Institution: Cranfield University		
Unit of Assessment: 12		
Title of case study: Efficient liquid to gas mass transfer in the water sector		
Period when the underpinning research was undertaken: 2008 to 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Ewan McAdam	Professor in Membrane Science and Technology	2008 – Present
Phil Hart	Professor in Energy and Power	20/08/2018– Present
Athanasios Kolios	Reader in Risk Management & Reliability Engineering	01/02/2009 - Present
Bruce Jefferson	Professor in Water Engineering	01/04/1997 – Present
Period when the claimed impact occurred: August 2013 to December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

Cranfield University's research on liquid-to-gas mass transfer has underpinned development and deployment of separation technology in both drinking water treatment and non-sewered sanitation. The research has demonstrated how controlling the driving force for dissolved gas separation can minimise energy demand, enhance separation efficiency and improve the quality of recovered products, subsequently enabling opportunities for reuse. In addition to economic, regulatory, and environmental benefits, this research informed and influenced the structure and thresholds within the recently published ISO 30500 standard on non-sewered sanitation, which has been adopted by 18 countries.

2. Underpinning research (indicative maximum 500 words)

Many industrial processes (healthcare, food, and beverage) now preferentially use bubble-free liquid-to-gas mass transfer technologies to improve gas transfer efficiency. Contemporary challenges on compliance and energy recovery have advanced penetration of this technology into the water sector. However, water quality, solute chemistry, and industry's desire to recover and convert separated gases into products, makes solute transfer (e.g., Trihalomethanes (THMs) and methane) from liquid to the receiving gas phase (typically air) more complex. Energy demand is also emphasised since municipal water flows are significant.

Research initiated in 2008 by Prof. McAdam has established novel scientific approaches for dissolved gas separation, ultimately delivering technological solutions for the separation [R1, R2], purification [R3, R4] and transformation of dissolved gases [R5, R6] into the water industry. Dissolved gas removal is achieved by establishing a concentration gradient to encourage migration from the liquid to a sweep gas. Currently industry apply an excess of sweep gas to maximise this concentration difference as this reduces technology capital cost, but as a consequence increases energy demand and prevents product recovery. An enabling contribution of this research for permanent (carbon dioxide, methane) and non-permanent gas (e.g., THMs) separations has been to show that:

(i) Dissolved gas mass transfer can still be effectively controlled at lower concentration gradients [R2, R3],

(ii) High interfacial area technologies can offset capital cost versus conventional approaches [R1]; and,

(iii) Counter diffusion of ternary gases from the sweep gas can enhance product quality beyond that theoretically predicted based on the concentration gradient established [R3].

The collective contribution of this research (2008-2020) is that low energy, compact and inexpensive dissolved gas separation can be achieved, coupled with the co-creation of gas products that can be applied directly to energy generation [R3] or resource recovery (e.g., water via a phase change) [R4, R6].

This scientific approach on liquid-to-gas mass transfer was extended to clean water production from heavily contaminated sources (e.g., toilet wastewater), in which sweep gas was used to introduce a vapour pressure difference between gas and liquid phases, subsequently initiating the selective separation of water vapour (non-permanent gas) from wastewater, to produce a high-quality water product from contaminated water sources [R2, R4]. Investigation of this separation revealed that dissolved gas mass transfer is not constant when concentration gradient is purposefully limited, which contradicted long held assumptions [R2]. This insight fostered a generic approach to mass transfer characterisation on which new liquid-to-gas mass transfer technologies were developed [R1, R2], including the 'nanomembrane toilet', an integrated household scale system for water recovery from wastewater [R4]. A further contribution of this research has been to identify that surface fouling of transfer technologies is controlled by the high molecular weight organic fraction [e.g., R1], whereas inorganic adhesion is governed by a kinetically controlled metastable region [R6]. The proof of the kinetic trajectories required to avoid surface fouling have been provided through McAdam's European Research Council fellowship (2017 to 2022).

Named staff have collectively published over 20 related papers and submitted four patent applications, through research jointly funded by industry (Anglian, Northumbrian, Scottish, Severn Trent, Yorkshire Water), NGOs (Bill & Melinda Gates Foundation) and RCUK.

3. References to the research (indicative maximum of six references)

[R1] Cookney, J., Mcleod, A., Mathioudakis, V., Ncube, P., Soares, A., Jefferson, B., & McAdam, E. J., (2016) Dissolved methane recovery from anaerobic effluents using hollow fibre membrane contactors, *Journal of Membrane Science,* 502 141-150. https://doi.org/10.1016/j.memsci.2015.12.037

[R2] Wang, C.Y., Mercer, E., Kamranvand, F., Williams, L., Kolios, A., Parker, A., Tyrrel, S., Cartmell, E., & McAdam, E.J., (2017), Tube-side mass transfer for hollow fibre membrane contactors operated in the low Graetz range, *Journal of Membrane Science*, 523, 235-246. https://doi.org/10.1016/j.memsci.2016.09.049

[R3] McLeod, A., Jefferson, B., & McAdam E.J., (2016), Toward gas-phase controlled mass transfer in micro-porous membrane contactors for recovery and concentration of dissolved methane in the gas phase, *Journal of Membrane Science,* 510, 466-471. https://doi.org/10.1016/j.memsci.2016.03.030

[R4] Hanak, D.P., Kolios, A.J., Onabanjo, T., Wagland, S.T., Patchigolla, K., Fidalgo, B., Manovic, V., McAdam, E., Parker, A., Williams, L., Tyrrel, S., & Cartmell, E., (2016), Conceptual energy and water recovery system for self-sustained nano membrane toilet, *Energy Conversion and Management*, 126, 352-361. https://doi.org/10.1016/j.enconman.2016.07.083

[R5] Bavarella, S., Brookes, A., Moore, A., Vale, P., Di Profio, G., Curcio, E., Hart, P., Pidou, M., & McAdam, E. J., (2020) Chemically reactive membrane crystallisation reactor for CO_2–NH_3 absorption and ammonium bicarbonate crystallisation: Kinetics of heterogeneous crystal growth, *Journal of Membrane Science* 599, 117682. https://doi.org/10.1016/j.memsci.2019.117682

[R6] Bavarella, S., Brookes, A., Moore, A., Vale, P., Di Profio, G., Curcio, E., Hart, P., Pidou, M., & McAdam, E.J., (2020) Is chemically reactive membrane crystallisation facilitated by heterogeneous primary nucleation? Comparison with conventional gas-liquid crystallisation for ammonium bicarbonate precipitation in a CO_2-NH_3-H_20 system, *Journal of Crystal Growth and Design*, 20 1552-1564. https://doi.org/10.1021/acs.cgd.9b01276

4. Details of the impact (indicative maximum 750 words)

Meeting drinking water quality standards (Scottish Water)

This research enabled the first direct deployment of liquid-to-gas mass transfer technology into the UK water industry for the removal of THMs from drinking water. The Water Industry Commission is the Regulator in Scotland and uses an Overall Performance Assessment (OPA) to gauge Scottish Water's performance. A key 'OPA component' is on drinking water quality where the level of service provided to customers is determined by the percentage of compliant samples. In 2013, Scottish Water embarked upon the first deployment phase (Phase 1) of liquid-to-gas mass transfer technology into 17 water treatment works serving rural catchments to reduce THM sample failures, in order to improve their OPA score, and ensure customer safety, as there is a suggested link between chronic exposure to elevated levels and carcinogenic effects.

During the design phase, McAdam was instructed to specify mass transfer technology, and operating conditions to achieve set THM treatment targets proposed by Scottish Water. Following commissioning, McAdam advised Scottish Water on technical modifications to newly commissioned liquid-to-gas mass transfer technologies, where design measures based on Cranfield University's low energy mass transfer research were applied to overcome site constraints which limited power and compressor options, in order to improve the targeted removal of THMs. The Capital Liaison Team Manager who oversaw implementation of these investments for Scottish Water noted,

> *" The advice from Cranfield helped us greatly and contributed to a better WQ [Water Quality] OPA position for Scottish Water".* [S1]

Cranfield's design measures continue to positively impact on water quality for Scottish Water within the present REF period (2014-Present) through improving compliance to the 17 works which underwent installation of liquid-to-gas transfer technology in the first implementation phase (Phase 1), as well as informing on the design of new installations (Phase 2). Scottish Water described how the,

> *"…information on bubble size, gas transfer and air to water ratio provided by Cranfield has continued to be applied including to two of our most recent systems installed in Ayrshire"* [S1] (Capital Liaison Team Manager).

These two systems were installed in 2019, as part of a Phase 2 rollout, bringing the total capital investment in liquid-to-gas transfer technology to GBP4,000,000, and increasing the total number of installations to 41 individual drinking water works across Scotland all of which were based on principles founded through Cranfield research.

ISO 30500 on non-sewered sanitation systems

Since 2012, Cranfield University has been developing liquid-to-gas mass transfer technology that permits selective separation of water vapour (non-permanent gas) from wastewater, by introducing sweep gas to create the necessary driving force for mass transfer, subsequently producing purified water from contaminated wastewater (PCT/EP2017/054816) [S2a&b]. This membrane technology has been licensed to a major sanitaryware manufacturer in China (contract reference, P15931) [S3].

This is the core technology within the 'nanomembrane toilet', developed by Cranfield through strategic investment from the Bill & Melinda Gates Foundation (B&MGF), within their 'Reinvent the Toilet Programme', which aims to provide access to equitable sanitation and hygiene for all to eradicate present practices which kill nearly 500,000 children under 5 each year. This represents an entirely new market, with an estimated value exceeding USD8,400,000,000 (03,2021). However, no ISO Technical Committee existed to address sustainable non-sewered sanitation systems. In 2015, Tüv Süd (Product Certification Service Provider) were instructed by B&MGF to develop a globally recognised consensus standard, beginning with a Private Standard, which transformed into an International Workshop Agreement (ISO IWA 24). ANSI subsequently adopted ISO IWA 24 for publication as an International Standard.

Tüv Süd requested advice from Professor McAdam on materials selection, product specifications, standards, and test protocols during Private Standard development. The Senior Program Officer, who led investments in International Standards for the Bill & Melinda Gates Foundation described how,

> *"Cranfield's technical expertise in developing the integrated 'Nano-membrane Toilet' system for non-sewered sanitation, greatly influenced development of the ISO 30500 standard"* [S4]. (Senior Program Officer, Bill & Melinda Gates Foundation)

McAdam and Kolios were subsequently appointed to the Private Standard technical committee to provide advice to Tüv Süd on the standards specification and thresholds adopted. They continued to serve on the IWA committee up until adoption of the IWA by the ISO (for confirmation, see p6, ISO PC305, August 2016 [S6]).

> *"Their specific expertise in separation of liquid/solid streams …was instrumental to understanding and assessing the state of the art for different processing technologies which in turn supported the development of a comprehensive yet practical standard. Cranfield made strong technical contributions across different standard development phases from first International Workshop Agreement (IWA) through to publication of the full ISO standard.* [S5b]

ISO30500: Non-sewered sanitation systems, was published in October 2018, providing general safety and performance requirements for the product design & performance testing of prefabricated integrated treatment units that are not attached to a network sewer or drainage system. The Standard has since been adopted nationally by over 18 countries: - North America (US, Canada), Europe (UK, France), Africa (e.g., Algeria, South Africa, Zimbabwe) and Asia (Bangladesh) [S7]

5. Sources to corroborate the impact (indicative maximum of 10 references)

[S1] Capital Liaison Team Manager, Scottish Water.

[S2a, b] [a] Treatment of Urine Family List of Patents Principal Investigator (PI),
[b] WO 2017/149035 A1 PCT/EP2017/054816 Patent Treatment of Urine.

[S3] P15931 Cranfield University – Jomoo License Agreement

[S4] Senior Program Officer, Bill & Melina Gates Foundation.

[S5a&b] Former Assistant Vice President, Business Development, Water Services, TÜV SÜD

[S6]	Final Draft IWA (ISO/PC 305) Sustainable non-sewered sanitation systems. On page 7, Athanasios Kolios is recognised as a committee member (August 2016). Evidence held on file.
[S7]	https://sanitation.ansi.org/Standard/StandardAdoptionMap