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Introduction

The Centre for Nuclear Engineering (CNE) at Imperial College, London, established in 2007, is housed predominantly in two physical centres: the CNE space in the Bessemer Building, and the Rolls-Royce UTC in the City and Guilds Building. While much nuclear-related research is performed outside of the Faculty of Engineering (notably on Fusion, Plasma and Shock Physics in the Faculty of Natural Sciences and the Chernobyl Tissue Bank in the Faculty of Medicine), this report covers the activity in the Faculty of Engineering exclusively over the period August 2014 to March 2016.

The CNE currently comprises 33 academics, 19 of whom are Fellows of the Royal Academy of Engineering, from 5 engineering departments - forming a comprehensive research and teaching group dedicated to nuclear engineering and science. The CNE continues its strong performance in established theme areas and has seen growth in new areas such as nuclear regulation, tribology, and severe accidents. Industrial ties are strong, with support from a range of national and international organizations keen to work with the CNE. With the nearing of the UK new-build programme...
and the recent financial commitment to nuclear indicated by UK Government, the CNE continues to position itself to provide research, education, and advice to industry and government in support of these ambitions.

Nuclear Engineering has been taught continuously at Imperial College since the 1950s and it presently offers three undergraduate MEng degrees: Mechanical & Nuclear Engineering, Chemical & Nuclear Engineering, Materials, and Nuclear Engineering. Annually 30-35 students graduate from these courses, most of whom join the nuclear industry (e.g. EDF Energy, Rolls-Royce, AWE) or pursue PhDs. In 2011 the CNE helped create an MSc in Nuclear Engineering and 10 students should graduate this September. The EPSRC funded Imperial Cambridge Open Nuclear Energy Centre for Doctoral Training (ICO-CDT) was established in 2014 in collaboration with the University of Cambridge and Open University, taking cohorts through a dedicated MRes programme followed by three years of PhD study. The CDT plans to graduate as many as 15 students per year of the 8-year scheme (see www.imperial.ac.uk/nuclear-cdt).

Overview of our plan and progress

Since our last report the CNE has had significant impact on the UK and international scene. We have won several new contracts, such as being part of the CAFFE (Carbides for Future Fission Environments) consortia, and the UK-Japan EPSRC-MEXT research programme in nuclear safety and decommissioning. With Cambridge and the Open Universities, our Centre for Doctoral Training, funded by EPSRC and industry, is now training two cohorts of 10 students and advertising for its third. The CNE continues to attract large research grants, appoint outstanding new members to our team, and generate important publications.

Details are given in this report, but it is worth highlighting the appointments of Dr Ben Britton to a RAEng Fellowship on the Physical Understanding of Micromechanical Mechanisms for Structural Integrity Assessment in Nuclear Engineering; Miss Emma Warriss as Manager for the CDT in addition to the CNE; and of Dr Jonathan Tate as CDT/CNE Administrator. Ben has also taken over responsibility for our nuclear teaching programmes, and with Emma and Jonathan give us an outstanding support team. They are aided by our newly refurbished and extended office space with the addition of a much-needed meeting room and links to the Engineering Alloys team headed up by Prof Fionn Dunn, Director of the Rolls-Royce Nuclear University Technology Centre (NUTC).

Three of our team (Profs Robin Grimes, Bill Lee and Laurence Williams) are on the influential UK NIRAB (Nuclear Innovation and Research Advisory Board) committee, which is currently advising Government on plans for the £250M awarded to support nuclear R&D in last year’s spending review. We also congratulate Prof Julian Bommer on recently being appointed the lead for the ground-motion characterisation project for nuclear power plants in Spain, and Dr Andrew Buchan’s EPSRC fellowship in nuclear modelling. Our researchers continue to excel: PhD student Dimitri Pletser won a prestigious $5,000 Roy G Post scholarship to attend the Waste Management conference in Phoenix, USA, and CNE students Jure Aleksejev and Alan Charles received the first and second William Penney (AWE) project prizes respectively. We
continue our regular Management Committee meetings, seminars, lunchtime lectures, and hosting international workshops and visitors.

We continue to be successful in working with industry partners: in particular Rolls-Royce, EdF/EdF Energy, Hitachi-GE and AWE. We attract significant research funding with a current portfolio of over £38M including recent awards as part of the EPSRC-funded CAFFE consortia with Cambridge, Oxford and Manchester universities; with AWE in Additive Manufacturing, and grants with Oxford, Manchester and New South Wales Universities, Rolls-Royce, ANSTO, NNL and CCFE. We continue to play on the global stage, a recent highlight being the funding of two UK-Japan EPSRC-MEXT proposals to Chris Pain and Bill Lee for collaborations with the Universities of Tokyo, Kyushu and Tohoku.

The key areas where we plan to concentrate our efforts in the next 5 years include in building the CNE team, attracting more students (especially women) at all levels into nuclear engineering, working more closely and so acquiring more support from industry, from Government and international collaborators as well as improving our access to active facilities.

Prof Bill Lee
Director of the Centre for Nuclear Engineering –March 2016
Local Management team

The CNE was initially set up by Prof Robin Grimes in 2007: Prof Bill Lee took over as Director in November 2012 while Robin remains as Founding Director.

The Local Management team covers the day-to-day running of the CNE. Its members are:

» Prof Bill Lee – Director
» Dr Mike Bluck – Deputy Director
» Dr Norman Waterman - Strategy
» Prof Robin Grimes - Founding Director
» Dr Ben Britton - Teaching Coordinator
» Miss Emma Warriss - Manager
» Dr Jonathan Tate – Administrator

CNE Management Committee

The CNE Management Committee (CNEMC) meets monthly and its members are:

» Prof Bill Lee – Chair
» Dr Norman Waterman – Strategy
» Miss Emma Warriss – Manager
» Dr Jonathan Tate – Secretary
» Prof Robin Grimes – Founding Director of the CNE
» Dr Ben Britton – MEng/MSc Coordinator
» Dr Mark Wenman – Materials Representative
» Dr Mike Bluck – Mechanical Engineering Representative

» Prof Geoff Hewitt – Chemical Engineering Representative
» Dr Andrew Buchan – Earth Science and Engineering Representative
» Dr Katerina Tsiampousi – Civil Engineering Representative
» Dr Steve Garwood - RRUTC
» Dr Michael Rushton - PDRA Representative
» Mr Frederic Sebellieu – PhD Representative

The CNEMC monitors and acts on issues affecting Centre: such as nuclear developments in each Department, teaching, national and international issues, research proposals, communications, and seminars.

We have particularly strong links with Hitachi, AWE, EdF/EdF Energy, and Rolls-Royce through the UTC. The Annual Reports of these centres give details of progress and we summarise them briefly later. Dr Norman Waterman is the CNE representative with Hitachi, Prof Bill Lee with AWE, Dr Mark Wenman with EdF/EdF Energy, and Dr Mike Bluck with Rolls-Royce.

Nuclear Advisory Committee

The CNE Nuclear Advisory Committee (NAC) is composed of leading nuclear industry representatives, and consults on the structure and content of the Undergraduate and Postgraduate courses and on the CNE’s research strategy.
The NAC meets in London and prior to the meeting the CNE submits to the NAC the following for comment:

» The CNE’s Annual Report.
» An updated Business Plan.
» Minutes of the previous meeting.

The NAC involves a drinks reception and dinner on the first evening and a full-day meeting on the second day, which takes the format of a mini-conference.

Members for 2015-16 are:

» Tony Kelly, Mott MacDonald  
tony.kelly@mottmac.com
» Rob Harrison, Rolls Royce  
robert.harrison@rolls-royce.com
» Bruce McKirdy, NDA  
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» Xavier Mamo, EdF Energy  
xavier.mamo@edfenergy.com
» Simon Middleburgh, Westinghouse  
middlesc@westinghouse.com
» Si Dilks, DECC  
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» Sarah Williamson, Laing O’Rourke  
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» Gavin Nicol, Weir Group  
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» Tatsuro Ishizuka, Hitachi  
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» Martin O’Brien, CCFE  
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**AWE, EdF, NNL and RR UTC Management**

In January 2014 Imperial and EdF signed a new 5 year General Framework Agreement (GFA) covering R&D, Education and Training, and Technical Services on nuclear engineering, and also technologies related to electrical power transmission and end use. This new agreement includes EdF Energy and all current and future subsidiaries of EdF created for the new nuclear build programme. The Steering Group retains overarching responsibility for the successful implementation of all aspects of the GFA and is supported by a Strategy Committee advising on R&D priorities and a Monitoring Committee for the R&D Projects that are underway.

In a bid to capitalise on its intellectual capital and to further develop its activities in the nuclear sector, Rolls-Royce established a Nuclear University Technology Partnership (UTP) based at both Imperial College and Manchester University, in May 2010. Given the current resurgence in interest in nuclear power generation (both civil and military), the NUTP seeks to provide Rolls-Royce with state-of-the-art capabilities in a broad range of nuclear related disciplines and foster interdisciplinary working in-
ternally and collaboration externally. Since its establishment, the UTC has developed a range of work-streams in thermal hydraulics, reactor physics and structural integrity.

R-R UTC

The key management roles in the UTC are:

» **Director** (Prof Fionn Dunne, Imperial).

» **Deputy Director** (Dr Mike Bluck, Imperial).

» **UTC Coordinator** (Dr Rob Harrison, Rolls-Royce).

The UTC management structure has been developed to address short term, medium term and strategic issues. Monthly meetings are held between the UTC Coordinator and UTC Director and Deputy Director.

Monitoring the progress of research themes (amongst other items) is undertaken by appropriate review at quarterly management meetings (QMM) of the UTC management group. In addition, PhD and EngD students give seminars at these meetings.

The aim is for these to feed directly back to Rolls-Royce to ensure that our activities match closely with the needs of the Rolls-Royce business units. Overall oversight is provided by the UTC steering committee which meets annually (usually coincident with the annual review). The last Annual Review took place in Derby in October 2015 and was combined with the sister UTC based at Manchester.

AWE - CEMS

The AWE Centre for Engineering and Manufacturing Studies (CEMS) Management Board meets every 6 months with Neil Alford, Bill Lee, and Emma Warriss attending for Imperial and the key AWE contacts being Neil Seagrave, Norman Godfrey and Daryl Landeg.

NNL-Imperial College Alliance

The NNL-Imperial College Alliance meets every four months to develop collaborative research and training programmes. From Imperial, Simon Walker is a NNL Senior Fellow and Laurence Williams a Senior Visiting Fellow, and NNL Alliance members included Andy Sherry, Mike Angus, Scott Owens, Richard Stainsby and Dominic Rhodes.
People

The CNE possesses an impressive breadth and depth of nuclear expertise which the academic profiles in this section abundantly demonstrate.

Staff

Dr Mike Bluck IMechE, IET
Senior Lecturer
Department of Mechanical Engineering
Deputy Director RR NUTC

Mike Bluck obtained his BSc (Hons.) in Mathematics (mathematical physics) from the University of Kent. At Imperial College London, Mike completed a PhD Thesis on: ‘Integral equation methods for transient wave propagation’ with applications to acoustic scattering, RCS computation and antenna design before becoming involved in nuclear engineering. He is a Senior Lecturer in the Nuclear Engineering group of the Mechanical Engineering Department, and also the Deputy Director of the Rolls-Royce Nuclear University Technology Centre. His interests cover nuclear thermal hydraulics, neutronics and associated computational methods. He is an investigator on current grants totalling over £2M, including Computational Modelling for Advanced Nuclear Power Plants, collaborations with India (BARC) on thermal hydraulics, development of advanced radiation transport schemes (Rolls-Royce) and applications of CFD to nuclear (Rolls-Royce). He has ~40 publications, and has supervised 7 students to PhD completion and currently supervises or co-supervises 14 EngD and PhD students.

Prof Julian Bommer
Senior Research Investigator
Civil and Environmental Engineering

The core of Julian’s research is related to the characterisation and production of strong ground-motion, including establishing the influence of different ground-motion parameters on structural response and damage. The second major area is seismic hazard assessment, such as the identification, interpretation and treatment of uncertainties, and the practice of probabilistic seismic hazard analysis.

Julian is engaged in seismic hazard projects around the world, primarily for nuclear applications but also related to large dams, bridges, and other major infrastructure projects, including the Panama Canal expansion.

Dr Ben Britton
Lecturer
Department of Materials
Director of the MSc in Advanced Nuclear Engineering

Ben was recently appointed as a Lecturer in Materials and is also holder of a Royal Academy of Engineering Research fellowship studying “better materials for safer reactors”. His research group focus on understanding the behaviour of high value-high risk materials. For nuclear applications,
this focusses on zirconium alloys, nickel and hydrogen embrittlement in steels. He is a specialist in micromechanics and characterisation of materials, developing novel experimental and computational tools to understand microstructural performance at the microstructural lengthscale with a view towards component manufacture and performance, through new alloy design and managing materials use in extreme environments. In addition to his research activity, Ben is Director of the MSc in Advanced Nuclear Engineering, coordinates all nuclear teaching across the college, and sits on the CNE Management Committee. He is a Chartered Scientist and Member of the Institute of Materials, Minerals and Mining.

Dr Andrew Buchan
Research Fellow
Department of Earth Sciences and Engineering

Andrew’s research interests are in the simulation and prediction of the coupled physics of neutron transport and multi-phase fluid flows within nuclear systems. He is involved in developing the latest and novel numerical models at Imperial College, including the FETCH and RADIANT codes, and my areas of research now cover the fields of adaptive finite elements, sub-grid scale methods, linear and non-linear stabilization schemes, Krylov solvers, multigrid preconditioners, reduced order models, immersed body methods, multi-scale techniques, spherical wavelets, uncertainty quantification, error metrics and adaptivity schemes.

Andrew’s research also includes the study and reconstruction of historical criticality accidents, liquid fuel experiments, and the analysis and prediction of both liquid and solid fuel reactors. I am currently the scientific coordinator of a large grant to design the new radiation transport model RADIANT.

Andrew sits on the CNE Management Committee as the Earth Sciences and Engineering representative.

Prof Nick Buenfeld, FREng
Head of Department of Civil and Environmental Engineering, Professor of Concrete Structures

Nick specialises in long-term performance of concrete structures. He heads a multi-disciplinary group advancing the understanding of deterioration processes to develop more effective methods of design, assessment and repair of concrete structures. His current interests include life prediction, wireless condition monitoring and novel approaches to high durability. Nick’s Department has excellent facilities ranging from labs for casting and loading large structural elements and for simulating different exposure environments, down to advanced techniques for characterising. Nick has advised on specification of concrete for new nuclear power stations in the UK and on nuclear waste disposal elsewhere in Europe.

Prof Peter Cawley, FREng, FRS, FIMechE, M Brit Inst NDT
Head of Department of Mechanical Engineering

Peter leads the Non-Destructive Evaluation (NDE) research group (www.imperial.ac.uk/nde). He is also the principal investigator of the UK Research Centre for
NDE (RCNDE) that has its head office at Imperial College. Peter is also a director of two spin-out companies set up to exploit technology developed in his research group (Guided Ultrasonics Ltd [www.guided-ultrasonics.com] and Permasense Ltd [www.permasense.com]).

Dr Frederic Cegla
Senior Lecturer
Department of Mechanical Engineering
Member of the Dynamics and Non-destructive Evaluation (NDE) groups

Frederic’s research interests are in the fields of high temperature ultrasonic monitoring, structural health monitoring, ultrasonic material property measurements and ultrasonic transducers. He is a board member of the UK Research Centre in NDE (RCNDE).

Dr Trevor Chambers
CONSORT Manager
Silwood Park

Trevor runs the CONSORT reactor at Silwood Park and is now working with Areva on its decommissioning. He hosts student training visits to the reactor and teaches on nuclear safety management.

Prof Chris Cheeseman
Professor of Materials Resource Engineering
Department of Civil and Environmental Engineering

Chris leads a major research group working on the beneficial reuse of waste materials and resource efficiency within the Environmental and Water Resource Engineering (EWRE) Section in Civil Engineering. He is also Director of the Centre for Doctoral Training in Sustainable Civil Engineering. Chris’s research interests are in both hazardous and radioactive waste glasses and cements.

Prof John Cosgrove
Professor of Structural Geology
Department of Earth Science and Engineering

John researches links between stress, fracture and fluid flow, movement of fluids through low permeability rocks and the generation of fractured rock masses and their properties. In 2006 he was a member of the Swedish Nuclear Fuel & Waste Management Site Evaluation and Review Group.

Dr Catrin Davies, AMIMechE, ProfGrad IMM
Senior Lecturer within the Mechanics of Materials Division
Department of Mechanical Engineering

Catrin was awarded an EPSRC Career Acceleration Fellowship (2010-2015) in partnership with EdF Energy and E.ON. She manages the High Temperature Centre at Imperial College and has over 40 publications relating to experimental testing and finite element modelling of creep deformation, damage, creep crack initiation and growth, low-cycle fatigue, weld simulations, prediction and measurement of residual stresses and failure analyses. Her research has been incorporated into industrial codes and testing standards.
Prof Fionn Dunne, FREng, MIMechE
Chair in Micromechanics
Department of Materials
Director of RR NUTC

Prior to coming to Imperial in 2012, Fionn was Professor of Engineering Science at Oxford University. His current research is in the fundamentals of deformation and failure, particularly relating to hcp polycrystal and Ni alloys and includes computational crystal plasticity, discrete dislocation plasticity, micro-deformation, fatigue crack nucleation, texture and dislocation structure development and polycrystal sonics for NDE. He leads the EPSRC programme grant Heterogeneous Mechanics in Hexagonal Alloys across Length and Time Scales (http://www3.imperial.ac.uk/hexamat), directs the Imperial Rolls-Royce Nuclear University Technology Centre (http://www3.imperial.ac.uk/rrnuclearutc), and Co-Directs the AVIC-BIAM Centre for Materials (http://www3.imperial.ac.uk/avic-biam).

Fionn is a consultant to Rolls-Royce, a member of their Core Materials Working Group and was a Royal Society Industry Fellow in 05/06, which he spent with Rolls-Royce. He is Honorary Professor with the Beijing Institute of Aerospace Materials, and is Emeritus Fellow of Hertford College Oxford.

Dr Matthew Eaton
Lecturer in the Nuclear Engineering Group
Department of Mechanical Engineering

Matthew researches computational radiation transport, computational fluid dynamics, nuclear criticality, cloud radiation physics, nuclear reactor physics, radiation shielding and dosimetry, infra-red optical tomography, high-resolution finite volume methods, sub-grid scale modelling, non-linear Petrov-Galerkin methods, mesh generation, coupled radiation/heat/fluid dynamic problems and algebraic multigrid solvers.

Matthew is also the NEA databank representative for Imperial College and as such deals with the dissemination of nuclear data, computer programmes, and associated documentation.

Dr Joy H. Farnaby
Junior Research Fellow
Department of Chemistry

Joy joined the Chemistry Department in 2014 as a Junior Research Fellow on a project entitled, ‘New routes to multi-metallic nano- and bulk materials containing f-block elements.’
Her research interests are in the bonding, structure and magnetism of the lanthanides and actinides and in the design, development and applications of new materials containing these elements.

Prof Robin Grimes, FREng, FIIMMM, FlnucE, FInstP, FAcers, CEng
Professor of Materials Physics
Department of Materials
CNE Founding Director

Robin’s primary research interest is the application and development of computer simulation techniques to predict structural and dynamic properties of inorganic materials. Topics of particular interest include radiation damage, nuclear fuels and waste form behaviour and performance (in collaboration with industry and national laboratories), ionic conductivity and defect processes for fuel cell materials, surface structural processes and interfaces between glass and ceramic.

Since 1984 Robin has authored over 240 peer-reviewed publications. From 2008 until 2013 he was Director of the Imperial Centre for Nuclear Engineering and from 2010 to 2013 he was Director of the Imperial College Rolls Royce University Technology Centre in Nuclear Engineering. He was appointed Principal Investigator of the Research Councils Nuclear Champion consortium in 2010. In 2011 he was Specialist Advisor to the House of Lords Select Committee on Science and Technology for their report on Nuclear Research and Development Capabilities and in 2013 was made a Fellow of the Royal Academy of Engineering. He is currently the Chief Scientific Adviser to the Foreign and Commonwealth Office.

Prof Geofferey Hewitt, FREng, FRS
Emeritus Professor
Department of Chemical Engineering

Geoff specialises in multiphase flow systems, with particular reference to channel flow and heat transfer. He has had a wide experience of industrial application through his founding of the Heat Transfer and Fluid Flow Service (HTFS) at Harwell and through extensive consultancy and contract work. His contributions to the field have been recognised by his election to the Royal Society, the Royal Academy of Engineering and the US National Academy of Engineering in addition to international awards.

Geoff sits on the CNE Management Board as Chemical Engineering representative.

Prof John-Paul Latham
Senior Lecturer
Department of Earth Science and Engineering

John-Paul is a major contributor to research supporting the VGeST Open Source Tools for the application of Discontinuum Modelling to fracture, fragmentation and granular processes, forces and stresses in concrete armour units for breakwaters, wave-structure modelling with Fluidity and Y3D, fracture patterns and flow in reservoir rocks and rock mechanics.
Prof Bill Lee, FREng, FI MMM, FA CerS, FC GI, C Sc i, Chair in Ceramic Engineering

Department of Materials
Director of the CNE
William Penney Fellow

Bill is Director of the Centre for Nuclear Engineering at Imperial College London, a William Penney Fellow, a member of the Government advisory committee The Nuclear Innovation and Research Advisory Board (NIR-AB). He is also a member of the Leverhulme Trust Panel of Advisors, the Royal Academy of Engineering International Activities Committee, the Scientific and Environmental Advisory Board Tokamak Energy Ltd and The Technical Advisory Board of the National Laboratory. Bill was Deputy Chair of the Government Advisory Committee on Radioactive Waste Management (CoRWM) from 2007-2013, has acted as special advisor nuclear to the House of Lords Science and Technology Committee (2013) and is an IAEA Technical Expert.

Bill’s research interests include ultra-high temperature ceramics and nuclear fuels and wasteforms. Bill has published over 350 peer-reviewed papers and has also been awarded research grants totalling over £50M, including £5.5M from EPSRC to set up the Centre for Advanced Structural Ceramics (CASC) and over £2M as co-investigator with Mike Finnis on the programme grant Materials in Extreme Environments (XMat) with Jon Binner at Loughborough. He is also external examiner for the Nuclear Engineering MSc at Khalifa University in Abu Dhabi.

Prof Mike Lowe, FREng, FI Mech E, Flinst P, Flinst NDT

Professor in Mechanical Engineering
Deputy Head of the Department of Mechanical Engineering

Mike’s research is in Non Destructive Testing (NDT), with particular interests in structure-guided ultrasound, wave theory, and analytical and numerical modelling. His teaching interests are in mechanics, mathematics, vibration, and Finite Element modelling. He is a member of the board of the RCNDE.

Mike is also a director of Guided Ultrasonics Ltd (www.guided-ultrasonics.com), a spin-out company which was set up to commercialise the outputs of research in ultrasonic guided waves.

Dr Christos Markides
Senior Lecturer in Clean Energy Processes
Department of Chemical Engineering

Christos’s research interests include technologies, processes and methods for the recovery, utilization, conversion and storage of thermal energy for cooling, heating and power, novel ‘total energy’ integration schemes in high-efficiency systems with emphasis on low-grade waste heat, and solar-thermal energy utilization. In the context of nuclear energy, he studies thermohydraulics and thermodynamics power systems.
Dr Na Ni
Junior Research Fellow
Department of Materials
Na joined Imperial College on a Junior Research Fellowship in 2014. She works as part of the Ceramics and Glasses and Nanoscience and Nanotechnology Research Groups. Completed at Oxford University, her PhD was titled ‘Study of Oxidation Mechanisms of Zirconium Alloys by Electron Microscopy’.

Dr Marcos Millan-Agorio
Reader in Chemical Engineering
Department of Chemical Engineering
Marcos’s research includes catalytic upgrading of heavy oil and coal-derived hydrocarbons, characterisation of fuels and carbonaceous materials in terms of their molecular weights and chemical structures, and thermochemical processing of solid fuels such as coal, biomass and wastes.

Prof Kamran Nikbin
Professor of Structural Engineering
Department of Mechanical Engineering
Kamran performs research into experimental testing, numerical modelling and the verification of component lifting methods which are associated with failures due to brittle, ductile, fatigue and creep fracture. The main aim has been directed towards developing techniques for predicting failure using fracture mechanics, continuum damage mechanics and micro to meso-scale modelling techniques, which are validated through appropriate experiments. In particular, the main impetus has been in the field of high temperature creep/fatigue crack growth by considering the experimental and metallurgical aspects, micromodels and numerical predictions associated with it. A considerable knowledge base has been accumulated on advanced steels, single crystals and high temperature protective coatings. The consequence of this research has been the development of life assessment codes that have been adopted by a range of industrial bodies; substantial input has been made to a number of codes including BS7910, ASTM, ASME, API, British Energy R6/R5 codes, ISO standards dealing with residual stresses and component creep/fatigue testing and also the design code for the ITER super magnet structure which includes fatigue fracture criteria for cracked components.

Prof Chris Pain
Professorial Research Fellow
Department of Earth Science and Engineering
Head of the Applied Computation and Modelling Group (AMCG)
AMCG specialises in the development and application of innovative and world leading modelling techniques for earth, engineering and biomedical sciences. The group has core research interests in numerical methods for ocean, atmosphere and climate systems, engineering fluids including multiphase flows, neutral particle radiation transport, coupled fluids-solids modelling with discrete element methods, turbulence modelling, inversion methods, imaging, and impact cratering.
Prof Mary Ryan FREng, FIMMM
Professor of Materials Science and Nanotechnology
Department of Materials

Mary’s current research is in the area of applied electrochemistry and corrosion, with a focus on deposition of nanostructures and the study of self-forming nanocrystalline oxides; as well as fundamental work on degradation and stability of metal systems.

She is a Fellow of the Institute of Materials Mining and Minerals (member of the Corrosion Committee and Corrosion Network 2015-) and a member of the International Society of Electrochemistry (Materials Division Chair 2013-2015).

Dr Luc Vandeperre, FIMMM, FHEA
Senior Lecturer
Department of Materials.

Luc has two main research themes: first, the thermomechanical properties of structural ceramics, investigating ceramics for use in high temperature environments and as ballistic protection; second theme is environmental technologies: He is involved in research into new cements and geopolymers for nuclear waste encapsulation, tailoring materials for removal of radionuclides from water, carbon capture and recycling of difficult wastes in plastic products.

Dr Simon Walker, FIMechE, IET
Head, Nuclear Research Group
Department of Mechanical Engineering

Simon researches nuclear thermal hydraulics and reactor safety. He leads the Rolls Royce Nuclear Reactor Thermal Hydraulics programme, and the EPSRC “Computation for Advanced Reactor Engineering” (CARE) project, and is active in advisory roles for MoD and RR submarine propulsion programme. Simon is also an NNL Senior Research Fellow.
Dr Mark Wenman
Lecturer
Department of Materials
Mark was the British Energy (now EdF Energy) Research Fellow in Nuclear Fuels and Lecturer in the Reactor Engineering Group at the Nuclear Department, HMS Sultan in Gosport.

Mark set-up the MSc in Nuclear Engineering at Imperial College in 2010 and was course director for 3 years. His key research interests are in the field of nuclear engineering materials and include micromechanisms of fracture, hydrogen embrittlement, irradiation damage, stress and strain measurement and finite element modelling from continuum to microscales. Materials include zirconium alloys, stainless steels and ferritic steels. Mark serves on several committees including the TAGSI (Technical Advisory Group Structural Integrity for UK nuclear industry) sub-committee on radiation damage in steels and is the NTEC and NAILS. Mark also sits on the CNE Management Board as Materials representative.

Prof Laurence Williams FREng, FIMechE
Senior Research Fellow
Laurence is one of the world’s leading experts in nuclear safety regulation. He was Her Majesty’s Chief Inspector of Nuclear Installations and the Chief Engineer and Director for Nuclear Safety, Security and Environment at the Nuclear Decommissioning Authority. He is currently the Chair of the Committee on Radioactive Waste Management (CoRWM), which advises the Government and the Devolved Administrations on the geological disposal of radioactive waste, and a member of NIRAB. He is also the UK Member of the Higher Scientific Council of the European Nuclear Society, Senior Visiting Fellow at the National Nuclear Laboratory (NNL), and Chair of EC High Level Panel to review the EURATOM FP7 and FP7+2 Nuclear Fission and Fusion Research Programme. Laurence is also currently supervising and examining several MSc theses.

Dr Hong Wong
Senior Lecturer
Department of Civil and Environmental Engineering
Hong’s research aims to advance the understanding of how microstructure influences the performance, ageing and degradation of concrete structures. His work focuses on developing and applying imaging techniques to characterise microstructure, studying the mass transport processes that control concrete degradation and developing models to predict macroscopic properties from microstructure. He has expertise in 2D and 3D microscopy, X-ray microanalysis, image analysis, mass transport characterisation and computer-based modelling. Current interests include understanding the influence of microcracks and self-healing on the long-term performance of cement-based wasteforms.

Prof Robert Zimmerman
Chair in Rock Mechanics
Department of Earth Science and Engineering
Robert conducts research on the hydromechanical behaviour of
fractured and porous rocks, petrophysics, fluid flow in porous media, rock failure and fracture, and on the relationship between microstructure and the physical properties of heterogeneous materials, with applications to petroleum engineering, underground mining, radioactive waste disposal, and subsurface carbon sequestration. His research interests include modelling of geomechanical and hydrological processes related to geological disposal facilities for nuclear waste.

Robert’s research has been funded by, among others, BP, Chevron, Halliburton, Norsk Hydro, Rio Tinto, Schlumberger, Shell, EPSRC, NERC, NDA, and the European Commission. He has been a PI on the US Department of Energy’s Yucca Mountain radioactive waste repository project, and was the principal investigator on the €3M THERESA project, funded by the European Commission Euratom Program. He is currently PI on the multi-university NERC RATE project: ‘Hydromechanical and Biogeochemical Processes in Fractured Rock Masses in the Vicinity of a Geological Disposal Facility for Radioactive Waste.'
### Researchers (PDRAs)

<table>
<thead>
<tr>
<th>Materials</th>
<th>Mechanical Engineering</th>
<th>Earth Science &amp; Engineering</th>
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<tbody>
<tr>
<td>Paul Fossati (RG)</td>
<td>Nicolas Cinosi (SW)</td>
<td>Anozie Ebigbo (RZ)</td>
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<tr>
<td>Denis Horlait (BL)</td>
<td>Christopher Cooling (ME)</td>
<td>Dimitrios Pavlidis (CP)</td>
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<tr>
<td>Sam Humphrey-Baker (BL)</td>
<td>Jozsef Kophazi (ME)</td>
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<tr>
<td>Chinnam Rana Krishna (BL)</td>
<td>Bo Lan (ML, PC, FC)</td>
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<tr>
<td>Navaratnarajah Kuganathan (RG)</td>
<td>Kausik Nandi (SW)</td>
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<td>Michael J D Rushton (BL)</td>
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<td>Eugenio Zapata-Solvas (BL)</td>
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### Visiting Academics/Visitors

A number of outside experts are part of the CNE team and hold Visiting Academic positions at Imperial College. They are:

- Prof Dan Cacuci (University of South Carolina) – ESE
- Prof Alex Chroneos (Open University) - Materials
- Visiting Professor Alan Copestake (Rolls-Royce) - Mechanical Engineering
- Visiting Professor Mamdouh El-Shanawany (Lloyds Register, ex-IAEA) – Mechanical Engineering and Materials
- Visiting Lecturer Dr Robert Harker (AWE Aldermarston) - Materials
- Prof Tim Haste (IRSN) – ESE
- Honorary Visiting Lecturer Ms Marion Hill (CoRWM) - Materials
- Prof Kym Jarvis (Viridian Partnership) – Materials
- Dr Alan Jones - ESE
- Mr Brian Metcalfe (ex-AWE) - Materials
- Michael Navon (FSU) – ESE
- Dr Scott Owens (NNL) - Materials
- Anil Priger (University of New Mexico) - ESE
- Dr John Roberts (Manchester University) - Materials
- Visiting Professor Dr Neil Smart (NDA) – Materials
- Prof Richard Smedley-Stevenson (AWE) – ESE
- Prof Paul Smith (AMEC) – ESE
- Visiting Professor Dr Ali Tehrani (ONR) - Materials
- Dame Sue Ion OBE, FREng, FIC, FICG, FIM - Materials
In addition we are regularly visited by members of the broader nuclear community, just a few of whom are listed below.

» Lyndon Edwards, Greg Storr, Simon Middleburgh (ANSTO, Australia)

» Robert Holmes (Atomic Energy of Canada Ltd)

» Neil Seagrave, Daryl Landeg, Norman Godfrey, Peter Roberts, Arfon Jones, Mark Swan, Matthew Gilbert, Shirley Fong, Mark Swann, Mike Cox, Claire Leppard, Tim Paget, Mark Storr (AWE)

» Arnab Dasgupta (Bhaba Atomic Research Centre (BARC), India)

» Dr W Horak (BNL)

» Dr David Parfitt (Coventry University)

» Si Dilks and Sarah Swash (Department of Energy and Climate Change)

» Michael Barsoum (Drexel University, USA)

» Richard Jones, Jean-Claude van Duysen, Erwan Galenne, Xavier Mamo, Daniel Bentham (EdF/EdF Energy)

» Naoki Ito, Fumiaki Tonoki, Atsushi Oku, Tatsuya Ito (Embassy of Japan)

» Neil Bateman (EPSRC)

» David Powell (GE Hitachi)

» Abdulhamid Nassouri, Azzah Al Sharhan, Ausaf Hussain (Emirates Nuclear Energy Corporation)

» F. Murata, K Moriya, K Hida, K Sato, T Yudate, N Ooshima, J Miura, N Tanikawa, H Soneda, Kazuhiro Yoshikawa, H Saishu, Yoichi Wada, Y. Ishiwatari (Hitachi-GE)

» Masao Chaki, Yasunori Sota, Ryo Ishaibashi (Hitachi, Japan)

» Parul Goel (Homi Bhabha National Institute and BARC, India)

» Mark Tippett (Horizon)

» Tony Turnbull (Independent/NFIR)

» Phil Beeley (Khalifa University, UAE)

» Bob Williamson, Paul Collings, Scott Owens, Andy Sherry, Stephen Pilditch, Howard Sims, Jim Henshaw, Robert Gregg, Dan Shepherd, Mike Angus, Allyson Dixon (NNL)

» Prof Bill Nuttall, Prof John Bouchard (Open University)

» A Yamaguchi (Osaka University, Japan)

» Dr Masroor Ahmad (Pakistan Institute of Engineering and Applied Sciences (PIEAS)

» Rob Harrison, Dave Stewart, Alison Tesh, Steve Curr, Mike Asprey, Carrie Miskowska, Ted Darby, Aidan Cole-Baker, Rob Bentley, Mike Martin, Paul Moreton, John Molyneau, Paul Stein, Henner Wapenhans (RR)

» Julie Cairney (Sydney University, Australia)

» Dr Ian Farnan (University of Cambridge)

» Philip Platt, Chris Race, Michael Preuss, Prof Francis Livens (University of Manchester)
» Graham Davies, John Fletcher  
(University of New South Wales, Australia)

» James Marrow, Chris Grovenor, Michael Moody (University of Oxford)

» Prof Ted Bessman (University of South Carolina, USA)

» Paul Blair, Simon Middleburgh  
(Westinghouse, USA)

» Gabriel Meric de Bellefon (Wisconsin-Maddison, USA)
## PhDs

<table>
<thead>
<tr>
<th>Department</th>
<th>Students</th>
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<tbody>
<tr>
<td>Centre for Environmental Policy</td>
<td>Ben Pearce</td>
</tr>
<tr>
<td>Chemical Engineering</td>
<td>Niccolo Le Brun, Eneritz Fernandez, James Hickson</td>
</tr>
<tr>
<td>Civil Engineering</td>
<td>Giulia Ghiadistri, Vasileios Mantikos, Daniel Martinez Calonge</td>
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<td>Earth Science &amp; Engineering</td>
<td>Philipp Lang, Robin Thomas</td>
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<td>Ji-Soo Ahn, Morgan Cowper, Jack Egerton (EngD), Joshua Elliott (EngD), Giovanni Giustini, Susann Haensch, David Harland, Golam Majumder, Azrudi Mustapha James Petit (EngD), Richard Phillips (EngD), Lavinia Raganelli, Frederic Sebilleau, Fan Shi, Ashraf El-Shanawany, Keith Tarnowski, Ronak Thakrar, Michael Wolfendale</td>
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<tr>
<td>Department of Materials</td>
<td>Nor Ezzaty Ahmad, Bartosz Barzdajn, Benjamin Bell, Patrick Burr, Eleonora Cali, Michael Cooper, Claudia Gasparrini, Conor Galvin, Edoardo Giorgi, Robert Harrison, Tom Haynes, Zoltan Hiezl, Yun-Hao Hsieh, Charles Hutchison, Alexandros Kenich, Ben Nash, Mitesh Patel, Tsvetoslav Pavlov, Kristijonas Plausinaitis, Dimitri Pletser, Giuseppe Scatigno, Vivian Tong, Filippo Vecchiato, William White, Simon Wyatt</td>
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### Nuclear Engineering MSc

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<tbody>
<tr>
<td>Ahmad Abdulsalam</td>
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<td>Oliver Adams</td>
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<td>Borja Artes Artes</td>
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<td>Chan Boon Hwee</td>
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<td>Arun Khuttan</td>
<td>Paco Suárez Ortiz</td>
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### MEng Undergraduates

#### Year One

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<thead>
<tr>
<th>Chem Eng</th>
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<tr>
<td>James Buckley</td>
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<td>Henry Fi-Fi</td>
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<td>Stefan Vollmer Firenze</td>
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<td>Enrico Manfredi-Haylock</td>
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<td>Kenneth Tan</td>
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#### Year Two

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<tr>
<td>Nikola Evripidou</td>
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<td>Huize Fan</td>
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<td>Naoki Okutsu</td>
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<td>Zackary Youssef</td>
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### Year Three

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<tr>
<td>Lincoln Ang Yuen Kai</td>
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<td>Alexander Orchard</td>
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<td>Angelo Bonzanini</td>
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<td>David Bowskill</td>
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<td>Alexander Jackson</td>
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<td>Oscar Tucker</td>
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<td>Charlotte Whelan</td>
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<tr>
<td>Bilal Khan</td>
<td>Thomas Ferrer</td>
<td>Jules Cheongvee</td>
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<td>James Metcalfe</td>
<td>Shoki Hoshino</td>
<td>Vlad Podgurschi</td>
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<td>Nicholas Parkin</td>
<td>Christian Korte</td>
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<td>Natalie Yip</td>
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<td>Rebecca Telford</td>
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## ICO-CDT

### Cohort 1 (2014-2018)

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<tbody>
<tr>
<td>John Brokx</td>
<td>Richard Pearson</td>
</tr>
<tr>
<td>Alan Charles</td>
<td>Hassan Qarra</td>
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<tr>
<td>Alexandros Kenich (Cohort Rep)</td>
<td>William White</td>
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<tr>
<td>Mark Mawdsley</td>
<td>Andrew Wilson</td>
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<td>Sophie Morrison</td>
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### Cohort 2 (2015-2019)

<table>
<thead>
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<th>Name</th>
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<tbody>
<tr>
<td>Peilong Dong</td>
<td>Nathan Read</td>
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<tr>
<td>Said El-Chamaa</td>
<td>Giles Rought-Whitta</td>
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<tr>
<td>Lloyd Jones</td>
<td>Thomas Whiting</td>
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<tr>
<td>Robbie Lyons</td>
<td>Kathryn Yates</td>
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<tr>
<td>Dhan-sham Rana (Cohort Rep)</td>
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</table>
The overwhelming majority of CFD codes in use throughout the world have their origins at Imperial College (Star CCM, Fluent, Phoenix), and the college is at the forefront in the development of their research-level successors (e.g. Fluidity). These codes are being actively developed and applied to a range of nuclear engineering issues, in collaboration with major industrial nuclear players such as a Rolls-Royce and EdF/EdF Energy. Three general purpose finite element codes, developed at Imperial (Fluidity, RADIANT and EVENT) together with specialised codes such as the coupled multiphase CFD and radiation transport code, FETCH, provide a numerical framework for research. The FETCH asymmetric transient model, for example, has been applied to the HTR10 pebble bed high temperature gas reactor.

Structural Integrity of metallic materials based research is being examined using numerical modelling for predicting creep, fatigue and brittle/ductile failure using fracture mechanics, continuum damage mechanics and micro to meso-scale modelling techniques. Atomic scale modelling is applied to problems associated with the physics and chemistry of nuclear materials, and particularly their interaction with defects and molecules. Significant achievements include predictions of the radiation tolerance of ceramics as nuclear waste forms, as new nuclear fuel matrix materials and associated metallic systems. Fundamental atomic scale processes responsible for radiation tolerance have also been identified. Recently this has been extended to fusion related materials. In addition processes have been identified that

Capabilities and Facilities

Advanced modelling and simulation applied to nuclear engineering is the cross-cutting theme in the CNE. Modelling and simulation is of course not sufficient on its own, with experimental validation absolutely vital, and we are heavily involved in nuclear-related experimental programmes with collaborators both in the UK and overseas. We are also developing in house experimental ability including active facilities at Silwood Park. A key aspect is our ability to bring numerical methods to bear on nuclear issues across the fuel cycle and world-class modelling of multi-scale multi-physical processes, across the areas of thermal hydraulics, reactor physics and materials modelling.
enable the accommodation and transport of an extensive range of fission products in uranium oxide, nitride and carbide fuel forms.

The Departments which make up the CNE have a range of facilities available for use some of which are listed below; however, as our facilities always being changed to reflect research needs, you should visit the departmental websites via http://www.imperial.ac.uk for more information. The CONSORT low power research reactor is in final shutdown, the fuel has been removed and decommissioning is expected to take about seven years. However, this does provide an extended period for training students in decommissioning.

Civil Engineering

Experimental

- Soil-water retention curve desiccators
- Temperature- and suction controlled oedometer
- Temperature- and suction controlled triaxial
- Temperature-controlled hydraulic permeability/thermal conductivity cell
- Temperature-controlled triaxial cell (EPSRC small scale equipment grant)
- Miniature tensiometer for measuring suctions up to 1.5MPa (EPSRC ref. GR/J14325)
- Suction-controlled osmotic oedometer (GR/L36451)
- Suction-controlled triaxial apparatus (GR/K77723)

Numerical

- In-house developed finite element code ICFEP; thermo-hydro-mechanical (THM) 2D and 3D analysis of geomaterials and geotechnical structures
- LAMMPS molecular dynamics code for simulating behaviour of granular materials. Licences for the commercial discrete element software PFC, which can model thermal effects in granular materials. Potentially these codes can be applied to look at pebble bed reactors.

Mechanical Engineering

- Range of conventional and specialist ultrasound NDT equipment
- Ultrasound array imaging equipment
- Finite Element Simulation software
- 100kN Instron load frame with High temperature vacuum furnace
- Thermal Mechanical Fatigue System
- Gleeble 3800
- Creep Machines
- Guided Wave testing equipment for pipelines
- Laser interferometers for vibration displacement measurements
- Creep Monitoring system
- Pipe wall thickness remote monitoring equipment
- HPC Cluster
» Flow rig for PIV measurements in non-circular channels

**Materials Science and Engineering**

» PANalytical X’Pert MPD diffractometer.
» PANalytical Empyrean diffractometer
» Philips X’Pert MPD diffractometer with Buhler HDK 2.4 high temperature stage.
» Philips X’Pert MRD diffractometer’s.
» Bruker D2 Phaser desk-top diffractometer.
» Tof-SIMS (IonTof GmbH, TofSIMS5)
» LEIS (Iontof GmbH, Qtac100)
» FIB-SIMS (FEI Corp, FIB200 SIMS Workstation)
» Optical Profilomentry using vertical scanning interference microscopy (Zygo Corp., NewView 200)
» Bruker Innova AFM
» Asylum MFP-3D AFM
» TITAN 80/300 TEM/STEM
» JEOL 2000FX TEM
» JEOL 2010 TEM
» Helios NanoLab 600 FIB-SEM
» Zeiss Aruga Cross BEAM FIB-SEM
» LEO Gemini 1525 FEGSEM
» JSM6400 SEM
» JSM5610LV SEM

» Simultaneous TG-DTA to 2000°C
» Laserflash (thermal diffusivity) to 2000°C
» Dilatometer (thermal expansivity) to 2400°C
» Auriga (SEM, FIB, EBSD, EDX)

**Chemical Engineering**

» Our experimental equipment was designed and commissioned to study hydrogen adsorption of different carbon materials immersed in molten salts at high temperatures. The equipment is used to study the viability of using carbon materials as effective tritium removal technology in fluoride-salt-cooled high-temperature reactors. We also have instruments for determining the thermal conductivity of molten salts at high temperatures.
» Glovebox and fume-hoods for synthetic uranium chemistry.
Fuel Design and Performance

CNE research in the fuel area covers both performance and degradation mechanisms of current ceramic PWR fuels and metal cladding systems and development of accident tolerant fuels new fuel systems for Generation IV reactors.

PDRA Projects

**MAX Phases for Accident-Tolerant Fuels**

Researcher: Dr Denis Horlait  
Supervisor: Prof Bill Lee  
Sponsor: EPSRC through XMat and CAFFE programme grants

A loss-of-coolant accident (LOCA) leads to temperature building-up in the reactor core, leading to a chain reaction between steam and the Zr-based alloy constituting fuel cladding. This reaction between H₂O and Zr produces massive amount of H₂ and associated explosion risks. Recent Fukushima events for which this scenario happened had led to increase R&D efforts for the “Accident Tolerant Fuel” (ATF) concept. The ATF goal is to develop clad and fuels that can prevent or at least postpone such events.

For cladding, some ternary layered carbides belonging to the “MAX phases” family display interesting characteristics, such as irradiation, thermal shock and high-temperature oxidation resistance (notably for the Al-based ones). One of these carbides could thus possibly be used as an external protective coating for the Zr cladding.

The global aim of this project was thus to prospect for MAX phases materials for ATF. This was done by selecting promising composition then attempting to synthesize them and finally testing their oxidation resistance above 1200°C. The research focused on Zr₂AlC and derived compositions, (Cr,Ti)ₙ₊₁AlCₙ, and pre-oxidised Ti₃SiC₂. If the latter subject was a dead-end, the work on Zr₂AlC derived compositions led to the synthesis of several new quaternary MAX phases, some even including new elements in the MAX phases family (Sb and Bi), while the research on the Cr-Ti-Al-C system evidenced the possible reinforcement of oxidation resistance of MAX phases by the deliberate addition of Al-Cr alloys.
Understanding the behaviour of fission gas in nuclear fuel is critical to improving the simulation of fuel performance. Indeed, fission gases can be detrimental in different ways whether they accumulate in bubbles in the fuel or between the fuel pellets and the clad. This project aims at simulating two aspects of the interaction between dislocations and fission gases, particularly xenon. The first one is the change in the mechanical behaviour of UO$_2$ caused by individual xenon atoms or small bubbles slowing and pinning dislocations. The other facet is the enhanced mobility of xenon caused by the strain fields surrounding the dislocations cores, and its effect on long-range xenon diffusion. Both aspects are also of significant interest for the description of the formation of the high-burnup structure, which involves both dislocations piling up and gas bubbles but is not yet understood at the atomistic scale. This project is part of the Consortium for Advanced Simulation of Light Water Reactors (CASL), which is focused on fuel performance simulation.

Fundamental Properties of Thoria Based Mixed Oxides

Researchers: Dr. Navaratnarajah Kuganathan
Supervisor: Prof. Robin Grimes
Sponsors: EPSRC

Thoria (ThO$_2$) has attracted a great deal of interest as the next generation nuclear reactor fuel due to its higher abundance, higher thermal conductivity, higher chemical stability, higher melting temperature, higher corrosion resistance and lower thermal expansion compared to uranium based fuels. During operation in reactor, uranium, thorium and plutonium atoms undergo fission producing a variety of fission products such as Xe, Kr, Cs, Ba, Br and I. Fission product inert gases (Xe and Kr), produced during fission in nuclear fuels, are estimated to be 15% of the total fission yield but are insoluble in the fuel matrix. These inert gases are initially accommodated at defect sites in the fuel lattice and are known to have a deleterious effect on fuel performance, particularly at high levels of burn-up.

Using first-principles density functional theory (DFT), we calculate perfect lattice properties of ThO$_2$, the energetics of defects and the interaction of Xe and Kr atoms and clusters with the defects. This project aims to calculate the structures of atoms and clusters of noble gases with defective ThO$_2$ to provide soundly based models for the experimentalist to use in the interpretation of experimental data. Quantum mechanical calculations, in addition to giving structural information, have the added bonus of elucidating electronic structure and properties. Our simulation results are validated with experiments carried out by our collaborators at Bhabha Atomic Research Centre (BARC) in India. This project is funded by EPSRC as part of the INDO-UK project.

ZrC and MAX Phases for Future Fission Environments

Researchers: Dr. Eugenio Zapata-Solvas
Supervisor: Prof. Bill Lee
Sponsors: EPSRC CAFFE Consortium

The aim of this project is to develop new Zr-based carbides, including Zr-based MAX phases, for coating Zr-alloys cladding, providing accident tolerance in fission reactors of future nuclear power plants. Powders are synthesised and densified by hot press and spark plasma
sintering and microstructures characterised by XRD, SEM and TEM. Ceramics will be supplied to Manchester and Cambridge universities for irradiation and irradiation plus corrosion studies among others. A second stage of the project includes the study of oxidation, corrosion under water pressurized reactor conditions, mechanical and thermal properties of the developed Zr-based carbides. Further areas of interest include the mechanical reinforcement and study of the plasticity of ultra-high temperature ceramics and flash sintering of ceramics.

PhD/EngD Projects

Atomic Scale Modelling of Factors Affecting Hydrogen Pickup in Zirconium Based Fuel Cladding

Researcher: Benjamin Bell
Supervisors: Dr Mark Wenman and Prof Robin Grimes
Sponsor: Rolls-Royce

Zirconium based alloys have seen increasing usage as nuclear fuel cladding materials in water-cooled reactors due to the extremely low capture cross-section for thermal neutrons exhibited by zirconium. This allows a lower enrichment of uranium-235 to be used in the fuel than would be required by other cladding materials, such as stainless steel, reducing the cost of production and the proliferation risk associated with the fuel. During in-reactor life, zirconium alloys absorb hydrogen from the coolant water, leading to the precipitation of hydrides in the cladding matrix. Zirconium hydrides are very brittle, and cause a decrease in the ductility of the cladding, increasing the risk of brittle failure. This is of particular concern in the case of reactor transients or accidents that result in environmental changes within the reactor. The result is that the amount of hydrogen that can be allowed to dissolve into the cladding material must be limited to a safe level, thus an upper limit is imposed on the in-reactor lifetime of zirconium based alloys; an issue for potential high burn-up applications.

Various alloys have been developed in an attempt to mitigate the problem of hydrogen pick-up, however the mechanism by which the pick-up occurs is not well understood and so new cladding materials can only be developed through a trial-and-error approach. This project uses ab initio quantum mechanical simulation, using density functional theory (DFT), to help further the understanding of the pick-up mechanism by investigating the behaviour of hydrogen within the cladding material. More specifically, this project focuses on the zirconium oxide (ZrO$_2$) layer that forms on the outer surface of the cladding (in contact with coolant water) due to in-reactor corrosion, investigating the effect of stress and alloying elements on the behaviour of hydrogen within oxide phases.

Chloride-Induced Transgranular Stress Corrosion Cracking of Austenitic Stainless Steel 304L

Researcher: Giuseppe Scatigno
Supervisors: Dr Mark Wenman, Dr Finn Giuliani and Prof Mary Ryan
Sponsor: EPSRC

Stress corrosion cracking of austenitic stainless steels has been a known failure mode for more than 50 years and it continues to be a major cause of concern in the nuclear industry. This work focuses on the effect of cold work on the propagation of chloride-induced transgranular crack growth in 304 L and 316 L type stainless steel for dry-cask storage of spent nuclear fuel.

Several characterisation techniques, such as focused ion beam, secondary ion mass spectroscopy, scanning electron microscopy and
electron backscatter diffraction were used. Their purpose is the 3D reconstruction of the crack itself, to obtain a full elemental and microstructural map at a sub-micron resolution. The maps will be used to obtain a model with the final objective of producing a crack growth model (based on a finite element framework) capable of predicting growth rates under a range of cold work and chloride conditions.

**Atomistic Modelling of Alloys and Intermetallic Compounds for Nuclear Applications.**

**Researcher:** Patrick Burr  
**Supervisors:** Prof Robin Grimes and Dr Mark Wenman  
**Sponsors:** ANSTO and EPSRC DTA

Zirconium alloys play a crucial role in water cooled nuclear power plants: their integrity helps ensure that the nuclear fuel is separated from the biosphere. Similarly, beryllium is the main candidates for selected components in fusion reactors.

The projects investigates, by means of atomic scale modelling, the role of intermetallic second phase particles found in zirconium alloys, and in particular how they interact with hydrogen, which is one of the main causes of alloy failure. The ultimate aim of the project is to provide valuable information for the development of new improved Zr alloys, with higher safety margins, and able to sustain longer nuclear fuel cycles (which in turn would reduce the cost of electricity production). Concurrently, the project also investigates the effects of intermetallic phases and alloying addition in metallic beryllium, with particular interest to partitioning and retention of hydrogen isotopes, helium atoms and other impurities relevant to fusion applications.

**Diffusion Properties and Processing of Non-Stoichiometric Zirconium Carbide**

**Researcher:** Edoardo Giorgi  
**Supervisors:** Prof Bill Lee and Prof Robin Grimes  
**Sponsor:** EPSRC

The high temperature properties of zirconium carbide are of great interest for nuclear fuel applications such as with the Tri-Structural Isotropic (TRISO) particles. As a group IV transition metal carbide ZrC exists over a wide sub-stoichiometric ratio over which its properties (such as thermoconductivity) vary. Within the life cycle of a TRISO particle the deposited sub-stoichiometric ZrC as a fission product barrier acquires carbon from the surrounding graphitic environment. It is hence important to evaluate whether this affects the effectiveness of ZrC at retaining the metallic fission products.

The research project includes a processing investigation looking into the Reactive Spark Plasma Sintering (RSPS) carbothermic route to rapidly manufacture non-stoichiometric ZrC monolithic samples. The main focus of the project is a combined computational and experimental study of the effect of non-stoichiometry on the diffusion properties of ZrC looking at defect clustering and diffusion mechanisms.

**Finite Element Modelling of Pellet Clad Interaction in Advanced Gas-Cooled Reactors**

**Researcher:** Thomas Haynes  
**Supervisors:** Dr Mark Wenman and Dr Catrin Davies  
**Sponsors:** EPSRC and EdF Energy

This project centres on improving the understanding of a number of areas of fuel performance though local continuum FE, non-local continuum FE and bond-based peridynamics. It considers the role of operating strategy upon clad bore crack growth; the formation, development, properties and effect of hairline ‘ladder cracks’ in a sliver of fuel bonded to the clad-
Heterogeneous Deformation in Zirconium Alloys

Researcher: Vivian Tong
Supervisor: Dr Ben Britton
Sponsors: Rolls-Royce

Zirconium is used in the nuclear industry in thin walled tubes and is therefore of practical importance for engineering applications. It has anisotropic mechanical properties leading to strong crystallographic textures, twinning, and heterogeneous plastic strains during forming operations such as sheet rolling and tube reducing.

Micromechanical modelling cannot at present accurately predict how plastic strain concentrations and cracks develop, or which deformation modes are favourable in HCP materials. Therefore, high quality experimental characterisation is needed to determine how different types of deformation and heat treatments affect the grain growth, texture, and mechanical properties, and how these are related to the deformation mechanisms (slip, twinning, recrystallisation, etc.). In particular, this project aims to characterise twinning behaviour of zirconium, focussing on its dependence on strain rate, grain size, geometrically necessary dislocation density, and local texture.

Electron backscatter diffraction (EBSD) is being used to characterise the micro and macro texture, grain size, and twinning fraction. Digital image correlation will be used to measure macroscopic strain and strain rate. High resolution EBSD (HR-EBSD) will be used to characterise microscopic elastic and plastic strain during deformation. The accuracy and limitations of HR-EBSD are also explored to validate the technique.

Inverse Numerical Method for Calculating the Temperature Dependent Thermal Conductivity of Nuclear Materials

Researcher: Tsveti Pavlov
Supervisors: Prof Robin Grimes, Dr Mark Wenman, and Dr Paul Van Uffelen (Institute for Transuranium Elements)
Sponsors: European Commission and Imperial College London

In the general context of nuclear fuel safety and after the accident in Fukushima, investigating the behaviour of nuclear materials under extreme conditions is of prime importance for the analysis of the reactor operational limits. Relevant experiments in an experimental reactor are time consuming, expensive and their analysis is challenging because of limited instrumentation possibilities.

Thus, this project will focus on the development of a method for the calculation of thermophysical properties such as thermal conductivity. The technique will be validated and applied to commercial and novel fuel materials at high temperatures. The proposed method uses experimental thermograms obtained via laser-flash heating of a disc-shaped sample in combination with finite element analysis and parameter optimization. The experimental part involves heating samples to a steady state temperature via two lasers (on the back and front sides) and subsequently subjecting the front sample surface to a short laser pulse, resulting in a temperature transient (thermogram). A thermal camera records the temperature transients at 30 points along the radius on the rear surface of the sample. An optimization technique known as the Levenberg-Marquardt method is applied, whereby 5 parameters (emissivity,
heat transfer coefficient and three constants $k$, $b$, $c$, representing the thermal conductivity as a function of radius $\lambda = k + b \times r + c \times r^2$ are altered and used as inputs in finite element software (FlexPDE). The parameters are changed until the least square difference between the numerical and experimental thermograms reaches a minimum.

**Deformation Modelling of Hard-facing Alloys**  
Researcher: Bartosz Barzdajin  
Supervisors: David Stewart Prof Fionn Dunne and Tony Paxton  
Sponsors: Rolls-Royce

The goal of this project is to develop hierarchical theoretical framework that will further the understanding of phenomena behind galling and wear resistance of hard facing materials, particularly duplex stainless steel RR2450 and establish a link between some key characteristics like chemical composition and microstructure with the performance in this scope. We hope that this research will result in guidelines for chemists and process engineers who are working on improving existing alloys and development of new ones. Galling and wear is associated with local elastic and plastic deformations that define stress states that may result in formation of cracks and material separation as a consequence of the crack growth. We expect that the biggest impact on galling resistance will be due to microstructure i.e. phase fractions, texture and morphology.

To study the influence of this type of characteristics, the most suitable method is crystal plasticity finite element (CPFE) method that will be used to perform systematic studies on galling resistance as a function of phase fractions in duplex systems. Our CPFE models will use a physically based slip and hardening rule, allowing it to be informed by quantum mechanical methods, such as density functional theory (DFT) or tight-binding (TB), through evaluation of key CPFE parameters extending its predictive value by taking influence of chemistry into account.

**Simulation of Materials for Nuclear Fusion Reactors**  
Researcher: Matthew Jackson  
Supervisors: Prof Robin Grimes and Dr Sergei Dudarev  
Sponsors: Culham Centre for Fusion Energy

Beryllium and its compounds such as Be$_{12}$Ti and Be$_{12}$V are under investigation for use as a first wall material and neutron multiplier for tritium breeding in nuclear fusion reactors: applications in which they will be subjected to extreme temperatures and radiation. Density functional theory and empirical potentials in conjunction with molecular dynamics have been used to investigate the processes occurring during radiation damage in these materials on an atomic level, calculating key parameters such as the threshold displacement energy and defect formation enthalpies that can be fed into models to predict the long term behaviour of these materials.

**Understanding Crystallographic Texture Evolution in Two-Phase (hcp/bcc) Alloys**  
Researcher: Simon Wyatt  
Supervisor: Dr Ben Britton  
Sponsors: Rolls-Royce

Metals are widely used for load-bearing applications in complex environments. Their properties are dependent on the underlying behaviour of the material microstructure, which is naturally anisotropic due to the discreet and crystallographic nature of slip and anisotropic elastic properties. This project focuses on developing efficient methods of modelling the evolution of crystallographic texture in two-phase alloys.
using efficient crystal plasticity based upon the fast Fourier transform. Working with Rolls-Royce plc, materials will be characterised using HR-EBSD to determine textures which will further stimulate the computational work.

**Discrete Dislocation Dynamics coupled with Discrete Solute Diffusion to Model the Effect of Hydrogen in Steel**
Researcher: William White
Supervisor: Dr Ben Britton
Sponsors: EPSRC CDT and Rolls-Royce

Plastic deformation in metals is due to the motion of mobile dislocations subject to shear stresses in excess of a critical value. At particular strain rates and temperatures mobile solutes form atmospheres at the base of dislocations pinning dislocation motion. This results in an inverse strain response, jerky plastic flow and decreased ductility. In the worst case, ductility is reduced significantly and brittle fracture may occur. We attempt to understand the interaction and effects of mobile dislocations and solutes in metals using discrete dislocation dynamics coupled with an appropriate discrete solute diffusion model. In the first instance our model will be developed to describe carbon solutes in saturated iron. A generalized model will be developed so as to give insight to the deleterious effects of hydrogen in industrial steels.

**Atomic-scale Simulation of Mixed Oxide and Conventional Nuclear Fuel**
Researcher: Conor Galvin
Supervisor: Prof Robin Grimes
Sponsors: Los Alamos National Laboratory and CASL

Mixed actinide oxides have been used as nuclear fuel material, furthermore conventional UO₂ fuel effectively becomes a mixed oxide during reactor operation due to transmutation and decay. Moreover, there is growing interest in ThO₂ mixed oxide fuel due to the beneficial
features of ThO$_2$. As a result understanding the behaviour of mixed oxides is of considerable importance.

Atomic scale simulations based on empirical potentials are employed to investigate the behaviour of these fuels. It is difficult to obtain experimental data at higher temperatures for mixed oxides; therefore these simulations provide important insight for systems that are still not sufficiently well understood. Another consequence of transmutation and decay in nuclear fuel is the presence fission products (among them rare gases such as Xe, Kr or He). Micro-structural change arises from the diffusion of fission gasses through a lattice causing more defects or the formation of bubbles of trapped fission gasses in voids created by radiation damage. Since practically all crystals contain dislocations any diffusion may contain a dislocation-mediated contribution. Atomic simulations are also used to investigate the influence of dislocations in UO$_2$ (⟨100⟩, ⟨110⟩, ⟨111⟩ ⟨110⟩ edge dislocations and the screw ⟨110⟩ dislocation) on He diffusion in the temperature range 2300 - 3000 K.

**Atomistic Simulation of Fission Products in Zirconia using DFT**

Researcher: Alexandros Kenich
Supervisor: Prof Robin Grimes
Sponsors: EPSRC CDT and Westinghouse

The thin zirconia layer which decorates the interior surface of all zirconium-based fuel claddings is the last, and often only barrier between corrosive fission products and the bulk metal. It is very difficult to conduct experiments to analyse this system as it is obscured from view during operation, active due to high irradiation, and has phases which are stress-stabilised. This presents a perfect opportunity to utilise the latest atomistic simulation methods to conduct defect analyses in zirconia with fission products such as iodine and caesium, thereby guiding the work of experimentalists and paving the way to improvements in fuel pin performance.
Reactor Operation, Design and Monitoring

The Reactor Operation, Design and Monitoring theme has built on the rapid expansion of the previous year. The thermal hydraulics group has been fortunate to recruit Dr Vittorio Badalassi from Rolls-Royce (Civil Nuclear) on a prestigious Royal Society Industrial Fellowship. With a background in two phase flows, Dr Badalassi will add valuable expertise to the group.

The thermal hydraulics (TH) group, led by Simon Walker, continues its work in the area of flow modelling in naval and civil PWRs, supported by Rolls-Royce (Civil and Marine). The team of investigators (Simon Walker, Mike Bluck, Vittorio Badalassi, Raad Issa and Geoff Hewitt) supervise two PDRAs and six PhD students on a range of projects focusing on critical reactor systems: boiling and critical heat flux are studied at a range of length scales, leading to the development of models for incorporation into both CFD and systems codes. Natural circulation is studied via computational fluid dynamics (CFD) and experimental investigation. Such phenomena are extremely difficult to predict reliably. The group supports this work via the EPSRC India 1 & 2 collaborations, where detailed measurements are carried out in sophisticated facilities unavailable in the UK. As part of this programme, an Indian PDRA is currently on secondment at Imperial from BARC in India. The group are currently in the process of bidding for the next tranche (EPSRC-India 3) of funding in this area. The coupling of CFD and systems codes is a key aspect of the work and two PhD students (sponsored by R-R and CD-Adapco) are involved. The TH group also continues a programme of work in the area of probabilistic safety assessment (PSA), with 2 PhD/EngD students sponsored by Corporate Risk Associates. A key aim of this work is to incorporate uncertainties in deterministic calculations (eg CFD, etc) into PSA.

Work in the area of nuclear fusion has expanded with support from CCFE. Two PhD students are studying aspects of fusion blanket design, particularly those involving liquid metal coolant and/or breeder configurations. The first of these projects involves the coupling of computational magnetohydrodynamics (CMHD) with systems codes similar in kind to those used in the study of thermal hydraulics in LWRs. The second project involves the development of novel isogeometric methods for CMHD, to address the particularly challenging boundary layer issues that arise in such flows.

In radiation transport and reactor physics, led by Matt Eaton, work continues on the development of the RADIANT deterministic radiation transport code. With a team of nine students and two PDRAs, funded by Rolls-Royce, AWE, and EdF, this work involves benchmarking, validation and verification; parallelization and the development of efficient numerical schemes and multiphysics coupling. In particular, novel isogeometric methods have shown great potential for a step improvement in efficiency. In addition, uncertainty quantification (UQ) is an aspect of simulation of growing in importance due to its obvious implications for safety. The group is an international leader in this area, employing intrusive and non-intrusive polynomial chaos in the quantification of uncertainty in a range of radiation transport problems. The
The group organized the 2013 SARNET seminar on Severe Accidents, attended by many international experts.

In non-destructive evaluation (NDE) – led by Peter Cawley and Mike Lowe - work on the modelling of ultrasonic response from rough defects has continued, supported by Rolls-Royce (Marine). In 2014, the NDE Centre for Doctoral Training has been renewed for a further 5 years, ensuring the future of this internationally respected group.

**PDRA Projects**

**CFD Study Of The Flow In Crud-coated Nuclear Rod Bundles**  
*Researcher: Dr Nicolas Cinosi*  
*Supervisor: Dr Simon Walker*  
*Sponsor: Rolls-Royce*

Crud is the name commonly given to the result of metal oxides precipitation and deposition on the fuel cladding in nuclear water reactors such as pressurized water reactors (PWR). These rough deposits have been proved to have various consequences on reactor operation, but no results are available concerning the potential hydraulic effects of crud deposits. It is expected that the presence of crud-coated rods induces a modification of the flow distribution, reducing the coolant velocity and the mass flow rate in the most affected sub-channels. As a consequence the efficiency of the fuel-to-coolant heat transfer is reduced and the coolant along the fuel assembly is subject to an increase of temperature.

**PhD/EngD Projects**

**Remote Assessment Technologies for Alpha-contaminated Material**  
*Researcher: Ben Pearce*  
*Supervisors: Prof Susan Parry and Prof Kym Jarvis*  
*Sponsors: NDA*

A significant proportion of the materials in the UK's radioactive waste inventory, particularly those arising from reprocessing activity, are contaminated with alpha-emitting radio-nuclides. Many of these materials represent a significant characterisation challenge during the decommissioning of legacy facilities as methods typically employed, such as gamma spectrometry, are disputed due to the typically low energy or low intensity emissions of such radionuclides. This leads to difficulty in the quantification, localisation and assessment of alpha-emitting contaminants.

This project is focused on the development and testing of a new device, an alpha detector sensitive to brief, weak flashes of UV light emitted when alpha particles interact with air, for use in the characterisation and detection of such materials. The use of secondary light emission means that detection can be achieved far beyond the small range of alpha particles (<3cm). It has been demonstrated that quantification of contaminants can be achieved at distance, and even through transparent media, with an appropriate traceable radiometric calibration. Finally it has also been demonstrated that through process automation the detector lends itself to the rapid, accurate assessment of alpha-contaminated materials into waste categories (e.g. LLW/ILW) – potentially representing a significant cost reduction compared to methods currently employed.
Nuclear Thermal Hydraulic Analysis using Coupled CFD and Systems Codes
Researcher: Antonello Palazzi
Supervisor: Dr Mike Bluck
Sponsor: EPSRC and CD-adapco

Nuclear reactors comprise a complex network of pipes, heat exchangers pumps, valves and vessels. Understanding the thermal hydraulic performance of this system is important, especially as regards studying its response under fault conditions. “Systems codes” are the long-standing workhorses for such analysis, and they do a very good job in predicting the behaviour. However, modern computational fluid dynamics (CFD) techniques are needed to predict flows in complex geometries in greater detail, and in particular under the conditions that will be experienced during natural circulation in modern “passive” reactor designs. However, these codes are far too expensive to be applied to the whole system. The thrust of this project is to generate modelling which couples the two classes of code, using the more capable but expensive CFD code where it is needed, but continuing to use the much simpler and cheaper “systems code” representation where it is adequate. In particular, this project involves the STAR-CCM+ code from Computational Dynamics Limited also known as CD-adapco, and the reactor systems code RELAP. STAR-CCM+ is one of the two main CFD codes in use around the world, and it is widely used for nuclear reactor analyses. The RELAP code is by far the most widely used systems code. It originates with the United States Nuclear Regulatory Commission, and is in use for reactor analysis all around the world. This project, sponsored by CD-adapco, will develop and demonstrate the coupling of the codes, and their application to nuclear reactor thermal hydraulics.

Computational Analysis of Buoyancy Driven Flow
Researcher: Frederic Sebilleau
Supervisor: Dr Raad Issa and Dr Simon Walker
Sponsor: Rolls-Royce

With the current thrust to rely as much as possible on natural forces for cooling during accidents, there is a growing need to be able to understand and predict reliably flows caused by temperature and density differences. This need is quite general, with applications in a number of parts of the plant, and under a number of different circumstances. The project aims at predicting reliably complex natural circulation flows.

Fundamental Microscopic Multi-Physics Modelling of Boiling
Researcher: Giovanni Giustini
Supervisor: Dr Simon Walker
Sponsor: Rolls-Royce Civil Nuclear

Heat transfer enhancement by boiling is commonly employed in several industrial applications. From that point of view, a particularly effective boiling mode is the nucleate boiling regime, in which bubbles nucleate and grow (and eventually detach and are carried away by the flow) at certain hot spots that are present at a solid wall. The hot spots hosting the nucleation of bubbles are cavities in which a small quantity of a non-condensable gas is trapped. Such a non-condensable seed is the bubble embryo that, under favourable circumstances, will eventually grow to reach the dimensions of an actual vapour bubble. A key to understand the boiling process, and thus build predictive models of it, is to understand the nucleation mechanism. Attempts at this have been carried out in a few simplified cases, making use of geometrically idealized cavities. Such an approximation is rather crude, since it doesn’t take into account the realistic structure of the
surfaces hosting nucleation, and, in the case of forced convection boiling, the related micro-scale flow pattern. Micro-scale Computational Fluid Dynamics (CFD) simulations of the interaction between the near-wall flow and the nucleation process are believed capable of giving a privileged point of view on the boiling phenomenon, representing a kind of “virtual experiment” that can provide the basis for the development of predictive models of nucleation.

The aim of this project is to develop an understanding of nucleation in the case of forced convection boiling, making use of CFD simulations of the microscopic processes that take place at rough surfaces. Based on the knowledge of the boiling phenomenon acquired in this way, improved models of boiling will be proposed. Micro-scale simulations of the interaction of nucleating bubbles and near-wall fluid flow require taking into account peculiar mechanisms in addition to the standard CFD practice. For example, the evolution of an interface and of the bubble contact angles must be captured, while some additional physics must be as well taken into account, such as capillary forces, since they considerably influence the dynamic of the studied phenomenon. In addition, even though the physics is the same as the one described by the universally exploited Navier-Stokes fluid motion equations, the direct simulation of flow in the vicinity of a rough surface is a novel research area, and the know-how acquired during the advancement of research on that topic has to be transferred to the present area of investigation.

Single-Phase Flow in Non-Circular Ducts

Researcher: David Harland
Supervisor: Dr Simon Walker
Sponsor: Rolls-Royce

Thermal-hydraulics in nuclear reactor channels has long been the subject of detailed study, partly because of the great importance of having reliable core heat evacuation systems in order to prevent Critical Heat Flux (CHF). In a Pressurised Water Reactor (PWR) it is important to prevent even localised nucleate boiling wherever possible, in order to maintain high heat transfer coefficients and prevent sudden temperature spikes. In non-circular channels, relatively small secondary flow components carry heat away from the corners, smearing temperature profiles to help prevent hot-spots. Detailed knowledge of the velocity fields is therefore essential in understanding heat-transfer within these channels. For channels of smaller dimensions, even small blockages can cause important modification of the flow and heat-transfer characteristics. Small bubbles attached to channel sides are therefore important to envisage and allow for, even if the flow in general remains liquid. Small blockages are therefore important to investigate as part of the building up a broader picture of the effects of unwanted phase change within nuclear reactors. It is also desirable to understand the mechanisms governing detachment and subsequent carrying away of bubbles by the bulk flow. This has already been the subject of work in the civil sphere, but with less focus on flow perturbation due to relatively large channel dimensions. Single phase flows in rectangular channels actually present surprisingly complex problems for modelling, because of their re-entrant corner regions. The Boussinesq assumption of isotropic turbulent diffusivity breaks down in the corners.

The more sophisticated turbulence models - such as non-linear KE, Reynolds Stress Trans-
port (RST) or Large Eddy Simulation (LES) models - have to be used to predict these corner zones where recirculation and corner vortices occur. In order to improve the degree of confidence with which these models can be used, it is essential to conduct experimental measurements in order to ensure that the assumptions inherent in these models are well-founded. It is possible to carry out very accurate measurements within experimental ducts by using transparent panels through which lasers can penetrate. Particle Tracking Velocimetry (PTV) or Particle Image Velocimetry (PIV) are modern measurement techniques that present considerable advantages over the more invasive Pitot Tube and Hot-wire Anemometry methods used in the past. The resolution in space and time that can be achieved is more than sufficient to capture the degree of detail needed to validate numerical simulations.

**Advanced Component-scale CFD Modelling of Nucleate Boiling**

*Researcher: Ronak Thakrar*
*Supervisor: Dr Simon Walker*
*Sponsor: Rolls-Royce*

In a nuclear reactor, uncontrolled boiling can lead to the hazardous condition often referred to as the “critical heat flux” (or CHF) which can result in the fuel clad no longer being wetted and the integrity of the fuel being compromised; this condition defines the upper limit for safe reactor operation and therefore there is an essential requirement for the engineering capability to predict the onset of this condition (and hence to accurately predict the behaviour of boiling flows). Today’s state-of-the-art in boiling modelling in CFD embodies a significant degree of empiricism by way of using correlations to define the overwhelming majority of closure terms in the modelling formulation. In addition to this, the formulation is itself unrepresentative of the many interacting heat transfer mechanisms at work during the boiling process. These factors impose an upper bound on the predictive capability (and range of application) of the CFD code, which limits its representation. CFD packages are capable of providing a detailed three-dimensional model of flow yet this comes at a great expense in the form of computational time.

Therefore there is a growing interest in the technique of coupling of the two modelling systems; where a systems code can be used where it is adequate with the more detailed CFD being used where necessary. Although work has been done on this subject for a number of years it is still an embryonic aspect of computational physics and there is vast room for improvement and refining.
usefulness as an engineering tool. Whilst some empiricism will inevitably tend to remain due to the multifaceted nature of the boiling phenomenon, incorporating more mechanistically-based (or semi-constitutive) models to describe these closure terms and/or to describe the various heat transfer mechanisms should permit improvements to today’s CFD capability, and this is an endeavour that has been gaining momentum in the academic community for some time.

This project involves the identification, implementation and subsequent demonstration of such improvements to the current state-of-the-art in “component-scale” modelling of boiling and CHF prediction in CFD codes with an emphasis on applications in nuclear reactors (under conditions of high-pressure turbulent flow boiling in non-circular geometries). The CFD code to be applied (and augmented) during this research is CD-adapco’s STAR-CCM+ code which represents today’s state-of-the-art in commercial CFD.

**Determination of the Parameter Space to Allow for a Passively Safe Low Pressure Reactor**

Researcher: Azrudi Mustapha  
Supervisors: Dr Simon Walker and Prof Geoff Hewitt  
Sponsor: Malaysian Government

A low pressure reactor design is being investigated to meet safety challenges as occurred in the Fukushima accident. The primary circulation is through wholly passive means including natural circulation and independence from the necessity of having high pressure injection safety systems. A pool type boiling water reactor is envisioned to meet these challenges. Unfortunately this will result in low thermal efficiencies and higher cost per unit electricity produced.

**Modelling of Boiling in Cross-Flow over Tube-Bundle**

Researcher: Golam Majumder  
Supervisors: Dr Simon Walker and Prof Geoff Hewitt  
Sponsor: Bangabondu Fellowship of Science and ICT (Ministry of Science and Technology (Republic of Bangladesh))

Cross-flow boiling in tube bundle, which is commonly found in many industrial applications such as, horizontal steam generator, kettle reboiler, etc. presents significant complexity due to the local two-phase flow conditions in the presence of heat transfer. Their optimum operational parameters and performance depend essentially on the shell-side two-phase flow structures that ultimately influence the overall heat transfer and the total pressure drop of the system. Therefore, this research project aims to gain a position of understanding of cross flow boiling in tube bundles in general and that in a VVER (PGV) type horizontal steam generators in particular: taking into consideration the local flow phenomena. Experimental and analytical literature on cross flow boiling related to the relevant geometries will be considered. Efforts will be made to become familiar with computational methods for multiphase flow and in particular to produce a model of cross flow boiling over tubes/tube-bundles which might be ultimately used within an overall model for the VVER steam generator.

**Uncertainty in Probabilistic Safety Analysis**

Researcher: Ashraf El-Shanawany  
Supervisor: Dr Simon Walker  
Sponsor: EPSRC, Corporate Risk Associates

This work aims to identify and quantify sources of uncertainty in Probabilistic Safety Analysis, and to provide a methodology for incorporating such identified sources of uncertainty into PSA analyses. A significant example of a source of uncertainty is the success criteria which determine whether a system fulfils its required
function. Success criteria for safety systems are determined by a range of methods including experimental validation and phenomenological modelling, which often include some estimation of the associated uncertainties. However, current PSA methods use strictly conservative estimates, based on the supporting analysis, and this is reflected in single deterministic-style fault trees.

Measuring Crack Initiation and Growth in the Presence of Large Strains using the Potential Drop Technique

Researcher: Keith Tarnowski
Supervisor: Dr Catrin Davies
Sponsor: EdF Energy

Accurate laboratory measurements of crack initiation and growth are of vital importance for characterising material behaviour for use in the residual life assessment of structural components. The Potential Drop (PD) technique is one of the most common methods of performing these measurements, but such measurements are also sensitive to large inelastic strains which are often erroneously interpreted as crack growth. Despite the maturity of the PD technique, the extent of these errors is not fully understood and the most appropriate method of suppressing them is unknown.

I have developed a sequentially coupled structural-electrical FE based tool capable of predicting the influence of strain on PD measurements. Using this tool in conjunction with experimental measurements, performed using a novel low frequency alternating current potential drop system, I have demonstrated that errors due to the presence of inelastic strains when measuring crack extension can be extremely large. The standard approaches of measuring crack initiation and growth during fracture toughness and creep crack growth testing of ductile materials are not fit-for-purpose. Alternative methods of interpreting the test data have been proposed which greatly improve the accuracy of these laboratory measurements.

A Coupled Systems Code – CMHD Solver for Fusion Blanket Design

Researcher: Michael Wolfendale
Supervisors: Dr Mike Bluck and Dr Ben Chuilon
Sponsors: Culham Centre for Fusion Energy and AMEC

Fusion blankets are required to operate in a harsh environment under the influence of a number of interdependent and synergistic physical phenomena, working across several length scales. For magnetic confinement reactor designs using a conducting fluid as coolant/breeder, the difficulties in flow modelling are challenging due to interactions with the large magnetic field. Blankets comprise a number of common features such as ducts, manifolds and connections. As such, blankets are an ideal candidate for the application of a code coupling methodology, with a thermal hydraulic systems code modelling portions of the blanket such as the ducts, amenable to 1D analysis, and CFD providing detail where necessary. It is the aim of this study to develop such a modelling approach, enabling extensive thermal hydraulic simulation of the blanket and associated systems and accounting for MHD effects in a computationally efficient manner that lends itself to the design process.

Improvements in Ultrasonic Inspection Techniques for High-Density Polyethylene Pipe Joints

Researcher: Jack Egerton
Supervisors: Prof Mike Lowe, Dr Peter Huthwaite, Dr Tariq Dawood and Dr Harshad Halai
Sponsors: EDF Energy

This project aims to improve ultrasonic non-destructive evaluation (NDE) of welds in high-
density polyethylene (HPDE) pipes, which EDF Energy is currently using in an increasing number of their existing and planned nuclear power stations to replace cast iron pipework that is susceptible to high levels of corrosion and other forms of degradation and fouling. In contrast, HDPE is not subject to such degradation. Ultrasonic inspection is of great importance in this area as HDPE pipe welds can sometimes become contaminated with defects during the welding process. The welds can also be produced under suboptimal conditions, leading to areas where the pipe ends have not correctly fused together. These defects and others considered can reduce the strength of the weld and therefore provide unwanted uncertainty in the operational lifetime of the pipe, which is not acceptable in the nuclear sector where safety is of primary concern. A major focus of this project is on simulation of ultrasound produced by ultrasonic transducers in NDE of the pipe welds so that experimental data can be better understood and supported by the findings. Coupled with this, current work involves the accurate determination of phase velocity and attenuation of HDPE over a range of frequencies, temperatures, and other parameters relevant to ultrasonic NDE. These data will be used within the simulations to ensure accuracy and reliability.

**Finite Element Methods for MHD Modelling with Application to Fusion Blankets**

*Researcher: Ji Soo Ahn*
*Supervisor: Dr Mike Bluck*
*Sponsor: Imperial College PhD Scholarship*

Finite element methods for Magneto Hydro-Dynamic (MHD) modelling are being applied to fusion blanket. Developing an accurate and efficient numerical solver for MHD is desired in fusion engineering because of the limitations of testing facilities. The boundary layers near the Hartmann walls and side walls can have significant impact on flow behaviour and heat transfer capabilities in the presence of a strong magnetic field. Analysing the flow behaviour in these layers is thus crucial when designing the fusion blanket. This process can be costly because the smallest thickness of the layer is in the order of Ha-1 and the Hartmann number (Ha) is often greater than 10^4 under fusion conditions.

**Thermohydraulics of DRACS Passive Safety System in Fluoride High-Temperature Nuclear Reactor**

*Researcher: Niccolo Le Brun*
*Supervisors: Dr Christos Markides and Prof Geoff Hewitt*
*Sponsor: Centre for Nuclear Engineering*

Molten salt reactors are currently being scrutinised as an alternative to conventional nuclear power plants because of their inherent safety. In a molten salt reactor passive safety systems, which do not rely on human intervention and/or supply of power, can be used to assure the removal of decay heat under various critical scenarios. DRACS (Direct Reactor Auxiliary Cooling System) is a passive safety system currently being considered as a viable design component. The aim of this project is to assess the feasibility of DRACS from a thermo-hydraulic point of view. In particular several aspects of molten salts as coolants need to be considered for a safe design. One of the most critical point which was recognised in the current study is the possible catastrophic freezing of the coolant during DRACS operation.
Integrated Ultrasonic Imaging for the Inspection of Near-Surface Defects in Safety-Critical Components

Researcher: Joshua Elliott
Supervisor: Prof Michael Lowe and Dr Peter Huthwaite
Sponsors: EPSRC, Rolls-Royce, and Amec Foster Wheeler

Ultrasound imaging using Full Matrix Capture (FMC) has brought a step change to the capabilities of phased arrays for the detection and characterisation of defects for Non-Destructive Evaluation (NDE). The majority of the algorithms used to process FMC data are based on the Beam-Forming (BF) approach. This has a theoretical resolution limit that has long been held as the best possible for imaging. However, recent research has shown that this theoretical resolution limit may be surpassed by extracting additional information in the data related to the interaction of waves between multiple scatterers. Such new approaches are known as Super Resolution (SR) algorithms. The images in Figure 1, constructed from experimental measurements, illustrate this potential very clearly.

The research project will develop these SR algorithms further and use them in ultrasonic defect sizing of safety critical components in the nuclear industry. The application focus will centre on the specific, but commonly arising, problem of the detection and characterisation of a defect at or adjacent to the back wall of a component. The goal is to overcome the challenge existing where the reflected signal from the back wall can overwhelm the reflections from the defect, which are often much smaller.
Spent Fuel and Waste Management

A central component of the public acceptance for a new nuclear build programme is a demonstrated ability to safely manage and dispose of high- and intermediate-level wastes from legacy nuclear operations. CNE research linked to work in the Decommissioning, Immobilisation and Storage solutions for NuClear wasTe InVentories (DISTING- TIVE) and RCUK/NDA spent fuel university consortia is contributing to the UKs radwaste management programmes by providing fundamental understanding of key issues including behaviour of spent AGR fuel in storage and disposal and development of novel wasteforms for some difficult wastes.

PDRA projects

Modelling the Thermal Output of High Dose Spent Absorbents used in the Clean-up of Fukushima

Researcher: Dr Michael Rushton
Supervisors: Prof Bill Lee and Dr Luc Vandeperre
Sponsors: EPSRC and Hitachi-GE Nuclear Energy

One of the main problems facing the remediation of the Fukushima Daiichi site is the treatment of the effluent cooling water from Units 1 – 3. Large volumes of water were injected into the reactor cores and the spent fuel pools which was subsequently treated in a series of sophisticated systems. These have left large quantities of highly contaminated adsorbents. These are termed High Dose Spent Adsorbents (HDSAs) and are currently stored on-site while a suitable method of long term disposal is developed. To this end, a low temperature processing route is being developed at Imperial College by which the HDSAs may be immobilised in a low melting point glass.

To support this activity, the current project aims to develop a model across finite element and microstructural length scales to help underpin the assessment of wasteform options, including the feasibility of using the decay heat to drive self vitrification. A radiolytic heat generation tool is being developed to calculate the temperature distributions in HDSA bearing wasteforms and to provide predictions for possible wasteform thermal/stress damage which will aid in the optimization of processing conditions. The project is in collaboration with the Immobilisation Science Laboratory at Sheffield University and with partners in Japan at the universities of Kyushu and Tohoku and at Hitachi-GE Nuclear Energy and is part of a recently-awarded EPSRC grant “Advanced Waste Management Strategies for High Dose Spent Absorbents”.

PhD/EngD Projects

Surface Analysis of Simulant UK High Level Waste Glass

Researcher: Nor Ezzaty Ahmad
Supervisors: Prof Bill Lee and Prof Julian Jones
Sponsors: Ministry of Higher Education Malaysia and Universiti Teknologi Malaysia

Immobilisation of high level radioactive waste (HLW) arising from reprocessing of spent nuclear fuel in a stable solid matrix is important to make it safe and minimise the hazard associated with its storage and to reduce the potential for escape of radionuclides. The most common method of immobilisation is to mix the waste materials with glass forming additives.
and then to vitrify them. An important criterion when dealing with the waste glass is its leaching resistance.

This project is characterising the OH-containing products and improving understanding of the corrosion mechanism of simulated waste glass in aqueous environments. The glass samples are UK Magnox and borosilicate blend glasses. The type of corrosion test used is the MCC-1 type test. As well as standard aqueous corrosion, deuterium (D) labelled solutions will be used to improve the detectability of the OH-containing layers using SIMS. Characterisation of the glass (and possibly some simulated HLW ceramic wasteforms) outer surfaces before and after corrosion test and depth profile is being investigated using XRD, SEM, TEM and SIMS.

Glass Composite Materials for Radioactive Waste Immobilisation

Researcher: Claudia Gasparrini
Supervisor: Prof Bill Lee
Sponsor: NNL industry case award (EPSRC) as part of the DISTINCTIVE consortium

A legacy of the UK's early research into nuclear reactors is a range of waste types including some from research and other reactors using fuels which are grouped under the title “exotic”. This project will examine some uranium carbide (UC) fuel from the Dounreay Fast Reactor programme for which no waste management decision has been made. This study is improving our understanding of the oxidation mechanism of carbide fuels, so enabling the development of a suitable oxide wasteform. Baseline work has been performed on an inert carbide material, zirconium carbide (ZrC) at Imperial College. Oxidation studies on UC are underway using the NNL (National Nuclear Laboratory) Preston Laboratory facility, UK. The study on both carbides involves characterisation of the initial material via XRD and SEM-EDX before oxidation experiments performed in air atmosphere using TGA/MS and furnaces. The oxidation products are then characterized via XRD, SEM-EDX, TEM, FIB-SIMS and BET. The in-situ monitoring of the oxidation mechanism of these carbides is performed in collaboration with the Laboratory for the Study of Matter in Environmental Conditions, Marcoule Institute for Separative Chemistry (ICSM), Marcoule, France. In addition, the understanding of the oxidation mechanism of mixed carbide fuels will be carried out on a surrogate of (U,Pu)C.

Glass Composite Materials for Radioactive Waste Immobilisation

Researcher: Claudia Gasparrini
Supervisor: Prof Bill Lee
Sponsor: NNL industry case award (EPSRC) as part of the DISTINCTIVE consortium

This project examines Glass Composite Materials (GCMs), which may contain several crystal phases, as wasteforms for some of the Difficult Intermediate level Wastes from the Legacy Ponds and Furloes at Sellafield. The GCMs have been made by Plasma Vitrification and Joule Heated In-Container Vitrification (JHICV). Standard characterisation techniques such as XRD, SEM and EDX are being used to determine the phases in GCMs before and after leach studies, in varying conditions. This will allow tracking of how crystalline components affect the durability and ultimately whether these GCMs can be safely disposed of.
olution to the planet’s growing energy demand. Research interests include the processing and characterisation of non-oxides for use in Generation IV nuclear reactors with main interest focused on the gas cooled fast reactor (GFR).

Several reference fuel concepts exist for the GFR one being Inert Matrix Fuels which consist of a dispersion of a non-oxide fissile phase (such as uranium carbide or uranium nitride) in a non-fissile material in the form of a pellet. Zirconium carbide and zirconium nitride are both promising candidates for use as the inert phase due to their high hardness, high melting point and good electrical and thermal conductivities. The carbothermal reduction-nitridation process was used to fabricate powders of ZrC and ZrN from ZrO$_2$ to firstly investigate this processing route to non-oxide fuel matrices but with the additional benefit that Zr could act as a simulant for uranium or plutonium, in addition the effects that impurities, such as oxygen and carbon and vacancy defects may have on the thermophysical properties of ZrN has been examined. Electrical and thermal conductivities of several zirconium carbonitrides have all exceeded those of commercially available ZrC and ZrN. Finally this project aims to examine the effects of proton irradiation on microstructural and thermophysical properties by collaboration with the Dalton Institute at the University of Manchester.

Processing and Microstructural Characterisation of UO$_2$-based Simulated Spent Nuclear Fuel Ceramics for the UK’s Advanced Gas-cooled Reactors

Researcher: Zoltan Hiezl
Supervisor: Prof Bill Lee
Sponsor: EPSRC and NDA.

As the planet’s demand for energy increases, one solution is to extend the number and the life time of current nuclear power plants and build new ones. As a result more radioactive nuclear waste will be generated making its management crucial. As part of the UK Spent Fuel Research Group, with members from Imperial, Cambridge University and Lancaster University, the work at Imperial involves fabricating UO$_2$ based simulant (SIMFuel) samples of spent Advanced Gas-cooled Reactor fuel.

The aim is to develop a ceramic that reproduces both core and rim microstructures of spent AGR fuels at various times after discharge from reactor (100, 1000, 10000 and 100000 years) containing nuclides predicted to be present. Initially the type and amount of fission products have been calculated using the FISPIN programme. These fission products are then grouped and their atomic percentages are calculated within the spent AGR fuel. SIMFuel samples have been made in which inactive surrogate metal oxides are mixed with depleted uranium dioxide before sintering at 1700°C for 5 hours in H$_2$ atmosphere then grinding and polishing the dense samples. Such samples are being characterised using optical microscopy, SEM, TEM and XRD and have been supplied to the other universities for further study. To date, SEM-EDX analysis revealed metallic and oxide precipitate (grey phase) formation. The main components of the metallic precipitates are Mo, Rh, Ru and Pd, whereas in the grey-phase Ba, Zr and Sr can be found. Several fission product surrogates are dissolved in the UO$_2$ matrix, such as Ce and Nd. These results are in good agreement with atomistic modelling using empirical pair potentials calculated by Michael Cooper in the Centre for Nuclear Engineering at Imperial. With the help of SIMFuel, different properties, such as: thermal conductivity, oxidation, dissolution,
radiation damage, leaching and corrosion can be studied without the danger of a high radiation field. These features would be extremely difficult and expensive to investigate using real spent nuclear fuel.

**Atomistic Simulation of UK Spent Nuclear Fuel**

**Researcher:** Michael Cooper  
**Supervisor:** Prof Robin Grimes  
**Sponsor:** NDA and EPSRC

The UK has had an active nuclear industry since the early 60s. As such it has accumulated a significant amount of nuclear waste primarily from Advanced Gas-cooled Reactors (AGRs). The planned closure of the Thermal Oxide Reprocessing Plant (THORP) at Sellafield means that the National Decommissioning Agency (NDA) is now interested in the option of deep geological disposal of unprocessed Spent Nuclear Fuel (SNF). This project aims to use an atomistic modelling approach to investigate the suitability of AGR-SNF for this form of disposal. In particular, the transferability of data from the well characterised Pressurised Water Reactor (PWR) SNF is of interest.

As part of the UK Spent Fuel Research Group, with members from Imperial College, Cambridge University and Lancaster University, this project aims to support their experimental work on UO$_2$ based simulant (SIMFuel) samples of AGR-SNF. The atomistic modelling techniques implemented include both static and dynamic simulation using empirically fitted potentials in addition to electronic structure calculations utilising Density Functional Theory (DFT). Problems that are suitable for investigation using such techniques include: He bubble resolution, fission product (FP) solution in UO$_2$ and secondary SNF phases, FP migration and the behaviour of dislocations. To date the partition energies for the transfer of FPs between UO$_2$ and the secondary phases, (Ba/Sr)ZrO$_3$ has been investigated by static energy minimisation using empirical pair potentials. The results of these calculations predict the segregation of large trivalent fission products (Sm$^{3+}$, Nd$^{3+}$, Pr$^{3+}$, and La$^{3+}$) into BaZrO$_3$ from stoichiometric UO$_2$. Furthermore, excess Cr$^{3+}$ in the fuel results in the partition of Y$^{3+}$, Dy$^{3+}$, and Gd$^{3+}$ as well as the above FPs. This work has been submitted to the Journal of Nuclear Materials. A similar approach is now being applied to CrUO$_4$. In parallel to the work on (Ba/Sr)ZrO$_3$ an investigation into the migration of uranium vacancies as a function of UO$_2$ stoichiometry is being undertaken. It is thought that this may underpin the method of Xe and Kr transport though SNF.

Finally, a new method of empirically modelling UO$_2$ that better reproduces the temperature dependence of various mechanical and thermodynamic properties is being studied. Understanding the effect of temperature on UO$_2$ is expected to be one of key differences between PWR-SNF and AGR-SNF.

**Low Melting Glass Wasteforms for Fukushima Absorbing Membranes**

**Researcher:** Dimitri Pletser  
**Supervisor:** Prof Bill Lee  
**Sponsor:** Hitachi-GE

The accident at Fukushima in Japan has led to the generation of enormous volumes of High Dose Spent Adsorbents (HDSA) which are currently stored on site but need to be immobilised in a solid wasteform and then permanently disposed of. The majority of the radionuclides in the HDSA are Cs and Sr with relatively short half-lives so that the level of performance of the wasteform is not as demanding as for vitrified High Level Waste. The process used to im-
mobilise the HDSA wastes will be simple, low cost and low temperature to avoid volatilisation of the Cs and Sr, and will produce a wasteform that does not form hydrogen over timescales of hundreds of years via radiolysis when in contact with water. This project is examining options using low-melting temperature borate and borosilicate glasses to vitrify the HDSA. This project will develop the processing route and characterise the wasteforms produced using inactive Cs and Sr radionuclides in the UK and active ones in Japan. Characterisation will be done using XRD, thermal methods, FTIR, NMR and electron microscopy techniques and long term stability examined using leach testing.

Virtual Reality in Nuclear Decommissioning
Researcher: Ben Nash
Supervisors: Prof Bill Lee and Trevor Chambers
Sponsors: AWE

The use of computer graphics has long been recognised as a valuable tool in visualising both design data and results from computational models. As a part of the CONSORT II research reactor decommissioning project a simulation has been created to aid in the training of staff undertaking the decommissioning of the reactor. A major outcome of the project will be a comparison of methods between using Virtual and Physical mock-ups. By overlaying the results from a particle transport simulation with engineering design data, a new tool for predicting and analysing occupational dose in real-time is currently being developed. The aim of creating these tools is to provide improved training and improved procedures for decommissioning to minimise a workers exposure to ionising radiation.

Nanoscale Investigation and Control of Radionuclides in Waste Management
Researcher: Eleonora Cali
Supervisors: Prof Mary Ryan, Dr Luc Vandeperre and Thomas Carey (NNL)
Sponsors: EPSRC DISTINCTIVE Consortium

The rapid development of the nuclear industry and the associated production of toxic waste, especially heavy metals, has created a large demand for the development of new novel materials. The treatment of contaminated water has been and continues to be a technical challenge as it is necessary to remove soluble metals and radionuclides for safe and efficient waste disposal. The Legacy Ponds and Silos (LP&S) at Sellafield Nuclear Site, built to develop an underwater radioactive waste temporary storage system, contains large amounts of waste and sludge from corroded fuel accumulated from
the 1950s, as well as solubilised metal ions, the removal of which is the target of this project. Recent years have seen the development of nanotechnologies that have the potential to be used for this application, as nanoparticles offer advantages as nanosensors in rapid and high-throughput detection methods. Specifically, magnetite (Fe$_3$O$_4$) nanoparticles (MNPs), given their capability of showing superparamagnetic behaviour if in a particular size range, could be a potential tool in separation technologies. Through the application of external magnetic fields, the nanoparticles could be used as adsorbents in water treatment to provide a convenient approach for separating and removing the water contaminants in the LP&S.

The aim of the project is to provide a device capable of selectively target radionuclides and heavy metals in solution and sequester them via specific or non-specific ligand agents, thereby tuning their magnetic properties for sensitive detection. In order for this system to be highly effective, the nanoparticles need to be stable in wastewater systems and, ideally, to regenerate and hence to be reusable for more than one cycle. As last goal, in collaboration with Loughborough University (Laura Mayne, a PhD student also in EPSRC DISTINCTIVE programme) the MNPs will be silica coated and further used in nanopore technology for contaminant separation purposes. The use of a magnetic core structure will lead to better direction and sensing capability.
Repository Science and Engineering

The UK government’s policy associated with nuclear waste management is enshrined in the 2008 White Paper “Managing Radioactive Waste Safely” (MWRS) based on the 2006 recommendations of the Committee for Radioactive Waste Management (CoWRM). The Nuclear Decommissioning Authority (NDA) is responsible for the delivery of the policy and the ultimate goal for higher level waste disposal in a mined geological repository. CNE academics have contributed to various international programmes in geological disposal and we plan an expanding contribution to the UK’s fundamental understanding and technology in this area. This will be underpinned by the award as part of the NERC RATE (Radioactivity And The Environment) programme with the universities of Birmingham and Leeds, of a £1.5M project entitled “Hydromechanical and Biogeochemical Processes in Fractured Rock Masses in the Vicinity of a Geological Disposal Facility for Radioactive Waste”, Bob Zimmerman is leading this project, which will run from 2013-2017.

PDRA Projects

Hydraulic Transmissivity of Geologically Realistic Fracture Networks
Researcher: Dr Anozie Ebigbo
Supervisor: Prof Robert Zimmerman and Dr Adriana Paluszny
Sponsors: RATE Programme (NERC/RWM/EAP)

Fractures can serve as flow paths for fluids through otherwise impervious rocks. Since mobile fluids in the vicinity of nuclear-waste-storage sites can be detrimental to the environmental, it is important to be able to quantify the conductance of rock masses at these sites. Fracture networks in rocks are usually characterised statistically using information gathered from outcrops (surface exposure of once-buried rock) or generated using geomechanical models. Given these characteristics, is it possible to deduce the conductance (or transmissivity) of fractured rock masses with simple mathematical expressions? Such analytical expressions would be very useful in the stochastic assessment of environmental risk or site suitability. Their derivation for realistic, three-dimensional fracture networks is the goal of this project.

PhD/EngD Projects

Coupled Thermo-Hydro-Mechanical-Chemical Processes in Rock Fractures
Researcher: Philipp Lang
Supervisors: Prof Robert Zimmerman and Dr Adriana Paluszny
Sponsors: RWM (NDA)

The coupling of Thermal, Hydraulic, Mechanical and Chemical (THMC) processes for fractured rocks is an extremely complex area of scientific research that may have a significant bearing on the potential design and performance of radioactive waste disposal facilities. Under the umbrella of the DECOVALEX 2015 project, an international research and model comparison
collaboration, this project is concerned with the accurate modelling of intrinsically coupled processes in rock fractures to predict changes in their long-term mechanical and hydraulic behaviour. A multi-scale approach is employed: mechanical-chemical pore-scale models investigate changes in fracture surface topology as a result of the balance between dissolution and precipitation processes in the presence of surface contact pressure. Fractured core flood experiments are modelled and validated against to investigate localization of fluid flow in single fractures. Fracture network investigations show the large-scale flow behaviour as a result of the in-situ stress field and fracture network geometry. The ensuing findings aid the rigorous assessment of fractured rock as host to geological disposal facilities. Accurate computation of the permeability tensor of a fractured rock mass

**Hydraulic Transmissivity of Fracture Networks generated through Geomechanical Fracture-growth Simulations**

*Researcher: Robin Thomas*  
*Supervisors: Prof Robert Zimmerman, Prof John Cosgrove, and Dr Adriana Paluszny*  
*Sponsors: RATE Programme (NERC/RWM/EAP)*

Most previous modelling of the field-scale transmissivity of fractured rock masses has been based on stochastically generated fracture networks, with lengths, orientations and apertures taken from statistical distribution functions. The purpose of this project is to inject more “geological reality” into this process. To achieve this, an in-house, three-dimensional geomechanical finite element simulator is being used to generate fracture networks. The fracture orientations and shapes, and their apertures, will therefore be governed by the laws of fracture mechanics, rather than being stochastically generated from some statistical distribution. The transmissivities of the result-
such as elastic moduli, fracture toughness, and mechanical heterogeneity, have on field-scale hydraulic transmissivities

**Experimental Investigation of the Thermo-Hydro-Mechanical Behaviour of Soils**

*Researcher: Daniel Martinez Calonge*

*Supervisors: Dr Way Way Sim and Prof Lidija Zdravkovic*

*Sponsors: EPSRC and Geotechnical Consulting Group*

In recent years, the study of the thermo-hydro-mechanical (THM) behaviour of soils has been a growing area of research within the geotechnical community due to its importance in a wide range of contemporary civil engineering applications and activities, such as underground nuclear waste storage, energy geostuctures or ground heat storage. The project firstly focuses on the development of new experimental capabilities at the Imperial College Geotechnics Laboratory, presenting a new temperature-controlled triaxial apparatus for saturated soils, its thermal performance, the calibration of its components for the effects of temperature and the strategies for measuring thermal strains. It also describes the calibration and compares the use of the single needle and the dual-probe heat-pulse needle techniques for the measurement of thermal properties of soil. The second part of the project focuses on the characterisation of several aspects of the THM behaviour of London clay. Three different topics are considered: the volume changes induced by temperature cycles in reconstituted samples at different stress levels and histories, the influence of temperature cycles on the strength and stiffness of reconstituted samples at different stress levels and histories and the study of the thermal properties of reconstituted and intact London clay samples.

**Numerical Study of Bentonite Buffer Homogenisation upon Re-saturation**

*Researcher: Giulia Ghiadistri*

*Supervisors: Prof Lidija Zdravkovic, Prof David Potts, Dr Katerina Tsiampousi*

*Sponsors: AMEC Foster Wheeler*

A good understanding of the Thermo-Hydro-Mechanical-Chemical (THMC) behaviour of highly expansive clay, such as bentonite, is important in some of the designs of the Engineered Barriers Systems (EBS) for nuclear waste disposal. In a Geological Disposal facility (GDF), coupled interactions take place involving the EBS, the host rock, the groundwater and the heat generated by the radioactive waste.

One of the disposal concepts being considered in the UK is to dispose of High Level Waste (HLW) and Spent Fuel in containers surrounded by a buffer material consisting of bentonite. Bentonite’s capacity to swell provides a low hydraulic conductivity barrier and protection of the container.

The bentonite blocks or pellets will be emplaced in an unsaturated state. This bentonite then undergoes a process of re-saturation from the groundwater from host formation. Studying bentonite resaturation is a challenging task, as it involves swelling upon wetting from groundwater in the host formation and shrinkage induced by heat coming from the energy generated by the nuclear waste in the container. Nevertheless, it is important to build confidence in the long-term behaviour of the EBS.

For the investigation of the behaviour of unsaturated soils, commonly adopted constitutive models are the Barcelona Basic Model (BBM) and the Barcelona Expansive Model (BExM): within this project, the aim is to develop a BExM-type model aimed at studying bentonite re-saturation.
Nuclear Policy, Safety, Security and Regulation

Nuclear policy and its impact on energy generation scenarios within the UK and for other countries that are developing nuclear power. Generation of base-load electricity by nuclear power stations with minimal emissions. Questions surrounding the economic viability, and perceived risks and public acceptability associated with powerplant operations and radioactive wastes.

PhD Projects

**Formal Verification of Treaty Processes**

*Researcher: Paul Beaumont*  
*Supervisor: Prof. Michael Huth, Prof. Chris Hankin*  
*Sponsor: AWE*

This research project aims to extend and combine mathematical modelling approaches to work with the inherent lack of available data in the domain of nuclear arms control treaty design and implementation.

We have been working with Bayesian Belief Networks, dynamical systems and game theoretic frameworks to model potential arms control arrangements with under-specified symbolic parameters. Our unique contribution is to assert equations for the beliefs and inspections control processes in a piece of software known as Satisfiability Modulo Theories (SMT). This offers a general purpose approach to the automated analysis of mathematical models and we use SMT to analyse the under-specifications and build confidence through robust analysis. These new modelling and analysis methods allow for a much more sophisticated approach to modelling arms control: we have harnessed a supercomputer to analyse over 134 million possible inspection timelines that the software would compute an ‘optimum’ regime schedule over a treaty lifespan of 2 years.

The models and results can then be studied and their expected outcomes assessed by AWE for predicting behaviour and assisting in decision making situations regarding proposed inspection regime treaties.
CNE Research Portfolio

The total level of funded projects in the CNE stands at over £38M. Some of our most recent and valuable awards that our researchers are involved in are the third phase of the UK-India Civil Nuclear Collaboration, the EURATOM In-vessel Melt Retention Severe Accident Strategy, and the EPSRC-sponsored and very collaborate Responsive Mode Grant on Neutron Irradiation Defects in Advanced Manufacture of Ferritic Steels.

Funded Projects


» 2012-2016 M Ryan, (Imperial, Manchester, Loughborough and Diamond), EPSRC/NDA, ‘Atomic and Macro-scale Studies of Surfaces’, £910K.

» 2012-2017 G Thomas, NCI of the US, The Chernobyl Tissue bank – Co-ordinating Centre, £725K

» 2013-2016 S Walker, Imperial College, Nuclear Thermal Hydraulics, PhD Scholarship, £120K.


» 2013-2017 WE Lee with J Binner (PI, Lboro), M Finnis and M Reece (QMUL), EPSRC Programme Grant, ‘Understanding and Designing Materials Systems for Extreme Environments’, £2.8M.

» 2013-2017 R Zimmerman, NERC/RATE Programme Grant, HydroFrame Project, £1.6M.


» 2013-2018 F Dunne, EPSRC, with Michael Preuss at Manchester University, ‘Heterogeneous Mechanics in Hexagonal Alloys across Length and Time Scales’, £5M.


» 2014-16 WE Lee, AWE, PDRA Ag Wetting, £140K.
» **2014-17** WE Lee Lloyd Register, Support for Chair in Nuclear Regulation, £150K.

» **2014-17** WE Lee EPSRC, with Bill Nuttall (OU) and Ian Farnan (Cambridge), Equipment for Nuclear Energy CDT, £293K.

» **2014-17** C Pain, A Buchan EPSRC, ‘Reactor Core-structure Re-location Modelling for Severe Nuclear Accidents’, £244K.

» **2014-18** WE Lee University of New South Wales, Australia, ‘Wasteforms for Advanced Fuel Cycles’, PhD, £180K.


» **2014-2018** M Wenman, C Davies, EPSRC and Rolls-Royce Case Award, ‘Predictive Models and Experimental Analysis of delayed Hydride Cracking’, £100K.

» **2014-2018** WE Lee, UNSW, Synroc Durability PhD, £180K.


» **2014-2019** WE Lee, EPSRC, Sellafield, NNL, and NDA, DISTINCTIVE Consortium. £450K.

» **2014-19** WE Lee, M Bluck, EPSRC, with Cambridge and the Open University, Nuclear Energy Centre for Doctoral Training: Building UK Civil Nuclear Skills for Global Markets, £4.1M.

» **2015** B Britton - Royal Academy of Engineering Research Fellowship, £0.8M.

» **2015** WE Lee Leverhulme Trust, Visiting Fellow Michel Barsoum, £16K.

» **2015** M Bluck, S Walker, EPSRC UK-India Civil Nuclear Collaboration Phase 3, £0.7M.

» **2015** M Wenman, AWE, PhD Studentship, ‘Laser Additive Manufacture of Metallic Components’, £100K.

» **2015-2019** C Pain, EURATOM, In-vessel Melt Retention Severe Accident Management Strategy for Existing and Future NNPs, €8.2M.

» **2015-17** M Wenman, S Walker, Nuclear Department HMS Sultan, PDRA, ‘Flow Rig Corrosion of Zr Alloys with Zn Dosing’, £240K.


2015–17  S Walker, M Bluck, G Hewitt
EPSRC, ‘Premature Oscillation-induced Critical Heat Flux’ (Premature OICHF), £112K.

2015-18  B Britton, Imperial College and Rolls-Royce, CASE Studentship (Simon Wyatt) £50K.

2015-18  B Britton, EPSRC Nuclear CDT and AWE, PhD Studentship (William White) £50K.

2015-18  WE Lee, L Vandeperre et al
EPSRC UK-Japan Nuclear Research Call, with NC Hyatt (Sheffield University, PI) ‘Advanced Waste Management Strategies for High Dose Spent Absorbents’, £440k.

2015-18  WE Lee, EPSRC, with Ian Farnan (Cambridge, PI) and Phillip Frankel (Manchester), ‘Carbides for Future Fission Environments (CAFFE)’, £0.55M.


2015-19  S Walker, M Bluck, G Hewitt, EPSRC, Grace Time, £0.68M.

2016  B Britton, AWE, PhD funding for CDT studentship, £50K.

2016  M Wenman, EPSRC Responsive Mode Grant, with Rolls Royce, ANSTO, UNSW, NNL and CCFE and Oxford and Manchester universities, ‘Linking Microstructure to Neutron Irradiation Defects in Advanced Manufacture of Ferritic Steels’, £3.2M.
Publications

The volume and quality of our published work continues to remain high both in journal papers, books and book chapters and conference proceedings.


Teaching

At Imperial College we continue in our mission to deliver the highest quality teaching across a broad range of nuclear engineering topics. Delivery of our key courses span both undergraduate (MEng), post graduate (MSc and MRes) and research level degrees (PhD). Our graduates continue to achieve excellence and many of our alumni are now employed in planning for the next generation of reactors, both fission and fusion, managing the existing fleet, and in decommissioning and waste management. Our graduates are employed not only in the UK, but also across the world, providing a global impact in securing a low CO$_2$ future. Our programmes all build upon our long standing interests in nuclear and at Imperial we have been nuclear engineering continuously at ICL since the 1950s.

We have three undergraduate MEng degrees in Mechanical & Nuclear Engineering, Chemical & Nuclear Engineering, Materials & Nuclear Engineering. Annually 30-35 students graduate from these courses, most of whom join the nuclear industry (e.g. EdF Energy, Rolls-Royce, AWE) or pursue PhDs.

We have our flagship one-year MSc in Nuclear Engineering which graduated a cohort of 30 students last year, drawn from the Centre for Doctoral Training (CDT) and 1 year taught masters cohorts. This year we have split this into an MSc in Advanced Nuclear Engineering and the MRes in Nuclear Energy. The MSc is designed to transition a budding nuclear engineer into an expert well targeted for developing a leading industry career or further PhD study. The MRes enhances the research aspect of the programme and is part of our leading CDT programme, led by Imperial but together with Cambridge and Open Universities (the ICO team).

The MSc in Advanced Nuclear Engineering consists of focussed 1 year programme. It is broadly split into three sections: Core Courses that cover essential topics for any nuclear engineer, ranging from nuclear physics towards materials selection for cladding materials; Short Courses provide a state-of-the-art taster of important and exciting emerging and growing areas, such as Nuclear Fusion (kindly provided by col-
leagues from CCFE) and the new Nuclear Energy Policy Course (kindly provided by Open University to the MSc & MRes cohorts at Imperial, and the MPhil students in Cambridge); and finally a chance to undergo hands-on research at Imperial or a partner institution.

The MRes in Nuclear Energy has grown from the MSc to provide a fast track CDT students into research, while still providing a fundamental underpinning in Nuclear Engineering taught courses. We feel that this strand of teaching, with several core course at an advanced level leveraged together with cohort building activities and an extended research project, enables us to enhance our work in tackling the so-called ‘generation gap’ and provide a well-structured path for higher research for talented, enthusiastic and well-rounded individuals. In particular, the 1st year of the ICO CDT hosted at Imperial enables students from a wide range of backgrounds to get a head-start on their research with an appreciation of many of the wider issues at stake within the nuclear energy supply chain. Once this MRes year is complete, students continue onto a 3 year PhD project at their host University. The cohorts are brought back together annually at varies activities, such as the Cambridge and Imperial public engagement festivals, the winter school (hosted jointly with the Manchester led CDT) and further trips abroad to research reactors.

In the 4-year MEng programmes, students spend the first two years in their host department learning core material expected from...
graduates of Imperial College. In years three and four, students now take specialist option courses focusing on Nuclear Engineering. These are based not only in their host department, but also in the other sister departments within the CNE. This provides broad, whole systems training in the subject, covering all aspects from design and build, through operation to decommissioning and final disposal. Students graduate from the programme not only with a core understanding of their underpinning discipline, but also the expertise, knowledge and understanding imparted by the Centre for Nuclear Engineering family.

Ben Britton oversees teaching of nuclear engineering at all levels and is Director of the MSc. The external examiners for the MEng are those covering the undergraduate courses in the individual departments, the external examiner for the Advanced Nuclear Engineering MSc is Dr Tom Scott from Bristol, and the external examiner for the Nuclear Energy MRes is Prof James Marrow from Oxford.

**MEngs in Chemical, Materials and Mechanical with Nuclear Engineering**

Students taking the nuclear engineering undergraduate degree courses do 2 years full time in their core engineering subject (Chem Eng, Mech Eng or Materials) and then take a series of elective courses in their 3rd and 4th years that give them a basis for employment within the nuclear and related industries. Additionally, students pursuing the combined degrees are expected to carry out project work relevant to nuclear power and assistance is provided to find them placements in the nuclear industry during the summer vacation between their 3rd and 4th years. Our students have carried

### Current Undergraduate Student numbers

<table>
<thead>
<tr>
<th></th>
<th>Materials</th>
<th>Chem Eng</th>
<th>Mech Eng</th>
<th>Total</th>
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<tbody>
<tr>
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<td>6</td>
</tr>
<tr>
<td>Total</td>
<td>21</td>
<td>21</td>
<td>2</td>
<td>44</td>
</tr>
</tbody>
</table>

**NB:** Mech Eng does not separate cohorts in Year 1 or 2, so they will always have 0 students enrolled for those years.

Students are free to change options/streams typically until the end of Year 2 (and sometimes later, depending on the circumstances).
out placements with many companies around the world, including: EdF, Rolls-Royce, ANSTO, Westinghouse, JRC-ITU Karlsruhe and the IAEA. Imperial graduates approximately 30-35 students each year from the nuclear degrees, all of whom get jobs and about half join industry and a third go on to take higher degrees.

Students entering the combined degree course in the Autumn of their 3rd year will study the courses: Introduction to Nuclear Energy; Nuclear Chemical Engineering; Nuclear Thermal Hydraulics; Reactor Physics; Nuclear Materials. In addition project work is required for students pursuing the combined degree and every effort made to arrange placements in relevant industrial organisations in the long +vacation between the third and fourth years.

We make extensive use of guest lecturers with recent industry experience such as Dame Sue Ion (Government Nuclear Consultant), Dr Tony Judd (former Dounreay Fast Reactor Manager), Prof Cherry Tweed (Chief Scientist RWM) and Prof Neil Smart (Sellafield Sites).

**MSc in Nuclear Engineering**

The MSc in Nuclear Engineering provides training for engineers and scientists who want to become nuclear specialists. The MSc is taught by academics from the Departments of Mechanical Engineering, Chemical Engineering, Materials and Earth Sciences together with expertise unique to the UK university sector, from our Reactor Centre staff at the Silwood Park Campus who operate the CONSORT test reactor.

In this 12 month course students attend lectures in the following courses: An Introduction to Nuclear Energy, Nuclear Thermal Hydraulics; Nuclear Chemical Engineering; Reactor Physics; Materials for Reactor Systems; Modelling for Nuclear Engineers; Nuclear Safety Management; Nuclear Waste Management and Decommissioning. In addition to the core modules there are one week long short courses:

- Radiation Protection
- Fast Reactors and Nuclear Hydrogen Production
- Instrumentation
- Nuclear Fusion
- Nuclear Island Constructionarium
- Engineer in Industry

The MSc in Nuclear Engineering provides training for engineers and scientists who want to become nuclear specialists. The MSc is taught by academics from the Departments of Mechanical Engineering, Chemical Engineering, Materials and Earth Sciences together with expertise unique to the UK university sector, from our Reactor Centre staff at the Silwood Park Campus who operate the CONSORT test reactor.

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- Radiation Protection
- Fast Reactors and Nuclear Hydrogen Production
» Instrumentation
» Nuclear Fusion
» Nuclear Island Constructionarium
» Engineer in Industry

Students conduct a four month research project either within the college or ideally based in industry. We have had success in gaining sponsorship to the value of £20,000/annum for MSc students from EdF, EdF Energy and the Worshipful Company of Armourers and Braziers.
EPSRC ICO Centre for Doctoral Training in Nuclear Energy

Overview

The CNE with the University of Cambridge and The Open University was awarded over £4M in 2014 by the EPSRC to set up a Centre for Doctoral Training (CDT) in Nuclear Energy.

Building on world-leading modelling and experimental capabilities, the research performed in the ICO Nuclear Energy CDT is enabling future reactors to be developed, new reactors to be built and operated more safely, and current reactors to operate for longer. At the same time ICO research will support the clean-up and decommisioning of the UK’s contaminated nuclear sites and moves towards geological disposal in the UK and world-wide. ICO research is keeping the UK at the forefront of international programmes on future reactors for electricity and civil marine power. By doing so it is providing highly skilled and motivated cohorts of PhDs with a global outlook for the UK nuclear industry, regulators, government and academia.

Structure

The CDT will train 62 PhD students in five cohorts and is sponsored by EPSRC and the nuclear industry and associated international partners. The programme involves a one year MRes in Nuclear Engineering at Imperial followed by three years PhD study at either Imperial, Cambridge or Open (CDT → MRes + PhD). Students can select a PhD from the many projects covering the whole fuel cycle listed on the CDT website. The majority of projects are joint ventures with industry. Our industrial partners include among others: Rolls-Royce, AWE, EdF, Hitachi (Japan), UNSW (Australia), Westinghouse (USA), and NNL.

CDT Management and Committees

The CDT is managed by a CDT Committee, a Management Board and an International Advisory Board.

The CDT committee meets monthly and covers the day-to-day business of the CDT. The committee consists of:

» Bill Lee - CDT Director (Chair)
» Mike Bluck - CDT Deputy Director
» Ian Farnan - CDT Co-Director, Cambridge
Bill Nuttall - CDT Co-Director, The Open University

Dhan-Sham Rana - MRes Representative

Alexandros Kenich - PhD representative

Pat Bennick - Administrator Cambridge

Emma Warriss - Manager

The Management Board meets with representatives from industry partners including Rolls-Royce, EdF Energy, AWE and Horizon every six months. At meetings of this Management Board, stakeholders will hear reports on progress and plans, and be able to offer guidance. The board consists of the CDT Management Committee enumerated above, and the following:

Keith Parker - NIA (Chair)
Masao Chaki - Hitachi EU

Erwan Galenne - EDF Energy

David Geeson - AWE

Robert Harrison - Rolls Royce

Neil Batemen - EPSRC

Steve Roberts - University of Oxford

Gerry Thomas - Diversity Advisor

We have international input from our International Advisory Board, which meets annually and is jointly held with the Next Generation Nuclear (NGN) CDT led by Manchester University. Key global players such as Westinghouse, EdF, CEA, Massachusetts Institute of Technology, and ANSTO as part of the Board. We also have collaborations with international centres of excellence, such as universities and research centres in the USA (MIT, Idaho National Lab, PNNL, and Los Alamos), France (Limoges U, Ecole Centrale Paris, CEA Saclay & ValRho, and Areva), China (Tsinghua), Australia (ANSTO, UNSW), Germany (JRC ITU) and India (Bhabha ARC).

Progress

The CDT is in its second year and we are currently recruiting for the third cohort to start in October 2016.

Cohort one consists of nine students that started in October 2014; cohort two has also nine student, but they started on our newly approved MRes in Nuclear Energy in October 2015.

The CDT has been very successful at attracting matching funding from industry to support our projects as almost all our students are sponsored.

The CDT cohorts have participated in a wide variety of team-building activities, such as a three-day visit to the Institute for Nuclear Research in Romania, the Halden Reactor in Norway, a one-day trip to CONSORT Reactor at Silwood Park, and a Winter School in Birmingham. In the future we intend to host trips to EdF Energy’s training centre at Cannington Court in South-west England, and the BAE Submarine site in Barrow in North-west England.

More information on ICO CDT is available at www.imperial.ac.uk/nuclearcdt.
Outreach

Over the last 18 months the CNE has grown our networks and regularly give talks at national and international events. Communicating what we do and learning from others in a key aspect of working in the nuclear field

The research and ideas of the CNE academics are widely sought after across a variety of professional settings. Below you can find examples of recent lectures, seminars, and workshops delivered by our academics.

Ben Britton

2014

» Invited speaker “Understanding Micromechanical Deformation Behaviour with HR-EBSD,” Sheffield, UK, June.


2015

» Invited speaker “Metallurgy and the Nuclear Industry – a focus on the Micromechanics of High Performance Metals like Zirconium,” at Newcastle University, UK, January.

» Invited speaker “Deformation studies with High Resolution, Cross Correlation Electron Backscatter Diffraction (EBSD),” at Swansea University, UK, February.


» With Dunne FPE, Jiang J, Kuwabara A, Yang J, and Zhang, T “Fatigue Crack
Initiation near Inclusions in Ni Super Alloys – a SEM based Study with High Resolution EBSD,” ICM12, KIT, Germany, May.

» Invited speaker “Micromechanics of Deformation and Strength in Hexagonal Closed Packed Alloys,” Quarterly Rolls-Royce Nuclear UTC meeting, Imperial College, London, June.

» Britton TB, “Micromechanics of deformation and strength in hexagonal closed packed alloys at the quarterly Rolls-Royce Nuclear UTC meeting, Imperial College, London, June.

» Britton TB, “Nanomechanical testing of high performance alloys”, 2015 MRS Fall, Boston, USA, December.

2016


Joy Farnaby

» Invited speaker “Multi-metallic Materials Containing F-elements” ACS Award in Organometallic Chemistry 2014 Symposium for Professor William J. Evans, 249th ACS Denver, USA.

Bill Lee

2014


» Lee Hsun Award Lecture “Structural Ceramics for Extreme Environments,” Institute of Metals Research, Chinese Academy of Sciences, Shenyang, China, July.

» “Challenges and Opportunities for Advanced Ceramics and Composites in the Nuclear Sector”, National Nuclear Laboratory Lunchtime Seminar (Risley, Harwell, Springfields, Sellafield etc.), September.


» “The AWE-Imperial College Strategic Alliance,” Y-12 TN USA, October.

» “Nuclear-related Centres and Collaborations at Imperial College London,” Manufacturing Development Centre Oak Ridge National Laboratory, TN, USA October.

» “Structural Ceramics for Extreme Environments,” Dept. of Materials, Katholic University of Leuven, Belgium, November.

» “Nuclear Engineering Research at Imperial College,” UK Civil Nuclear Mission to the Argonne, Oak Ridge and Idaho National Laboratories USA, December.

2015

» Keynote Lecture “Structural Ceramics for Extreme Environments,” Intl. Symp. on Ceramics Nanotune Technology, ISCeNT 4, Nagoya Institute of Technology, Nagoya, Japan, March.

» “Nuclear Ceramics: Key Materials in Waste Management and Advanced Reactors,” Tokyo Institute of Technology, Tokyo, Japan, March.

» Expert panel member at “Workshop on Communicating Complex Scientific Information to the Public and Media,” British Embassy, Tokyo, Japan, March.

» “Progress in the Clean-up at Fukushima, including Wasteform Development” University of New South Wales, Sydney, Australia, April.

» “Nuclear Ceramics for Fuel and Wasteforms,” Australian Nuclear Science and Technology Organisation (ANSTO), Lucas Heights, Sydney, Australia, April.


» Centre for Nuclear Engineering Xmas Lecture, Imperial College London, “Why Radionuclides are Good for You”, December.

2016

» Inspiring Science Guest Lecture, “Why Radionuclides are Good for You,” School of Engineering, Mathematics and Science, University of Exeter, January.


Simon Walker (Research Group)


Ahn JS “Iso-geometric Analysis of MHD Flow in Fusion Blanket” UNTF 2015, April.


Mark Wenman

Invited speaker “Fuel Performance and Damage Modelling Using Finite Element and Peridynamics” Institute for Transuranium Elements, Karlsruhe, Germany, September 2014.


Laurence Williams

Invited Panel Member UK Global Threat Reduction Programme Workshop on Fundamentals of Physical Protection, London September 2015

Invited Panel Member UK Global Threat Reduction Programme Workshop on Nuclear Security Culture, Jakarta


Talk on “Why Nuclear” to U3A Science Group

Imperial Nuclear Constructionarium

Robert Zimmerman


“Deterioration of Surface Roughness and Hydraulic Transmissivity of a Rock Fracture due to Pressure Solution
Compaction,” Annual Meeting of the American Geophysical Union, San Francisco, USA, December 2014.


Conferences, meetings and engagement

The CNE sustains strong engagement with the nuclear and wider scientific community on a national and international scale. Below are a few notable examples of how our researchers are communicating their science, influencing views, and engaging constructively with other organisations.

IAEA General Conference

Prof Robin Grimes led the UK delegation to the International Atomic Energy Agency General Conference in Vienna: the first time that an academic has led the delegation. With the Conference held in September 2014, the delegation from the UK included experts from DECC, ONR and 15 UK companies from the UK nuclear Industry.

Japan-UK Nuclear Research Collaboration Symposium and ABWR Seminar

On the 10th and 11th September 2015 a two day event was hosted by the Embassy of Japan in London. This was organised to foster co-operation between researchers in Japan and the UK and to help introduce the Advanced Boiling Water Reactor planned for deployment at Wylfa. To this end, the first day showcased nuclear research where Anglo-Japanese collaboration is already bearing fruit being highlighted. Members of the Centre were at the fore with presentations from Profs Bill Lee, Robin Grimes and Chris Pain describing the benefits that our strong Japanese ties have brought.

The second day was a seminar on the ABWR reactor system. This was co-organised by the Centre and provided a comprehensive description of Hitachi’s reactor design, providing in-depth technical descriptions of many details from its in-built safety systems to fuel-management strategies. The two days were a great success.
and will have helped strengthen links between the universities and nuclear industries of both countries.

**UNTF 2015**

On the 31st of March to the 2nd of April 2015 the Open University at Milton Keynes hosted the annual Universities Nuclear Technology Forum (UNTF). The UNTF meetings are aimed at students and postgraduate researchers from UK universities working on nuclear-related projects. Imperial College was well represented by PhD and MSc students from the CNE, who gave talks and poster presentations on their research covering a variety of topics including nuclear materials, atomic scale simulations, fusion energy, thermal hydraulics and detector analysis. The audience consisted of students, post-docs, lecturers and people from industry. The event was a success with doctoral candidates from different universities networking, discussing and presenting their work.

**Sellafield Public Outreach**

On March 10 2015 CNE PDRA Dr Sam Humphry-Baker delivered a series of presentations in Cumbria, as part of Sellafield Ltd’s public outreach programme.

In the morning Sam gave two talks about Materials Science to around 700 primary school children from the neighbouring communities. The picture below shows one of the most popular demonstrations: making nylon fibres by drawing them from a beaker of two liquids. The biggest challenge however was after the talks, where he faced some fierce questioning from the young audience!
Sam delivered his third and final lecture to the Materials Society of Cumbria. The society is an affiliate of IOM³, and is mainly formed of James Walker, Sellafield, and NNL employees. At the evening lecture he gave a short overview of the CNE, followed by a more technical overview of his work on plasma-facing fusion reactor materials.

Imperial Festival

In May 2015 Imperial College hosted its fourth annual science festival, which aims to show to the general public in a user-friendly way the depth and variety of the work going within the College’s faculties.

The CNE’s stand attracted a significant amount of attention from the 12,000 visitors that attended the festival, including Imperial’s President Prof Alice Gast. The stand exhibited various aspects of nuclear energy, such as uranium glass and fuel rods. A real highlight was AWE-sponsored PhD student Ben Nash’s hot cell simulator, which enabled visitors to experience (virtually!) decommissioning operations. Although aimed at all ages, younger visitors particularly enjoyed having to find a uranium-bearing glass beads using ultra-violet light.

CNE volunteers included CNE Manager Emma Warriss, academics Mike Bluck and Ben Britton, PDRA Michael Rushton, PhD students Dimitri Pletser and Claudia Gasparinni, and CDT
student Mark Mawdsley. Dominic Rhodes MBE of NNL also lent his expertise. Their efforts in devising the exhibits, setting them up, and operating and explaining them to audiences were instrumental in making the CNE stand a prime attraction and contributed more broadly to the success of the Imperial Festival.

**Bhaba Atomic Research Centre**

During the week June 15th 2015 research associate Dr Navatnarajah Kuganathan and PhD student Conor Galvin visited the Bhabha Atomic Research Centre (BARC) in Mumbai, India.

They were given a tour of the site and saw the wide variety of research and work conducted at BARC, from medical isotope production to the nuclear energy sector. As thorium is a potentially valuable resource for India, considerable research has been done on the topic.

While at BARC, Dr Kuganathan presented his work on ‘Theoretical Simulations of Carbon Nano Materials, Cathode for Lithium Ion Batteries and Inorganic Electrides’ in the Materials Science Division Seminar room. The talk was received extremely well, with around fifty researchers from various disciplines attending. Overall, the trip was a great success and strengthened the existing bonds between CNE and BARC.

**Fukushima Visit**

In March 2011, an earthquake off the east coast of Japan triggered a tsunami, which crashed into the Fukushima Daiichi Nuclear Plant. This led to explosions and a partial meltdown of three boiling water reactors and the mass evacuation by authorities of citizens living in the surrounding area. In March 2015, Professor Bill Lee, Director of the Centre for Nuclear Engineering at Imperial, and PhD student Dimitri Pletser, also from the Centre, visited the clean-up operations. Since the accident, water has been used to cool the damaged cores. The site visit was part of Professor Lee’s and Mr Pletser’s research to develop ways of capturing and disposing of radioactive waste collected from the cooling water.

Prof Bill Lee offers some reflections on the lessons the UK and the global nuclear community can learn from the incident: ‘It must be remembered that Fukushima was, according to the Japanese Parliament Review, an “accident made in Japan”’. ‘It should never have happened’, Bill states, ‘and had Japan followed the same ap-
In early January 2016, as part of the new nuclear power MOOC (Massively Open Online Course), Dr Mark Wenman (Imperial) and Prof Bill Nuttall (Open University) were filmed at the Open University. The MOOC will be a five-week course and open to anyone through Future Learn. Aimed at graduates, it will provide the opportunity to learn about many aspects of nuclear power – such as its history, reactor physics, nuclear safety culture and accidents, and the economics of new build. The MOOC will launch around July 2016.

Fukushima Visit: PhD student Dimitri Pletser and Centre Director Prof Bill Lee visited Fukushima in March 2015 to see the progress of clean-up operations.

proach to regulation as is done in the UK none of the reactors would have been significantly damaged.’ ‘A major lesson we can take home is the value of not becoming complacent about safety. Policymakers and engineers relied on past earthquake and tsunami data to design and construct their defences, which they thought could withstand any known impacts from the sea. Hindsight’, Bill concludes, ‘has taught us the very valuable lesson of expecting things that were originally considered beyond-design-basis to be entirely possible.’

MOOC: Dr Mark Wenman strikes a pose during filming of the new massively open online course being developed in conjunction with the Open University.
Seminars and Lunchtime Lectures

We continue to run a seminar series to bring leading researchers to the CNE to present their work. These take place monthly on a Wednesday afternoon for an around an hour, and refreshments are provided afterwards to facilitate discussion and networking opportunities for CNE researchers. The following seminars have taken place recently, or will take place in the near future.

» Dr Mike Bluck - ‘“Plumbing”, or Thermal Hydraulics in Nuclear Fission and Fusion’

» Prof Jonathan Hyde – ‘Materials Research in Support of Nuclear Power: UK Capabilities and a Case Study on RPV Embrittlement’

» Prof Francis Livens – ‘Actinide Behaviour in Natural and Engineering Environments’

» Dr Mark Sarsfield – ‘Americium-241 Production for use in Space Power Applications’

We run a series of informal lunchtime lectures with pizza for CNE researchers to describe their research and for researchers from outside the CNE but who may have valuable nuclear expertise to present their capability. These are advertised widely around the CNE, including to associated partners and have proven highly popular with attendance at 30-40 for all.

We also host a CNE Christmas Lecture. On December 16 2015, the Director Prof Bill Lee delivered a lecture entitled ‘Why Radionuclides are Good for You’ which highlighted how radioactivity is normally a benign phenomenon, how organic life is adapted to it, and how radionuclides will play an essential role in tacking future technological challenges. Attended by students, academics, and representatives from industry, such as AWE and Rolls-Royce, the lecture concluded with a drinks reception.

A selection of seminar slides can be downloaded at the following website address: http://www.imperial.ac.uk/nuclear-engineering/research/research-outputs

If you would like to attend the 2016 Christmas Lecture, please contact Jonathan Tate at j.tate@imperial.ac.uk.

Newsletter

We produce a quarterly (February, May, August and November) newsletter to raise awareness within the wider nuclear community of our activities and achievements. The newsletter can be found at www.imperial.ac.uk/nuclear-engineering and to be added to the circulation list please contact the editor, Jonathan Tate.
Collaborations, International and National Consortia

The scope and complexity of the nuclear energy field means that knowledge, skills, and facilities are necessarily pooled and shared not only across and within academia, government, and industry, but also between borders. The CNE plays a prominent role in these collaborative enterprises, the most important of which are listed below.

International

Although the CNE is based in London, we have a presence across the globe. Since our last report, our researchers have travelled tens of thousands of miles to engage with our international partners and work closely with them to help solve the many challenges facing the nuclear energy sector.

**Imperial-UNSW/ANSTO**  
CNE Representatives: Prof Bill Lee, Prof Robin Grimes, Dr Simon Walker, Dr Mark Wenman

Following an initiative between Robin Grimes (Imperial) and Graham Davies, then Dean of Engineering (UNSW), and Lyndon Edwards (ANSTO), a Collaboration Agreement was established in April 2014. The Agreement was between UNSW and Imperial College and used funds provided by the Bill Tyree Foundation to support a PhD in the CNE, and to fund academics to teach and help develop an MSc programme in Nuclear Engineering at UNSW.

Robin Grimes, Simon Walker and Mark Wenman have helped teach courses at UNSW (2014, 2015), and from October 2014 a PhD in Wasteforms for Advanced Reprocessing Wastes supervised by Bill Lee (Imperial), David Gregg and Lou Vance (ANSTO), and David Waite (ANSTO) is currently underway.

Other links include a visit by Wendy Timms (UNSW) to Imperial in September 2015, where she delivered a seminar on uranium mining. In addition, Robin Grimes’s group has provided Simon Middleburgh (ANSTO until early 2015) and Patrick Burr who recently joined UNSW as a Lecturer in Nuclear Engineering. Moreover, several CNE students have spent three months at ANSTO. In 2014 MSc Nuclear Engineering students Conor Galvin and Elizabeth Howett visited, and in 2015 MSc Nuclear Engineering student Alex Parnell and third-year MEng in Materials Science and Engineering student Robin Newman went across.

**DECOVALEX**  
CNE Representative: Prof Robert Zimmerman

The DECOVALEX project is an international research and model comparison collaboration for advancing the understanding and modelling of coupled thermo-hydro-mechanical (THM) and thermo-hydro-mechanical-chemical (THMC) processes in geological systems. Prediction of these coupled effects is an essential part of the performance and safety assessment of geological disposal systems for radioactive waste and spent nuclear fuel. The project has been conducted by research teams supported by a large number of radioactive-waste-management organizations and regulatory authorities. Research teams work collaboratively on selected modelling test cases, followed by comparative assessment of model results between different models. Through this collaborative work, in-depth knowledge has been gained of coupled THM and THMC processes associated with...
nuclear waste repositories, as well as the suitability of numerical simulation models for their quantitative analysis.

Source: http://www.decovalex.org/

ENEN

CNE Representative: Dr Matt Eaton

The “European Nuclear Engineering Network” project was launched under the 5th framework EC programme in January 2002. It established the basis for conserving nuclear knowledge and expertise, created a European Higher Education Area for nuclear disciplines, and initiated the implementation of the Bologna declaration in nuclear disciplines. The European Nuclear Education Network (ENEN) Association was established afterwards on the basis of the European Higher Education Area by the partners of the “European Nuclear Engineering Network” project. The general objectives of the ENEN Association are:

» to develop a more harmonized approach for education in the nuclear sciences and nuclear engineering in Europe;
» to integrate European education and training in nuclear safety and radiation protection; and
» to achieve better co-operation and sharing of academic resources and capabilities at the national and international level.

Our very own Dr Christopher Cooling was one of three winners of the 9th ENEN PhD Prize. The prize is given to the best three presentations and accompanying papers on the subject matter of the competitors PhD theses. The event was held in Nice and is a European-wide competition. The prize is €1000 to go towards attending an international conference and this was the first time a student based in the UK has won.

Source: http://www.enen-assoc.org

MUZIC II: in April 2015 the Centre for Nuclear Engineering hosted the MU IC II meeting at Imperial.
Indo-UK
CNE Representative: Dr Simon Walker

Both India and the United Kingdom have extensive civil nuclear power programmes. Recognising this, the two governments have, over the last few years, been supporting a series of joint nuclear science and engineering research activities. The intent of this is for both nations to gain, via “the whole being more than the sum of the parts”. This particular “Network” project is a part of this, and is intended to foster and facilitate interactions between United Kingdom participants, to help ensure that the United Kingdom gains the fullest value it can value its investment in this activity.

MUZIC II
CNE Representative: Dr Mark Wenman

The second Mechanistic Understanding of Zirconium Corrosion program (MUZIC-2) consists of 10 PhD projects at five universities with the goal of understanding hydrogen-pickup mechanisms during zirconium-alloy corrosion in order to improve component design and performances.

Under this programme, a combination of experimental and theoretical studies were conducted and compared to hypotheses for hydrogen pickup. The researchers use several complementary state-of-the-art techniques, including synchrotron radiation, cold neutron prompt gamma activation analysis (CNPGAA), atom probe tomography (APT), in situ electrochemistry, advanced micro-copy, and density functional theory (DFT). Recent technical accomplishments include the understanding that the hydrogen-pickup fraction is not constant throughout the corrosion process, and it is related to the electronic conductivity of the oxide. This finding has potential implications for mechanism and mitigation strategies. In addition, modelling efforts have been used to estimate alloying additives that may lead to reduced hydrogen pickup. Various zirconium alloys are being tested in an autoclave to calibrate and confirm these predictions.

Source:  http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002003068

NUGENIA
CNE Representative: Prof Kamran Nikbin

NUGENIA is an association dedicated to the research and development of nuclear fission technologies, with a focus on Generation II and III nuclear plants. It gathers stakeholders from industry, research, safety organisations and academia committed to developing joint R&D projects in the field. The work of NUGENIA is defined by the Strategic Research Agenda published by SNETP, the European stakeholder forum for nuclear technology.

» NUGENIA scope of activities covers 8 main technical areas:
  » Plant safety and risk assessment
  » Severe accidents
  » Improved Reactor Operation
  » Integrity assessment of Systems, Structures and Components
  » Fuel Development, Waste and Spent Fuel Management and Decommissioning
  » Innovative LWR design & technology
  » Harmonisation
» In-service Inspection and Non-Destructive Examination

As a product demonstrating the success of the 3 networks (SNETP TWG Gen II&III, NULIFE and SARNET), NUGENIA is the starting point of a more ambitious and united community to advance the safe, reliable and efficient operation of nuclear power plants. NUGENIA is providing, in a transparent and visible way, a scientific and technical basis by initiating and supporting international R&D projects and programmes. NUGENIA is contributing to innovation and facilitate implementation and dissemination of R&D results.

Source: http://www.nugenia.org/

SARNET

CNE Representative: Dr Matt Eaton

Despite the accident prevention measures adopted in nuclear power plants (NPP), some accident scenarios, in very low probability circumstances, may result in severe accidents (SA): with core melting, plant damage and subsequent dispersal of radioactive materials into the environment, thus constituting a hazard for the public health and for the environment. Large progress has been made since the 1980s, thanks in particular to the Framework Programmes (FP) of the European Commission, but several issues still need research activities to reduce uncertainties and consolidate SA management (SAM) plans.

SARNET tackles the fragmentation that exists between the different research national programmes, notably in defining common research programmes and developing common computer tools and methodologies for safety assessment. The network comprises most of the actors involved in SA research in Europe, plus a few non-European important ones (such as Canada, Korea, and India). A few organizations are covering a wide range of competences though not complete, whereas others are specialized in very specific areas and thus complementarities are developing. The critical mass of competences for performing experiments needed in the SA domain, analysing them, developing models and integrating them into the ASTEC integral computer code, is achieved for most types of NPPs in Europe.

Source: http://www.sar-net.eu

National

Imperial College’s outstanding reputation, combined with its location in the heart of the capital, means that the CNE is often a key player in national research collaborations. These collaborations aim to safeguard the UK nuclear renaissance, help solve domestic challenges, and foster the UK as an exporter of nuclear-related technology and services.

AMASS

CNE Representative: Prof Mary Ryan

The Atomic and Macro-scale Studies of Surface Processes (AMASS) consortium is a multidisciplinary team across four institutions in the UK (Imperial, Manchester, Loughborough and Diamond) that are working towards mechanistic understanding of surface reactivity and radionuclide binding mechanisms. The consortium received funding from EPSRC in April 2012 and is due to complete work in March 2016.

The project deals with four main points as follows:
To understand the evolution of mineral surfaces in a geological disposal facility—what surface chemistry and structure would a released RN ‘see’

To make surface sensitive in-situ measurements of RN deposition processes and relate these to bulk sorption data (synchtronon XAS, refLEXAFS, GIXRD)

To develop first principle models of RN-surface interactions

Provide scientific underpinning for RN sorption inputs into NDA safety case

**CAFFE**

CNE Representatives: Prof Bill Lee and Prof Mike Finnis

Starting June 2015 the Carbides for Future Fission Environment (CAFFE) consortium is investigating ZrC and Zr-C based MAX phase ceramics for application in nuclear environments. It is led by Ian Farnan at Cambridge with co-investigators Bill Lee and Mike Finnis (Imperial), Michael Preuss (Manchester), with links to groups in the USA and Europe.

**DISTINCTIVE**

CNE Representative: Prof Bill Lee

DISTINCTIVE (Decommissioning, Immobilisation and Storage solutions for Nuclear waste Inventories) is a multi-disciplinary collaboration of 10 universities and 3 key industry partners from across the UK’s civil nuclear sector. DISTINCTIVE will link a set of 32 world-leading research projects within the broad area of nuclear waste management, decommissioning and disposal.

DISTINCTIVE was formed following a call for proposals in the area of “Decommissioning, Immobilisation and Management of Nuclear Waste” from the Research Councils UK Energy Programme, and led by the Engineering and Physical Sciences Research Council, in June 2013. It follows on from the highly successful DIAMOND consortium, which ran from August 2008 to March 2013.

Our aim is to build a greater capacity for research and development (R&D) to underpin the strategic needs of the UK.

We will achieve this by:

Consolidating and expanding academic nuclear related R&D.

Fostering and developing collaboration with nuclear industry stakeholders.

Providing routes to innovative technology developments.

Training the next generation of UK researchers and potential employees in the sector.

Source: [http://distinctiveconsortium.org](http://distinctiveconsortium.org)

**Nuclear Champion**

CNE Representative: Prof Robin Grimes

The Nuclear Universities Consortium for Learning, Engagement And Research (Nuclear) was funded by EPSRC in May 2011 with the aim to develop a network to facilitate the effective UK academic engagement in nuclear research programmes by working for the nuclear energy groups and engaging groups with emerging interest in nuclear energy, thereby helping academics to apply new approaches to help solve challenging nuclear issues. This will be achieved through a four-strand strategy:
Growing the network by facilitating nuclear network meetings, seminars and an annual academically based nuclear research conference to share research challenges, research ideas and research outputs

Engaging effectively with UK industry to ensure research focus and effective knowledge transfer. This will include developing links with the Energy Generation and Supply Knowledge Transfer Network managed by TWI

Facilitating access to specialist research facilities in the UK and overseas including, for example, the National Nuclear Laboratory’s Central Laboratory, Manchester’s Dalton Cumbrian Facility, the Diamond synchrotron, the Advanced Test Reactor at INL, etc

Engaging with the international nuclear research communities to ensure that the UK’s strong reputation for academic research is strengthened through participation in developing consortia, especially when bidding for international research funds including EU Framework programmes. This strategy requires the network partners to buy in to a clear vision and to develop supporting material to be used by all members to make industry and global players aware of UK capability and the potential to make use of our research collateral.

Source: [http://www.nerc.ac.uk/research/funded/programmes/rate/](http://www.nerc.ac.uk/research/funded/programmes/rate/)

**XMAT**

CNE Representative: Prof Bill Lee

The development of next-generation ceramic and ceramic composite materials is vital for enabling the operation of machinery in extreme conditions, such as severe chemical and radioactive environments. A £4.2M EPSRC Programme Grant was launched in February 2013 to meet this challenge. It is led by Jon Binner University of Birmingham working with Bill Lee and Mike Finnis at Imperial College London and Mike Reece at Queen Mary London. The project is currently using as its foundation cutting-edge ceramics and composites developed at these institutions for nuclear fusion, fission, aerospace and other applications where resistance to radiation, oxidation and erosion are needed at very high temperatures.

Source: [http://www.xmat.ac.uk](http://www.xmat.ac.uk)
Impact

CNE has a number of key partners, but has particularly strong links with Rolls-Royce, EdF/EdF Energy, AWE, and Hitachi-GE.

**Key Partners**

Rolls-Royce Nuclear University Technology Centre

The Rolls-Royce Nuclear UTC opened in 2010 with the ambition to develop and capitalise on extant capabilities and to establish itself in a growing nuclear market. The 5-year UTC agreement ensured a funding commitment to nuclear research activity in the College in support of both naval and civil businesses.

The UTC (and the UTC model) has been an acknowledged success and 2015 saw the renewal of the UTC agreement for a further 5-year period. The Rolls-Royce Nuclear University Technology Centre has been relocated into newly refurbished offices in the City and Guilds Building, demonstrating the College commitment to the UTC. This new site offers space for 30 staff and students.

This year has seen continued activity in the four main theme areas – materials performance, reactor thermal hydraulics, radiation transport and reactor physics, and NDE.

In the materials performance theme, micromechanics and its impact on material properties (hydriding, blocky-alpha, etc) continues as a growth area under Fionn Dunne, Mark Wenman and Ben Britton. The impact on structural integrity is important and collaborative work streams are underway with Catrin Davies. In addition, new work streams on tribo-chemical effects are underway, led by Daniele Dini.

In reactor thermal hydraulics, the large project in the area of flow modelling in naval and civil PWRs, supported by Rolls-Royce (Civil and Marine) is nearing completion. The general thrust of this work, involving academic staff (Simon Walker, Mike Bluck, Raad Issa and Geoff Hewitt) with a mix of nuclear thermal hydraulic and CFD expertise, has been to conduct a range of research activities with the general theme of aiding the uptake into nuclear reactor analysis of advanced thermal hydraulic methods based on CFD, with particular reference to their application to small LWR systems, and especially those exploiting passive features. A follow-on 5-year programme of work is under development.

In radiation transport and reactor physics, Matt Eaton, continues to drive the development of the RADIANT deterministic radiation transport code. His team of PDRAs and PhD students continues to grow and the software is undergoing installation at the Rolls-Royce site in Raynesway, Derby.

In NDE - led by Peter Cawley and Mike Lowe, work on the modelling of ultrasonic response from rough defects has continued strongly.
EdF/EdF Energy

The relationship with EDF continues with about £1.8M of current investment at Imperial College in nuclear projects. This is in a large part through the long-standing and highly successful High Temperature Centre which had its contract renewed in February 2015, guaranteeing its operation until at least 2018. Work also continues in nuclear fuel performance, reactor physics, non-destructive testing; and after a workshop, held in April 2015, we are beginning work on stress corrosion cracking of nuclear fuel dry store containers. Meanwhile, EDF continue to sponsor MEng and MSc students on the nuclear programmes through funding from the EDF Foundation.

AWE

Imperial College has historically had extensive links with AWE Aldermarston established largely through William Penney who was an academic in College in the 1930s before being...
the UK representative on the Manhattan project and heading up the UK’s nuclear deterrent programme before returning as Rector from 1967-73.

There is an overarching Imperial/AWE Strategic Alliance Board of Management and extensive links (particularly with Physics) via the Institute for Shock Physics (ISP), the Centre for Inertial Fusion Studies (CIFS) and the Institute for Security Science and Technology (ISST). The links with Engineering have not been as strong and a policy of extending them has been instigated via a William Penney Fellowship to Bill Lee and the setting up of the Imperial-AWE Centre for Engineering and Manufacturing Studies (CEMS) with Bill as its Director in 2013. This has led to more extensive interactions via MSc/MEng projects in Mechanical Engineering, Materials and Chemistry, support for kick-start projects in areas such as Additive Manufacture, ceramic/metal interface modelling and H transport in metals including funding for 9 PhDs and 3 PDRAs. AWE also provide support for William Penney Prizes for the best research projects in the Nuclear Engineering and Advanced Materials MScs.

Hitachi-GE

The CNE and Hitachi-GE Nuclear Energy are working together to assist the UK Industrial and Academic Research Communities to take ownership of Advanced Boiling Water Reactor Technology.

The first Boiling Water Reactors in the UK are planned to be built at Wylfa Newydd on Anglesey after the completion of the UK Regulatory Process, and are expected to begin generating electricity in 2025 and will provide much needed low-carbon base load electricity.

The CNE will work together with Hitachi to assist with the research, development and delivery of the next generation of boiling water reactors.

NNL-Imperial Alliance

The NNL-Imperial Working Group meets every three months to identify joint opportunities for researching, training and public engagement. Simon Walker is an NNL Fellow and Laurence Williams is a Visiting Senior Fellow at NNL. The key contact for Imperial at NNL is Richard Stainsby.

Key areas for future collaboration are nuclear process engineering, reactor materials, reactor operation and safety, wasteforms development, and asset care.
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