EXCELLENCE IN SCIENCE

THE ROYAL SOCIETY

THEO MURPHY INTERNATIONAL SCIENTIFIC MEETING ON

Peaks and troughs of wave energy: the dreams and the reality

Wednesday 13 – Friday 15 October 2010
The Kavli Royal Society International Centre, Chicheley Hall, Buckinghamshire

Organised by Professor Francis Farley FRS, Professor Rod Rainey and Professor John Chaplin

- **Programme and abstracts**
- **Speaker biographies**

The abstracts that follow are provided by the presenters and the Royal Society takes no responsibility for their content.

Peaks and troughs of wave energy: the dreams and the reality

Wednesday 13 – Friday 15 October 2010

Organised by Professor Francis Farley FRS, Professor Rod Rainey and Professor John Chaplin

Wednesday 13 October		**Thursday 14 October**	
Session 1 – General theoretical framework of wave power conversion		**Session 2 – Experience at the full scale**	
Chair – Dr Richard Yemm, Pelamis Wave Power, UK		**Chair – Mr Allan Thomson, Aquamarine Power, UK**	
12.00	Registration and lunch		
13.45	**Welcome by Professor Francis Farley,** Organiser	**09.00**	**Review of oscillating water columns** Dr Tom Heath, Voith Hydro Wavegen, UK
14.00	**Hydrodynamic principles of wave power extraction** Professor Chiang Mei, Massachusetts Institute of Technology, USA	**09.30**	**Nearshore oscillating wave surge convertors and the development of Oyster** Professor Trevor Whittaker FREng, Queen's University, Ireland
14.30	**Key factors of wave energy** Professor Rod Rainey, Oil and Gas Division, Atkins Ltd, UK	**10.00**	Discussion
15.00	Discussion	**10.30**	Coffee
15.30	Tea	**11.00**	**Pelamis – experience from concept to connection** Dr Richard Yemm, Pelamis Wave Power, UK
16.00	**Heaving buoys, point absorbers and arrays** Professor Johannes Falnes, Norwegian University of Science and Technology, Norway		
16.30	**Discrete control strategies for resonant wave energy devices** Dr Alain Clément, Laboratoire de Mécanique des Fluides, Ecole Centrale de Nantes, France	**11.30**	**Historical impediments and ideas for removing them** Professor Stephen Salter, University of Edinburgh, UK
17.00	**Biodiversity impacts of wave energy** Dr Matthew Witt, PRIMaRE, University of Exeter, UK	**12.00**	Discussion
17.30	Discussion	**12.30**	Lunch
18.00	End of day 1		
18.30	Dinner		

Thursday 14 October		Friday 15 October	
Session 3 – New concepts		**Session 4 – The way ahead**	
Chair – Professor David Evans, University of Bristol, UK		**Chair – Professor AbuBakr Bahaj, University of Southampton, UK**	
14.00	**Rubber tubes in the sea** Professor Francis Farley FRS, University of Southampton, UK	**09.00**	**What can wave energy learn from offshore oil and gas?** Dr Rick Jefferys, ConocoPhillips, UK
14.30	**Laboratory testing the Anaconda** Professor John Chaplin, University of Southampton, UK	**09.30**	**Lessons from the wind power industry** Dr Andrew Garrad, GL-Garrad Hassan, UK
15.00	Discussion	**10.00**	Discussion
15.30	Tea	**10.30**	Coffee
16.00	**Coupled resonant absorbers** Dr Richard Porter, University of Bristol, UK	**Chair – Dr Andrew Garrad, GL-Garrad Hassan, UK**	
16.30	**Wave energy technology in China** Professor Yage You, Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, China	**11.00**	**Round table discussion: National plans and international collaboration** Mrs Georgina Grenon, General Directorate for Energy and Climate Change, Ministry of Ecology, Energy, Sustainable Development and the Sea, France ; Mr Eoin Sweeney, Ocean Energy Development Unit, Sustainable Energy, Ireland; Dr Teresa Pontes, INETI / LNEG - Laboratório Nacional de Energia e Geologia, Ministry of Economy and Innovation, Portugal; Dr Tom Counsell, Department of Energy and Climate Change, UK
17.00	**Pacific perspective: from Alaska to New Zealand** Dr Robert Paasch, The Northwest Marine Renewable Energy Center, Oregon State University, USA		
17.30	Discussion	**12.00**	General discussion
18.00	**End of day 2**	**12.45**	**Close**

Peaks and troughs of wave energy: the dreams and the reality

Organised by Professor Francis Farley FRS, Professor Rod Rainey and Professor John Chaplin

Wednesday 13 – Friday 15 October 2010

Synopsis

Wave energy machines are now deployed and working; some have clearly failed, while new devices are continually on trial. Speakers at this meeting will cover the fundamental physics, engineering, the effects of large forces but low velocity, deployment, maintenance and survival; dreams that did not work, what works but is too expensive, what might work better. This meeting will address issues such as how much energy is available and what can we expect from this technology?

Day 1 – Wednesday 13 October 2010

12.00 Registration and lunch*

13.45 Welcome by Professor Francis Farley FRS, Organiser

Session 1 – General theoretical framework of wave power conversion
Chair – Dr Richard Yemm, Pelamis Wave Power, UK

14.00 Hydrodynamic principles of wave power extraction
Professor Chiang Mei, Massachusetts Institute of Technology, USA

In this article, we review the hydrodynamic principles common to many existing designs of WECs, and describe a few recent efforts, based exclusively on the linearized theory.

Specifically, the hydrodynamic principles common to many wave power converters are reviewed via two representative systems, the first involves one or more floating bodies and the second water oscillating in a fixed enclosure. It is shown that the common basis is impedance matching and resonance, for which the typical analysis can be illustrated for a single buoy and for an oscillating water column. We then examine the mechanics of a more recent design involving a compact array of small buoys which are not resonated. Its theoretical potential is compared with that of a large buoy of equal volume. A simple theory is also given for a two-dimensional array of small buoys in well separated rows parallel to a coast. The effects of coastline on a land-based oscillating water column are examined analytically. Possible benefits of moderate to large column sizes are explored. Strategies for broadening the frequency bandwidth of high efficiency by controlling the power-takeoff system are discussed. Computational methods and the mooring systems are left out. Nonlinear theories which are crucial to the survivability of WECs in stormy seas are not yet well developed, hence are not discussed.

14.30 Key features of wave energy

Professor Rod Rainey, Oil and Gas Division, Atkins Ltd, UK

This paper is an attempt to summarise the key features of wave energy, as now agreed amongst the cognoscenti – or if not agreed, that will be evident at this meeting!

First, the reason why wave energy is so difficult is that water speeds are so low – power is force times speed, and force means cost. The higher density of water compared with air is immaterial – wave power is much more difficult than wind power, because the water speed is much less than the air speed. Also the dynamic range required of the power train is enormous – even in steady conditions, the peak power is waves of more than 20 times the average. Finally, survivability is a great challenge – whereas a wind turbine can simply stop and feather its blades.

The conventional measure of the wave power resource, kW/m, could be improved. More revealing is the power available per unit volume change (source strength), for a small source. This shows that for volumetric efficiency, a wave power device can only be a simple monopole or dipole if it is small. For economic amounts of power, we need an array – e.g. a longitudinal array, like Pelamis or Anaconda.

Estimating the capital cost of a wave energy device is relatively straightforward. Estimating the power is a lengthy exercise, but feasible – the non-linear features are as important as the linear ones. Estimating the maintenance cost is extremely contentious – Harrison's ship borne chronometer (1762) proved easy to maintain, the hovercraft did not.

15.00 Discussion

15.30 Tea

16.00 Heaving buoys, point absorbers and arrays

Professor Johannes Falnes, Norwegian University of Science and Technology, Norway

Absorption of wave energy may be considered as a phenomenon of interference between incident and radiated waves generated by an oscillating object, a wave- energy converter (WEC) that displaces water. If a WEC is small in comparison with one wavelength, it is classified as a point absorber (PA) if very small; otherwise as a 'quasi point absorber' (QPA). The latter may be a dipole-mode radiator, for instance an immersed body oscillating in the surge mode or pitch mode, while a PA is so small that it should preferably be a source-mode radiator, for instance a heaving semi-submerged buoy. The power take-off capacity, the WEC's maximum swept volume, and preferably also its full physical volume, should be reasonably matched to the wave climate. To discuss this matter, two different upper bounds for absorbed power are applied in a 'Budal diagram'. It appears that, for a singleWEC unit, a power capacity of only about 0.3 MW matches well to a typical offshore wave climate, and the full physical volume may, unfortunately, be significantly larger than the swept volume, unless phase control is utilised. For a sizeable wave-power plant, an array consisting of hundreds, or even thousands, of WEC units is required. The distance between individual units is also a matter of consideration.

16.30 Discrete control strategies for resonant wave energy devices

Dr Alain Clément, Laboratoire de Mécanique des Fluides, Ecole Centrale de Nantes, France

Abstract not available at time of print.

17.00 Biodiversity impacts of wave energy

Dr Matthew Witt, PRIMaRE, University of Exeter, UK

Marine Renewable Energy Installations (MREI) are likely to became a larger part of the energy-mix of the future. The potential to capture energy from waves has seen increasing interest, with pilot developments across a number of countries. Although technology for harnessing wave energy lags behind that of wind generation, it clearly has the potential to provide a significant contribution to renewable energy production. As Wave Energy Converter (WEC) technology matures and upscales from small test arrays to commercial scale wave farms, it is likely to result in large-scale transformation of seascapes, particularly in coastal seas. Such changes are accompanied by a considerable uncertainty regarding their impacts on the environment and key aspects of biodiversity. To date, impacts have not yet been adequately assessed as WEC have not yet been fully developed. There is an urgent need to build a synthetic framework of understanding regarding potential impacts, underpinned by transferable methodologies that can be used across sites to facilitate meta-analytical analysis. With specific reference to our ongoing work at the Wave Hub (a wave energy test site in Cornwall, UK) we review the methodological approaches that are needed to assess impacts on biodiversity made by wave energy installations in the marine environment. We highlight the lessons that must be learned from wind energy and the need for research clusters across the UK, Europe and Internationally. We should capitalise upon lessons learned in the wind energy sector so to accelerate the implementation of MREI within a coherent understanding of their potential impacts, both positive and negative.

17.30 Discussion

18.00 End of day 1

Day 2 – Thursday 14 October 2010

Session 2 – Experience at the full scale
Chair – Mr Allan Thomson, Aquamarine Power, UK

09.00 Review of oscillating water columns
Dr Tom Heath, Voith Hydro Wavegen, UK

The paper considers the history of OWC systems from Whistling buoys to grid connected power generation systems. The power conversion from the wave resource through to electricity via pneumatic and shaft power is discussed in general terms and with specific reference to Voith Hydro Wavegen's LIMPET plant on Islay and OWC breakwater systems. A report on progress of other OWC systems and power take off units under commercial development is given and the particular challenges faced by OWC developers reviewed.

09.30 Nearshore oscillating wave surge convertors and the development of Oyster
Professor Trevor Whittaker FREng, Queen's University, Ireland

Oscillating Wave Surge Converters (OWSCs), exploit the enhanced horizontal fluid particle movement of waves in the nearshore coastal zone. The characteristics of the nearshore wave resource are described along with the hydrodynamics of OWSCs. The range of variables in the OWSC design space are discussed along with a presentation of some of their effects on capture width, frequency bandwidth response and power take off characteristics.

It is concluded that nearshore OWSCs are serious contenders in the mix of wave power technologies. The nearshore has a narrower directional spread than offshore, the largest waves are filtered out and the exploitable resource is only 10% to 20% less in 10m depth compared to 50m depth. A key conclusion is that devices such as Oyster are point absorbers and are not limited to a capture factor of 50%. Also Oyster is not a drag device moving in phase with the horizontal fluid velocity. The hydrodynamics of Oyster is dominated by inertia with significant added inertia. It is unlikely that individual flap modules will exceed 1MW in installed capacity due to wave resource, hydrodynamic and economic constraints. Generating stations will be made up of line arrays of flaps spaced along the 12m depth contour with communal secondary power conversion every 5 to 10 units.

10.00 Discussion

10.30 Coffee

11.00 Pelamis – experience from concept to connection
Dr Richard Yemm, Pelamis Wave Power, UK

PWP has been developing and refining its 'Pelamis' line-absorber machine for over 12 years. This has seen the technology move from initial creation of the concept and operating principle, through extensive and ongoing numerical analysis and model testing, to the construction and testing of a total of 5 full scale grid connected machines. The latest in this line is the second generation 'P2'

machine, the first of which has been built and commissioned under contract to E.ON Climate & Renewables. The machine is currently undergoing initial grid connected trials at the European Marine Energy Centre in Orkney. A second P2 machine is currently under construction for ScottishPower Renewables and further orders for evaluation machines are anticipated shortly. This presentation will focus on how key development challenges have been tackled, what has worked and what hasn't, and what PWP could have done better with the benefit of hindsight.

11.30 Historical impediments and ideas for removing them

Dr Stephen Salter, University of Edinburgh, UK

Impediments can be technical ones of engineering or mathematics or administrative ones of politics, finance, management and law. They can be the lack of something that is needed or, less obviously, something that is present but wrong. Technical ones can be hard items of mechanical and electrical equipment or soft ones of mathematical analysis, control algorithms, data on materials and environmental conditions. Some impediments are immovable but a full identification may allow them to be bypassed. The definition of a problem can often point to its solution and the more precise the definition the closer the approach to the solution. This paper attempts to list impediments to the development of wave energy and suggest some solutions.

Early wave plant has shown itself to be unreliable and very expensive to install or recover. The paper will describe purpose-designed installation vessels with high agility, rapid connection and disconnection to wave plant but short range. It will discuss the design of a seabed robotic machine-tool for work on the seabed attachment. We want to drill holes of a wide range of diameters and depths at any angle. We should be able to insert explosives, detonators, post-tension stands and grout. We should be able to direct water jets or abrasive wheels to cut away unwanted outcrops of rock. We should be able to insert pins and tighten nuts with a controlled torque. We should be able to dig cable trenches and align power cables in them. The equipment should be as easy to transport on land as standard sea containers. It should be stable in large waves even in shallow water and in the highest current speeds of the Pentland Firth. The paper will make the case for a component test raft which can operate large batches of small components in parallel in the correct chemistry and biology of the sea.

Successful projects should have highly skilled leaders with determination to win, who have easy access to accurate information and all the power to make rapid decisions. The first UK wave programme was controlled by highly skilled people who were determined that it should fail. This was followed by a policy to have no policy but to let the market decide. At present the power of political and financial decision makers is inversely proportional to their technical knowledge. The decision response time is of the order of one year. Most developers do everything they can to impede information flow to competitors. Big companies act like psychopaths. The paper will explain these difficulties.

12.00 Discussion

12.30 Lunch*

Session 3 – New concepts
Chair: Professor David Evans, University of Bristol, UK

14.00 Rubber tubes in the sea
Professor Francis Farley FRS, University of Southampton, UK

Traces the invention of the Anaconda sea energy converter. Initial theory of bulge waves predicting a bulge growing along the tube, confirmed by tank tests. Understanding tube stability and aneurisms. Videos of time domain simulations and bulges in the tank. Estimates of wave radiation by the bulge and radiation damping lead to better calculations which agree well with experimental data. Predictions for full scale tubes. Fatigue in rubber, design philosophy for optimum life and survival. Energy storage in rubber leads to an estimate of the quantity of rubber required.

14.30 Laboratory testing the Anaconda
Professor John Chaplin, University of Southampton, UK

This paper discusses laboratory measurements of the performance of the Anaconda, a wave energy converter consisting of a submerged water-filled distensible tube aligned with the incident waves. The experiments were carried out at a scale of around 1:25 with a 250mm diameter tube, 7m long, constructed of rubber and fabric. Measurements of the tube's circumferential strain at ten cross sections were made with novel liquid metal strain gauges. These enabled us to track the progression and growth of the bulges in the tube that were generated by water waves, and to estimate the rate at which external wavepower was captured in the internal flow. The tube was terminated in a single linear power take-off system with adjustable impedance.

The results are compared with a rudimentary numerical model in which the external flow is represented as the sum of the potentials of a row of pulsating sources placed along the axis of the tube. Source strengths are determined by matching circumferentially-averaged kinematic and dynamic boundary conditions, that simultaneously satisfy the internal equations of motion.

Measurements and predictions are in reasonable agreement, showing capture widths up to about 0.5m over a range of wave frequencies and power take-off impedances. Attention is given to the issues of power losses through hysteresis in the tube walls, and wave radiation.

15.00 Discussion

15.30 Tea

16.00 Coupled resonant absorbers
Dr Richard Porter, University of Bristol, UK

In this presentation a range of problems and theories will be introduced which will build towards a new wave energy converter (WEC) concept with the acronym 'ROTA' standing for Resonant Over-topping Absorber. First, classical results for wave power absorption for WECs constrained to operate in a single degree of freedom will be reviewed and the role of resonance in their operation highlighted. Emphasis will then be placed on how the introduction of further resonances can improve power take-off characteristics by extending the range of frequencies over which the efficiency is close to a theoretical maximum. Methods for doing this in different types of WECs will

be demonstrated. Coupled resonant absorbers achieve this by connecting a WEC device equipped with its own resonance (determined from a hydrodynamic analysis) to a new system having separate mass/spring/damper characteristics. It is shown that a coupled resonant effect can be realised by inserting a water tank into a WEC and this idea forms the basis of the ROTA device. In essence the idea is to exploit the coupling between the natural sloshing frequencies of the water in the internal tank and the natural resonance of a submerged buoyant circular cylinder device which is tethered to the sea floor allowing a rotary motion about its point of attachment.

16.30 Wave energy technology in China

Professor Yage You, Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, China

In China, wave energy technology study started in 1980. Before 2001, the research concentrated on Oscillating Water Column (OWC) Wave Energy Converters (WECs), 3, 5, 20 and 100 kW OWCs wave build. The research reveals the deficiencies of the OWCs, the biggest one is their low efficiencies. A rough calculation shows the possible cause of the low efficiency – either the inertia of the turbo-generator or the acceleration of the air current is too large, therefore, minus output and stall of turbine appear frequently. That also reveals the reason why a ram in an Oscillating Bodies (OB) WEC is usually more efficient than a turbine in OWC.

In 2001 – 2006, we started to develop our OB in the first stage – to develop the hydraulic power take-off (PTO). To fulfil the task, we built an Onshore Oscillating Buoy (OOB) in 2006 as a rig for testing PTO. Though the OOB was destroyed by a strong typhoon, the PTO was proved efficient.

In the second stage after 2006, we tried to develop a floating OB WEC based on the PTO of OB. After optimization, we got a design of a floating Duck with an underwater appendage, fault-tolerant PTO and energy storage mooring system. A prototype 10 kW floating Duck are now under trial to find the mistakes of design.

17.00 Pacific perspective: from Alaska to New Zealand

Dr Robert Paasch, The Northwest Marine Renewable Energy Center, USA

This paper illustrates the status of wave energy development in Pacific Rim countries by characterizing the available resource and introducing the region's current and potential future leaders in wave energy converter development. It also describes the existing licensing and permitting process as well as potential environmental concerns. Capabilities of Pacific Ocean testing facilities are described in addition to the region's vision of the future of wave energy.

17.30 Discussion

18.00 End of day 2

Day 3 – Friday 15 October 2010

Session 4 – The way ahead
Chair – Professor AbuBakr Bahaj, University of Southampton, UK

09.00 What can wave energy learn from offshore oil and gas?
Dr Rick Jefferys, ConocoPhillips, UK

Wave energy devices and the marine structures used in oil and gas exploration and production share a common environment and both are subject to wave, wind and current loads, which may be evaluated with well validated, albeit imperfect, tools. Both types of structure can be designed, analysed and fabricated using similar tools and technologies. They fulfil very different missions and are subject to different economic and performance requirements, hence 'offshore' design tools must be used appropriately in wave energy project and system design and 'offshore' cost data should be adapted for 'wave' applications.

This paper reviews the similarities and differences between the fields and highlights the differing economic environments; offshore structures are typically a small to moderate component of field development cost, while wave power devices will dominate overall system cost.

The typical 'offshore' design process is summarised and issues such as reliability based design and design of not normally manned structures are addressed. Lessons learned from poor design in the past are discussed to highlight areas where care is needed. Opportunities for innovation and optimisation in wave energy project and device design are discussed.

This paper is a personal viewpoint and not an expression of a ConocoPhillips position.

09.30 Lessons from the wind power industry
Dr Andrew Garrad, GL-Garrad Hassan, UK

This paper considers the early experiences of the development of wind turbines and the wind energy industry in order to try and identify lessons learned which could now be applied to the developing marine renewables technology and industry. It considers both political and commercial incentives and engineering development. It traces the development of the turbines through commercial incentives and also through large scale government grants. It shows how the intervention of the EC through its R & D programmes played a central role in accelerating development. Some analysis is presented of the different ways in which different types of incentive affect development. The reasons why some countries have been successful in creating an industrial base and why others have not is also investigated. Although the paper draws upon global, if personal, experience it draws together recommendations specifically for the UK marine renewable industry.

10.00 Discussion

10.30 Coffee

Round table discussion
Chair – Dr Andrew Garrad, GL-Garrad Hassan, UK

11.00 National plans and international collaboration

Mrs Georgina Grenon, General Directorate for Energy and Climate Change, Ministry of Ecology, Energy, Sustainable Development and the Sea, France;
Mr Eoin Sweeney, Ocean Energy Development Unit, Sustainable Energy, Ireland;
Dr Teresa Pontes, INETI / LNEG - Laboratório Nacional de Energia e Geologia, Ministry of Economy and Innovation, Portugal;
Dr Tom Counsell, Department of Energy and Climate Change, UK

12.00 General discussion

12.45 Close

12.45 Lunch*

**For speakers/chairs/organisers and participants who have purchased lunch/dinner*

Organiser, speaker and chair biographies

Professor AbuBakr Bahaj, University of Southampton, UK (Chair)
AbuBakr S Bahaj is Professor of Sustainable Energy at the University of Southampton. Over the last 20 years, Professor Bahaj has established the energy theme within the University and directed his Sustainable Energy Research Group, which is now considered to be one of the UK's leading university-based research groups in renewable energy and energy in buildings. He initiated and managed research in ocean energy conversion (resources, technologies and impacts), photovoltaics, energy in buildings and impacts of climate change on the built environment in the University. This work has resulted in over 200 articles published in academic refereed journals and conference series of international standing.

Professor Bahaj is the head of the Energy and Climate Change Division (ECC) within the highly rated School of Civil Engineering and the Environment. The aims of the Division and SERG are to promote and execute fundamental and applied research and pre-industrial development in the areas of energy resources, technologies, energy efficiency and the impact of climate change.

Professor Bahaj is an experienced research team director and has many internationally-focused research projects including collaborative projects in China, the Middle East and Africa. He is also the co-ordinator of the UK's Engineering and Physical Sciences Research Council (EPSRC), Eco-region research networks that aim to develop research themes and projects to study eco-city development encompassing resource assessment, technology pathways for the production and conservation of energy, planning, and social and economic studies required in establishing eco-regions in China and elsewhere. He is a member of the Editorial Boards of *Renewable Energy*, the UK's Institute of Civil Engineering journal *Energy*, and a member of the Tyndall Centre for Climate Change Research Supervisory Board. From 2001 to 2007 he was a member of the Department of Business and Regulatory Reform (BERR), (now Department for Business Innovations and Skills, BIS), Technology Programmes Panels on Water (including ocean energy) and Solar Energy.

To address training in the areas of energy and climate change Professor Bahaj has recently coordinated and developed a set of MSc programmes that address, traditional energy generation and distribution, energy in transport, energy resources and climate change and energy in the built environment.

Professor John Chaplin, University of Southampton, UK (Organiser and Speaker)
John Chaplin graduated with a BSc in Civil Engineering from the University of Bristol in 1967 and was awarded a PhD from the same department in 1971. Between periods in industry he has since held posts at the Universities of Karlsruhe and Liverpool, and at City University, London. Now a Research Professor at the University of Southampton, his research activities focus on experiments on various aspects of water wave mechanics and fluid/structure interaction, and related analysis.

From the mid-1970s, when wave loading on stationary and compliant components of offshore oil and gas systems was far from well understood, he worked on developing an understanding of interactions between waves and structures, with particular emphasis on wave-induced and vortex-induced vibrations. The results of this work have been fed into offshore design practice and continue to be used in validation of numerical models. Other areas of research include the two-phase flow in breaking waves in the ocean, and

contributions to the understanding and development of several wavepower devices, including, since 2006, the Anaconda.

Dr Alain Clément, Laboratoire de Mécanique des Fluides, Ecole Centrale de Nantes, France (Speaker)

Alain H. Clément was born in Paris in 1953. In 1975, he received the degree of Engineer in Naval Engineering from Ecole Centrale de Nantes (France). After four years of research, he obtained a PhD from the same Institution a PhD for his work entitled: *Theoretical and numerical study of the motions of floating bodies in regular waves and water of uniform finite depth*. He obtained in 1998 the HDR, french diploma giving access to full Professor chair. His favourite research topics include time-domain simulation of free surface flows by BEM methods, design and optimisation of wave energy devices, real time control of wave energy devices. In this field he has published 30 articles in international peer reviewed Journals or books, and has given 83 communications at international conferences. He has supervised 21 PhD students since 1983, and has given lectures on various topics including gravity waves theory, unsteady hydrodynamics and wave forces on large structures for post-graduate students at Masters level. He is a referee for a number of international journals in this field, including Journal of Fluid Mechanics, International Journal for Numerical Methods in Fluid, Applied Ocean Research, Journal of Engineering Mathematics. Currently he is still working at Ecole Centrale de Nantes where he is, since 1998, the Director of the Laboratoire de Mécanique des Fluides, a joint research unit between ECN and CNRS.

Dr Tom Counsell, Department of Energy and Climate Change, UK (Panellist)

Dr Tom Counsell is an assistant to Professor David MacKay, the Chief Scientific Advisor at the UK Department of Energy and Climate Change. He has been heavily involved in the department's work exploring how to reach the UK's 2050 climate change target, is on secondment from the Carbon Trust and his degrees are in engineering from the University of Cambridge.

Professor David Evans, University of Bristol, UK (Speaker)

Professor Evans obtained his BSc in Mathematics from the University of Manchester in 1962 and his PhD in 1966 under the supervision of Professor Fritz Ursell. He spent two years in the USA, first at the Davidson Laboratory in Stevens Institute of Technology in New Jersey and then in the Department of Naval Architecture and Marine Engineering at MIT working under Professor Nick Newman before returning to the UK to a lectureship in Applied Mathematics at Bristol in 1969. He was appointed to a Personal Chair in 1986. He served as Head of Department from 1984 to 1993, Dean of Science from 1993 to 1996 and Pro-Vice-Chancellor from 1997 to 2002.

Professor Evans works mainly on theoretical problems associated with the interaction of waves and structures. In 1975 he turned his attention to wave energy problems and produced a number of theoretical results. He also invented the Bristol Cylinder wave energy device which received considerable government funding between 1977 and 1983.Together with Professor Newman he was responsible for initiating the annual International Workshop on Water Waves and Floating Bodies (IWWWFB) which celebrated its 25th meeting in Harbin, China, in 2010.

Professor Johannes Falnes, Norwegian University of Science and Technology, Norway (Speaker)

Johannes Falnes, now Professor Emeritus at NTNU, graduated as 'siv.ing.' (M.Eng) in 1957 and as 'dr.techn.' in 1972, both from the Norwegian Institute of Technology (NTH), Electrotechnical Department. He was employed at NTH, Trondheim, Norway, 1956-1959, CERN, Geneva, 1959-1961, University of Bergen, Norway, 1961-1964 and NTH (subsequently Norwegian University of Science and Technology - NTNU), Trondheim, 1965-2001.

Since retirement he has been a Visiting Scientist at CeSOS (Centre for Ships and Ocean Structures), NTNU, 2005-2010. He and his colleague Kjell Budal became active in wave-energy 1973. Until external financial support, from the Norwegian Ministry of Petroleum and Energy, ended in 1983, they managed R&D projects on phase-controlled point-absorber buoys. Falnes has taught at and organised several courses and events on ocean-wave energy, and he is author of the textbook *Ocean Waves and Oscillating Systems: linear interactions including wave-energy extraction*, published in 2002. He co-authored the book *Wave Energy Conversion*, published in 2003, which provided a review of the state-of-the-art in wave-energy technology.

Professor Francis Farley FRS, University of Southampton, UK (Organiser and Speaker)
An experimental physicist with experience of radar, electronics, reactors, particle physics, cancer treatment and wave energy. Built the first 3 cm ground based radar controlling the 15" guns at Dover (1942). Added a new Doppler system to detect moving vehicles on land, used by the army in Italy. Experiments with first British/Canadian reactor at Chalk River (1945). Taught physics in New Zealand, delegate to UN Conference on Peaceful Uses of Atomic Energy (1955). Particle physics at CERN and Brookhaven, precise tests of relativity, measured the magnetic moment of the muon to better than 1 part in a billion. Cancer treatment with particle beams in Nice. Professor FarleyHas worked on wave energy since 1977, inventor of the triplate, the buckling resonant raft, the distensible buoy, the wave powered hydraulic ram, co-inventor of Anaconda.

Graduated University of Cambridge, PhD, ScD Fellow of Royal Society (1972), Hughes Medal (1980), Honorary Fellow, Trinity College Dublin (1987)

Publications: Methuen monograph *Elements of Pulse Circuits* (1955), papers on the above subjects.

Dr Andrew Garrad, GL-Garrad Hassan (Speaker and Chair)
Andrew Garrad was, until July 2009, the Managing Director of the Garrad Hassan (GH) Group, the world's largest renewable energy consultancy, which he founded in 1984. In July 2009, Germanischer Lloyd's renewables activities and Garrad Hassan merged into a single company employing 750 people in the renewables business. Dr Garrad is the President and General Manager of this new business.

Dr Garrad has been involved in wind energy for more than 30 years. He founded Garrad Hassan in 1984. He is a past Chairman of the BWEA, a board member of the EWEA and a Trustee of the Centre for Sustainable Development. He is a Chartered Engineer, a Fellow of the Institution of Mechanical Engineers, a Fellow of the Royal Aeronautical Society and a Fellow of the Energy Institute. His first degree from Oxford University is in Engineering Science and his PhD is in Theoretical Fluid Mechanics.

In 2006 he received the European Wind Energy Association's Poul la Cour prize for outstanding achievement in the wind energy field. He was awarded the honorary degree of Doctor of Engineering by the University of Bristol in July 2009.

Mrs Georgina Grenon, General Directorate for Energy and Climate Change, Ministry of Ecology, Energy, Sustainable Development and the Sea, France (Panel)
Georgina Grenon is a Policy Advisor on Strategic Development of Renewable Energies for the French Ministry of Ecology, Energy and Sustainable Development. Her main responsibilities include the definition of the national strategy and industrial policy elements for Solar, Wind and Ocean Energies, in consultation with different stakeholders such as industry, academia, NGOs, regions and the French Administration. She is also the focal point for different related activities, both in France and internationally.

Previously, she worked for almost 10 years with Booz & Company (ex-Booz Allen Hamilton), based in the Paris office, where she started as a strategy consultant focused on Energy markets. Her last position with Booz was Global Director for the Operations Service Offering, with worldwide responsibilities for business development, intellectual capital efforts and marketing involving sustainability, sourcing, manufacturing and cross-industry supply chain and services issues, targeting the C-suite, top management, government leaders and academia.

Before joining Booz, Georgina worked in several new business development functions at Repsol-YPF, the international Oil and Petrochemicals Company. Georgina holds an MSc with honours in Chemical Engineering from the Instituto Tecnologico de Buenos Aires and an MBA with distinction from INSEAD. She's fluent in English, French and Spanish, with working knowledge of Portuguese and Italian.

Dr Tom Heath, Voith Hydro Wavegen, UK (Speaker)
A Member of the IMechE, Dr Tom Heath has worked on wave power projects since the founding of Wavegen in 1992 and has been involved in the study and testing of a wide range of wave energy converters. Before that he worked in the carbon fibre industry specialising in manufacturing technology. He was Project Manager on the LIMPET shoreline project and was responsible for coordinating the design of turbo-generation and control equipment for that plant. Since the acquisition of Wavegen by Voith Hydro he has been responsible for all aspects of engineering at Wavegen leading the team developing power take of systems for breakwater OWC units. With ten years experience in the field operation of OWC plant he is one of the most experienced of practical wave energy technologists.

Dr Rick Jefferys, ConocoPhillips, UK (Speaker)
Rick Jefferys received a degree in Engineering and a PhD on Wave Energy from Cambridge University. He subsequently researched wave and tidal power at the CEGB, then moved to University College London, lecturing in Mechanical Engineering and Naval Architecture for six years. In 1986, he joined Conoco as a hydrodynamicist, working in London and Houston on design and analysis of floating structures, including the Heidrun TLP, and development of probabilistic design methods. He worked in gas commercial on real options, storage, markets and economic analysis, moving into sustainability with a focus on emerging technologies and greenhouse gases. His work in the Houston based Emerging Technology and Alternative Energy groups has concentrated on renewable energy, energy storage and, carbon capture and storage.

Professor Chiang Mei, Massachusetts Institute of Technology, USA (Speaker)
Chiang is Ford Professor of Engineering Emeritus, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology. He is a hydrodynamicist with focus on the linear and nonlinear dynamics of ocean wave in general, including their propagation in coastal waters, effects on fine sediment transport and interaction with offshore structures. He has contributed to theory of wave power extraction since 1970, and is the author of a graduate text, *Applied Ocean Surface waves* (Wiley 1983) and a coauthor of its expanded sequel, *Theory and Applications of Ocean Surface Waves, vols I and II*, (World Scientific). A part of these texts is devoted to the theory of wave power extraction by floating bodies. In a recent collaboration with the Centre for Wave Energy Research, Technical University of Lisbon, he has studied the effects of coastline geometry on Oscillating Water Columns. His current interests include the dynamics of compact and sparse arrays of wave-absorbing buoys. For his past contributions to wave mechanics he has received the International Coastal Engineering Award, Moffat-Nichol Harbor Engineering Award, and Von Karman Medal in Engineering Mechanics, all from American Society of Civil Engineers, and the Life-time Achievement Award by the Offshore and Arctic Mechanics Technology Section of American Society of Mechanical Engineers.

Dr Robert Paasch, The Northwest Marine Renewable Energy Center, Oregon State University, USA (Speaker)
Robert Paasch is the Boeing Professor of Mechanical Design in the School of Mechanical, Industrial and Manufacturing Engineering at Oregon State University, and the Director of the Northwest National Marine Renewable Energy Center, a partnership between Oregon State University and the University of Washington.

Dr Paasch has 20 years of academic research experience in the areas of automated monitoring and diagnosis, probabilistic and robust design, and design theory and methodology. He began working with Dr. Annette von Jouanne on marine renewable energy three years ago. He also has 10 years of industrial experience as a project engineer and engineering manager at Hewlett Packard, Lawrence Livermore National Laboratory, Lawrence Berkeley Laboratory, and Marvin Landplane. He received his B.S. from the California Polytechnic State University, San Luis Obispo, his MSc from the University of California at Davis, and his PhD in Mechanical Engineering from the University of California at Berkeley. He is a registered Professional Engineer in California.

Dr Teresa Pontes, INETI / LNEG - Laboratório Nacional de Energia e Geologia, Ministry of Economy and Innovation, Portugal (Panellist)
Dr Teresa Pontes has a PhD on Mechanical Engineering from Lisbon Technical University and has published more than 70 papers on wave energy (resource assessment, site selection, policies). She has been involved in 25+ national and international contracts, namely: European Wave Energy Pilot Plant on the island of Pico, Azores, Portugal; Wave Studies and Development of Resource Evaluation Methodology and European Wave Energy Atlas (general coordinator); Wave Energy Network; Co-ordination Action on Ocean Energy; Wavetrain (I and II); Prediction of Waves, Wakes and Offshore Wind; ORECCA. ONDATLAS (Nearshore Wave Climate and Energy Atlas – Portugal mainland and Madeira Islands) and PEMAP (Potential of Marine Energies in Portugal) a GIS database for wave energy site selection.

Dr Pontes is a member of the Steering Committee on Wave Energy, DGXII CEC (1991-1993, that launched the EC R&D programme on Wave and Tidal Energy); delegate to Working Part on Renewable Energies (IEA) since 1994, she is also the Vice-Chair of the ECOR/IOC/UNESCO Working Group on Wave Energy Conversion (1996-2003). She launched the Implementing Agreement on Ocean Energy Systems (IEA) being the first ExCo Chair (2001- 2004). She is a member of the Board of Directors (2004-2006) and President of the Scientific Council (since 2008) of the Wave Energy Centre (Portugal). Dr Pontes is also the Lead Author of Ocean Energy chapter in the IPCC Special Report on Renewable Energy and Climate Change Mitigation – SRREN (2009-2010) and project evaluator for the EC, EUREKA and EPSRC (UK).

Dr Pontes is Principal Researcher of INETI (Ministry of Economy and Innovation) where she founded the Ocean Energy Group in 1985. Having retired in December 2009, she continues to work in collaboration a Resident Researcher. She has been a Collaborator of the Institute of Mechanical Engineering/IST since December 2009.

Dr Richard Porter, University of Bristol, UK (Speaker)
Richard Porter gained a 1st class Honours degree in Mathematics from the University of Bristol in 1992 and completed a PhD in Mathematics in 1995, again at the University of Bristol under the supervision of Professor David Evans. He then became a Research Assistant with David Evans at Bristol for another 3 years. Following this, Richard worked for BAE Systems for just 6 months as a research scientist at the Sowerby Research Centre in Filton, Bristol before returning to the Department of Mathematics in 1999 to take up a post as a temporary lecturer for one year before being made a permanent lecturer in 2000. He was made a

senior lecturer in 2008. His research interests include problems involving wave interactions with structures in the field of ocean waves, acoustics and elasticity.

Professor Rod Rainey, Oil and Gas Division, Atkins Ltd, UK (Organiser and Speaker)
Rod Rainey read first engineering, then maths, at Cambridge University, graduating in 1971. He also has an MSc from Imperial College London, in control theory. He worked as a design engineer for Yarrow shipbuilders on the Clyde, and as a research fellow at Imperial College, before joining Atkins Oil and Gas division in 1978, where he has been ever since. He specialises in the scientific analysis of ships and offshore structures, and was responsible for the development of the AQWA suite of computer programs, which are the world's most widely used in this field. He has written a number of well-known scientific papers, on slender body theory (*JFM* 1989, *Proc.R.Soc* 1995), on freak waves (*J.Eng.Maths* 2007), and on tidal barrages (*JFM* 2009). He has been closely associated with the development of the Pelamis and Anaconda wave energy devices. He is a visiting professor at the University College London and Southampton University.

Professor Stephen Salter, University of Edinburgh, UK (Speaker)
Stephen Salter was born in Johannesburg South Africa in 1938. He served an old fashioned apprenticeship in the aircraft industry with Saunders-Roe on the Isle of Wight as a fitter, tool-maker and instrumentation engineer eventual working on the Black Knight rocket project before reading physics at Cambridge University where he stayed for six years doing research.

His interests have always been on the border of mechanics and electronics. He moved to The University of Edinburgh to build robots in Artificial Intelligence and then, in 1973, to Mechanical Engineering to work on wave energy. That required the design of new kinds of directional wave tank with absorbing wavemakers and new types of high-power, computer-controlled hydraulic pumps and motors. Small versions are now being installed in the transmissions of road vehicles where they allow improved engine management and the recovery of energy which would have been wasted in braking. These machines may, in future, be used for wind and tidal-stream energy. They enable the design of variable-displacement pumps which despite a low machinery weight can absorb the very high torque needed for multi-megawatt tidal-stream generators suitable for use in the full depth of the Pentland Firth.

Other interests are fatigue reduction in wind turbine blades, desalination using energy from sea waves, improving road-traffic congestion and the capacity of congested bridges, Stirling engines, the mathematics of nuclear disarmament, variable-pitch air turbines, unconventional ways of teaching design engineers and inventors, mine clearance, flood-prevention, the suppression of explosions and the reversal of global warming by increasing cloud albedo.

His research group has its own mechanical and electronic workshops and runs a wide tank with directional absorbing wave-makers. In 1986 he was awarded a Personal Chair in Engineering Design. He is a Fellow of the Royal Society of Edinburgh and an MBE. Rumours of his retirement in 2004 are exaggerated.

Mr Eoin Sweeney, Ocean Energy Development Unit, Sustainable Energy, Ireland (Speaker)
Eoin has a Masters degree in Economics from University College Dublin. His work has focussed on Natural Resource development. Until recently, he managed the Discovery Programme, a major component of SeaChange, the Strategic Programme for the marine sector 2007-2013, within Ireland's Marine Institute.

He is currently Head of the newly established Ocean Energy Development Unit, created to implement the government's strategy to accelerate development of ocean energy. The Unit is located in Sustainable Energy Ireland. In this role he is responsible for initiating and co-ordinating a wide-ranging suite of measures –

developing research and test facilities, funding industry research and prototyping, developing a planning and permitting framework and commissioning expert and consultant reports, e.g. on OE engineering infrastructure and macroeconomics.

Mr Allan Thomson, Aquamarine Power, UK (Chair)
Company founder, Allan Thomson has created several specialist organisations servicing heavy steel construction industries, principally for power generation, petrochemical and offshore oil and gas projects.

He's initiated research and development companies to develop underwater and portable land friction welding systems to solve challenging environmental or material combinations.

Allan founded a research organisation developing pulsed combustion and thermo-acoustic devices to drive rapid pressure swing air separation, then pulsed combustion driven Wells turbines for power generation.

He has also formed commercial alliances with leading academics and institutions to research develop and demonstrate a number of systems for harnessing wave energy. Wavegen developed shoreline oscillating water columns and Aquamarine Power is demonstrating near-shore oscillating surge power converters.

Allan continues to be angel investor and mentor in Scottish start up technology companies.

Professor Trevor Whittaker FREng, Queen's University, Ireland (Speaker)
Trevor is Professor of Coastal Engineering at Queen's University, Director of Research for Environmental Engineering and Head of Marine Renewables. He is one of the founding members and technical advisor to the board of Aquamarine Power Ltd., a company formed to commercially develop the Oyster™ wave power system. One of his significant engineering achievements has been as project manager of the team which designed, constructed and operated Britain's first wave power station located on the Isle of Islay. Prior to decommissioning in 1998, the 75kw plant was one of only four stations in the world supplying electricity to a national distribution grid. The significance of this work was recognised when the team was presented with The ESSO Energy award in 1994 by the Royal Society. This work lead to the construction of the 500kW LIMPET plant which was commissioned in 2001 and is now being commercially developed by Voith Hydro Wavegen Ltd. His latest wave power device, Oyster™ was deployed at EMEC on Orkney in 2009 by Aquamarine Power Ltd and is providing a vital step towards the global development of multi MW wave power farms. Currently Oyster 2 is under development and will be deployed in 2011.

Dr Matthew Witt, PRIMaRE, University of Exeter, UK (Speaker)
Dr Witt's research focuses on both fundamental and applied aspects of marine vertebrate ecology, including foraging behaviour, habitat-use, population assessment and human-wildlife space conflict. Acquiring knowledge on the distribution and behaviour of marine vertebrates is often logistically challenging. Dr Witt therefore uses a variety of remote data collection technologies in his research, such as satellite tracking, archival data loggers, acoustic detection and tracking, and satellite-based earth observation. His work in the field of wave energy focuses on a detailed and long-term assessment of the potential impacts of wave energy on marine biodiversity from benthic to pelagic ecosystems at the Wave Hub site off the north coast of Cornwall (UK).

Dr Richard Yemm, Pelamis Wave Power, UK (Speaker and Chair)
From a background in the wind energy sector, Richard founded Pelamis Wave Power in 1998. He is now the company's Chief Technical Officer, responsible for all aspects of the technology R&D and product

development programmes. Richard is also a Board Director of the Scottish Renewables Forum, Scotland's renewables industry trade association.

Richard graduated with a first class BSc Honours degree in Mechanical Engineering from the University of Edinburgh in 1989, and was awarded a PhD in 1993.

Professor Yage You, Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, China (Speaker)
Professor You has a Masters from Harbin Institute of Ship Engineering in Marine Engineering. He is currently Professor and Director of Ocean Energy Lab of Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences.

Professor You has engaged in the research of wave energy conversion since 1988, having developed a floating Duck Wave Energy Convertor of 10 kW in capacity, designed and constructed a 100kW OWC wave power converter and a 50 kW oscillating buoy wave power converter. He has also developed a hydraulic-electrical power take-off system with self adaptive damping, stable output and an efficiency of 60%, developed a boundary element method for analyzing the flow fields of wave energy converters with arbitrary shape, onshore or offshore. He has also developed a numerical method for finding roots of nonlinear algebraic equations by Lie Group. Professor You owns 8 patents for wave energy conversion.

He was the first awardee of a second class Science and Technology Progress Award of Guangdong Province in 2005 and second awardee of a second class Natural Science Award of CAS in 1992.