Institution: University of Oxford		
Unit of Assessment: 12 – Engineering		
Title of case study: Improving Efficiency and Accuracy in the Singapore Bunker Fuel Industry using Coriolis Flow Metering		
Period when the underpinning research was undertaken: Jan 2000 – Dec 2016		
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:**
Manus Henry	Associate Professor	1987-present
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Ronaldo Mercado	Post-Doctoral Researcher	2003-2008
Period when the claimed impact occurred: Jan 2015 – 31 Dec 2020		
Is this case study continued from a case study submitted in 2014? N		

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

The accurate measurement of fuel oil transferred to a marine vessel (in a process called bunkering) is technically difficult. Prior to the introduction of MFM (Mass Flow Metering, i.e. Coriolis Metering) the standard tank dipping technique was widely regarded as inaccurate, leading to widespread abuses and contractual disputes. From 2005-08, the Oxford team worked with Invensys and BP Marine to develop a pioneering Coriolis-based bunkering system. After lab trials in UK and Singapore, a demonstration system was installed on a bunker barge. Consequently, the Maritime Port Authority of Singapore (MPA, the world's largest bunkering port) trialled and introduced a mandatory MFM standard (2015), leading to economic and policy impact in the current REF period.

MFM has provided operational efficiency savings of around 3 hours per bunker, resulting in 10% more traffic through Singapore. Abuse cases are reduced, and the dispute rate is now 0.1%. Mandatory MFM use has been extended to include distillate fuels (2019), and is viewed by MPA as essential in supporting the International Maritime Organisation's (IMO) 2020 low sulphur regulations. In parallel, a MFM-based 'Net Oil&Gas Skid' (i.e. a standalone metering system), developed by the Oxford team, has been formally approved in Russia for the challenging problem of metering mixtures of oil, water and gas produced by oil wells. This skid supports improved efficiency and productivity in oil reservoir management.

2. Underpinning research (indicative maximum 500 words)

MFM is a widely-used industrial measurement technology which, until the pioneering work of the Oxford group, had a well-documented issue: poor operation with mixtures of liquid and gas, a common condition in industrial processes. [**R1**] The Oxford group, in a research collaboration with industry partner Invensys, pioneered the move from analogue to digital drive for Coriolis metering, with Invensys' first commercial product being launched in 2002 (US Patent 6,311,136). [**R2**] The Oxford group conducted research into the development of novel Coriolis drive techniques, able to overcome digital delay to precisely match the phase of the output drive signal to that of the flowtube sensor signals, while also being able to start oscillation in a flowtube where the resonant frequency is initially unknown. This was achieved in the first instance using a mixture of processor and Field Programmable Gate Arrays (FPGA) implementation (US Patent 6,950,760). [**R3**] While the resulting device demonstrated improved precision and dynamic response, the most significant advantage was its ability to maintain operation in presence of two-phase (gas/liquid) flows. [**R2**]

Even when flowtube oscillation is maintained, mixtures of liquid and gas introduce potentially large errors in the mass flow and density measurements, which have complex dependencies on a variety of factors including fluid properties and flowtube geometry. Further research identified the application of neural net modelling to provide measurement corrections (US Patent 6,505,519), so that the Coriolis meter can be used as an effective flowmeter in two-phase flow conditions. [**R4**] The Oxford Group's work entailed the development of robust research prototypes and extensive experimental programmes in a variety of laboratory and field conditions, including at the National Flow Laboratories of the UK and Russia; industrial commercial laboratories in Houston, Colorado, Boston and Singapore; and field trials in Texas, Wisconsin, Northern Alberta, Russia and Singapore. These field trials included monitoring the outputs of conventional oil wells and natural gas wells (with variable liquid content), as well as monitoring the injection of carbon dioxide into wells for enhanced oil recovery.

More recently the Oxford group further extended the technique to develop measurement for 'three-phase' mixtures of oil, water and gas produced in the upstream oil and gas industry. Additional instrumentation is required, including an infrared water cut meter indicating the relative proportion of water and oil, and pressure and temperature sensors, along with refined experimental programmes and modelling to solve the three-dimensional measurement correction problem. A prototype system matching the full operational requirements of upstream oil and gas systems was developed by the Oxford team. [**R5**]

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

[**R1**] Henry, M., Duta, M., Tombs, M., Yeung, H., Mattar, W. "How a Coriolis mass flow meter can operate in two-phase (gas/liquid) flow" Technical Papers of ISA, 454, pp. 17-30, 2004. Supplied on request. (Conference proceeding)

[**R2**] Henry, MP, Clarke, DW, Archer, N, Bowles, J, Leahy, MJ, Liu, RP, Vignos, J & Zhou, FB. "A self-validating digital Coriolis mass flowmeter: an overview", Control Engineering Practice 8: pp. 487-506, 2000. doi:10.1016/S0967-0661(99)00177-X (Journal article)

[**R3**] M. Zamora and M. P. Henry, "An FPGA Implementation of a Digital Coriolis Mass Flow Metering Drive System," in IEEE Transactions on Industrial Electronics, vol. 55, no. 7, pp. 2820-2831, July 2008. doi:10.1109/TIE.2008.925646 (Journal article)

[**R4**] Henry, MP, Tombs, M, Duta, MD, Zhou, F, Mercado, R, Kenyery, F, Chen, J, Morles, M, Garcia, C. "Two-phase flow metering of viscous oil using a Coriolis mass flow meter: a case study", Flow Measurement and Instrumentation 17 (2006), pp. 399-413, doi:10.1016/j.flowmeasinst.2006.07.008 (Journal article)

[**R5**] Henry, MP, Tombs, MS, Zhou, FB. "Field Experience of Well Testing using Multiphase Coriolis Metering", Flow Measurement and Instrumentation, 52 (2016), pp. 121-136. doi:10.1016/j.flowmeasinst.2016.09.014 (Journal article)

Grants

[**G1**] Clarke, DW, Henry, MP and Clark C. "Advanced Coriolis Mass Flow meter design". Awarded GBP320,000 by the EPSRC jointly to Oxford and Brunel Universities, Oct 2003

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

Pathway to Impact

It is surprisingly difficult to measure accurately how much fuel oil a cargo vessel takes on board when refuelling (known as bunkering). Marine fuel has high viscosity and the bunker transfer process frequently causes entrained air to mix with the fuel, rendering conventional measurement techniques unreliable. Prior to the research described above, the bunkering industry had long seen industry-wide dissatisfaction with the standard 'tank dipping' measurement due to inaccurate readings, widespread abuses and disputes in measurement. This had led to the desire to find an "irrefutable measurement". [**S1**]

In 2005 BP Marine, aware of the work of the Oxford/Invensys partnership, approached them to develop a Coriolis-based bunkering demonstrator. Given the large quantities of fuel transferred, a large flowtube with 8” diameter pipework was selected, and prototype electronics and software were developed at Oxford. This system included a communication system enabling remote monitoring and data transfers between Oxford and Singapore. After qualifying trials at the UK National Flow laboratory and a Singapore flow lab, a BP bunker barge operating in Singapore was fitted with the meter and a 3-month trial was carried out. Over the course of 80 commercial bunker transfers, the Coriolis meter results were compared with the conventional tank-dipping values, and a detailed analysis of the presence of entrained air in each transfer. In 2008 the BP Marine Project leader and Chairman of the International Bunkering Industry Association (IBIA) presented the results of the bunker barge trial carried out at Oxford at SIBCON 2008 which demonstrated that Mass Flow Metering was a technically and practically proven alternative to conventional methods. [**S1**]

Arising from this trial activity, in 2009 the Maritime and Port Authority of Singapore (MPA, the largest bunkering port in the world) announced a Standardization Committee to develop a standard for the adoption and use of mass flow metering in bunkering. This enrolled the technical committee that had been overseeing the Oxford/BP trial, providing direct continuity from the research phase into the standardization process in Singapore. [**S1**]

Between 2008 and 2010, the leading trade journal Bunkerspot published articles and held a series of workshops in Miami, Singapore, Antwerp, Rotterdam, and Dubai to further promote metering for bunkering, all chaired by Prof Henry. The Singapore session in 2009 included a presentation by the Chairman of the Technical Committee for Bunkering on the need for, and the path towards creating, an international standard for bunker metering, via the establishment of a Singapore standard utilising Coriolis Mass Flow Metering. [**S2, S3**]

Standardization in Singapore

Economic Impact – quicker, cost effective bunkering and a more transparent industry

In 2015 the Singapore MPA made Mass Flow Metering (MFM) the mandatory standard. The standardization in Singapore of MFM bunkering has led to significant cost savings within the industry in this REF period. Singapore is the largest and busiest bunkering port in the world where fuel transfers were 49,798,800t in 2018; with a typical price of approximately USD400 (10-2020) per tonne, sales are approximately USD20,000,000,000 (10-2020) a year. [**S4**] For context, the next largest bunkering port is Rotterdam where transfers of fuels were 9,890,091t the same year (only 20% of the volume that Singapore transferred).

MFM technology results in time and money saved for customers and the MPA Singapore. In 2014 OW Bunker (the largest bunker supplier at 7% of the global total, in 2014) reported a decrease of 50% in time taken to supply bunkers: as the average day rate for a Very Large Crude Carrier is USD24,000 (09-2014) this time equates to savings of around USD4,000 (09-2014) per day, based on a typical bunker duration of 8 hours for the trial barge. [**S5**] Likewise, ExxonMobil fitted its first MPA Singapore accredited MFM meter in 2015 and immediately began reporting similar savings: USD5,000 (12-2015) and up to 3 hours per delivery. [**S5**] These savings in time also benefit the port of Singapore; as a result of MFM, MPA reported average savings in time of 2.5 to 3 hours per bunker delivery (25% less than the original 12 hours) in the first 6 months of implementation, resulting in an increase of 10% in bunker tanker deliveries. [**S6, S9**] From 2014-19 the number of ships bunkering at Singapore every year increased from 22,218 to 25,059 vessels, with gross tonnage increasing from 707,464t to 929,854t. [**S6**] Thus, MFM has improved operational efficiency in delivery and turnaround for customers and the Marine Port Authority of Singapore.

MFM adoption has led to fewer disputes and improved transparency – an issue identified as prevalent in the industry. For example, Maersk estimated USD7,000,000,000 (12-2008) spent on fuel with an estimated average of 1.5% in discrepancies between supplier and vessel, totalling losses of USD100,000,000 (12-2008) to Maersk alone. The MPA Deputy Director (Port Services) at SIBCON 2018 informed delegates that, to date, there had been 70,000 MFM-based bunker deliveries, and now, owing to the accuracy of MFM, only around 0.1% of deliveries were subject to bunker disputes. [**S7**] Previously, speaking at the International Bunker Industry Association's (IBIA) Annual Convention in Singapore 2017, the Assistant Director of the MPA's Bunker Services Department reported that owing to the transparency this accurate measurement system offers, companies who falsify their records, are not compliant with the MFM systems, or have technical deficiencies have had their licences removed. From 2014-19 the number of licensed bunker suppliers has decreased from 59 to 45. [**S6**] This has resulted in a more level playing field across the bunkering community and a more transparent industry with fewer abuses. [**S7, S9**]

Policy and Environmental Impact of Mass Flow Metering – mandatory adoption and supporting the promotion of low sulphur initiatives

The Oxford team's development and demonstration of irrefutable quantity measurement for bunkering, led in turn to its gradually expanded scope and application to different fuel types, additional classes of fuel transfer operations (e.g. deliveries at oil terminals), and broader environmental considerations. The work of the Singapore standard committee, and the positive economic results from MFM, resulted in a mandatory requirement known as TR-48 (2015). TR-48 stated that from Jan 2017, Coriolis MFM metering was to be used for all bunker transfers. The first Singapore technical standard TR-48 was later revised as SS-648 (2019). [**S9**] This revision expanded the scope of MFM usage in Singapore and included deliveries of distillates, as well as marine fuel oil. MFM forms the backbone of the revision. The Chairman of the Technical Committee for Bunkering stated:

> *"Metrology and system integrity are the twin foundations of SS648 providing the base for MFM system approval and the bunker custody transfer process as detailed in the metering procedure. Extending these principles to bunker fuel transfer or delivery at oil terminals in a new Singapore Standard is the next major initiative to strengthen the Singapore's bunker supply chain, and build trust and confidence in the Singapore bunker industry."* [**S9**]

This SS-648 standard also included provision to support the International Maritime Organisation (IMO) 2020 low sulphur initiative for environmental protection, aimed at preserving the marine environment by minimizing pollution of the oceans and seas as laid out in MARPOL annex VI (2008). In order to comply, from 01 January 2020, the sulphur content of fuel oils on board ships must not exceed 0.50%. [**S8**] The press release for the SS-648 launch, in November 2019, entitled "New Standard to Support Maritime Sector's Shift to More Sustainable Fuels", included the following regarding MFM and how it will assist the shift environmental sustainability:

> "*The Singapore Standards Council has launched a new Singapore Standard, SS-648 - Code of Practice for Bunker Mass Flow Metering (MFM), to enhance the operational aspects for MFM bunkering and support the changing needs of the bunker industry as it transits to a low sulphur fuel oil regime in January 2020 to meet International Maritime Organisation (IMO) regulations. Harnessing technology and innovation, the use of MFM has led to numerous benefits for the bunker industry since its implementation. This includes improving the measurement process, increasing transparency, and boosting operational efficiency*." [**S9**]
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> "*SS-648, the first standard of its kind in the world, has an expanded scope and application to cover marine fuel oil and distillates as compared to TR-48 developed in 2015. Replacing TR-48, the new standard supports the industry's shift towards environmental sustainability*." [**S9**]

The Global Head of Commercial Operations, Maersk Oil Trading Singapore (n.b. Maersk is the largest global shipping company) said:

> "*The predecessor of SS-648, TR-48, has set the highest standards of transparency and accuracy for custody transfer of bunker fuels. It is not just about fitting a better piece of equipment, but aims to encompass a total system of trust within an industry otherwise fraught with ambiguity. The new Singapore Standard matches Maersk's core value of Constant Care so closely that Maersk Oil Trading is aiming to become the first physical supplier in the world to enforce SS-648 procedures on our barges globally*." [**S9**]

Beyond Singapore – Russia Oil and Gas Use

The impact of Oxford research in Mass Flow Metering extends beyond the bunkering industry, and MFM technology is being used to improve productivity in the oil and gas extraction industry in Russia. The NetOil&Gas measuring skid's core technology, developed at Oxford and produced by Invensys Foxboro [**R5**], received approval from the Russian standards agency GOST for use in upstream oil and gas applications in March 2012. In a partnership with Russian oil industry service provider HMS, Invensys sold systems to provide oil well testing equipment, either for fixed deployment or for truck-based mobile testing systems. [**S10**] As with bunkering, early field trials confirmed that the MFM method was more accurate, provided more reliable data, is quicker, and can improve oil output from wells when compared to conventional measurement methods. [**S10**] Later, the results of several hundred well tests confirmed these findings. [**R5**]

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

[**S1**] **a**) Letter from BP Marine project leader, IBIA Chair corroborating the flaws in the bunkering technology pre-MFM (2020) and **b**) presentation to SIBCOM 2008 corroborating the benefits and practicality of MFM due to the Oxford trials for bunkering, and the need for this over the existing methods (2008)

[**S2**] Petrospot Bunker Seminar by the MPA Chairman of the Technical Committee for Bunkering corroborating the benefits of, and establishing the case for, MFM for bunkering and the need for establishment of international standard (2009)

[**S3**] **a**) Letter from Managing Director, Bunkerspot and Petrospot corroborating the promotion of MFM bunkering via presentations and publications (received 2020) and **b**) a Bunkerspot news article evidencing MPA establishing the Singapore Standard (2009)

[**S4**] **a**) Ship and Bunker news article evidencing the fact that Singapore's 2018 sales were the second best ever annual bunker sales (2019) and **b**) Ship and Bunker website's "Daily Average Bunker Prices" corroborating the value of bunkering fuels (accessed 09-10-2020)

[**S5**] Bunkerspot news articles quoting bunkering companies corroborating the savings in money and time by adopting MFM on their VLCC bunkers from **a**) OW Bunker (2014) and **b**) ExxonMobil (2015)

[**S6**] **a**) Bunkerspot news article evidencing the savings made by MPA Singapore due to MFM and the number of licensed vessels decreasing (2017), **b**) MPA Singapore website download documenting the number of licensed bunker vessels in 2018 and 2019 (downloaded Oct 2020), and **c**) MPA Singapore website download evidencing the total number of vessels and gross tonnage 2014 to 2020 (downloaded Jan 2021)

[**S7**] **a**) Presentations by Maersk Oil Trading corroborating the discrepancies in the pre-MFM bunkering method (2008) and **b**) a Bunkerspot news article with the MPA Deputy Director (Port Services) evidencing fewer disputes in the industry due to MFM (2018)

[**S8**] IMO low sulphur initiative guidebook and corroborating how MFM is critical in implementing the standard (2020)

[**S9**] MPA Singapore press release describing the new SS-648 standard expanding MFM use in the port to distillate fuels and how MFM will support Singapore in switching to low sulphur initiatives (2019)

[**S10**] Evidence supporting improvements of MFM usage in the Russian oil and gas industry compared to conventional methods: **a**) Casimiro, R., et al., "New multi-phase flow metering technology available for industrial measuring units in the oil and gas industry, *Oil Field Equipment*, (2014) and **b**) the GOST approval (2017)