Institution: University of Southampton

Unit of Assessment: 15 General Engineering

Title of case study: 15-08 The Impact of Bubble Acoustics

1. Summary of the impact

The question 'Why do brooks babble?' inspired Southampton research into the acoustics of gas bubbles in liquids, bringing medical, military, industrial and environmental breakthroughs with global reach, including:

- New needle-free injectors to treat migraines (over 1 million sold);
- New sensors used on over 200 patients undergoing kidney treatment;
- Co-authoring the current guidelines for every foetal ultrasonic scan in the world since 2008 (around 700 million births);
- The world's only sonar capable of detecting mines in bubbly seawater;
- Sensors for the US Department of Energy's $1.4 billion neutron-scattering facility;
- Ultrasonic cleaning invention licensed to several multinational companies.
- Extensive public engagement including 15 TV and video shows (by David Attenborough, Richard Hammond etc.); 24 radio shows; and secondary reach evidenced via ~200 articles by the public and journalists, and via inspiring people from outside academia to compose music, put on fashion and planetarium shows, and rewrite the script for whale watching tour guides.

2. Underpinning research

Gas bubbles injected underwater sound notes – the smaller the bubble, the higher the note, just as a large wineglass emits a deeper note than a small wineglass when tapped with a spoon (Leighton explaining this on in BBC TV's 'Secret lives of waves' available from **[5.0]**, noting it has received 4726 Youtube hits with comments including *'Unfortunately, I found this incredibly interesting'; 'This was one of my all time favourite documentaries. Everyone who contributed brought insights to it that were either fascinating, poetical, beautiful, or a combination of all three. Bravo!'; 'I get it - if the math were a bit different the brooks would be silent. Would change Tennyson's "I chatter over stony ways, In little sharps and trebles ; I bubble into eddying bays, I babble on the pebbles"*').

Listening to these notes allows the measurement of bubble size. But like any object that can produce sound, bubbles vibrate sympathetically when sound of the correct pitch is projected at them: they emit notes in response, and can even implode (just as a certain voice can 'ring' and shatter a wine glass). An imploding bubble can damage its surroundings. This needs to be controlled as sometimes damage is desirable (as in ultrasonic tumour treatment) and sometimes it is not (e.g. during ultrasonic foetal scanning).

Shortly after joining the University of Southampton (UoS) in 1992 as a Lecturer, Leighton published the most cited work in the field (2000 citations) **[3.1]**, predicting how research into the above phenomenon could generate research and impact in oceanography, biomedicine and industry. Since then, in over 30 peer-reviewed journal papers he has researched and developed these principles to deliver real-world applications united by the acoustics of gas bubbles in liquids. He has received 6 international medals and 4 international awards. The 2009 R.W.B Stephens Medal citation from the Institute of Acoustics states:

> "*Tim Leighton is an outstanding and internationally recognised acoustician who is known worldwide for his rigorous and ground-breaking research relating to acoustics in liquids. He has made significant contributions in the areas of biomedical ultrasonics, cavitation, acoustical oceanography and industrial ultrasonics. As well as this, he has delivered many practical applications from acoustics research, taking the studies from the fundamentals to deliverable instruments in the clinic, industry, ocean or laboratory. His work has resulted in my pioneering advances, from a clinical device to be used in hospitals for assessing the efficacy of lithotripter kidney surgery, to the first system to count bubbles in the surf zone.*"

From 1995-2012, Leighton and Prof Paul White (who was appointed lecturer in UoS in 1988) showed how **the sound made by gas bubbles injected into water** can be used to estimate the size and number of bubbles produced by breaking ocean waves, leaks from undersea gas pipelines and carbon capture and storage facilities, and methane seeps **[3.2]**.

Studying how **sound is scattered by bubbles when sound is projected at them**, Leighton and

White (2001-2012) invented acoustic sensors to count bubbles in the ocean **[3.3]**, leading to the world's first count of bubbles in the surf zone. The sensors were later adapted for the ceramics and neutron spallation industries **[3.4]**, and deployed in national programmes to estimate the amount of gas transferred by bubbles between atmosphere and ocean (which accounts for over 1 billion tonnes of atmospheric carbon alone in the global annual budget).

Although such strong acoustic scattering by bubbles is useful in detecting them, it allows enemy mines to be hidden at sea. Bubbles confound sonar searching for mines in the same way that fog confounds car headlights. Leighton & White countered the bubble scattering to invent the only sonar in the world capable of detecting targets in bubbly water **[3.5]**. The theory was used in Ministry of Defence (MoD) sonar prediction codes, and in the world's first 3D Chirp sub-bottom profiler (collaborating with Prof Bull, Dr Henstock and Dr Dix of Ocean and Earth Sciences, UoS).

Studying **the shock waves and luminescence emitted when bubbles implode,** Leighton:

- collaborated with the Institute of Cancer Research (2007-10) to study how these bubble effects affect ultrasonic tumour treatment;
- collaborated with Guys' & St Thomas' Health Trust (GSTT) to detect these shock waves in clinic to diagnose when kidney stones are successfully shattered by shock wave therapy **[3.6];**
- collaborated with Dr Peter Birkin (Chemistry, UoS) to clean by bubble collapse (1998-2013);
- built conical bubbles to intensify collapses, the basis of needle-free injector work (1996-2002).
- made the world's first experimental quantification of the extent to which living human tissue cavitates in such ultrasonic fields compared to water (1994) **[3.1]**. This finding contributed to his being invited to join the working party of the World Federation for Ultrasound in Medicine and Biology (WFUMB), which in turn drew up the safety guidelines under which all foetal ultrasound scans have been conducted since 2008.

3. References to the research (the best 3 indicating quality of research are starred)

[3.1] Leighton TG, *The Acoustic Bubble*, Academic Press, 1994, 640 pp. (over 2000 citations).
[3.2] Leighton TG and White PR, 2012. Quantification of undersea gas leaks from carbon capture and storage facilities, from pipelines and from methane seeps, by their acoustic emissions. *Proc. Royal Society London A* 468, 485-510. **[3.3]*** Leighton TG, Meers SD and White PR, 2004. Propagation through nonlinear time-dependent bubble clouds, and the estimation of bubble populations from measured acoustic characteristics. *Proc. Royal Society London A* 460(2049), 2521-50. **[3.4]*** Leighton TG, Baik K and Jiang J, 2012. The use of acoustic inversion to estimate the bubble size distribution in pipelines, *Proc. Royal Society London A* 468, 2461-2484.
[3.5]* Leighton TG, Finfer DC, White P R, Chua GH and Dix JK, 2010. Clutter suppression and classification using twin inverted pulse sonar (TWIPS), *Proc. Royal Society Lond A* 466, 3453-78.
[3.6] Leighton TG, Fedele F, Coleman AJ, McCarthy C, Ryves S, Hurrell A M, De Stefano A and White P R, 2008. A device for monitoring the efficacy of ESWL using passive acoustic emissions, *Ultrasound Med. Biol.*, 34(10), 1651-1665.

4. Details of the impact Numbers in **[]** refer to sections 3 or 5.

MEDICINE - Quoting Toby King, CEO, Bowman Power Group **[5.1]**, who was with Weston Medical:

"*Fundamental published work on conical bubbles by Leighton et al. informed Weston Medical in the development of a **needle-free injector** (for subcutaneous drug delivery).In 2002 the business was worth £6 million, but development was stalled by performance issues. Weston Medical contracted Leighton to address performance. His solution enabled further development, such that in 2006 the company Zogenix was formed around this technology, and has now raised a total of over $150 million of Venture capital and loans, primarily to fund approval (successfully achieved in the USA in last year) and marketing of the product with a migraine drug, now called Sumavel Dosepro. The current global market for just this one drug (Sumatriptan) is over $1 billion per year. The needle-free injector is now selling well in the US and the EU - they have just made their millionth device, and quarterly revenues have grown from nothing to $7 million in only a year*".

Every **diagnostic ultrasound scan** performed in hospitals worldwide since 2008 has been undertaken under the safety guidelines **[5.2]** which Leighton co-authored for WFUMB, and which were informed by his research **[3.1]**. This amounts to around 700M births in the REF period **[5.2]**.

The 'Smart Stethoscope' device (now LithoCheck™) won The Engineer's" 'Medical and Healthcare' award 2008, and was finalist in the 2009 Unico's National Business Impact Award and finalist for a

2007 NHS Innovations award. Quoting Dr Fiammetta Fedele, Senior Physicist, GSTT **[5.3]**:

> "*Prof. Leighton's predictions of the acoustic signals emitted when bubbles collapse against kidney stones during* ***shock wave lithotripsy*** *(SWL) led (through collaboration with GSTT and Precision Acoustics Ltd.) to a £5,000 passive acoustic sensor (patent applied for)). When placed on the patient's skin this sensor diagnoses successful SWL treatments (with 94.7% accuracy in clinical trials, compared to the 36.8% achieved by clinicians with the current ~£1M state of the art equipment suite)* ***[3.6]****. An accurate diagnostic is needed to conform with the 2004 'THE NHS IMPROVEMENT PLAN: PUTTING PEOPLE AT THE HEART OF PUBLIC SERVICES' of reducing the 'patient pathway', because currently 30-50% of SWL patients require re-treatment and an unknown number are overdosed. The device won The Engineer's 2008 Medical and Healthcare award. The NHS is trialling it as part of major plans to reduce inaccurate diagnoses and ineffective treatments. GSTT has used the sensor on over 100 patients* [from 2008-2012]".

INDUSTRY - The **ultrasonic cleaning** research by Leighton and Birkin (appointed lecturer in UoS in 1994) led to a patented cleaning device **'**StarStream**'** that won the Royal Society's £250,000 Brian Mercer Award for Innovation 2011. StarStream also won the 2012 Institute of Chemical Engineering Award for "Water Management and Supply" (sponsored by Veolia Water). Three multinationals have paid £130k to the University in the last 2 years for licenses and associated contracts, Leighton and Birkin are collaborating with Philips (who funded the development of a prototype) with regards to consumer products. Sellafield Ltd. also funded the development of 2 prototypes (one now in radioactive zone at Sellafield): to quote Alex Jenkins **[5.4]** *"the University staff have embraced the opportunity of working with industrial partners to see their technologies making a difference in the workplace and wider society".* Prototypes have been tested for cleaning artwork for the Tate Gallery, and are now on trial in 3 labs for hospital decontamination, dental and orthopaedic uses. The MD of Ultrawave Ltd. **[5.5]** described StarStream as "*the only true technological leap forward in ultrasonic cleaning that we have seen for decades*" (see **[5.0]**).

As cited in his 2012 election to the Royal Academy of Engineering, Leighton developed ultrasonic bubble sensors for the US Dept. of Energy's for the Oak Ridge National Laboratory's (ORNL's) US$1.4 billion **Spallation Neutron Source (ORNL SNS) [3.4]** which serves numerous industries.

The acoustic technology for **quantifying underwater gas leaks [3.2]** was reported by Norwegian oil and gas industry to be '*at least two orders of magnitude more sensitive than current model-based techniques for large, long pipelines'* (to quote Statoil and Gassco experts in **[3.2]**). Statoil invited Leighton & White to help shape their plan for deployment of their hydrophone acoustic logging unit, and funded them to analyse the data from it.

The **3D Chirp sub-bottom profiler** was licensed for production to GeoAcoustics Ltd., and has been used in archaeological expeditions, by the MoD for the identification of unexploded ordnance, and to investigate offshore geohazards (Norwegian Deepwater Project oil industry consortium). This work has also culminated in a commercialization agreement for 3D Chirp with Kongsberg-GeoAcoustics Ltd. (2004-present), which has just sold its first system (First Institute of Oceanography, Qingdao, China).

DEFENCE - Regarding **TWIPS, the world's only sonar which can work in bubbly waters [3.5]** (which led to the acclaimed TWIPR radar **[5.0]**), Dr Trivedi (senior engineer, BAE Systems) said:

> "*Following publication of the world's only sonar which can work in bubbly waters [3.5] we commissioned further study from Leighton and White to investigate the applicability of their sonar technique in underwater scenarios of interest to us (details classified). This is a top priority for BAE Systems Maritime Services*" (see **[5.6]**).

The MoD asked Leighton: to advise on Improvised Explosive Devices technology as a member of its **Brains Trust** (Science and Technology Rapid Assistance to Operations programme), leading to TWIPR radar **[5.0]**; to become an ordinary member of the Defence Scientific Advisory Council, MOD (2004-8), in particular working on the **Maritime Mine Countermeasures Workgroup**; to provide training to military staff on littoral sonar; with 3 others from Defence Scientific Advisory Committee, to conduct a **Review of Underwater Acoustics Research** throughout all of MoD and related industry (the classified report now informs MOD policy).

The research on **sonar in turbid waters** was cited in the award of the 2006 Institute of Physics Patterson medal as giving MOD the sonar predictive ability to assess sonar performance in such waters in post-2008 operations (details classified).

ENVIRONMENT - Leighton's quantifying **air/sea gas flux** was part of the Natural Environment Research Council's UK Surface-Ocean/Lower Atmosphere Study (SOLAS). SOLAS advised the House of Commons Science & Technology Committee **[5.7]** and informed a UNESCO report **[5.8]**. The **acoustic undersea leak detection technology [3.2]** has been included in *Science for Environment Policy* **[5.9]**, the European Commission's environmental news service for policy makers, distributed to 14,000 subscribers.

PUBLIC ENGAGEMENT - Example items (these, and more, can be downloaded from **[5.0]**):

• **Sound in space** - The equations developed for StarStream were adapted to produce a device to simulate sounds on other planets (including a voicechanger). This was licensed to Intech's Astrium Planetarium for the world's first planetarium 'sound in space' show (shown to audiences since April 2012) which 93% of 545 audience responses rated 'good' or 'great'. Also covered (April 10, 2012) by Discovery Channel TV (115 Youtube hits incl. 'Let's get building some robots, get them there, test this stuff out'); and was basis for a question in 19th annual Dutch national TV Christmas Science Quiz (140 Youtube hits incl. 'This was my favourite show'). Secondary impact via 15 radio shows in New Zealand, Ireland, UK, a feature on Pod Academy (online comments include 'Excellent piece. Thought-provoking'), more than 20 articles by the public and journalists, around 10 public exhibitions (incl. plenary lectures at Brighton Science Festival and Southampton Multidisciplinary week – 332 Youtube hits), and even a fashion show! (see **[5.0]**).

• **Ultrasonic cleaning -** The Starstream technology featured in the top national science TV shows in Italy (2621 Youtube hits, including 'Bellissimo video, Grazie'), Germany (325 Youtube hits), UK (117 Youtube hits incl. 'She is right - that cleaning machine is magic!'). Videos were posted on the Royal Society (2739 Youtube hits incl. 'such a great idea!') and Ultrawave Ltd. websites (1151 Youtube hits incl. 'It is amazing'). Secondary impact was via 7 radio shows in UK, Germany and Ireland, and >50 blogs by public and journalists (see **[5.0]**).

• **TWIPS sonar -** The Royal Society produced a video for their webpage, and a 1-hour interview in USA was on *Dr Kiki's Science Hour TV, (TV Episode 139)* 'How do we sound' (339 Youtube views including 'bloody hooked!'). Secondary impact was via one national radio show and over 60 blogs/articles by public/journalists (see **[5.0]**).

• **Humpback whale bubble netting -** In a direct precursor to TWIPS, in 2004 Leighton pioneered the theory of how humpback whales produce 'walls of sound' when catching prey using bubble nets. Now standard patter for whale watching tour guides, it featured (without naming Leighton) in BBC1's "*Nature's Great Events: 3*-The Great Feast" *(Sir David Attenborough)*; National Geographic TV "Humpbacks: Cracking the Code", 2008 (363 Youtube hits, incl. 'wonderful!'), CBBC (Children's BBC) 'Deadly Top 10' (1054 Youtube hits, incl. 'me and my kids love this'); and inspired a Russian composer Leighton had never met to compose a piano sonata on whale themes and dedicate it to him (see **[5.0]**). Leighton gave guest lessons to primary and secondary schools on this.

• Leighton's **apparatus for ORNL SNS** was developed into a teaching demo and filmed for BBC1 TV *Richard Hammond's Engineering Connections,* Series 3 Episode 5 "Space Shuttle" (broadcast 5 June 2011; 39,762 Youtube hits); and 12 blogs by journalists and the public (see **[5.0]**).

5. Sources to corroborate the impact

[5.0] Download TV, radio and blog clips from http://www.southampton.ac.uk/engineering/research/impact/bubble_acoustics.page?#media
[5.1] Managing Director, Moog Insensys Ltd. **[5.2]** Barnett S *et al.* (*incl. Leighton, co-author esp. for chapters 2 and 4*) 1998. *World Federation for Ultrasound In Medicine and Biology, Task Group Report for Safety Committee of the* WFUMB: Conclusions and recommendations on thermal and non-thermal mechanisms for biological effects of ultrasound. *Ultrasound in Medicine and Biology*, 24, Supplement 1 (59 pages). **[5.3]** Medical Physicist, GSTT. **[5.4]** Technical Specialist, Sellafield Ltd**. [5.5]** Managing Director, Ultrawave Ltd. **[5.6]** Consultant Engineer, BAE Systems. **[5.7]** House of Commons Science & Technology Comm. 'Marine science: 9th Report of Session 2012–13' HC727 (11/4/13) http://www.publications.parliament.uk/pa/cm201213/cmselect/cmsctech/writev/727/contents.htm
[5.8] Ocean Fertilization: A Scientific Summary for Policy Makers (2011) UNESCO http://unesdoc.unesco.org/images/0019/001906/190674e.pdf **[5.9]** 'New bubble-based technique for leak detection at CCS offshore sites,' "Science for Environment Policy": European Commission DG Environment News Alert Service DG ENV News Alert Issue 267 (2011) ec.europa.eu/environment/integration/research/newsalert/pdf/267na6.pdf