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Report

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National Measurement System Programme for Acoustics and Ionising Radiation Metrology - October 2007 to September 2010

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Department for **Innovation, Universities** & **Skills**

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Approved on behalf of the Managing Director, NPL
by Dr Martyn Sené, Director, Quality of Life Division

Executive Summary

This report summarises the 2007-2010 Acoustics & Ionising Radiation Programme, one of the Knowledge Base programmes in the National Measurement System. The key driver for the programme is Quality of Life: major aspects of the work are the safety and effectiveness of cancer therapy, the safety of the workforce and protection of the environment. Much of the programme is therefore concerned with developing the standards and infrastructure to meet changing regulatory requirements. Rapid technological developments are also driving measurement needs - new generations of instrumentation for acoustical measurement (based on micro-electro-mechanical systems) and radioactivity (micro-fluidic devices) are just two examples. Changing needs in the energy sector (for example, the measurement of noise from wind farms) and decommissioning the legacy nuclear sites also bring new challenges to metrology.

A dossier of projects is set out in the document, describing the work to be performed to develop the primary standards and the associated measurement infrastructure, and to run the Knowledge Transfer activities. To maximise the impact of the outputs from the projects, the management of the programme includes the new role of 'Impact and Formulation Leader (IFL)'. The IFL will be responsible for the rolling programme formulation process, maintaining and developing links with the user communities, and recommending changes to the scope of projects in response to user needs.

The programme is divided into four technical themes (acoustics, radiation dosimetry, neutron metrology and radioactivity) plus Knowledge Transfer and programme management (which includes the cost of meeting the stringent regulatory and security requirements for working with ionising radiation).

Following the formulation of the programme, one sub-project (R5.2 – a study of the feasibility of using micro-fluidic devices for radiochemistry) has been transferred to the NMS Innovation R&D Programme.

Acknowledgements

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1. Introduction

This document summarises the 2007-10 Acoustics and Ionising Radiation Programme, one of the Knowledge Base programmes in the DIUS National Measurement System. The projects described in this document were developed following extensive consultation with the user communities and were recommended for inclusion by the Acoustics and Ionising Radiation Working Group at a Decision Conference held on 5th July 2007.
The document includes a brief summary of the rationale for the Programme, and goes on to explain changes to the programme since the Decision Conference. A short description is given of each project in the portfolio.

2. Mission of the Programme

The aim of the Acoustics and Ionising Radiation Programme is to enable all users in the UK to carry out measurements for acoustics, radiation dosimetry, radioactivity and neutrons to an accuracy that is fit for purpose and at the forefront of good practice internationally.

To that end, the programme seeks to provide primary measurement standards, associated services and knowledge transfer mechanisms, and to support UK industry and user communities in the innovation of instrumentation and measurement methodologies in line with government policy.

3. Background

The Acoustics and Ionising Radiation aspects of the programme address different user communities and use different technologies, but have a common focus in improving the quality of life for the general public, patients and the workforce.

The applications of acoustical measurements include the collection of information for product specifications and contracts, demonstration of compliance with regulations, access to markets, assessment of public nuisance, comparison with safe exposure limits, ensuring accurate diagnosis and effective therapy, and enabling accurate underwater positioning, mapping and detection. Increasingly, conventional acoustical measurement methods are inadequate to meet requirements and a new generation of instrumentation is in development, based on Micro-Electro-Mechanical Systems (MEMS) and wireless communications technology.

The work in Ionising Radiation enables the benefits of using ionising radiation in medicine and industry to be realised, while minimising the associated health risks. It seeks to achieve this through facilitating accurate radiation dosimetry and radioactivity metrology, so that the radiation exposure of patients, workers and the general public is known to be within acceptable limits. With such health concerns in mind, the use of ionising radiation is heavily regulated - much of the NMS work is therefore concerned with supporting the relevant regulations (such as the Ionising Radiations Regulations 1999) and Codes of Practice.

The key drivers for different user communities are summarised in Section 10.

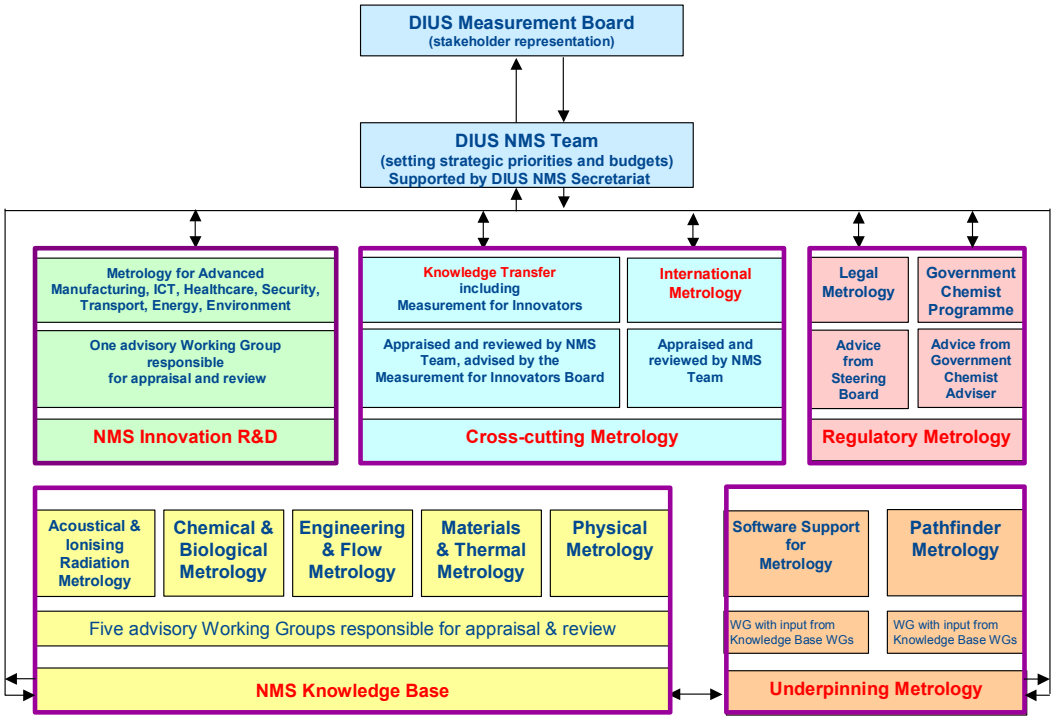
4. Outcomes from the Decision Conference

All the sub-projects described in this document were selected for inclusion at the Decision Conference. The sub-projects have been combined into a small number of large projects and re-numbered accordingly.
In line with the Knowledge Transfer strategy agreed at the Conference, a fixed budget was set aside for Knowledge Transfer projects. The sub-projects were selected to fit into this budget, but two sub-projects were transferred to simplify project management:

1) The sub-project concerned with collaborations in the field of industrial dosimetry was transferred out of Knowledge Transfer into project D4.
2) The sub-project concerned with the effectiveness of UK radiation dosimetry protocols (including audits) was transferred out of the Programme Management theme into Knowledge Transfer.

5. Mapping to the new NMS Programme Structure

Structure of the NMS Programme Portfolio from April 2007



The Acoustics and Ionising Radiation Programme was reviewed by the Working Group, against the criteria established for a Knowledge Base programme. However, it was recognised that some sub-projects might be a better fit to the NMS Innovation R&D. The sub-projects were reviewed in a meeting at NPL chaired by the DIUS Key Account Manager, and only one sub-project was identified for transfer. This sub-project was R5.2 “Conduct a feasibility study of using nanotechnology (microfluidic

devices) for rapid radiochemical assays, report on results from experimental trials and review of existing methods."

6. Extension of the programme to include work at AWE

In the 2004-7 Ionising Radiation Programme, one part of the national measurement system was delegated to AWE under a separate contract. This contract is in place for historical reasons and covers the provision of the UK primary standard for photon-emitting large area reference sources. This standard is used to calibrate surface contamination monitors for photon emitting radionuclides for applications in radiation protection and nuclear decommissioning, and implements ISO8769 part 2. Management of this contract will now transfer to NPL.

7. Programme Governance Arrangements

NPL recognises that the DIUS-NMSPU and the Working Group requires a carefully managed approach to the programme. In particular, the approach needs to ensure that the DIUS and the Working Group are regularly updated on progress and that the impact of the programme is regularly reviewed and reported. This will enable the DIUS to make appropriate strategic decisions in a timely and informed manner.
The programme will be managed following the Office of Government Commerce's guidance 'Managing Successful Programmes' ISBN-13: 978-0113310401. The first step in implementing this guidance has been the appointment of an 'Impact and Formulation Leader' whose job is to build close links with user communities and to maximise the impact of the programme.
The second step is the establishment of a Programme Board. The DIUS Programme Supervisor will attend the board meetings, which will review the project portfolio, project progress, the delivery of impact and programme risks, on a rolling basis. The terms of reference for programme boards and the processes for implementing rolling programme formulation are in development at the time of writing.
Individual projects will be managed using the NPL Project Management Methodology. Based on principles of PRINCE2 (Managing Successful Projects with PRINCE2 ISBN-13: 978-0113308910), the methodology provides a robust and proven framework for risk management and progress monitoring.

8. Overview of the Programme

The Programme is divided into 6 Themes:

- Acoustics
- Radiation Dosimetry
- Neutron Metrology
- Radionuclide Metrology
- Knowledge Transfer
- Programme Management & Formulation

The projects in each theme are described in Section 9. Project costs are set out in Section 10.

9. Project summaries

ACOUSTICS	
Project: A1	**Provision of traceable standards, development of new services and research into future requirements for airborne noise and hearing conservation**
Aim The aim of this project is to provide and develop internationally validated standards and methods so enabling accurate acoustical measurements within the UK, for a wide range of applications including environmental noise, hearing screening of new-born babies, development of test protocols for digital hearing aids and to support UKAS-accredited laboratories who disseminate these standards further. The main impact of the project is to ensure the quality of the environment through reliable measurements of noise in all its forms, leading to informed decision making and noise policy, and the ability to diagnose and correct (or avoid) hearing impairment, avoiding the consequent enormous detriment to quality of life. The development of several new or updated IEC and ISO specification standards and provision of new and low cost calibration methods together with a simplified free-field demonstrator will benefit the user community directly by filling gaps in currently available methods and services.	
Sub-projects	
A1.1	**Existing measurement systems and services available for the provision and dissemination of airborne standards, UKAS-accredited where necessary; updated facility for pressure calibration of working standard microphones commissioned and validated; new calibration services launched for phase and for low cost calibrations of non-standard microphones; simplified free-field calibration demonstrator available and contributions made to the development of associated international specification standards and to international committees**
A1.2	**New UKAS-accredited service for impulse response of ear simulators launched; 3 reports completed on requirements for new IEC specification ear simulators and bio-simulators; study completed on objective test methods for performance of DSP hearing aids and contributions made to the development of associated international specification standards and to international committees**

ACOUSTICS	
Project: A2	**Measurement of sound in air using novel technologies - MEMS (miniature electro-mechanical system) based microphones and primary optical techniques**

Aim

The first aim of this project is to develop a new breed of low-cost measuring instruments with a measurement grade performance to meet the need of complex measurement challenges, such as those arising from EU Directives on noise exposure and pollution. MEMS will also provide noise measurement solutions for long-standing problems such as urban noise mapping, and support renewable and sustainable energy generation. The economies offered by mass production will lead to new ways of conducting measurements, which are currently impossible or prohibitively expensive, and there will be consequent implications for developing new approaches to calibration, focussing on bulk calibration and the consideration of transducer arrays, rather than individual devices. The main impact is therefore wide-reaching and covers a range of industrial sectors including environmental monitoring (especially related to transportation and renewable energy), industrial noise control, healthcare and security.

The second aim of this project is further development of primary level calibrations where optical techniques continue to offer the greatest potential for interrogating an acoustical field non-invasively to directly quantify the field parameters. This technique, if successful, should eventually replace reciprocity as the primary calibration method, resulting in new specification standards and a calibration method directly traceable to SI units.

Sub-projects	
A2.1	**MEMS-based demonstrator measuring systems developed and tested to show performance capability, related paper submitted, guidance note produced and contributions made to the associated international standardisation committees**
A2.2	**Bulk calibration capability for MEMS-based systems developed and tested, and related publication submitted**
A2.3	**Validated optical system for primary microphone calibration, tested against existing microphone standards**

ACOUSTICS	
Project: A3	**Provision of traceable standards, development of new measurement techniques and primary standard calibration method for underwater acoustic measurements in the marine environment**

Aim

The main aim of this project is to support manufacturing in the UK - the UK continues to be the most active European country in the manufacture of underwater acoustics systems, with UK industry supplying worldwide markets with systems for positioning, communications, navigation, echo sounding, sub-sea control, seismic measurements, water quality measurement, sonar, and weapons systems.

In general, within underwater acoustic metrology, there is a lack of "headroom" between the best measurement capability of national primary standards and the general capability in industry. This places limitations on the ability to disseminate accurate standards, and this project aims to eventually reduce this limitation through adoption of a new primary standard methodology.

Also, increasing environmental concerns over the exposure of marine life to man-made noise has led to the requirement for environmental impact assessments before offshore activities can commence. It is therefore planned to develop new methods and services as well as using existing capability to meet these needs. The drivers are EC legislation such as the Habitats Directive (92/43/EEC) implemented as UK legislation in 2001 (UK Offshore Petroleum Activities (Conservation of Habitats) Regulations 2001) and administered by DIUS and DEFRA. There is a direct impact on many fields in particular the Renewable Energy industry (offshore wind farms, wave and tidal power), where inability to accurately assess environmental impact is currently a serious impediment to progress. New challenges in measurement and in performance of acoustic materials have been set as the offshore industry moves to sourcing oil and gas from deeper waters, and as defence and security interest moves away from deep cold-water applications toward applications in coastal waters, for protection of ports and harbours from mines and potential terrorist threats. Also, in oceanographic science, acoustic methods are used to study ocean properties that affect the global environment.

The main impacts of the project will be: continued support for the UK manufacturing industry; the improved ability of industry to conduct Environmental Impact Assessments for the effect of noise on the marine environment by underpinning the regulations with valid metrology, developing improved measurement methodologies and contributing to the development of methods for mitigating the effect on marine life; and the ability of industry, academia and OGDs to assess the full performance of underwater acoustic systems over a range of environmental conditions by use of the world-class national facilities maintained by NPL.

Sub-projects	
A3.1	**Existing and enhanced measurement systems and services, UKAS-accredited where necessary, available for the provision and dissemination of free-field standards for hydrophone and transducer calibration; new service launched for in-air hydrophone calibrations and contributions made to the associated international standardisation committees**
A3.2	**Existing services available for the provision and dissemination of standards at simulated ocean conditions; improved capabilities developed and tested for materials characterisation; related papers submitted and entry made in Key Comparison database**

ACOUSTICS	
Project: A3	**Provision of traceable standards, development of new measurement techniques and primary standard calibration method for underwater acoustic measurements in the marine environment**
A3.3	**Validated optical technique for hydrophone calibration adopted as new method for primary calibration; tomographic capability for three-dimensional imaging of sonar fields available; effect of burial of hydrophone in sediment determined, and related papers submitted**
A3.4	**Tested and published method on measuring noise in situ in shallow water sites; joint publications on measuring underwater radiated noise in test tanks and on noise of vessels and platforms using portable ranges submitted; 3 technical guides launched and Underwater Acoustics course hosted, and contributions made to the associated international standardisation committees**

ACOUSTICS	
Project: A4	**Provision and enhancement of services for medical applications of ultrasound and research into the development of new methods for quantifying ultrasonic dose and characterising high amplitude ultrasonic fields**

Aim

The aim of this project is to support the use of ultrasound in medicine through provision of traceability and development of methods allowing measurements to be made in a meaningful, traceable way, which is key to ensuring the safety and efficacy of medical ultrasound applications. Ultrasound is now one of the most common imaging modalities with 6 million scans undertaken in England in 2005 – 2006, covering obstetric scans, use of lithotripters, ultrasound scanners, ultrasonic foetal heart beat detectors and physiotherapy units employed mainly within the NHS. The range and capabilities of diagnostic equipment is rapidly improving, bringing with it the need to determine key characteristics of the applied acoustic field over a wider range of frequencies. Also, use of extremely high acoustic intensities essentially to burn cancerous tissue is becoming assimilated into the clinical mainstream, and the heating potential of these systems raises stringent requirements for developing new measurement techniques that are able to quantify the applied acoustic powers, acoustic intensities and the spatial distribution of these quantities.

Within all areas of medical ultrasonic applications, to aid risk assessment and clinical management, it is essential to gain a better understanding of how ultrasound behaves in tissue, thereby allowing development of appropriate measurement methods providing improved estimates of exposure and dose, ensuring the safety of ultrasound as well as optimised treatment planning. Benefits of the project are widespread and the primary beneficiaries are: clinical users who will have greater confidence in the diagnostic and therapeutic equipment they use; healthcare patients who will be able to receive benefits of the latest developments in medical ultrasound whilst having confidence in its effectiveness and safety, and UK manufacturers of ultrasonic devices who will have better tools and services for product development and access to markets.

Sub-projects	
A4.1	**Existing and enhanced measurement systems and services, UKAS-accredited where necessary, available for the dissemination of hydrophone calibration standards; contributions made to the associated international standardisation committees and related papers submitted**
A4.2	**Existing and new measurement systems and services, UKAS-accredited where necessary, available for the provision of ultrasonic power standards; contributions made to the associated international standardisation committees; related papers submitted and 2 web guides posted**
A4.3	**Existing services available for the provision of ultrasonic field and characterisation measurements, related paper submitted and contributions made to the associated international standardisation committees**

ACOUSTICS	
Project: A4	**Provision and enhancement of services for medical applications of ultrasound and research into the development of new methods for quantifying ultrasonic dose and characterising high amplitude ultrasonic fields**
A4.4	**New services launched for high intensity ultrasonic medical systems including the new IEC 61949 procedure for nonlinear fields; papers submitted on use of fibre-optic hydrophones for measuring pressure and temperature and on acousto-optic/vibrometric methods; completed assessment of methods of assessing heating distribution**
A4.5	**Validated computational model for predicting heating distribution from non-linear ultrasound fields in tissue and completed evaluation of tissue mimics; a validated thermal test object for high intensity focussed Ultrasound (HIFU) and related paper submitted**

ACOUSTICS	
Project: A5	**Development and enhancement of methods for industrial applications of ultrasound including ultrasonic cleaning systems, research into the methods for monitoring acoustic and hydrodynamic cavitation and cavitation dose, and provision of services for acoustic emission sensors**

Aim

The first aim of this project is to address a strong user demand for the development of suitable standardised measurement techniques for acoustic cavitation, leading ultimately to an accepted unit. Cavitation is the driving force behind the ultrasonic cleaning process, and is now being harnessed by new processors in the pharmaceutical and food industries in the control of crystallisation processes, and in wastewater treatment to break down sewage sludge. However, there are no standardised, traceable cavitation measurement techniques and existing NHS Standards require use of something as simple and qualitative as aluminium foil to characterise the performance of ultrasonic vessels used in surgical instrument cleaning. Ultrasonic cleaning is very widespread across industry and healthcare, with over 20 UK manufacturers turning over £40M, and a worldwide market of £2Bn. Similarly, the use of liquid pumps is inherent in flow systems of all types, and the UK market alone is worth around £900M. Cavitation in pumps is well known and causes process inefficiencies, leading to costly failures of industrial systems. Pumps are estimated to consume 14% of the UK's total electricity, so there is a clear need to develop reliable methods for quantifying cavitation occurring in flow systems, which should lead to extensive energy savings through better pump selection, installation and operation. Reliable cavitation detection methods are also required on ships, where failures can result in dry-dock repairs with costs of £100k per day.
The second aim of this project is related to condition monitoring of safety-critical systems (such as engines and pressure vessels) by use of acoustic emission sensors, of the type increasingly being used for real-time structural integrity monitoring of airframes during take-off, landing and flight. To underpin their performance, there is a critical requirement for traceable measurement, and a new calibration service for sensors and a reference source transducer demonstrated in an industrial environment are key aims of this project.
The principal beneficiaries will be manufacturers and users of cleaning vessels, providing them with a measurement capability applicable to development, QA and servicing, users of high power ultrasound processors in manufacturing (in particular, pharmaceuticals), providing them with the capability to optimise and scale-up processes, leading to innovation and wealth creation, pump and aerospace manufacturers and users, who should gain access to measurement techniques enabling them to operate systems efficiently and more safely, leading to significant savings.

Sub-projects	
A5.1	**Industrially-trialled protocol for medical instrument cleaning vessels reported in a peer reviewed journal and at an international conference; technical meeting for high power users hosted and Measurement Club established with 2 meetings held**
A5.2	**Meetings of Advisory Group on establishing a measurement unit of cavitation activity/dose held; validated multiple frequency reference facility; related papers submitted and presentations given; completed user trial of JIP-developed cavimeters**

ACOUSTICS	
Project: A5	**Development and enhancement of methods for industrial applications of ultrasound including ultrasonic cleaning systems, research into the methods for monitoring acoustic and hydrodynamic cavitation and cavitation dose, and provision of services for acoustic emission sensors**
A5.3	**Completed partner trial of measurement methods for quantifying damaging pump and propeller cavitation, following published scoping study and established and tested experimental facility at NPL**
A5.4	**New calibration service for acoustic emission sensors available; completed comparison of commercial sensor sensitivities for both out-of and –in plane displacement; technical paper submitted and web guide posted; completed demonstration of reference source transducer in industrial environment and joint paper submitted**

RADIATION DOSIMETRY	
Project: D1	**Provision and dissemination of therapy and industrial level primary standards of absorbed dose**

Aim

The continued dissemination of the quantity absorbed dose will require a transition from existing calorimeters near the end of their life, to an improved calorimeter for high-energy photon and electron beams, ensuring continued traceability to primary standard absorbed dose calorimeters for radiotherapy dosimetry for cancer patients. The development of calorimeters for situations in which dosimetry procedures are not yet well established will continue, as a growing number of patients are treated each year with other modalities, among these, proton therapy (mainly in mainland Europe, US and Japan), brachytherapy, small field and IMRT. Primary standards of absorbed dose will be developed and disseminated at industrial dose levels in order to meet the requirements of the EU Medical Devices Directive, UK/EU Food Irradiation Regulations and FDA regulations.

Sub-projects	
D1.1	**Existing therapy level photon beam calorimeter maintained and compared internationally**
D1.2	**Existing therapy level electron beam calorimeter maintained and compared internationally**
D1.3	**New electron-photon primary standard therapy level calorimeter tested, commissioned and compared with existing standards**
D1.4	**New therapy level proton beam calorimeter tested, commissioned and compared with ionisation chambers with improved perturbation correction factors**
D1.5	**New brachytherapy calorimeter tested and commissioned**
D1.6	**New small field and IMRT calorimeter designed, built and tested**

RADIATION DOSIMETRY	
Project: D2	**Provision and dissemination of ionometry-based primary standards at therapy and protection levels**
Aim Ionometry based primary standards for very low, low and medium energy x-ray beams, and therapy and protection level ^{60}Co, ^{137}Cs and HDR Brachytherapy ^{192}Ir will be maintained and disseminated. This will ensure accurate and safe delivery of radiation dose to cancer patients and support the infrastructure for diagnostic and protection level dosimetry as required by UK law and IPEM and IAEA codes of practice.	
Sub-projects	
D2.1	**Therapy and protection level 50 kV free air chambers developed, compared and reported**
D2.2	**300 kV free air chamber developed, compared and reported**
D2.3	**Existing primary standard cavity chambers maintained and replacement chambers commissioned, compared and reported**

RADIATION DOSIMETRY	
Project: D3	**Development of new dosimetry techniques for existing and new healthcare applications**
Aim Expertise in a variety of dosimetry systems will be maintained and developed for the measurement of spatial dose distributions in radiotherapy treatment verification and diagnostics. Examples include 3-dimensional dose mapping around small brachytherapy sources and for complex treatment deliveries using small field segments such as IMRT and Tomotherapy, quantitative non-reference dosimetry at a point for radiotherapy treatment verification and imaging for diagnostics. Development of traceable user measurements for small field and IMRT dosimetry will result in better accuracy and better consistency with conventional radiotherapy dosimetry resulting in improved outcomes for cancer patients. The ability to underpin innovative radiotherapy techniques will be further developed, extending the application of alanine dosimetry at therapy-levels and establishing NPL as a world-leading centre in this field.	
Sub-projects	
D3.1	**Developed and commissioned quantitative optical tomography system for readout of 3D-dosimeters and suitable dosimeters investigated. Use of radiochromic film for quantitative 2D dosimetry investigated.**
D3.2	**Report on dosimetry requirements associated with novel radiotherapy techniques, such as IGRT, grid therapy, etc. including recommendations on suitable instrumentation and measurement techniques.**
D3.3	**Validated protocol for traceable absorbed dose measurements in small fields and pilot audit of user measurements.**
D3.4	**Agreed definition of valid reference conditions for reference dosimetry in IMRT fields including enhanced alanine dosimetry service, for example with improved spatial resolution and lower doses.**

RADIATION DOSIMETRY	
Project: D4	**Provision and dissemination of industrial standards and services**
Aim High dose (industrial) irradiation standards and reference dosimeters and services will be provided as necessary for compliance with UK, EU and FDA regulations for the sterilisation of medical devices and the irradiation of foodstuffs. Enhanced dosimetry techniques will be developed as required for innovative industrial processes such as the use of cryogenic irradiation and "in-line" low energy electron beam and x-ray sources. Enhanced facilities and dosimetry techniques will be provided for the radiation hardness testing of electronic devices in the defence and aerospace industries that require specialist irradiation and dosimetry techniques, particularly with respect to the rise time and spectra of pulsed electron beam irradiations.	
Sub-projects	
D4.1	**^{60}Co self-shielded irradiators and industrial dosimetry measurement equipment maintained and enhanced, including investigation into new source/irradiator supplier and replacement of obsolete hardware and software.**
D4.2	**Industrial ^{60}Co and electron beam irradiation and reference dosimetry services provided and enhanced, including UKAS accreditation, extension to dose ranges and operating temperatures, calorimetric validation of high dose rate alanine response and comparison internationally.**
D4.3	**Active support and collaboration maintained with industrial user groups, including development of mathematical modelling and dosimetry based statistical process control techniques, training courses, proficiency tests and revision of published calibration guidelines.**

RADIATION DOSIMETRY	
Project: D5	**Development and maintenance of facilities**
Aim A wide range of radiation fields will be developed and maintained in order to enable the rest of the Programme to be fulfilled and to allow for the provision of the Radiation Dosimetry calibration services. Equipment used on all of the facilities that underpins all of the work carried out by the group will be maintained, developed and calibrated. Modelling capabilities and facilities will be maintained and enhanced in order to support the increasing and diverse modelling requirements in the development of standards and facilities in Radiation Dosimetry.	
Sub-projects	
D5.1	**Existing research linac maintained and developed as needed for programme delivery**
D5.2	**New clinical linac accepted and commissioned, initially for reference dosimetry, and this extended to cover treatment planning system, multi-leaf collimator, small fields etc. with the schedule dependent on machine delivery date.**
D5.3	**X-ray facilities maintained.**
D5.4	**Therapy level ^{60}Co unit (Theratron) maintained and re-sourced.**
D5.5	**Protection level (Mainance) facility developed and maintained.**
D5.6	**HDR Brachytherapy unit upgraded and re-sourced and facility measurement software developed. Beta Ray facilities maintained and extended to include dose profiling.**
D5.7	**Ancillary equipment maintained and calibrated and new equipment purchased and calibrated as required for programme delivery**
D5.8	**Maintained and developed capability to perform Monte Carlo simulations, to include grid-enabling MC codes where appropriate, validation and acceptance testing of MC codes needed for programme delivery, and a study of the propagation of uncertainties in MC radiation transport simulations.**

NEUTRON METROLOGY	
Project: N1	**Primary neutron standards**

Aim

Project N1 will ensure that neutron metrology primary standards are maintained, developed, improved where necessary, and extended to new energies and higher intensities, all requirements identified by the end-user communities. The requirements originate from the nuclear industry, defence, academic and industrial research for example at high-energy accelerators, and for applications in national security. This project covers the standard neutron fields produced at NPL using both radionuclide sources and a charged particle accelerator. The accelerator-based neutron facility is one of only three such facilities available at a national metrology laboratory. Also covered in this project is the newly constructed manganese bath facility for measuring neutron source emission rates – the new facility is now probably the best in the world, and one which provides a service used by other national laboratories.

One of the reasons why a neutron standards facility is important is that available devices for measuring neutron dose equivalent, i.e. area survey dosemeters and personal dosemeters, are, in many cases, far from being fit for purpose. Thus, in addition to providing calibration fields for regulatory purposes, usually with radionuclide sources, it is very important that there is a facility in the UK for investigating, characterising, and performing radiological type tests for new and innovative devices which may improve the present unsatisfactory position. These capabilities are provided by the Van de Graaff accelerator, which can provide monoenergetic neutrons over a range of important energies, and also thermal neutrons and simulated workplace fields.

The specific aims of the project are to ensure that:

- radiation protection measurements for all persons in the UK who encounter neutron radiation fields are traceable to national standards, for compliance with the Ionising Radiation Regulations,

- a testing capability is available for determining radiological characteristics of neutron detecting instruments which can give UK manufacturers a competitive advantage in validating the performance of their devices,

- facilities are available which allow research to be undertaken, by NPL staff and others, to improve neutron dosimetry by understanding and solving the measurement problems.

Sub-projects	
N1.1	**Provision of neutron emission rate standards for all types of radionuclide neutron sources ranging from 10^3 to 10^9 neutrons per second.**
N1.2	**Improvements to radionuclide source based standards.**
N1.3	**Validation and improvement of accelerator-based neutron standards.**
N1.4	**Extension of the energy range of monoenergetic neutrons to energies below 50 keV, and to energies above 15 MeV**
N1.5	**Utilisation of time-of-flight techniques**
N1.6	**Extension of intermediate energy and high intensity neutron standards.**
N1.7	**Maintenance of the Van de Graaff**
N1.8	**Developments of the Van de Graaff and low-scatter facility.**

NEUTRON METROLOGY	
Project: N2	**Development and innovation in neutron metrology**

Aim

The overall aim is to improve neutron dose estimates in workplace fields. To this end the project will ensure that a neutron spectrometry capability is available to evaluate neutron doses correctly in all fields regardless of the energy distribution and to make quantitative estimates of the degree of misreading by area and personal dosemeters. This is a capability, which will be used within NPL and at workplaces where neutron fields are encountered. The existing spectrometers will be improved in terms of their reliability and usability particularly for applications in problematic areas where spectrometry will be needed in the future such as: mixed n/γ fields, around novel pulsed accelerators, or checking for the illicit transport of radioactive sources.

This project also includes the continued demonstration of the equivalence of NPL neutron standards to those of other national laboratories and participation in EUROMET projects.

Work will be undertaken to improve and make more reliable the dosimetry for aircrew, concentrating particularly on the problem of solar events.

Finally an investigation will be undertaken of the problems inherent in the directional nature of workplace neutron fields, e.g. the implications for personal dosemeters, which are calibrated for normal incidence but used in rotationally symmetric fields.

Sub-projects	
N2.1	**Maintenance and regular checks of spectrometers and a programme to replace obsolescent electronics.**
N2.2	**Spectrometer developments including: finalising the response matrices for the NPL NE213 spectrometers, maintenance of the SpktBib library of neutron spectra, refurbishment of the existing ^{3}He gridded ion chamber spectrometer, undertaking a review of how to make the best use of available detection and data handling technologies (including digital signal processing) in neutron spectrometers.**
N2.3	**Comparisons and demonstration of equivalence. Maintenance of UKAS accreditation is also included.**
N2.4	**Capabilities for cosmic ray and high-energy dosimetry. Identified tasks include: expansion of NPL's solar flare dose monitoring service (Flarewatch) including supporting calculations in time for the peak in solar activity, maintain capability for high energy, mixed field dosimetry using TEPCs, including support for MSSL project to develop permanently installed in-flight TEPC (in conjunction with SELEX)**
N2.5	**Investigation of angle effects in neutron personal dosimetry. Tasks to be undertaken include: a feasibility study of developing a device to measure the angle dependence of neutron fields, measurement of personal dosemeter responses in unidirectional and rotationally isotropic fields, and publication of paper describing the results of these measurements.**

RADIOACTIVITY	
Project: R1	**Primary Measurement Standards and Systems**
Aim Primary standardisations of radionuclides will be carried out, with both results and radioactive sources being sent to BIPM to meet NPL's obligations to link radioactivity measurements in the UK to the international measurement system. Existing measurement systems will be upgraded and expanded to allow improved measurements of radionuclides, in particular those difficult using existing equipment. These hardware upgrades will be accompanied by new software (i.e. digital processing). Nuclear data evaluations will be carried out to contribute to the existing body of knowledge, and efforts made to disseminate this knowledge to the UK and internationally through various media. Users of radioactive gas standards will be supported by a rejuvenated gas counting facility, and the implementation of a dedicated service for positron in air monitors.	
Sub-projects	
R1.1	**Compliance with the Mutual Recognition Arrangement through submission of Key Comparison results to BIPM. Submission of primary standards to the SIR system and extension of the system to short-lived and beta-emitting radionuclides**
R1.2	**Design and construct a replacement high-pressure proportional counter, update related software for this and the TDCR system, and standardisation of 'difficult' radionuclides (^{55}Fe and ^{63}Ni).**
R1.3	**Evaluate nuclear decay data for ^{232}U, ^{231}Pa and ^{228}Ac provided for the IAEA Co-ordinated Research Programme, and disseminate knowledge to users through continued provision of an advice service, recommended nuclear data on the NPL web site, and publication of data in formats compatible with commercial γ spectrometry systems**
R1.4	**Provide users with primary standards for radioactivity-in-gas. Standardise tritium cylinders, including investigation of activity trapped in steel. Through consultation with the user community establish a calibration service for positron-in-air monitors, following instrument development and calibration against the primary standard.**
R1.5	**Report on the options for establishing a primary standard for radioactive aerosols and a report on the options for using new detector materials for primary standards.**

RADIOACTIVITY	
Project: R2	**Infrastructure for Secondary Measurement Standards of Radioactivity**
Aim The principle secondary standards facilities will be maintained, upgraded and expanded to enable primary standards to be disseminated to users. In parallel, equipment in the source preparation facilities will be upgraded to support the provision of secondary standards. A Tritiated water comparison will be organised, underpinning measurements of Tritiated water both nationally and internationally. The associated provision of tritium standards will also support the CIEMAT/NIST secondary standardisation technique, enhancing the provision of pure β particle emitting radionuclides. Our capability will be demonstrated through accreditation by UKAS, and the scope extended to enable us to offer additional services to users.	
Sub-projects	
R2.1	**Development and Validation of Methods for Secondary Standards of Radioactivity, including gamma spectrometers, ionisation chambers, large area reference source counters and associated support equipment**
R2.2	**Conduct an International comparison of Tritiated water, including preparation of sources, distribution to participants, analysis of results and publication through an NPL report and conference paper.**
R2.3	**Maintenance and extension of our accreditation to ISO 9001:2000and to ISO 17025:2005 through surveillance visits by UKAS and LRQA. Extension of our UKAS accreditation to include ISO Guide 43-1 (proficiency test exercises) and ISO Guide 34:2000 (reference materials).**
R2.4	**Provision of Radiochemical Support to Radioactivity and Neutron Team, and upgrading of source preparation facilities including data collection and analysis software. Work with Neutron Metrology Group to carry out low flux irradiations at NPL, and external facilities to cover the loss of Imperial College Reactor and Hammersmith Cyclotron Unit.**

RADIOACTIVITY	
Project: R3	**Provision of measurement infrastructure for nuclear medicine**
Aim Standardisations will be carried out on radionuclides being introduced to the field of nuclear medicine. These will result in the ability to measure samples in several different matrices such as brachytherapy seeds. Radionuclides will be measured in the ionisation chamber systems, and resulting calibration factors will be derived for use in nuclear medicine departments. Under Knowledge Transfer project K1, two meetings of the RCUF will be held to share expertise with the user community, and the Radionuclide Calibrator Good Practice Guide will be revised.	
Sub-projects	
R3.1	**Standardisation of radionuclides used in nuclear medicine (e.g., ^{177}Lu, ^{111}In) and provision of a new measurement service for ^{125}I brachytherapy seeds. Extend availability of calibration figures for NPL ion chamber for non-standard geometries and short lived isotopes**
R3.2	**Validation of correction factors for ionisation chambers, including the use of Cu-filters**
R3.3	**Development of a protocol for testing electrometers for radionuclide calibrators**

RADIOACTIVITY	
Project: R4	**Infrastructure for Environmental Radioactivity Standards**
Aim Primary standardisations will be carried out of nuclides specifically required by users on the environmental radioactivity community. Reference materials will be developed, to support practical measurements by users, and these will be disseminated physically and through the publication of data. The environmental proficiency test exercise will be conducted annually, taking advantage of the additional reference material matrices being developed. Under Knowledge Transfer project K1, it is intended to hold two user fora (annually), targeted specifically to users in the environmental and site operation communities (rather than to users of specific measurement equipment). These user fora would replace the existing NSUF and LSUF. A final decision on the content of these fora will be made after discussion with the user communities.	
Sub-projects	
R4.1	**Carry out primary standardisations of radionuclides required for environmental applications (^{208}Po or ^{209}Po, ^{241}Pu and ^{227}Ac)**
R4.2	**Development of two non-aqueous reference materials for radioactivity monitoring, submission of a technical paper to Applied Radiation and Isotopes, and presentation at suitable meetings.**
R4.3	**Annual Environmental Radioactivity Proficiency Tests, including preparation of sources, distribution, collation of results, running a workshop and publication of the exercise report, and dissemination of results through a technical paper submitted to Applied Radiation and Isotopes, and at suitable meetings.**

RADIOACTIVITY	
Project: R5	**Measurement infrastructure for radiation protection**
Aim The photon emitting large area reference source standard will be maintained. A feasibility study into the use of nanotechnology for radiochemical assay will be carried out, with the long term intention of developing suitable equipment for use in the field. A comparison of true and apparent activities on stack discharge filters and surface wipes will validate methods for assessing the release of radionuclide particulates into the atmosphere. The study of tritium monitoring equipment will similarly back up assessment of doses to the public through releases. Under Knowledge Transfer project K1, the IRMF and ARMUG user meetings will continue to give a platform for transfer of knowledge and discussion of issues within the radiation protection community. These will be augmented by the publication of user guides in response to user requirements.	
Sub-projects	
R5.1	**Provision of photon emitting large area reference source standard, through maintenance of the primary standard and replacement of obsolete equipment**
R5.2	**(This sub-project was subsequently transferred to the NMS Innovation R&D programme.)** **Conduct a feasibility study of using nanotechnology (microfluidic devices) for rapid radiochemical assays, report on results from experimental trials and review of existing methods.**
R5.3	**Comparison of true and apparent activities on stack discharge filters and surface wipes, through measurement of emission rate from monitoring and activity from radiochemical analysis, prepare report and disseminate to users. Assessment of response of instrumentation to Tritium gas in different chemical forms (HT and HTO), analysis of data and preparation of report with recommendations**

RADIOACTIVITY	
Project: R6	**Measurement Infrastructure for Nuclear Decommissioning**
Aim New reference materials specifically required by users in the nuclear decommissioning industry will be developed and disseminated. A Good Measurement Practice guide on Mathematical Modelling will further support the community, backed up by expert advice from NPL. A report will be published on the use of surface contamination monitors under typical real world conditions, i.e. for varying surfaces, prior to disposal of waste. Under Knowledge Transfer project K1, the Nuclear Industry Code of Practice will be revised with the inclusion of a chapter on the use of Bayesian statistics.	
Sub-projects	
R6.1	**Production and certification of Certified Reference materials for nuclear decommissioning.**
R6.2	**The use of mathematical models to estimate the radioactivity content of waste materials, and the establishment of a Consultancy and audit service on the use of mathematical models.**
R6.3	**Publish NPL Report and/or a journal paper on the characterisation of surface contamination monitors for responses to radioactivity in different materials**

KNOWLEDGE TRANSFER	
Project: K1	**Knowledge Transfer**

Aim

Knowledge Transfer is a fundamental component of the Programme, aiming to maximise its impact through:

- Disseminating best practice, through influencing international and national standards, developing and publishing Measurement Good Practice Guides and publishing in scientific and trade journals
- Helping user communities to recognise and implement the beneficial outputs of the programme, through developing training courses, organising User Forums, contributing to/organising meetings of professional bodies and maintaining a technical enquiry service
- Increasing awareness and recognition of the value of the National Measurement System, through contributing to newsletters, the NPL web-site, attendance at trade exhibitions and organising visits to NPL for key influencers

Many of the proposed activities seek to involve the user communities to add value by their participation. For example, joint development of Measurement Good Practice Guides enables best practice to be interpreted in a way that is practical to implement. The activities are often two-way, creating a feedback loop with benefits to NMS and NPL for programme formulation.

Knowledge Transfer activities specifically linked to a technical project (for example, the publication of a scientific paper) are included in the technical project itself.

Sub-projects	
K1.1	**Dissemination of best practice, including the development of Good Practice Guides, contributions to the development of national and international standards, and the publication of general reports and papers.**
K1.2	**Programme take-up, including the provision of User Forums, training courses, conferences and responding to technical enquiries.**
K1.3	**Awareness of the NMS Programme, including contributions to newsletters, development of the website and attendance at exhibitions.**

PROGRAMME MANAGEMENT	
Project: P1	**Programme Governance**
Aim Management of the programme in accordance with best practice, providing regular updates on progress and the impact of the programme.	
Sub-projects	
P1.1	**Management of the project portfolio, including project and programme board meetings and provision of monthly reports**
P1.2	**Annual reports**

PROGRAMME MANAGEMENT	
Project: P2	**Rolling Programme Formulation**
Aim The aim of rolling programme formulation is to enable the programme to respond rapidly to the changing needs of the user communities and to pro-actively manage the impact of the programme (the impact of the outputs from a project often happening after the project(s) concerned have been completed). The process for formulation and impact measurement is in development at the time of writing but the intention is to assess impact through a combination of case studies and market audits.	
Sub-projects	
P2.1	**Programme Formulation**
P2.2	**Impact measurement**

PROGRAMME MANAGEMENT	
Project: P3	**Regulatory Compliance**
Aim This project is concerned with meeting the requirements of the Ionising Radiations Regulations (1999), the Radioactive Substances Act and the security regulations associated with the use of ionising radiation. The work includes maintaining staff dose records, monitoring of laboratories, maintaining an inventory of radioactive source holdings, leak testing of sources, preparing and submitting reports required by Euratom and other bodies, staff training and the disposal of radioactive waste.	
Sub-projects	
P3.1	**Compliance with safety and security regulations**
P3.2	**Disposal of radioactive waste**

10. Key drivers for the Programme

The key drivers for the Acoustics and Ionising Radiation Programme are summarised below, based on extensive consultation of the user communities during the programme formulation process.

Drivers for defence and security

Neutron facilities are used for instrument calibration in the defence and security sectors, and neutron expertise is important in developing security devices such as portable monitors etc.
The installation of **radioactivity** monitors, for both gammas and neutrons, at points of entry to the UK ('Project Cyclamen') has highlighted the need for reference materials that demonstrate that the monitors are working and there is a requirement for rapid methods to assay **radionuclides** that are impossible to detect with direct measurement.
Defence applications of **underwater sound** include active and passive sonar, stealth technologies, weapons systems and mine hunting. A current priority is that of detecting mines in shallow coastal waters, both during and after conflicts.

Drivers for energy (generation and conservation)

With strong growth in world energy demand, an average growth of 8% in subsea oil wells is predicted over the next five years. **Acoustics** is an essential enabling technology, playing a vital role in applications such as geophysical surveying, positioning, navigation, echo sounding and communications. In the area of **marine renewable energy**, concern over the environmental impact of the offshore wind farm, tidal and wave energy technology with regard to noise pollution has led to the need for standard assessment methods.
The ability to measure **ionising radiation** is important to operators of nuclear power stations, fuel fabricators, re-processors and waste storage and disposal facilities. These are regulated by the Nuclear Installations Inspectorate for compliance with the Atomic Energy Act and with the Ionising Radiations Regulations. Discharges and the movement of radioactivity from sites are the responsibility of the two Environment Agencies, EA and SEPA.
Oil exploration uses a variety of well logging tools that use radioactive sources and they also have problems with NORM (Naturally Occurring Radioactive Material), both at the extraction stage and post combustion. The problems they encounter cover **X-ray, gamma, and neutron dose rate**, surface contamination, discharges to air and water and bulk contamination.

Drivers for protection of the environment (including Decommissioning)

Over the next few decades, the UK faces the problem of **decommissioning** and clearing its legacy nuclear sites. Accurate and traceable measurement of the **radioactivity** content of waste materials is needed to ensure they are consigned to the correct waste stream.
Measurements of **neutrons** are important for the nuclear industry in support of normal operation, **decommissioning**, fuel transport and waste assay. If anything, this will be enhanced if new nuclear power stations are constructed.

Noise is recognised by statute to represent both a cause of nuisance and a hazard to hearing. There is an extensive body of regulations in place in the UK to control noise and to limit its emission many of which enforce EC Directives.
Government policy on **radioactive discharges** into the environment from the **nuclear industry** and other users of **radioactivity** is to 'progressively and substantially reduce discharges'. The policy is enforced by a system of licensing discharges and compliance with this policy is monitored by a network of about 100 laboratories. There is a need to develop standards to support environmental monitoring, including primary standards for **gaseous discharges of radioactivity**.
Exposure of marine life to **underwater man-made noise** is an issue of growing concern as the effects of **noise pollution** in the ocean begin to be understood. Regulation is providing a driving force in this area, for example from the EU Habitats' Directive 92/43/EC, and from EC Directive 2001/42/EC implemented in the UK as the Environmental Assessment of Plans and Programmes Regulations 2004. Increasingly, an Environmental Impact Assessment is required before activities, which may generate **underwater acoustic noise** commence. Although regulation is beginning to be introduced, the underpinning metrology and standardisation are still not fully established.
Additionally, **underwater acoustics** continues to play an important role in the study of the marine environment within oceanographic science, ranging from tomographic measurements of ocean currents and temperature (e.g. for climate monitoring) to measuring sediment transport processes (e.g. to assess coastal erosion).

Drivers for healthcare

Cancer therapy is critically dependent on measurement standards for **radiation dosimetry**: external beam **radiotherapy** demands greater measurement accuracy than any other application. We can expect strong growth in various forms of Intensity Modulated Radiotherapy (IMRT) and Image Guided Radiotherapy (IGRT), and at some point the UK can be expected to follow the international growth in proton therapy. Awareness of the need for accurate dosimetry in **Targeted Radionuclide Therapy** is developing.
One of the major uses of **radionuclides** is in medicine, for diagnostic imaging or for therapy. There are approximately 670,000 administrations of **radioactive pharmaceuticals** in the UK per year, and the use of these drugs has grown by 30% over the last ten years. This growth is likely to be maintained in the long term, due to an investment in **Positron Emission Tomography** centres for diagnosing and staging cancer.
Neutron measurements must be performed around hospital LinAcs for protection of staff and patients, requiring very specialist **neutron measurement** expertise. LinAcs used for **radiotherapy** generate **adventitious neutrons**, which contribute to staff and patient doses which have to be monitored. Similarly, air travel results in enhanced doses from **cosmic rays,** which have a strong **neutron** component. An understanding of the level of this exposure is essential in characterising risks to flight crew and passengers.
Medical uses of **ultrasound** include foetal monitoring, diagnostic imaging, Doppler blood-flow studies, physiotherapy, the non-invasive destruction of kidney stones (lithotripsy) and also tissue ablation using high intensity focussed ultrasound or HIFU. An accurate knowledge of the **acoustic pressures and powers** generated, and consequent tissue heating, is crucial for this the safe and effective use of the

equipment. Similarly, effective therapy and lithotripsy depend on well-characterised treatment systems.
Hearing loss has been a prescribed occupational disease eligible for compensation by the Department of Social Security (DSS) since 1974. **Audiometric measurements** to detect hearing loss in an objective and standardised manner are therefore critical.

Drivers for manufacturing (including advanced materials)

Noise emission measurements are now a common requirement for UK industry to demonstrate compliance with EC Directives.
Within the **Medical Ultrasound** area, the US Food and Drug Administration requires manufacturers to comply with **acoustic output limits** for specific clinical applications.
Ionising radiation is used extensively in the polymer industry to initiate polymerisation and cause effects such as cross-linking and degradation – a related area is the testing of electronic components for **radiation hardness** as required in the aerospace industry, requiring specialist dosimetry techniques.
Within the area of industrial **ultrasonics**, high-power applications of sound include cleaning, materials processing and sonochemistry. The application of high power ultrasound demands reproducible measurements, both due to the need to successfully replicate and scale-up industrial processes from pilot-plant level, but also in order to monitor and control processes effectively.

Drivers for the radiation processing Industry

The **medical device**, **pharmaceutical** and **food irradiation** industries are all subject to stringent national and international regulation and there is a general requirement that dose measurements are traceable to appropriate national or international standards.

Drivers for safety at work (including Radiation Protection)

There are approximately 250,000 workers in the UK exposed to **ionising radiation**, including approximately 40,000 Classified Persons whose radiation doses are closely monitored. Employers must comply with the Ionising Radiations Regulations which include a requirement to monitor the workplace for surface contamination of **radioactivity** (if open **radioactive sources** have been used). The instruments used for these measurements have to be tested annually, and there is a network of about 20 secondary standards laboratories carrying out these tests. Primary standards are needed for traceability for these tests, covering **beta**, **alpha** and **photon-emitting radionuclides**.
Radiation protection for **neutrons** is significantly more complex than for photons, many problems remain to be solved, not least that of deriving suitable devices to measure the dose, and work is continuing on device development in this area. These developments are impossible without facilities to test their properties.
One area of increasing concern is the need for standards for **radioactive aerosols** to calibrate and test monitors for **radioactivity-in-air** in the workplace.
Occupational noise exposure is controlled in the UK by the Noise at Work regulations, which implement Directive 86/188/EC. Noise levels of at least 85 dB(A) (the first action level under the regulations) are thought to be present at more than 80,000 workplaces throughout Britain.

Drivers for the instrumentation and testing industry

The UK is Europe's leading producer of **underwater acoustical systems**, with some 20 companies involved in manufacturing sonar systems. Accurate measurement of system performance is crucial for ensuring unambiguous specification and acceptance testing.

Through the need to undertake dosimetric measurements of **neutrons**, there comes a strong underpinning requirement for instrument testing facilities for **neutrons**. The instruments cover **radiation protection** devices, and all other **neutron** measuring devices including those used in reactor control.