societal Challenges in the Horizon 2020 programme of the EU.

Synergies with other projects / programmes

This project will rely on the radiation dosimetry facilities that are maintained as part of AIR DC2 as well as the absorbed dose standards that have been developed under AIR DC1 and AIR DD1. This project additionally relies on expertise developed under AIR D4. This project will link with EMRP MetrExtRT.

Risks

There is a risk that IPEM will decide not to replace the 1990 Code of Practice for MV photon dosimetry: this project should commence once the outcome of this decision is clear.

Knowledge Transfer and Exploitation

Outputs of this project will be disseminated via a new Code of Practice for MV photon dosimetry and launch meeting. Updated training material in use of the new dosimetry Code of Practice for MV x-ray therapy would be delivered as part of the NPL practical course in reference dosimetry.

Co-funding and Collaborators

This project will be carried out in collaboration with the IPEM and partners in the EMRP project MetrExtRT (the use of integral quantities in very small and irregular fields).

Deliverables

1	**Start: 01/7/2014**	**End: 31/12/15**	
Deliverable title: New calibration beams specified, absorbed dose standard commissioned and calibration techniques validated for a range of FFF beam qualities, small field sizes and measurement depths.			
2	**Start: 01/01/2015**	**End: 30/06/2016**	
Deliverable title: A reference class ionisation chamber validated for use in small fields			
3	**Start: 01/01/2016**	**End: 30/6/2017**	
Deliverable title: A new dosimetry Code of Practice for MV x-ray therapy in the UK, developed in collaboration with IPEM, with a protocol for the use of integral quantities in very small and irregular fields.			

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Neutron metrology projects 2014

Project No.	AIR/2014/N1	Price to NMO	£211k
Project Title	Portable fast-neutron spectrometer	Co-funding target	
Lead Scientist	Catalin Matei	Stage Start Date	1 January 2014
Scientist Team	David Thomas, Nigel Hawkes, Andrew Bennett	Stage End Date	31 December 2016
		Est Final Stage End Date	31 December 2016
Sector	1.1 Energy generation and distribution; 5.1 National security	Activity	Methodology for New Capabilities

Summary

In recent years, our ability to measure fast-neutron fluences has been greatly exceeded by the precision and complexity of the required measurements. Existing spectrometers require multiple measurements with different detectors and complicated unfolding procedures to determine fluences for higher energy neutrons. The aim of this proposal is to build a fast-neutron spectrometer which will be used to address the current metrological and industrial needs.

The Need

NPL has limited capability to measure fast neutrons with good resolution at external locations. Fast neutron detection in intense gamma-ray backgrounds has applications in homeland security, fusion reactor diagnostics, and in radiation field characterization for metrological purposes. In homeland security it is required to detect weak neutron sources with a high confidence level and under short sampling periods. Neutron spectroscopy is used to calculate various plasma parameters in fusion devices. Measuring the energy spectrum and angular distribution of fast neutrons is extremely important for a number of rare-event physics experiments. The field of neutron dosimetry also requires the improved detection of fast neutrons.

In April 2012 members of the Neutron Metrology Group provided neutron spectrometry services for Urenco's UF6 storage facility in the Netherlands. The Bonner sphere system used for measurements is bulky and requires a complicated unfolding procedure to derive a very poor resolution neutron spectrum. NPL has also been approached in the past by the fusion community to measure neutrons around fusion facilities. The state of our fast neutron measurement capability is inadequate to meet the current needs. NPL would greatly advance its ability to characterize the fast neutron region of the spectrum and expand its services and expertise into new areas.

The Solution

To address these needs this project aims to design and build a fast-neutron spectrometer which is versatile and easily deployable. New liquid and solid scintillation materials with high light output and good pulse shape discrimination have recently become available. Developments in photomultiplier tube construction and digital pulse processing allow us to build a portable neutron spectroscopic system capable of delivering fast and accurate results.

The fast-neutron spectrometer will be carefully characterized for detection efficiency and energy resolution using Monte Carlo simulations and benchmarking experiments.

Project Description (including summary of technical work)

The main research challenge is to build a fully characterized, functional instrument. Tests will be carried out to identify the best combination of scintillation material and photomultiplier tube to achieve the required neutron detection efficiency and energy resolution. Monte Carlo simulation codes will be used to optimize the size and shape of the sensitive volume. We will also investigate the long term stability of the system and develop techniques to automatically calibrate the device.

The main components of the proposed portable fast-neutron spectrometer are the sensitive detector assembly and the signal processing unit.

Candidate sensitive detectors include the following scintillation materials and photomultiplier tubes:

- EJ-309 liquid scintillator. Available commercially from Eljen Technology with low toxicity and high flash point, retaining all the characteristics of NE213-type detectors.
- P-terphenyl organic single crystal with high light output and low pulse shape discrimination threshold. Difficult to acquire but successfully tested at several laboratories.
- New PPO-PVT plastics with efficient neutron-gamma discrimination. Soon to be available commercially and successfully tested at several laboratories including NPL.
- Hamamatsu H8500 flat-panel type multianode PMT assembly. This is a 64 cell, low-powered PMT available commercially.

The signal processing unit would use a fast digitizer card with digital pulse processing algorithms providing on-line and off-line neutron spectrum analysis and gamma rejection. Pulse processing algorithms will be developed and tested for neutron-gamma discrimination and time resolution. Improvements in detection efficiency and neutron-gamma discrimination may be achieved by developing new pulse shape analysis methods.

Impact and Benefits

This project will address critical UK and EU needs in border security and radiological safety. A portable fast-neutron spectrometer will be easily deployed for neutron spectroscopy and fluence measurements in remote areas and potentially be used in homeland security applications and as a neutron diagnostic tool in fusion reactors. It will, for the first time, give NPL the ability to extend high-resolution spectrometry to neutron energies above 20 MeV where there will be future needs for contaminant field measurements around proton therapy facilities.

A well-characterized fast-neutron spectrometer could be developed into a standard detector for the fast neutron region of the spectrum.

Support for Programme Challenge, Roadmaps, Government Strategies

This work is in line with the Neutron roadmap and touches several enabling sciences: ‘Higher energy spectrometry’ and ‘Digital electronics’ to advance to deliverables: ‘Field measurement capability’ and reach targets: ‘World leading neutron standards for radiation protection and security’.

Synergies with other projects / programmes

When successfully developed, the portable fast-neutron spectrometer will be a valuable tool to study neutron production from accelerator targets (AIR/2013/N1).

Risks

The risk that the portable fast-neutron spectrometer will not be completed or fail to work is **medium**. The proposed instrument is based on proven technologies and there is considerable existing expertise in novel detection materials and digital pulse processing within the team. There is a risk that scintillation materials which give the best neutron-gamma separation will not be available on the market or take too long to purchase and we will have to settle for a second-tier product. This risk is mitigated by building a highly modular instrument that can be easily upgraded with the latest technology.

Knowledge Transfer and Exploitation

Intended routes for knowledge transfer are:

- Presentations at instrumentation and metrology conferences
- Publication in specialized journals

Exploitation potential:

- A new measurement capability for high-resolution neutron spectrometry will be offered to customers
- Patentable technology will be reviewed and protected

Co-funding and Collaborators

Potential collaborators include: manufacturers of neutron measuring devices, other NMIs with interest in fast-neutron spectroscopy, research or industrial entities which produce fast neutrons as a result of their activity and have an interest in measuring the associated neutron fluences.

This project will benefit from the existing collaboration agreement between NPL, IRMM, IRSN and PTB to identify the measurement needs in the area and to increase the level of expertise in designing and testing neutron instruments.

Deliverables

1	**Start: 01/01/14**	**End: 31/07/15**	

Deliverable title:

Main components testing and design of the fast-neutron spectrometer. Instrument construction and characterization.

2	**Start: 01/08/15**	**End: 31/12/16**	

Deliverable title:

Fluence measurements for fast neutrons. Optimization of measurement techniques. Recommendations for standard neutron detector in the fast-energy region. Scientific paper submitted to specialized journal.

Project No.	AIR/2014/N2	Price to NMO	£133k
Project Title	Neutron-producing target study	Co-funding target	
Lead Scientist	David Thomas	Stage Start Date	1 January 2014
Scientist Team	Catalin Matei, Neil Roberts, Graeme Taylor, Nigel Hawkes, Andrew Bennett	Stage End Date	31 December 2015
		Est Final Stage End Date	31 December 2015
Sector	1.1 Energy generation and distribution; 3.3 Health & safety	Activity	Development of Existing Capabilities

Summary

This project aims to keep the monoenergetic neutron fluence standards of the NPL Neutron Metrology Group at the forefront of international metrology in the neutron area. Nominally monoenergetic neutron fields always have some component of neutrons at energies other than the designated monoenergetic value. This is due to scatter effects in the target, unwanted components in the neutron-producing target layer or its backing, etc. Instrument responses to these unwanted components can in some circumstances be very high, increasing the uncertainty substantially and even casting doubt on the validity of the calibration. Knowledge of these unwanted components is thus vital and evidence brought to light in a recent comparison suggests that more needs to be done to identify and quantify these components.

The Need

NPL is one of only four NMIs in the world that offers accelerator-produced monoenergetic neutron fluence standards that are used, for example, for calibration of devices for radiation protection and spectrometers for in-field use in the nuclear industry, and for device performance testing (the other NMIs are in Germany, France, and Japan). One of the major problems with producing these calibration fields is in obtaining suitable neutron-producing targets and characterising the spectra of the fields they produce. The neutron-producing targets are thin layers of specific materials. These are bombarded with charged particle beams from the NPL 3.5 MV Van de Graaff, but because it is impossible to produce self-supporting targets there is always a problem with neutrons produced in the target backing and from scattering in the target can. There may also be problems with contaminants in the target layer. Thus, although we offer a service for irradiation with monoenergetic neutrons, these fields always contain contaminant lower-energy neutrons which must be taken into consideration when providing a calibration. For some instruments the response to the scattered neutrons may be a large fraction of the response to the monoenergetic ones.

The potential problems with lithium, deuterium and tritium targets have long been known but the full extent came to light in a recent key comparison at the IRSN lab at Cadarache in France. The detailed characterisation performed by the IRSN staff prior to the measurements by the participants identified key problem areas. In a recent instrument calibration for a customer at NPL implementation of the scatter corrections brought out in the comparison showed that a 20% correction needed to be made to the result from a measurement at 16 MeV. Uncertainties on monoenergetic fluences are normally in the region of 2% to 3% so a correction of 20%, or more as it can be for other instruments, needs to be properly understood.

We presently have new LiF, deuterium, and tritium targets; with two versions of the tritium target - one for proton bombardment and one for deuteron bombardment. Lithium targets are known to have problems because the LiF diffuses into the backing. Deuterium targets are made by absorbing the deuterium in a titanium layer on a backing material. There is a known problem with the titanium, and hence deuterium, diffusing into the backing. Tritium targets are similar to deuterium ones, with similar problems and with added problems of deuterium in the tritium from the manufacturing process. The fields from these targets need to be characterised in order for NPL to provide more robust calibrations with better defined field characteristics and hence lower uncertainties.

The Solution

The techniques to measure these fields are available at NPL although they require some improvements. Time of flight will work for all the targets, but has been difficult to implement on the NPL Van de Graaff of late. For neutrons produced by bombarding lithium targets with protons the spectrum can be measured using proton recoil counters. For the neutron field produced using the deuterium and tritium targets a scintillator can be used. In addition to the experimental approach, considerable information can be derived from neutron transport codes. These are available at NPL but cannot be relied upon without additional information, for example the deuterium contamination of tritium targets cannot be known except by time of flight measurements.

The present proposal is to undertake a concerted effort at NPL, in collaboration with other labs in Europe, using all available experimental and modelling techniques, to characterise the currently available targets, to improve the knowledge of the spectra and the sources of uncertainty thereby addressing limitations in the current calibration capability.

Project Description (including summary of technical work)

This project will involve various components

a) **Measurements with scintillator detectors.** NPL has a new pair of liquid scintillator spectrometers developed to replace an old set where the resolution had become too poor to be used. The new set has not yet been fully characterised. The two detectors are operational but the response functions have not yet been finalised. Response measurements will be performed and combined with calculations to produce response functions. These spectrometers will then be used to investigate monoenergetic fields with energies above about 2 MeV.

b) **Measurements with hydrogen recoil counters.** For neutron fields below 2 MeV hydrogen recoil counters will be used to investigate the spectra in particular looking for the effect of the LiF entering the backing material for lithium targets.

c) **Time of flight measurements.** The time-of-flight system at NPL will be optimised and used to measure spectra from all types of target.

d) **Calculation of spectra.** A program has been written at the PTB to calculate target scatter spectra. The materials available for target backings are, however, limited. This code will be further investigated, possibly extended, and other approaches investigated, e.g. the use of codes like MCNPX or a code to calculate the neutron spectrum from the target and another, e.g. MCNP to calculate target scatter effects.

e) **Materials analysis of the targets.** Investigations of the target layers on their backings can be made by tagging a section across a target. This destroys the target, which is an expensive proposition for the deuterium and tritium targets, but may be the best way to obtain the required information about the target/backing interface. This is something which might be done in collaboration with other European NMIs to save costs.

Impact and Benefits

NPL provides monoenergetic neutron calibrations for various customers, usually ones who are characterising the response of neutron protection devices as a function of energy and/or angle. Other devices that are calibrated are transfer devices for other NMIs. If these devices have responses which are high in the energy region where the contaminant neutrons occurs our calibrations can be wrong by amounts way outside the uncertainties normally quoted. There is thus a real danger of providing an inaccurate calibration with consequences for NPL's reputation and also possible legal consequences. This work will result in improved calibrations with known uncertainties thus providing, for example, improved confidence in health protection measurements. The full characterisation of the neutron fluence standards provides underpinning essential support for radiation protection, security, and power generation including new build.

Support for Programme Challenge, Roadmaps, Government Strategies

This project aligns critically with the Neutron group's roadmap by underpinning the standards activity, and supports the UK energy strategy. One of the new challenges for neutron dosimetry measurements is performing them around high energy accelerators, such as those for proton therapy. Standard neutron fields are required at high energies to characterise the instruments which will be used. The highest achievable energies at NPL are obtained using the T(d,n) reaction which is the one where the contaminant neutron problem is most severe.

Synergies with other projects / programmes

This is essentially a project to improve and validate calibration fields. If the neutron monoenergetic fluence standards are to remain world class this project needs to be undertaken and its results used to provide essential corrections when these fields are used both for customer calibrations and developments, e.g. of new instruments, under the NMS programme.

Risks

The biggest risk is that some of the instruments/techniques required to measure the contaminant spectral features will not provide the required information. The range of approaches a) to e) above should ensure that some useful information will be derived.

Knowledge Transfer and Exploitation

There is surprisingly little in the literature about the problems of obtaining good neutron-producing targets for monoenergetic neutron standards. Information from this project will be published in a peer review journal and will provide input for ISO Standard 8529 which is about to be revised and part 1 of which is about neutron standard field production.

Co-funding and Collaborators

The potential problems with lithium, deuterium and tritium targets have long been known but the full extent came to light in a recent key comparison. IRSN staff prior to the measurements by the participants identified key problem areas. IRSN, PTB in Germany, and the Euratom Lab IRMM in Belgium are keen to collaborate on sorting out these problems.

Deliverables

1	**Start: 01/01/2014**	**End: 31/12/2015**	

Deliverable title:

Improved uncertainties for monoenergetic neutron calibrations: scientific paper submitted to peer reviewed journal

Project No.	AIR/2014/N3	Price to NMO	£139k
Project Title	Thermal neutron field standardisation	Co-funding target	
Lead Scientist	David Thomas	Stage Start Date	1 January 2014
Scientist Team	Catalin Matei, Graeme Taylor, Nigel Hawkes, Andrew Bennett	Stage End Date	31 December 2014
		Est Final Stage End Date	31 December 2014
Sector	1.1 Energy generation and distribution; 3.3 Health & safety	Activity	Development of Existing Capabilities

Summary

The marked increase in use over recent years of the NPL thermal neutron pile standard fields mean that any doubts about the accuracy of these standards needs to be taken seriously. In a recent key comparison the NPL thermal neutron fluence results were between 6% and 9% from the key comparison reference value. Although there is some doubt about the reference value (there were only 4 participants and only two agreed within the uncertainties) the necessity to validate the NPL standard or discover why there is a discrepancy with the comparison reference value is now urgent.

The Need

NPL is one of only a few NMIs worldwide who can offer irradiations in thermal neutron fields, e.g. for reactor instrument testing and characterising thermal neutron sensors in neutron instruments. In a recent Consultative Committee for Ionizing Radiation (CCRI) international key comparison the NPL results for thermal neutron calibration of four devices with different sensitivities to the temperature of the neutron distribution (essentially the mean energy of the distribution) came out between 6% and 9% below the mean. There are still unresolved questions about the correct mean value because of the small number of participants in the comparison, and the fact that the mean was essentially defined by one participant whose uncertainties were very small, but discrepancies of this order in a measurement where the uncertainties are of the order of 2% to 3% need to be resolved.

The standard for thermal neutron measurements is the gold cross section. Thermal fluence rates are determined by measuring gold foil activity. At NPL this is done by measuring the induced beta count rate. This should be relatively straightforward except that the activity needs to be measured in foils. Because of their thickness the beta counting efficiency is only about 40% and there are a number of corrections which need to be applied. Historical values for these corrections are available; but they derive from work done so long ago there is no supporting evidence available. These corrections are now being questioned. There are also uncertainties in the numerous parameters required to convert gold activity to thermal neutron fluence. One of these, the temperature, is derived from a published parametric relationship involving a quantity called the cadmium ratio (derived from gold foil measurements bare and under a cadmium cover) but the parameters in the relationship differ in different publications. The metrology thus needs to be put on a sounder footing in order to understand the corrections that need to be applied and reliably quantify the measurement uncertainties.

The urgency to resolve this problem is the reason why this project has been condensed into 1 year.

The Solution

The complete process of deriving the thermal fluence from the activation of gold foils will be reinvestigated with particular emphasis on the correction terms applied in going from a measured beta count rate for an irradiated foil to the value of the induced gold activity. Possible differences between the corrections needed for isotropic and plane parallel fields will be explored. The expertise of the Radioactivity Group will be utilised and also the experience of other labs who measure thermal neutron fluences via the activation of gold foils. Other approaches to determining the temperature of the thermal neutron distribution will be explored.

Project Description (including summary of technical work)

The complete process of deriving the thermal fluence from the beta count rate for foils activated in the NPL thermal pile will be investigated. Beta counting efficiencies will be derived from new measurements with $4\pi\beta$-γ counters and the all-important corrections will be investigated using modern radiation transport codes. To help with this aspect, comparisons are planned with other NMIs. In a recent meeting of Section (III) of the CCRI (the section that deals with neutron standards) there were a significant number of laboratories who expressed a willingness to participate in a comparison of gold foil activity determination. Because of the short half-life of gold (2.5 days) this is not an easy comparison but could be achieved by a series of comparisons between smaller groups with links between the groups. The expertise of NPL's Radioactivity group will be used where appropriate.

One approach to investigating the validity of the beta counting efficiency is to use foils of varying thicknesses and to make measurements in both isotropic fields (within the thermal pile) and in a plane parallel beam (the column of the thermal pile). As the foils get thinner the corrections get smaller but the count rates become very low and the statistics poor. However, it should be possible to obtain useful information from the activation of foils having a range of thicknesses and hence a range of beta counting efficiencies.

Determining the gold activity is only the first step in deriving the neutron fluence, although perhaps the most important. The project will also re-evaluate, and if necessary re-calculate, the corrections applied, e.g. self-absorption, flux depression, and corrections for activation in the gold resonance. Many of these were derived a long time ago when computing power was poor and before the development of modern neutron transport codes.

To obtain better information on the temperature other techniques for deriving this quantity will be investigated. There is at least one technique based on activation and another approach is the use of a specially made ^{3}He detector with varying filling pressures.

Impact and Benefits

The impact on the Neutron Group's, and hence NPL's, reputation if incorrect calibrations are being performed will be significant. Many neutron instruments, including spectrometers which operate over a wide range of neutron energies, use a thermal neutron sensor at the centre of a moderator. With modern radiation transport codes the response functions of these instruments can be calculated provided the thermal neutron response of the sensor is known. A number of the calibrations performed at NPL have been for this purpose. Thus, in addition to calibrations of devices used for measuring thermal fluences, e.g. within nuclear reactors, the thermal standards are used to underpin the characterisation of a range of other instruments (e.g. for radiation protection). Any problems with the thermal calibrations thus have an impact outside the technical area of direct thermal neutron fluence measurement. This project is fundamental to NPL's aim to remain a world-leading NMI in the neutron metrology area.

Support for Programme Challenge, Roadmaps, Government Strategies

This project aligns well with the Neutron group's roadmap by underpinning the standards activity, and supports the UK energy and defence strategies. The NPL thermal pile is used nowadays for neutron performance testing of neutron monitors that go into reactors both as replacements for failed monitors and in new reactors. No other facility is available in the UK and the use of facilities outside the UK is very difficult because of transport problems with taking fissile material across borders and with security implications. The NPL facility is thus of vital importance to both programmes.

Synergies with other projects / programmes

The thermal pile is a vital element of the NPL range of neutron calibration fields. It is important to be able to cover as wide a range of neutron energies as possible and the thermal facility is the only means of covering the very lowest energies.

Risks

It is anticipated that the project will involve collaboration with other NMIs. It is difficult to have any control over collaborators, and thus represents an element of risk, but the project is not dependent on this.

Knowledge Transfer and Exploitation

The outputs of this project will be disseminated via publications in peer reviewed journals, by presentations at national and international conferences, and by direct interaction with colleagues at other NMIs.

Co-funding and Collaborators

Collaboration is planned with both the NPL Radioactivity Group and other NMIs who used gold foil activation for thermal neutron measurement. This does not only involve NMIs with their own thermal facilities but any NMI which offers a thermal neutron measurement capability.

Deliverables

1	**Start: 1/1/2014**	**End: 31/12/2014**	

Deliverable title:

Improved uncertainties for thermal neutron field standardisation: scientific paper, submitted to peer reviewed journal

Project No.	AIR/2014/N5	Price to NMO	£190k
Project Title	Improved tissue equivalence of sensors for personal neutron dosemeters	Co-funding target	
Lead Scientist	Nigel Hawkes	Stage Start Date	1 January 2014
Scientist Team	Nigel Hawkes, Graeme Taylor	Stage End Date	31 December 2016
		Est Final Stage End Date	31 December 2016
Sector	3.3 Health & safety	Activity	Methodology for New Capabilities

Summary

Explore novel neutron sensor technologies, with the aim of improving the dose response of active personal neutron dosemeters through the development of sensors that are intrinsically more tissue-equivalent than existing devices.

The Need

Active personal dosemeters are very useful because they provide a readout on demand and can sound an alarm immediately if preset values are exceeded. For neutrons, all such dosemeters are based in some way on a silicon diode. Unfortunately the way in which neutrons deposit energy in silicon is significantly different from the way in which they deposit energy in body tissue. Although these devices can be calibrated to give the correct dose equivalent value in a particular neutron field, they can and do misread significantly when used in a different field. For example, one typical design, when calibrated with ^{252}Cf, will over-read by a factor of six in a cosmic ray field. The international standards covering such dosemeters (e.g. IEC 61526) permit this shortcoming because nothing better was available when the standards were drawn up.

Novel materials and sensor technologies are now becoming available that potentially allow new types of detector to be produced with improved tissue equivalence. As a leading authority in personal neutron dosimetry, NPL needs to participate in such developments in order to facilitate improvements, develop new and improved international standards for dosemeters, and to be aware of metrology issues arising.

The Solution

Measure where possible, and / or model, the response of candidate sensors as a function of neutron energy, so as to assess the degree of tissue equivalence. The aim is to identify a sensor technology with an intrinsically good match to the ICRP dose response (International Commission on Radiation Protection). Previous NMS projects have shown that neutron signals from conjugated polymers cannot be detected straightforwardly, presumably because of poor charge mobility and/or high recombination. This project will address this issue by broadening the range of technologies to be studied. Candidate sensor types include the following, each with differing levels of tissue equivalence and readiness for exploitation:

- Monocrystalline diamond: diodes 1 cm^2 by 300 μm already feasible. Improved tissue equivalence over silicon, but lacks hydrogen.
- Carborane ($C_2H_{10}B_{12}$): p-n junctions already demonstrated, using different isomers of carborane to produce p and n type material. High efficiency for thermal neutrons because of the boron, and fast neutron detection might also be possible via recoil protons. Depletion regions need to be made thicker (presently a few microns).
- High impedance electric field sensors, e.g. EPIC device from Sussex or graphene-based GUARD device from Purdue. Interesting new approach to detection, although practical designs for neutron sensors have not yet been demonstrated.
- Silicon nanoparticles in a polymer matrix. Speculative. The aim is to achieve intimate mixing of the tissue-equivalent polymer with conventional p-n junctions in the silicon.
- Organic diodes. Excellent tissue equivalence. Devices can be produced in volume (although currently for optoelectronic and photovoltaic applications, not radiation detection). Pulse detection from individual neutron interactions has not been demonstrated, due (it is believed) to low charge mobility and a high probability of recombination.

Prototype sensors and signal processing expertise will be sought through collaborations with, for example, BAe Systems, University of Surrey, Purdue University.

Project Description (including summary of technical work)

- Carry out a literature search in the subject areas outlined above, and any other relevant areas that emerge, to identify promising sensor technologies.
- Establish or renew contact with the workers involved with these technologies. Arrange meetings to explain the dosimetry application and to obtain information on, and / or samples of, the new devices.
- **Stage gate**: project to progress only if sufficient supply of samples for evaluation are available within an appropriate timescale.
- Based on this information and the samples where available, carry out simulations and / or measurements of the neutron

signal. Assess the dose response and practicality of use.

Impact and Benefits

Active personal dosemeters allow the wearer's dose to be read at any time, and can trigger an alarm if limits are exceeded. The sensors studied here will, if successful, allow these advantages to be combined with greatly improved accuracy in the dose equivalent readings.

Improvements to dose equivalent measurements are in accordance with the ALARP principle and, where existing devices over-read, with the commercial imperative to avoid unnecessary curtailment of work.

Support for Programme Challenge, Roadmaps, Government Strategies

These topics appear on the current Neutron roadmap as '*Organic semiconductors*' and '*Neutron detectors using organic semiconductors*', as that was the technology envisaged at the time.

Synergies with other projects / programmes

This work builds on and broadens previous investigations of conjugated polymers, organic photodiodes and Purdue University's Graphene-based Ultrasensitive Advanced Radiation Detector (GUARD).

Risks

High risk. These novel technologies are speculative to various degrees, and reasonable expectations (e.g. that a p-n junction will be sensitive to recoil protons) may be frustrated by the detailed characteristics of the new device. For most of the technologies listed above, the ability to observe signals from individual neutron interactions has yet to be demonstrated. It is proving difficult to bring together expertise on the diverse areas of novel materials, signal processing, and neutron interactions. The potential rewards in terms of improved radiation monitoring, increased efficiency in UK industry, and intellectual property are, however, considerable.

It may prove difficult or expensive to obtain samples for testing. Theoretical studies would still be possible but carry less weight.

Knowledge Transfer and Exploitation

The results of this study will be disseminated via one or more of the following routes:

- Presentation at a conference with peer-reviewed proceedings published in a journal. This is the favoured option because of the face-to-face interaction with other delegates and the wide availability of the proceedings. The Neutron and Ion Dosimetry (NEUDOS) series is particularly appropriate for this work.
- Direct submission to a journal such as *Radiation Measurements*, *Radiation Protection Dosimetry* or *Nuclear Instruments and Methods in Physics Research*. This route will be used for lengthier contributions or if no suitable conference is scheduled within a reasonable time. All the journals named use the conventional subscription model; publication in an open-access journal has obvious advantages in terms of reach, but would require a publication budget.
- Presentations at NPL events such as the Neutron Users' Club (NUC). The NUC is held annually and typically attracts around 50 delegates from a wide variety of academic and commercial organisations. Its informality means that contributions can be prepared relatively quickly, providing an efficient means of reaching a well-targeted audience.
- Ultimately, successful sensor designs will be licensed to dosemeter manufacturers under an applicable commercial agreement.

Co-funding and Collaborators

Where possible, sample devices will be sought via collaboration with the originating organisations.

Deliverables

1	**Start: 01/01/2014**	**End: 31/9/2014**	

Deliverable title:

Identification of suitable and sufficient supply of samples for evaluation, available within the timescale of the project: **Stage gate decision**.

2	**Start: 01/10/2014**	**End: 31/12/2016**	

Deliverable title:

Assessment of response of prototype systems for improved neutron dosimetry; scientific paper submitted to peer reviewed journal

Project No.	AIR/2014/N7	Price to NMO	£67k
Project Title	Neutron dosimetry based on radiobiology	Co-funding target	
Lead Scientist	Nigel Hawkes	Stage Start Date	1 January 2014
Scientist Team	Nigel Hawkes, David Thomas, Graeme Taylor, Giuseppe Schettino	Stage End Date	31 December 2015
		Est Final Stage End Date	31 December 2018
Sector	3.3 Health & safety	Activity	Methodology for New Capabilities

Summary

Recent developments in the ability to measure nanoscale radiation effects in body tissue, and in the understanding of cell biology, are likely to lead to proposals for new ways of measuring radiation risk. There may be a step change in dosimetry concepts and techniques. This project will consider how these issues will affect the facilities and services that NPL needs to provide for neutron dosimetry in the long term.

The Need

The risk from neutron exposure is currently estimated using the crude measure of energy deposited per unit mass (multiplied by various factors). Recently, studies have been undertaken to link risk to actual observable processes in biological cells, such as DNA strand breaks and the production of radical and reactive oxygen species. NPL is currently participating in such a study, the EMRP project *Biologically weighted quantities in radiotherapy* (BioQuaRT). However, BioQuaRT is aimed at radiotherapy rather than radiation protection, and for the latter the main issue is not cell death but long-term changes in surviving cells.

Such studies may lead to proposals for new radiological quantities, along with new ways of measuring them, that replace the somewhat problematic concepts of dose equivalent and effective dose, and allow more accurate assessment of the radiological risk to exposed persons. Variations in susceptibility from one individual to another may become quantifiable to some extent.

These developments are likely to lead to an increased emphasis on cell biology and on measurements on the nanometer scale corresponding to DNA molecules. For example, double-strand DNA breaks are much more serious than single-strand breaks (which cells routinely repair very effectively), and the probability of these occurring depends on how ionisation events cluster together on such scales. If neutron standards for radiation protection are to remain relevant in the long term (10 years or so), the potential impact on the skills and facilities required in the Neutron Metrology Group needs to be considered.

The Solution

The Neutron Metrology Group will consult participants in BioQuaRT and in similar studies, to consider the impact on dosimetry for protection-level radiation exposures. Conclusions will be drawn on what changes will be needed to neutron standards, and to the skills and facilities required to maintain them, in order to ensure that they remain relevant.

A report will be written recommending a strategy for future radiobiology studies in neutron fields, potential facility upgrades (e.g. commissioning of a charged particle microbeam, and/or neutron-producing micro-targets), and key collaboration partners.

Project Description (including summary of technical work)

- Carry out a literature review.
- Consult researchers currently engaged in similar work, e.g. the Grosswendt group at Legnaro, Italy, and the BioQuaRT participants at NPL and elsewhere in Europe.
- Formulate a view on how these developments could lead to improved dosimetry that is soundly based on actual biological effects.
- Make recommendations on what new metrology techniques and facilities are likely to be needed in the medium to long term.

Impact and Benefits

The work outlined above will begin the process of planning for the changes that a shift to radiobiology-based dosimetry is likely to bring to neutron metrology for radiation protection. This will help to ensure that the UK retains its access to useful and effective neutron standards in the long term. Additionally, NPL and the UK will be part of the international discussion and will keep up-to-date in a subject where fundamental changes appear to be imminent.

Support for Programme Challenge, Roadmaps, Government Strategies

This topic is covered in the neutron roadmap under ‘Improved dosemeters and extending n dosimetry’ and ‘Provide neutron standards to meet radiation protection requirements’.

Synergies with other projects / programmes

Researchers at NPL are already participating in the EMRP-supported BioQuaRT project. This is aimed at therapy-level doses, where the main issue is cell death. In contrast, protection dosimetry is concerned with the more complex issue of cells that survive much lower doses but undergo long-term changes. The concepts and techniques are, however, similar in the two areas, particularly when considering peripheral doses from therapy beams.

Risks

Risks are low as this is a paper study.

Knowledge Transfer and Exploitation

This project is primarily intended to inform future NMS proposals. However, publication of the final report could still be appropriate via the following routes:

- An NPL report. These are reviewed internally and are published on the NPL web site.
- Presentations at NPL events such as the Neutron Users' Club (NUC). The NUC is held annually and typically attracts around 50 delegates from a wide variety of academic and commercial organisations. Its informality means that contributions can be prepared relatively quickly, providing an efficient means of reaching a well-targeted audience.
- Presentations at external meetings in this subject area, where contributions are kept on record but not necessarily peer reviewed.

In the longer term, successor projects are expected to lead to papers in a metrology journal, e.g. *Metrologia*, and to new international standards documents.

Co-funding and Collaborators

Informal collaboration will be sought with the leaders in this field, e.g. members of the Grosswendt and BioQuaRT groups mentioned earlier, in order to obtain and collate expert opinion.

Deliverables

1	**Start: 01/01/2014**	**End: 31/12/2015**	

Deliverable title:

Review and recommendations for future requirements for neutron dosimetry based on radiobiological risk (NPL report).

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Radioactivity metrology projects 2014

Project No.	AIR/2014/R2	Price to NMO	£354k
Project Title	Nuclear decay data	Co-funding target	Joint project with University of Surrey
Lead Scientist	Patrick Regan / Steven Judge	Stage Start Date	1 Jan 2014
Scientist Team	Lena Johansson, Cyrus Larijani, Simon Jerome, John Keightley	Stage End Date	31 December 2016
		Est Final Stage End Date	31 December 2016
Sector	1.1 Energy generation and distribution , 2.2 Pollution & waste reduction	Activity	Methodology for new capability

Summary

During the last few years, NPL has contributed to international efforts to establish a robust database of nuclear decay data (DDEP) through evaluating published results. This project is a change in this strategy: thanks to close links with the University of Surrey, NPL is in a unique position amongst NMIs to conduct new measurements of decay data to address known problems, including discrepancies in decay data for decay heat calculations and a paucity of data for long-lived radionuclides.

The project has three aspects:

- Development of a novel multi-gamma array for decay studies at NPL and as a resource for use at international facilities
- Measurement of decay data required for geological disposal of radioactive waste
- Measurement of decay data required for decay heat calculations for new build and disposal of radioactive waste

These measurements require a metrologically-sound detection system for analysing coincident gammas, emitted in the decay of radioactive sources or during irradiation. The instrument would be the world's first large-scale gamma spectrometry system that applies the learning from radionuclide metrology to nuclear decay data studies. It is a complex and challenging project that should result in publications in leading scientific journals including Physical Review.

The Need

The need for the work falls into two main categories:

1) The contemporary understanding of the heat which is deposited from the fission process in a commercial reactor assumes that approximately 10% of the total energy released in the fission process arises from gamma-ray emission. Approximately 40% of this comes from prompt gamma radiation directly following fission, with the remaining 60% associated with the decay heat from decaying fission fragments. Accurate estimates of the heat produced are needed for reactor design, for life extension studies and for the safety case for radioactive waste disposal options. This includes careful and accurate characterisations of the energies and multiplicities of gamma ray radiation emitted both from prompt, thermal neutron induced fission reactions (e.g. $^{235}U(n,f)$) and also following the subsequent radioactive (β^-) decays from the resulting fission fragment residues.

2) The longer lived fission and activation products form a significant portion of the UK Radioactive Waste Inventory beyond the 500-1000 year time horizon, including ^{41}Ca, ^{59}Ni, ^{79}Se, ^{93}Zr, ^{94}Nb, ^{107}Pd, ^{108m}Ag, ^{126}Sn, ^{129}I, ^{135}Cs, ^{151}Sm, ^{232}Th, ^{236}U, ^{238}U and ^{237}Np. There is a requirement to be able to quantify these radionuclides accurately in order to predict future dose commitments arising from the long term storage of such waste and the containment strategies. However, the decay data for these radionuclides are poorly known with some data based on work carried out in the 1950s, with large uncertainties in key parameters such as the half-life.

The Solution

The first part of the solution is to design and commission a state of the art coincidence gamma-ray detection set-up which would be based at NPL but is also modular in nature and therefore portable. It is envisaged that the proposed prototype detection array will be utilised in 'standalone' mode at NPL and in pan-European nuclear decay projects, such as the DESPEC experiment within the NUSTAR collaboration at the Facility for Anti-Proton and Ion Research. It is anticipated that the prototype gamma-ray detection system will allow both discrete gamma-ray spectroscopic evaluation and calorimetric measurements of electromagnetic radiation emitted following radioactive decays from nuclei with exotic proton to neutron ratios, including fission fragments associated with nuclear waste. The proposed gamma-ray detection system will also be available for use in experiments using thermal neutron-induced fission for measurements of the typical integrated prompt gamma-ray spectrum associated with fission of $^{236}U^*$ and $^{242}Pu^*$. Such measurements will provide important inputs into decay heat measurements.

The initial detector system would be a prototype design model for a future planned, highly modular joint Total Absorption Spectrometer (TAS) to perform state of the art measurements of decay heat and extract beta-decay strength functions with improved accuracy for a wide range of fission fragments. The prototype multi-detector array would build on the recent developments in scintillation materials which couple a high light output, which brings with it an acceptable energy resolution for selection of discrete gamma-ray line energies, with sub-nanosecond timing capabilities.

Project Description (including summary of technical work)

The technical work includes constructing an array of room-temperature, high resolution gamma spectrometers, commissioning the associated digital electronics, developing the analysis algorithms and commissioning the instrument to ISO17025 standards. The emphasis then shifts to measuring nuclear decay for priority radionuclides (in the laboratory) before offering the instrument as a national resource for use by research groups.

Impact and Benefits

- The initial impact would be to provide the NPL with a state of the art, coincidence gamma-ray detection set-up which would be used in both calibration and novel research measurement modes, with potential for future precision measurements of radioactive decay half-lives and activity concentration evaluations in calibration samples.
- Support, through accurate estimates of the heat produced, for reactor design, life extension studies and the safety case for radioactive waste disposal options.
- Future potential benefits would be related to developments in fundamental nuclear science in terms of potential contributions to novel and standardisation measurements of decay characteristics and decay heat profile of nuclear fission fragments. The detectors are also likely to make a scientific contribution to future studies of the structure of nuclei with unusual exotic proton to neutron ratios.
- The lack of liquid nitrogen cooling for such detectors may also provide opportunities for the system to be used in a portable 'lab in a van' mode for measurements in–situ at external locations.

Support for Programme Challenge, Roadmaps, Government Strategies

The project addresses government strategies in Energy, challenges in nuclear waste disposal, and aligns with the Radioactivity roadmap on Environment and Energy.

Synergies with other projects / programmes

The project builds on many years of experience at NPL of digital signal processing techniques and analysis algorithms for coincidence data. The technology in this project has synergies with the project to develop a mobile laboratory (AIR/2012/R7) and the proposed EMRP project on decommissioning (MetroDECOM and the related proposal R3).

Risks

This is a technically demanding and stretching project, only feasible due to the partnership with the University of Surrey.

Knowledge Transfer and Exploitation

Decay data obtained for the priority radionuclides would be disseminated through:

- Publication in high impact scientific journals
- Contributions to international databases
- Participation in IAEA workshops and international nuclear physics conferences

The collaboration with the University of Surrey means that the instrument will be part of the UK's contribution to international research in nuclear physics – a major new role for an NMI. The developments will be disseminated and exploited by:

- Publication in high impact scientific journals and in trade journals
- Presentations at scientific conferences
- Use in other projects (e.g. development of a mobile laboratory AIR/2013/R7)

Co-funding and Collaborators

The intention is that the University of Surrey will also apply for STFC funding via a Project Research and Development (PRD) grant. The project would contribute to the decay spectroscopy project at the GSI Laboratory in Germany.

Deliverables

1	**Start: 1/1/2014**	**End: 1/9/2014**	

Design of multi-detector array

Design of multi-detector gamma-ray array consisting of up to 12 halide scintillation detectors which could be used in (a) standalone high-efficiency geometry (TAS mode); (b) combined with an existing NaI(Tl) TAS set-up for improved performance; and (c) 'high resolution coincidence' mode for decay studies of discrete gamma-rays decaying in cascade following either isomeric and/or beta-decay.

2	**Start: 1/10/2014**	**End: 31/3/2015**	

Construction of detector array

Constructed detection array (in collaboration with the University of Surrey).

3	**Start: 1/4/2015**	**End: 30/9/2015**	

Commissioning of detector array

Commissioned data acquisition system, based on digital signal processing systems for radionuclide metrology.

4	**Start: 1/1/2015**	**End: 31/12/2016**	

Nuclear decay data

Nuclear decay data for priority radionuclides, using the new detector array and mass spectrometry.

Project No.	AIR/2014/R3	Price to NMO	£569k
Project Title	Improved radionuclide metrology for decommissioning and remediation of the UK Nuclear Industry – EMRP MetroDECOM cofunding	Co-funding target	EMRP MetroDECOM
Lead Scientist	Simon Jerome	Stage Start Date	1 September 2014
Scientist Team	Lena Johansson, Andy Pearce, John Keightley, Julian Dean, Peter Ivanov, Michael de Podesta	Stage End Date	31 August 2017
		Est Final Stage End Date	31 August 2017
Sector	2.2 Pollution & waste reduction	Activity	Methodology for new capabilities

Summary

The overall scientific and technological objective of the project is to support decommissioning of nuclear sites with improved metrology and to minimise the environmental burden by providing means for improved sentencing of waste resulting from decommissioning. The aim is to create innovative metrological solutions and improved methods and measurement facilities that will have a significant technological and financial impact on the growing demands of the decommissioning industry. The project will provide suitable sampling techniques for radioactivity measurements at decommissioning sites and of radioactive waste, to conduct accurate, traceable measurements of long lived and difficult-to-measure radionuclides in complex matrices at the site of production, and provision of suitable reference materials. It will also develop a technique for repository temperature measurement.

The Need

Europe is facing an immediate, major challenge - the enormous costs of decommissioning legacy nuclear facilities. In particular, tens of the nuclear power plants made operational in the 1960s and 1970s are about to be phased out. There are huge costs involved, but it will be possible to make great savings by identifying best practices, standardising measurements and improving measurement techniques. Thousands of tons of waste must be either released into the environment or stored in radioactive waste repositories and clearance of sites must be performed in a manner which is both safe and cost-effective.

Many metrological requirements emerge from this issue, including the need for nuclear decay data described in project AIR/2014/R2 and reliable long-term temperature measurements. For this project proposal, the requirement that is highlighted is accurate determination of the radionuclide content of waste materials in a cost effective manner. The root cause is that a full analysis (identification and analysis of all the radionuclides present) costs about £20k per sample – clearing just one batch of waste usually needs about 20-30 samples, so this approach is uneconomic. Existing guidance (for example, the Nuclear industry Code of Practice for Clearance and Exemption, and US guidance such as DQO and MARSAME) does not address this issue, leading to a lack of clarity and consequent delays to decommissioning projects.

The need is for much cheaper measurement methods supported by clear, statistically-sound guidance on interpretation.

The Solution

The solution builds on the existing EMRP project MetroRWM to develop automated in-situ radiochemical analysis techniques to reduce the cost of analysis, and also to develop measurement protocols using a combination of gross and individual radionuclide analysis methods to reduce the costs of analysis whilst retaining traceability to national standards. New reference materials will be needed to test the methods. Furthermore, the project will develop a method suitable for temperature monitoring in radioactive waste repositories.

Project Description (including summary of technical work)

The development of methods for the radionuclide characterization of different types of materials present on sites being decommissioned:

- Improved mapping of activation and contamination inside nuclear facilities by the development of novel techniques
- Statistically based sampling methods, that will include Bayesian analysis, for representative samples for radiochemical analyses (building on MARSSIM, MARLAP etc)
- Automated radiochemical analysis procedures building on the outcomes of the EMRP project MetroRWM
- Studies to enable improved quantification of scale factors for estimating levels of indirectly measured radionuclides.
- The development of reference materials and standard sources (e.g. drums) for calibration, validation and testing of devices, instruments and procedures.
- The development of practical acoustic thermometry (PAT) technology and analysis for applications where temperature sensing is required in large extended volumes (e.g. throughout a storage tank, large building or underground facility).

Impact and Benefits

The potential impact of this project is in the tens (if not hundreds) of £M per year. The NDA's annual budget for decommissioning legacy nuclear sites is £3 billion, with the cost of waste disposal being a significant part.

A case study illustrates the impact of this work: under a previous project, NPL developed a new standard for ^{241}Pu. This standard enabled Magnox to characterise low level waste (LLW)/ intermediate level waste (ILW) borderline sludges, giving sufficient

confidence in the results so that the sludges could be consigned as LLW with the associated cost savings.
This work is in line with the needs of the Nuclear Decommissioning Authority (NDA) to provide planned waste disposal.

Support for Programme Challenge, Roadmaps, Government Strategies

This work is in line with the Radioactivity road map on Environment and Energy and the needs of the NDA to provide planned waste disposal.

The proposed topic is also in conformity with the document EC COM(2011)21 ("*A resource-efficient Europe – Flagship initiative under the Europe 2020 Strategy*"), and in particular addresses the following issues and statements:

- '*Increasing recyc*ling rates will reduce the pressure on demand for primary raw materials, help to re-use valuable materials which would otherwise be wasted, and reduce energy consumption and greenhouse gas emissions from extraction and processing.' (p.5)
- 'Expanding nuclear power can reduce carbon emissions but requires the further enhancing of nuclear safety, waste management and non-proliferation.' (p.5)

Synergies with other projects / programmes

The work in this project supports work elsewhere in the Radioactivity programmes, specifically the project AIR/2013/R7: Mobile laboratory

Risks

This project carries some risk in that the deliverables are dependent on contributions from partners in the EMRP project MetroDECOM and that the development of new techniques and procedures is inherently risky. The mitigation is that the management of the MetroDECOM project will be run (as far as possible) to minimise risk to NPL delivery of outcome. The development of new techniques is mitigated by using current experience and expertise within the group to devise technically sound solutions, tested at the first available opportunity.

Knowledge Transfer and Exploitation

The outcomes of this project will be disseminated by:

- Publication in high impact scientific journals – these will be diverse, such as (but not limited to) Applied Radiation and Isotopes for half-life work, Journal of Environmental Radioactivity for radioactivity and reference materials achievements and Analytical Chemistry for analysis techniques
- Participation in IAEA workshops as appropriate
- Presentations at scientific conferences
- Use in other projects (e.g. development of a mobile laboratory AIR/2013/R7)

Co-funding and Collaborators

This project will benefit from collaboration with the Nuclear Decommissioning Authority, and the Environment Agency/Scottish Environment Protection Agency to better target the needs in this area.
University of Loughborough; PTB; ENEA; IRMM; CMI

Deliverables

1	**Start: 1/9/2014**	**End: 31/8/2017**	
WP1A: Characterisation of materials on decommissioning nuclear sites (NPL-lead) - Co-funding EMRP MetroDECOM Developing instrumentation and procedures to map contamination in facilities and plant on decommissioning nuclear power sites.			
2	**Start: 1/9/2014**	**End: 31/8/2017**	
WP1B: Sampling protocols for radiochemical analysis (NPL-lead) - Co-funding EMRP MetroDECOM Development of sampling techniques (using Bayesian statistics) to increase confidence in waste sentencing.			
3	**Start: 1/9/2014**	**End: 31/8/2017**	
WP1C: Semi-automated radiochemical analysis techniques (NPL-lead) - Co-funding EMRP MetroDECOM Development of analytical equipment and procedures for measurements in-situ of 'difficult' radionuclides.			
4	**Start: 1/9/2014**	**End: 31/8/2017**	
WP4: On site monitoring and measurement in waste repositories (NPL-lead – Radioactivity Group) - Co-funding EMRP MetroDECOM Development of gas sampling instrument for measuring and monitoring radioactivity in waste repositories.			
5	**Start: 1/9/2014**	**End: 30/4/2017**	
WP4: Development of practical acoustic thermometry (NPL-lead – Temperature Group) - Co-funding EMRP MetroDECOM Develop practical acoustic thermometry (PAT) technology and analysis: paper submitted to refereed Journal.			
6	**Start: 1/6/2015**	**End: 31/7/2017**	
WP5: Development of a reference material (PTB-Lead) - Co-funding EMRP MetroDECOM Preparation of a solid matrix reference material (to include in the growing 'library' of reference materials worldwide).			

Project No.	AIR/2014/R6	**Price to NMO**	£279k
Project Title	Metrology for radiological early warning networks in Europe – EMRP MetroERM cofunding	**Co-funding target**	EMRP MetroERM
Lead Scientist	Hilary Philips, Paddy Regan	**Stage Start Date**	1 September 2014
Scientist Team	Lauren Perrie	**Stage End Date**	31 August 2017
		Est Final Stage End Date	31 August 2017
Sector	3.3 Health & safety, 5.1 National security	**Activity**	Methodology for new capabilities

Summary

The basic safety standards for the protection of public health against the dangers of ionising radiation are laid down in the Council Directive 96/29/EURATOM and are mandatory for all EU Member States. During a radiological emergency with trans-boundary implications in Europe, the European Commission will issue recommendations to EU Member States based on data from the national early warning networks. Metrologically sound monitoring data of ambient dose rate and airborne radionuclide activity concentrations, co-ordinated with data from international radiological networks, are a prerequisite for adequate environmental radiation monitoring in Europe. In collaboration with other NMIs and with support from national monitoring networks, this project aims to evaluate existing and proposed instrumentation, to develop reference materials and establish harmonised methods to establish a coherent early warning network.

The Need

The accurate early determination of airborne radioactive activity concentrations and deposition information arising from a major radiological emergency are fundamental to the planning of appropriate countermeasures for the protection of public health. Currently there are some 4500 air monitoring stations throughout Europe and previous effort has been spent on harmonising the procedures used by early warning networks in Europe by the AIRDOS project. There remains a need to improve the compatibility of data generated by these air monitoring networks, and to introduce unified calibration procedures for instrumentation used for the measurement of airborne radioactive aerosol based on sound metrological principles both for dose rate and radioactivity aerosol concentrations. The linking of existing European radioactive air monitoring networks to a uniform calibration procedure will enable greater data compatibility and lead to improvements in the information provided to governments to inform crisis management.

The Solution

- The evaluation of novel detectors based on new materials (e.g. LaBr3, Cd-Zn-Te) and improved instrumentation for field station use for both airborne radioactive particulate monitoring to determine detector characteristics, spectral resolution, and to evaluate de-convolution methods used with interfering radioactive response (e.g. internal radiation)
- The development of novel traceable reference materials by extending the capability of the NPL radioactive aerosol facility to enable testing of field instruments with beta / gamma emitting nuclides using particles similar to those anticipated during incident conditions.
- The production of standard sources for proficiency test and comparison exercises to quantify airborne radioactivity and dosimetry field station performance.

Project Description (including summary of technical work)

NPL will lead the work package for airborne radioactivity monitoring networks which will be focussed on the detection of radioactive aerosols, building on the current project to develop a primary standard in this field. The main steps will be:

1) Experimental evaluation of existing commercial and emerging detector technologies (e.g. internal interfering radiation in $LaBr_3Ce$ detectors)
2) Development and characterisation of novel reference materials for aerosol studies
3) On-site testing of monitoring equipment to evaluate derived operational changes

Other parts of the project (conducted by other NMIs) involve developing algorithms for radon correction, evaluation of chemical methods for aerosol detection, Monte Carlo simulations of detector response and data harmonisation protocols.

Impact and Benefits

- Early indication and better determination of affected areas, and the identification of radionuclides and contamination levels in real-time, enabling efficient deployment of countermeasures to protect the affected population, in particular during the early phase of an accident.
- Harmonisation of national early warning networks is essential to "eliminate political borders in contamination patterns".
- Implementation of a new procedure for radioactive aerosol measurements may minimise the follow-up costs; e.g. better determination of the affected area to reduce the need for exclusion zones, evacuation measures and banning contaminated agricultural products from the market. Note: A reduction of follow-up costs of 10% in the case of Chernobyl corresponds to about €40 bn.
- The project aims to harmonise calibration procedures and encourage good practice. By this, uncertainties in radiological data

can be reduced from typically some 10 % to 50 % to only 10 % or less.
- The project supports compliance with EU directives on protection of workers and radiological emergencies.

Support for Programme Challenge, Roadmaps, Government Strategies

The project is supported by Challenge driven R&D, Development of existing capabilities, and the Provision of standards from the NPL Roadmaps.

The project supports compliance with the following EU directives:

- Council Directive 96/29/EURATOM of 13 May 1996 laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation.
- “Convention on Early Notification in Case of a Nuclear Accident or Radiological Emergency”, adopted on 26 September 1986 at the 8th plenary meeting, Legal Series No.14, IAEA, Vienna (1986). Article 5.
- Council Decision 87/600/EURATOM of 14 December 1987 on Community arrangements for the early exchange of information in the event of a radiological emergency.
- Council Directive of 27 November 1989 on informing the general public about health protection measures to be applied and steps to be taken in the event of a radiological emergency (89/618/Euratom Article 6).
- Official Journal of the European Union, Notice No. (2006/C 155/02), Verification of environmental radioactivity monitoring facilities under the terms of Article 35 of the Euratom Treaty.
- EURDEP (European Radiological Data Exchange Platform): http://eurdep.jrc.ec.europa.eu/

Synergies with other projects / programmes

The work builds on the development of NPL’s new primary standard for radioactive aerosols (AIR/2012/R6)

Risks

The main risk associated with the project is persuading a diverse and large group of organisations across the EC to adopt coherent working practices and (possibly) new technology. Involvement of the regulators (including organisations such as EURATOM) is essential. It is recognised that this will be a difficult part of the project but a system that NMIs recommend is a prerequisite to making progress towards this vision.

Knowledge Transfer and Exploitation

This project aims to increase the capability of the NPL Radioactive Aerosol Facility (AIR/2012/R6) to include beta/gamma aerosol thus increasing the scope of the intended alpha aerosol measurement service; to improve the underlying metrology for the detection of radioactive aerosols; and to establish and to disseminate best practice to the European radioactive air monitoring networks by:

- The development of e-learning modules to disseminate best practice to monitoring networks
- The organisation of workshops at international conferences (e.g. IEEE, EURODOS) attended by monitoring networks
- The publishing of papers in the peer reviewed scientific literature, conference proceedings and trade journals
- The provision of a public web page containing information for monitoring networks linked to the current NPL ARMUG webpage and also the provision of a Sharepoint for the project
- Establishing links to organisations influential in the operation of national airborne radioactive monitoring networks (e.g. HERCA, EURADOS) and interaction with IEC standard committees (e.g. TC85)

Co-funding and Collaborators

EMRP funded project MetroERM in collaboration with PTB, CMI, ENEA, IFIN, CIEMAT, IRMM, ISSPRA, LNHB, NRPA, IRSN and supported within the UK by Sellafield, RIMNET.

Deliverables

1	**Start: 1/9/2014**	**End: 28/02/2017**	

Deliverable title: Airborne radioactivity monitoring network instrumentation (NPL Lead) - Co-funding EMRP MetroERM

Technical review of current monitoring network practices leading to the selection of detector types for performance evaluation and the development of best practice recommendations for field station operation, presented as e-learning modules.

2	**Start: 1/1/2015**	**End: 31/8/2017**	

Deliverable title: Reference materials for the early warning network - Co-funding EMRP MetroERM

Development and characterisation of novel aerosol and filter reference materials (aerosol produced using the NPL radioactive aerosol facility) and the production of standards, for use in comparison exercises to evaluate network performance and to validate detector system calibration methods and to be presented at Workshop.

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Facility review, regulatory, management and knowledge transfer projects 2014

Project No.	AIR/2014/M01	Price to NMO	£41k
Project Title	Review of neutron facility (M01)	Co-funding target	
Lead Scientist	David Thomas, Martin Rides	Stage Start Date	1 January 2014
Scientist Team	Paddy Regan, Nigel Hawkes, Graeme Taylor, Catalin Matei	Stage End Date	31 July 2014
		Est Final Stage End Date	31 July 2014
Sector	7. Underpinning metrology	Activity	Development of Existing Capabilities

Summary

The Van de Graaff accelerator, essential to the continued operation of the neutron facility as a world leading NMI, is an increasingly significant risk in maintaining this national infrastructural facility. It provides NPL with the capability of producing relatively high-intensity thermal neutron fields, monoenergetic neutrons, realistic neutron calibration fields, and if required in the future high-intensity fields in the MeV region. This project will review the current neutron facility, the national requirement for it, and the options for its future, secure continuation and expansion.

The Need

NPL's neutron facility is a national infrastructural facility supporting the UK's energy, defence and health sectors, supporting both industry and other government departments. As one of only four MNI facilities worldwide with monoenergetic neutron capabilities it is also an important facility on the world stage. However, the ageing Van de Graaff accelerator, essential to the operation of the neutron facility, is an increasingly significant risk in maintaining this facility. Although the majority of the components of the accelerator are replaceable, these are increasingly becoming difficult to find. Some components are irreplaceable, or at least very difficult to replace with fully equivalent items. The belt is a good example. Spares are available for most of these at present, but they will eventually run out. There are also potential problems with very old wiring. This project will review the current neutron facility, the national requirement for it, and the options for its future continuation so that the role it provides in supporting industry and OGDs can be continued without interruption.

The Solution

A review of the neutron facility and the options for its continued operation, with emphasis on the Van de Graaff accelerator will be undertaken.

Project Description (including summary of technical work)

This project will entail:

1. A review of current facility capability and a risk assessment of its on-going operation.
2. A review of national requirements for the neutron facility.
3. Identification and assessment of options for the maintenance and further development of the neutron facility, including examining options for enhancement of the capability.
4. Recommendations on the continued and future operation of the neutron facility.

The review will be undertaken in consultation with key customers.

Impact and Benefits

As a facility of national importance, non-availability of the neutron facility, through breakdown of the Van de Graaff accelerator, will have significant impact on the energy and defence sectors and on protection for radiation workers. Perhaps the most critical operation of the accelerator is in producing neutrons within the thermal pile. This is used for testing reactor control instruments; an activity which cannot be undertaken elsewhere in the UK. At present there is increasing demand for new reactor instruments and the unavailability of the NPL thermal pile facility would have serious implications. The thermal neutron pile is also used to provide activated manganese for calibrating the manganese bath, another important component of the overall neutron metrology capability of NPL. This project aims to avoid that scenario by making recommendations for the long term operation of the facility.

Support for Programme Challenge, Roadmaps, Government Strategies

This activity underpins the long term future of the neutron work in support of energy, defence and health sectors including protection of radiation personnel.

Synergies with other projects / programmes

This activity underpins future ionising radiation programmes.

A replacement accelerator could provide ion beams for other applications such as surface analysis. There are a number of techniques commonly undertaken with accelerators of about 3-4 MeV. These are Rutherford Backscattering Analysis, RBA, proton induced x-ray analysis, PIXE, proton induced gamma ray analysis, PIGE, and something we have been investigating which is proton induced neutron analysis, PINE. There are, however, issues with such a facility. Fitting a surface analysis capability into the existing neutron metrology building, B47, would require building work. Also, at present, our facility is very busy, it is booked up a good way into the future, and finding time to fit in another area of science would be a problem.

Risks

The risks with implementation of this project are low.

Knowledge Transfer and Exploitation The full report on the future of the facility will be confidential. Information on the proposed plans will be made more widely available as and when appropriate.			
Co-funding and Collaborators Key customers will be consulted in the review process. No co-funding or collaboration is anticipated as part of this activity, although co-funding of a replacement accelerator is a possibility.			
Deliverables			
1	**Start: 01/01/14**	**End: 31/07/14**	
Deliverable title: Confidential review report on the requirements for the Neutron facility and the options for its maintenance.			

Project No.	AIR/2014/M02	**Price to NMO**	£364k
Project Title	Regulatory Compliance (Radiation Safety)	**Co-funding target**	
Lead Scientist	Steven Judge	**Stage Start Date**	1 January 2014
Scientist Team	NPL Staff	**Stage End Date**	31 December 2014
		Est Final Stage End Date	Ongoing
Sector	7. Underpinning Metrology	**Activity**	Statutory and policy obligations

Summary

This project underpins the AIR Programme's radiation safety requirements to ensure safe working practices in the use of ionising radiations and radioactivity, and to ensure compliant disposal of waste radioactive materials.

The Need

Due to the nature of the work undertaken within the AIR Programme it is imperative that all activities meet the requirements of the Ionising Radiations Regulations 1999, the Environmental Permitting Regulations 2010 (formerly RSA'93), the HASS Regulations 2005, all EURATOM Safeguards regulations, and regulations for the transport of dangerous goods. Furthermore, this project ensures the use of safe working practices in the use of ionising radiations and radioactivity, and compliant disposal of waste radioactive materials. The variety of work carried out at NPL makes this regulatory compliance activity one of the more complex systems that is encountered by the regulatory inspectors who visit NPL.

As part of Regulation 28 of the Ionising Radiation Regulations (1999), NPL is required to account for radioactive sources and ensure that their locations are known. NPL meets this regulation by maintaining the necessary electronic and paper records, logging sources in and out of laboratories. The forms are collated at the end of every month and a source inventory database is updated manually. The accuracy of the database is checked annually by checking the location of every source on the record. With in excess of 4000 sources to account for, plus a risk of transcription errors, accounting for the sources is a time consuming and painstaking process.

The Solution

This project will maintain NPL's provision of a centralised resource to deliver the requirements within the Corporate Assurance Team to provide independent service to meet legislative requirements in regards to compliance with safety and security regulations and disposal of radioactive waste.

Project Description (including summary of technical work)

1. Compliance with safety and security regulations

- Providing advice to staff and management on safe working practices and compliance with all regulatory requirements
- Maintaining staff dose records
- Monitoring laboratories
- Maintaining an inventory of radioactive source holdings and ensuring compliance with conditions for holding radioactive materials as stipulated by EA Permits.
- Leak testing sources
- Reporting to Euratom Safeguards and other bodies as required
- Undergo audits as required by Environmental Agency, Euratom, Counter Terrorism Security Officers and Health & Safety Executive (five audits held in 2013 up to August)
- Staff training in radiation safety
- Risk assessment of scientific projects / experiments
- Maintaining an-up-to date knowledge of legal requirements and best practice through attendance at meetings, conferences and courses, and involvement with professional bodies (e.g. AURPO, SRP).

2. Disposal of radioactive waste

- Ensuring that all disposals of radioactive waste from NPL are fully compliant with the terms of the EA Permit and use Best Available Techniques (BAT).
- Segregation and recording of different waste types and disposal or packaging for transfer to authorised contractors.
- Reporting all disposals to the EA pollution inventory.
- Identification of routes and negotiation for disposal of non-standard waste items.

Impact and Benefits

This project ensures that any work involving the use of ionising radiations and radioactive materials across the NPL complies with all relevant regulations. Without this the NMS programme of work relating to Ionising Radiation as well as some work in Environmental Monitoring, Dimensional Metrology, Quantum Detection and Materials & Ceramics with their related measurement services could not be delivered.

Support for Programme Challenge, Roadmaps, Government Strategies

As a regulatory compliance project, the activities described in this proposal underpin all work involved with the use of ionising radiations, which in turn support the challenges, roadmaps and strategies of the UK Government and National Measurement System.

Synergies with other projects / programmes

This is an essential part of the Acoustics and Ionising Radiation Programme, as well as in environmental and dimensional metrology teams, as it enables any work carried out within NPL in the field of, or using, ionising radiations.

Risks

Failure to comply with regulations could render NPL liable to prosecution and/or to the withdrawal of essential permits to hold, store and dispose of radiation material; with an associated curtailment of scientific programmes. Failure to exercise necessary duty of care in providing a safe working environment for staff could also result in legal proceedings.

Knowledge Transfer and Exploitation

Best practice disseminated through internal advice and training, and also through involvement with professional bodies and attendance at meetings with other radiation safety professionals and regulators. Regulators have visited NPL, to look at the systems in place, as an aid to training their less experienced staff.

Co-funding and Collaborators

Not applicable

Deliverables

1	**Start: 01/01/14**	**End: 31/12/14**	**Cost: £364k**

Deliverable title: Compliance with safety, security and control of radioactive substances regulations as evidenced by Absence of action by regulatory authorities. Disposal of radioactive waste in compliance with EA permits.

Project No.	AIR/2014/M03	Price to NMO	£386k
Project Title	AIR National and International Representation	Co-funding target	
Lead Scientist	Susan Dowson	Stage Start Date	1 January 2014
Scientist Team	Multiple representatives from AIR Division	Stage End Date	31 December 2014
		Est Final Stage End Date	Ongoing
Sector	Knowledge transfer	Activity	International Obligations

Summary

This project aims to propagate globally UK best practice developed in NMS AIR projects, and to assess international best measurement practice to benefit UK industry competitiveness. Specifically, the project provides for international representation of the NMS and the UK on the most relevant BIPM Consultative Committees/Working Groups, EURAMET Technical Committees and Standards Committees.

The Need

In order to obtain full value from the AIR programme it is important that research outputs are available in an easily adopted form and that the UK has influence on the international stage. These needs are across all industry sectors and have increasing importance as more developing countries become competitive. Many of the outputs of the programme are generic and apply across different sectors and applications, and frequently appear as international standards. The Consultative Committee for Standards of Ionizing Radiations (CCRI), the Consultative Committee for Acoustics, Ultrasound and Vibration (CCAUV) and the European Association of National Metrology Institutes (EURAMET) are responsible for planning new key comparisons and are the forum for discussions of future service devolution and cooperation under projects such as EMRP, which will oversee the reshaping of NMI metrology research funding across the whole of the EU, with direct consequences for NPL and the NMS. EURAMET is heavily influenced by PTB (Germany) and this needs to be balanced by strong UK/NPL/NMS input.

The Solution

The UK through the NMS programme has a unique opportunity to lead international standards work. Although other NMIs are involved, the high degree of readiness of NMS outputs as completed drafts that have been used for interlaboratory trials, generating precision data, increases both the speed of adoption of UK proposals and their progress through the balloting stages.

Through a high and sustained profile in International standards and other network groups, NPL has a major opportunity to encourage the adoption internationally of UK's research outputs and preferences. The successful promotion by NPL of *"AIR metrology"* has raised the awareness of the importance of accurate and relevant measurements in innovation, healthcare, process control and certification and regulation.

Project Description (including summary of technical work)

The project will fund work by committee members and chairpersons, including travel and subsistence for attending meetings. Annual membership fees (where applicable) will be funded. The work is undertaken in the following linked themes:

A. BIPM Consultative Committees for: Acoustics, Ultrasound and Vibration (CCAUV); Ionising Radiations (CCRI)

BIPM Consultative Committee Working Groups:
CCAUV-WG Strategy (Zeqiri); CCRI Section (I) Radiation Dosimetry (Sharpe – Chair, Duane, Palmans); CCRI Section (II) Radioactivity (Johansson [KCWG, ESWG, TIWG], Jerome, Keightley - KCWG chair); CCRI Section (III) Neutron Metrology (Thomas – Chair, Roberts)

B. EURAMET Technical Committee: TC-Acoustics Ultrasound and Vibration (Barham, Robinson)

C. ISO, IEC, CEN, BSI and Other Committees
IEC TC87 WG3 High power transducers (Hodnett, Zeqiri); ISO TC87 WG8 Ultrasonic field measurement (Zeqiri, Hodnett, Rajagopal, Shaw); Ultrasonic Industry Association (Hodnett); BSI EPL87 Ultrasonics (Shaw), BSI CH/62 Electrical Equipment in Medical Practice (Shaw); IEC TC87 WG15 Underwater acoustics (Robinson); IEC TC87 WG14 Ultrasound exposure parameters (Shaw); IEC TC87 WG6 High intensity therapeutic ultrasound (Zeqiri, Shaw); IEC SC62B MT34 Medical electrical equipment (Shaw); IEC SC62D MT18 Therapy equipment (Shaw); International Society for Therapeutic Ultrasound (Shaw); BSI EH1/1 (Barham, Robinson, Dowson); IEC TC29 Electroacoustics (Dowson - Chair); IEC TC29 WG21 Head and ear simulators (Barham); IEC TC29 WG5 Measurement microphones (Barham); IEC TC29 WG21 WG4 Sound level meters (Dowson); ISO TC43 Acoustics (Barham); BSI EPL/87 Ultrasonics (Robinson); BSI SME/32/-/13 Underwater noise from shipping (Robinson - Chair); ISO TC 43 SC3 Underwater acoustics (Robinson); EU Marine Strategy Framework Directive Technical Subgroup 11 (Robinson); BSI EPL/29 Electroacoustics (Dowson – Chair); IEC TC29 WG17 Sound calibrators (Dowson); Institute of Acoustics Measurement and Instrumentation Group Committee (Dowson); UKAS Acoustical Industry Technical Committee (Dowson); IoP Physical Acoustics Group (Gelat – Chair); ISO TC85 WG2 Radiological Protection (Thomas – co-convenor); Panel on Gamma and Electron Irradiation (Sharpe – Chair of Dosimetry subgroup); ISO CH198 WG2 Radiation sterilization of medical

devise (Sharpe); ASTM Committee E61 Radiation Processing (Sharpe); International Committee for Radionuclide Metrology (Keightley); IPEM Radiotherapy SIG; EURADOS (Thomas, Taylor); BIR Radiation Physics & Dosimetry Committee.

D. Standards – Standards based on completed work requires continuing support that is not available without an on-going research project in the same technical area. The drafting, and revising, of a standard may take several years beyond the completion of the particular funded project. It is important that NPL expertise accumulated over the years in NMS funded projects is fully utilised to progress these drafts for the benefit of UK industry. NPL provides informed and independent expertise on International Standards that is recognised by industry as an important output of the research. NPL acts as project leaders in most cases based on the NMS produced drafts.

Impact and Benefits

In all of the international activity, the aim is to bring UK developments arising from the NMS programmes to implementation as international standards or equivalents. UK global competitiveness will benefit through implementation in international standards of research outputs and standards initially identified by UK industry. The NPL's position as the UK Centre of Excellence in acoustics and ionising radiations metrology provides a unique opportunity to collaborate with technically based organisations in the UK, Europe and around the world, on measurements and standards supporting the competitive position of UK industry. It is well established that NPL is able to consistently deliver the required standards and other documentary outputs.

Support for Programme Challenge, Roadmaps, Government Strategies

NPL will provide representation on the most critical and highest impact national and international committees, either by simple membership, or by chairing the committee or working group where this is of key benefit to the UK NMS. The provision of standards and regulations is critical to the success of new innovative products having economic and quality of life benefits, as recognised by, for example, the TSB. As such, this project particularly supports roadmaps and strategy of the NMS AIR Programme and roadmaps and strategy more widely available.

Synergies with other projects / programmes

This project has intrinsically considerable interaction with NMS AIR research projects in order to take their outputs through to implementation. Also this project enables feedback into the research projects on needs and measurement expertise identified globally.

Risks

This is a low risk project as it builds on existing well-founded interactions and uses the output of prior technical work undertaken in core projects in the AIR Programme, which was itself selected through extensive consultation with UK industry on their needs. The main risks is non–acceptance of UK work by the wider community, which is mitigated by ensuring up-to-date contacts with the wider stakeholders and by using a rigorous review process for acceptance of new work.

Knowledge Transfer and Exploitation

Dissemination routes will include BIPM/EURAMET consultative and technical committees, international and national standards committees, user and special interest group meetings, national meetings, conferences and seminars; direct interactions with UK industry and academia, measurement network and NPL publications. In many cases testwork and consultancy services will be provided, principally to UK stakeholders, providing industry with early experience and bench-marking opportunities of these new methods.

Co-funding and Collaborators

Collaborating organisations include NMIs (e.g. NIST, PTB, LNE), standards development organisations (e.g. BIPM/CIPM, ISO, IEC, BSI), regulators (e.g. UKAS), learned institutes (e.g. RS/RAE, IoP, IPEM), appropriate government departments and agencies, companies, and trade organisations.

Deliverables

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

Deliverable title: Representation at BIPM/EURAMET committees

Annual report on role of NPL representatives (e.g. Secretariat), WGs lead and their work programme and outputs, meetings held and dissemination achieved to UK stakeholders.

2	**Start: 01/01/14**	**End: 31/12/14**	

Deliverable title: Representation at ISO, IEC, BSI and other committees

Annual report on role of NPL representatives (e.g. Chair, Convenor), work undertaken, standards balloted and published; together with an assessment of dissemination undertaken, especially to UK stakeholders.

Project No.	AIR/2014/M04	**Price to NMO**	£204k
Project Title	Contract Management	**Co-funding target**	
Lead Scientist	Dai Jones	**Stage Start Date**	1 January 2014
Scientist Team		**Stage End Date**	31 December 2014
		Est Final Stage End Date	Ongoing
Sector	Management	**Activity**	Programme Management

Summary

This project will deliver effective contract management for the 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 while attending to all reporting and invoicing requirements of the NMO. 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. They will have oversight of all:

- Project delivery;
- Invoicing;
- Contract status and variations;
- Monthly and annual reporting.

- **Project Description (including summary of technical work)**
- Attend meetings as necessary to support contract delivery and the needs of the NMO
- Prepare reports monthly (invoices, progress report and financial forecasts)
- Liaison with working group, industrial advisory groups & clubs
- Manage delivery of the contract and submit change requests and contract amendments as necessary
- Analysis of programme performance and revenue forecasts for the financial year
- Ensure that the contract is managed to NPL's ISO 9001 accredited quality system
- Deliver annual report and present programme progress to working group and the NMO as required.

Impact and Benefits

This project will ensure that all operational, financial and reporting requirements for the programme are met. The work in the programme covers the oversight of delivery from all the technical projects and hence is where ultimate responsibility lies for the success of the programme.

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: January 2014**	**End: December 2014**	
Contract management including production of monthly invoices and reports to the NMO			
2	**Start: January 2014**	**End: December 2014**	
Produce annual report and present progress to the NMO and working group			

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Project No.	AIR/2014/M05	Price to NMO	£169k
Project Title	Programme Management and Formulation	Co-funding target	
Lead Scientist	Martin Rides	Stage Start Date	1 January 2014
Scientist Team		Stage End Date	31 December 2014
		Est Final Stage End Date	Ongoing
Sector	Management	Activity	Programme Management

Summary

This project will formulate a proposal of work for inclusion in the 2015+ 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;
- Implement and maintain a balanced scorecard for the programme as a measure of the impact of the programme on the UK economy and society.

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 sought 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 formulated into a series of projects for prioritisation by the independent programme working group. Projects that 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 implementation and maintenance of a balanced scorecard for the programme consisting of a number of key metrics. The balanced scorecard will be developed initially as part of the Pan-Programme KT activity.

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 Pan-Programme KT 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

This project has no technical risks but is dependent on the availability of senior staff to assess and interpret the societal drivers in order to develop the programme strategy and roadmaps and hence determine the future technical work required in the programme.

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: 01/01/14**	**End: 31/12/14**	

Deliverable title:

Programme Management and Formulation

Document amendment log

Document version	Change	Date agreed
V1	Issue	April 2014

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National Measurement System

The National Measurement System delivers world-class measurement for science and technology through these organisations

National Measurement Office

NPL National Physical Laboratory

LGC Setting standards in analytical science

nel technology for life

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).