Institution: Edinburgh Research Partnership in Engineering

(ERPE: Edinburgh and Heriot-Watt Universities joint submission)

Unit of Assessment: UoA12 Engineering

Title of case study: Digital Displacement® technology delivers fuel savings in transport and construction sectors

Period when the underpinning research was undertaken: January 2000–September 2011

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:
W. Rampen	Professor, Chair of Energy Storage	01/10/2014 – present
S. Salter	Professor	01/02/1967 – 30/09/2004
D. Caldwell	Research Associate	2003-2007
J. Taylor	Research Associate, Research Fellow	1994 – 1999 1/07/2000 – 30/04/2011
J. Chick	Senior Lecturer	5/01/1999 – present
A. Kiprakis	Senior Lecturer	01/11/2010 - present
G. Payne	Research Associate, Research Fellow	2006-2011 01/06/2013 – 30/04/2017

Period when the claimed impact occurred: September 2014 – December 2020

Is this case study continued from a case study submitted in 2014? Yes

1. Summary of the impact

ERPE research by the University of Edinburgh (UoE) led to the development of hydraulic digital displacement technology, which optimises fuel savings and operational capabilities. Through a partnership with Artemis Intelligent Power Ltd (Artemis) utilising the existing underpinning research findings by ERPE staff during the period 2000-2011, the multiple engineering, business and environmental impacts include:

(A) World-first utilisations of the Digital Displacement® technology with major transport industry partners, in hybrid buses, diesel rail cars and rail passenger carriages;

(B) Fuel savings between 10% and 25% were demonstrated on rail and hybrid buses, with commensurate reductions in pollution and CO_2 emissions;

(C) Digital Displacement® pumps were deployed in full-size 16 Tonne construction excavators for the off-road market, resulting in fuel savings of 10-28%;

(D) Artemis growth was supported through a GBP22M investment from the Advanced Propulsion Centre UK and world-leading hydraulics company Danfoss Power Systems, to establish a new UK manufacturing facility, supporting 60 existing and 30 new jobs to enable further inward investment, innovation and economic growth.

In 2015, Artemis was awarded the prestigious Royal Academy of Engineering MacRobert Award, based on the Digital Displacement® technology underpinned by the ERPE research.

2. Underpinning research

The team of ERPE researchers at the University of Edinburgh: Salter, Rampen, Caldwell, Taylor, Kiprakis, Payne and Chick; invented and pioneered the development of digitally controlled hydraulic drive technologies. Originally invented in 2001-2 to efficiently and flexibly convert variable, reciprocating-cyclic, slow-speed high-torque wave power [3.1] to uni-directional, constant high-speed drive power for generators, the technology was translated to

the independent control of single and distributed drive trains across diverse vehicle and renewable energy platforms.

The engineering research breakthrough was the development of high-speed digitally-controlled solenoid-operated poppet valves to individually control the admission and discharge of very high pressure oil into multiple chambers in hydraulic pumps and motors on a stroke-by-stroke basis. Annular ring-cams, driving pistons, distributed the working stresses over multiple lines of force and overcame the fundamental structural and fatigue limitations of previous technologies. From the earlier quasi-static control design, the concept achieved 'fully dynamic control' using the principle of Digital Displacement, registered as 'DD®' technology [3.2] and fundamentally enabled many tidal, wind and wave energy converter applications [3.3], all of which are characterised by high-force & slow-speed primary power [3.4]. Other applications included large and small vehicle drives [3.5] used in on- and off-road settings, including construction, agriculture, and storage. The published research led to international invitations to deliver keynote lectures at the Scandinavian International Conferences on Fluid Power, Linköping (2009, 2013 and 2017), American Society of Mechanical Engineers 2012, and the Institute for Fluids and Systems in Aachen, Germany (2014).

This novel digital electronic control increased the efficiency by enabling low-loss pumping strokes to be combined with very low parasitic-loss idle strokes, to meet the instantaneous flow requirements. Discharging the oil into high-pressure accumulators provided smoothing and energy storage. The reversible nature of the motors allowed them to return regenerated energy to store in the accumulators. The research developed adaptable algorithms that matched valve timing to shaft speed, pressure and flow, establishing a fluid power technology that offered increased part- and full-load efficiency over a wide range of input- and output-speed variation, as if the drive included a continuously variable-ratio toothless gearbox. Timing valves designed to operate at near zero flow velocities reduced losses and noise. Operating with multiple cylinders in a radial geometry that could be stacked axially, offered modular construction and increased power rating. The very fine control addressed the need for precision movement in materials handling, in end-product ranges from forklift trucks through front- and back-hoe excavators, to large earthmover drives.

This novel ERPE technology was developed in partnership with Artemis Intelligent Power Ltd and the company established new R&D state-of-the-art facilities (2008) in Midlothian near Edinburgh. Artemis and ERPE staff continued to collaborate in the development of the DD® engineering technologies through industrial PhD studentships. The company was acquired by Mitsubishi Heavy Industries Ltd (MHI) in 2010 and both organisations formed a strategic partnership to design the world's largest hydraulic transmission for MHI 7MW offshore wind turbine. In 2011 the first 1.5MW DD® wind turbine transmission was tested in the Artemis laboratory, which was expanded in 2012 to become a new 1,000 m^2 test facility. The research contributions underpinning Artemis DD® innovation were:

- Invention of high-speed digitally controlled valves, timed to control the flow of high pressure oil into multiple services in complex hydraulic systems [3.1];
- The design and system integration of a ring-cam to create a "hydraulic gearbox" [3.2] with one quarter of the losses of swashplate machines, ten times faster response and elimination of high-frequency noise;
- The development of computer control systems that included performance optimisation, on-line diagnostics and integrated automation;

These combined to enable Artemis to develop the world's largest and most efficient hydraulic transmissions, which could enable ever larger and more reliable wind and tidal turbines [3.3, 3.4], large off-road and other vehicles [3.5]. The paper [3.3] was the first dynamic model of a large hydraulic transmission. The Artemis system was engineered to be made from commonly available and recyclable materials (supporting circular economy objectives), using regular manufacturing processes to significantly reduce the cost and to ensure that the systems can be maintained by existing staff, making it globally accessible.

3. References to the research

[1] **Journal**. Salter, S.H., Taylor J.R.M. and Caldwell, N.J., "Power Conversion Mechanisms for Wave Energy", Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Marine Environment, Vol. 216, pp. 1-27, June 2002. https://doi.org/10.1243/147509002320382103 *This paper compares and contrasts energy conversion techniques from several international groups presenting 14 clear and concise design conclusions. It shows in detail the application of the Artemis DDTM technique for wave energy conversion.*

[2] **Journal**. Rampen, W., Ehsan M. and Salter, S.H. (2000) "Modelling of digital-displacement pump-motors and their application as hydraulic drives for non-uniform loads", Transactions of the American Society of Mechanical Engineers (ASME) Journal of Dynamic Systems, Measurement and Control, Vol. 122, No. 1, pp210-215.

https://doi.org/10.1115/1.482444 *A paper showing the fundamental operating characteristics of the DD® machines, also revealing transformation of fluid power along the common crankshaft for energy regeneration to an accumulator.*

[3] **Journal**. Payne, G.S., Kiprakis, A.E., Ehsan, M., Rampen, W.H.S., Chick J.P. and Wallace, A.R., (2007) "Efficiency and Dynamic Performance of Digital Displacement® Hydraulic Transmission in Tidal Current Energy Converters", Proceedings of the Institution of Mechanical Engineers Part A: Journal of Power and Energy, Vol. 221, No 2, (Paper 207), pp. 207-218, March 2007. https://doi.org/10.1243/09576509JPE298

[4] **Conference**. Rampen, W., Riddoch, F. and Taylor, J.R.M. (2006) "Gearless Transmissions for Large Wind Turbines", DEWEK –Conference of the German Wind Energy Association, Bremen, Nov. 2006. *This paper describes the DD® transmission for multi-megawatt wind turbines, revealing the general layout of an integrated pump and main rotor, with twin motor and generator units.*

[5] **Conference**. Taylor, J.R.M., Rampen, W., Robertson, C. and Caldwell, N. (2011), "Digital Displacement Hydraulic Hybrids", Japanese Society of Automobile Engineers Annual Congress 2011. *This paper details a drive system designed for a hybrid bus.*

4. Details of the impact

The strategic partnership with ERPE researchers and ensuing underpinning research led to a series of impacts through Artemis Intelligent Power Ltd (Artemis). This case study outlines and continues the significant impacts arising with Artemis during the REF 2021 period, 2014-2020, involving Artemis (the primary beneficiary of the underpinning research [3.1 – 3.5] relating to Digital Displacement pump technologies 'DD®' as detailed in the REF 2014 submission). The impacts with Artemis in this return period include the following.

(A) Digital Displacement Technology Transmissions Installed in Trains and Buses

During 2013-15 Artemis worked with leading engineering companies Ricardo and Bombardier on the project 'Digital Displacement Rail Transmission with Flywheel Energy Storage' which was supported by Innovate UK. Using the Artemis Digital Displacement pump-motors, based on [3.1, 3.2], the project demonstrated the recovery of braking energy from diesel multiple unit (DMU) rail cars, storage of the energy in advanced Ricardo flywheels and then its re-use to save diesel fuel during vehicle acceleration. Such energy recovery is commonplace in electric locomotives, but not diesel power units, and there are many rail routes where electrification is unlikely to be economically feasible in the foreseeable future. According to Ricardo this application *"achieved a fuel saving of 10% and …means that the technology has a potential return on investment of inside five years."* [5.1].

In 2014, Artemis in joint partnership with Lothian Buses and Alexander Dennis, an international coach manufacturer, building on [3.5], developed a hybrid bus system using the DD® technology and achieved a 2-3 year return on investment, under similar passenger-route-miles conditions, without subsidy [5.2].

(B) Demonstrated Fuel Savings Leading to Lower Pollution and CO_2 Emissions

The hybrid bus system using DD® technology demonstrated fuel savings of 25% [5.2]. In June 2018, Artemis was awarded the top environment prize at the UK National Railway Innovation Awards for their fuel savings and emissions reductions, following their partnership project with Scotrail [5.3]. By 2020, Artemis had demonstrated through various joint partnerships (2015-2019), that using DD® technologies across diverse rail stock types [5.4], could lead to fuel savings and environmental benefits such as:

- Diesel locomotives (saving 2,500 to 5,000 litres of fuel annually; and 6T to 13T reduction in CO_2 emissions);
- Track maintenance vehicles (saving 7,000 litres of fuel annually per vehicle; approx. 20%);
- Diesel Class 170 Scotrail Turbotrain carriage vehicles (saving 9,000 litres of fuel annually per vehicle, 6.7%), during a 7-month in-service assessment.

In July 2015, Artemis and staff were awarded the prestigious Royal Academy of Engineering *MacRobert Award* – the 'premier award for UK innovation in engineering' – for the invention and development of Digital Displacement technologies [5.5]. The award 'identifies outstanding innovation with proven commercial success and tangible social benefit'. The judging panel selected Artemis for helping *'to solve one of the most significant global challenges while demonstrating technical engineering excellence*' [5.6].

Dame Sue Ion DBE FREng, Chair of the judging panel, said "*The Artemis story is truly compelling…and has achieved a technical advance of global importance, and… facilitating the global goal of reducing CO_2 emissions. This is not simply evolutionary improvement but a complete step change, and one that took years of commitment to achieve*. *The Artemis Digital Displacement system is both an incredible piece of invention, and a brilliant example of detailed engineering design. It represents excellence in multiple facets of engineering, from control system technology to software and elegant mechanical design … Artemis has produced a unique, world-beating product and is realising significant commercial success as a result. As a UK SME, Artemis represents the very best of modern UK engineering with global significance*." [5.6]

(C) Digital Displacement® Pump in Full-size 16 Tonne Excavators (off-road market)

In 2016 Artemis entered the off-road arena by building on the Digital Displacement pumps research [3.2] for utilisation into a 16T excavator to demonstrate to major original equipment manufacturers (OEMs) the fuel economy and productivity benefits of the technology in the off-road machinery market, annually worth USD3.5 Billion.

Funded with support from Scottish Enterprise, the project replaced the existing pump with a tandem Digital Displacement pump. All modern excavators have a number of problems: the conventional mechanical pumps have substantial energy losses, as the valve systems waste fluid energy by throttling flow to control multiple axes. In 2017, Artemis reported that 70% of the engine shaft power of a modern excavator was lost as heat in the hydraulic system [5.7]. Using DD®, derived from the original underpinning ERPE research [3.1, 3.2], Artemis developed fine-control that unlocked the ability to convert engine power, delivered at the optimum operating point, into repeated linear motions. Comparative testing of the modified and standard excavators showed that when the modified excavator was operating in 'efficiency mode' a fuel saving of up to 21%, and a productivity improvement of 10%, was possible. In 'productivity' mode, a 28% productivity improvement was recorded with a 10% fuel saving [5.7].

(D) Company Support and New Jobs

Up to 2013, based on the technologies underpinned by the research reported, Artemis/MHI had accumulated a portfolio of 87 patent families and had secured support from Scottish

Enterprise, Energy Saving Trust, Carbon Trust, Technology Strategy Board and the Department for Energy & Climate Change.

In October 2018, and building on [5.7], Artemis secured GBP11,000,000 investment from the Advanced Propulsion Centre UK, to help develop the next generation of 'Digital Displacement' hydraulic pumps and motors [5.8] to be used in off-road vehicles such as excavators, wheel loaders and material handling equipment. This was part of an overall GBP22,000,000 project, collaborating with global mobile hydraulics manufacturer Danfoss and Scottish firm Robbie Fluid Engineering [5.8].

In November 2018, it was announced that, building upon the potential of Artemis and Danfoss leading edge technologies and engineering capabilities, a new multi-million pound manufacturing plant would be established near Edinburgh [5.9]. Many key ERPE researchers had already been employed among Artemis 60 staff, either directly or through secondments. This facility will increase the people employed to 90 staff.

From January 2021, Artemis will be called **Danfoss Scotland Digital Displacement Ltd.**
NOTE: Construction and completion of manufacturing plant has been delayed due to COVID-19 restrictions.

5. Sources to corroborate the impact

[5.1] Artemis webnews: Partnership with Bombardier and Ricardo – Fuel savings in rail vehicles of 25% (June 2015). http://www.artemisip.com/saving-fuel-in-rail-vehicles/

[5.2] Artemis brochure for bus vehicles, stating the 25% fuel savings (April, 2015)

http://www.artemisip.com/wp-content/uploads/2017/11/2017-11-07-Bus-brochure-v4-web.pdf

[5.3] 2018 National Railway Environment Award for Artemis (June, 2018)
http://www.artemisip.com/artemis-scoops-environment-prize-at-national-railway-innovation-awards/

[5.4] Article in 'Rail Professional'. Evidencing the fuel savings and CO2 reductions using the Artemis Digital Displacement technologies for diverse rail vehicles. (June, 2020)

http://www.artemisip.com/wp-content/uploads/2020/06/200601-Rail-Professional-June-2020.pdf

[5.5] News article, MacRobert Award (2015), http://www.artemisip.com/124-2/

[5.6] Royal Academy of Engineering – MacRobert Award, the premier award for UK innovation in engineering (July, 2015)

https://www.raeng.org.uk/news/news-releases/2015/july/artemis-intelligent-power-wins-macrobert-award-uk

[5.7] iVT-Off-Highway Annual 2018. Article - summarising fuel savings and productivity improvements of E-dyn 96 DD Hydraulic Pumps in modified 16Tonne excavator (Nov, 2017)

http://www.artemisip.com/wp-content/uploads/2017/11/iVT-Off-Highway-Annual-2018-4-pages.pdf

[5.8] Major investment to develop and manufacture digital displacement technologies for the off-road-vehicles market, such as excavators. (Aug, 2018)

http://www.artemisip.com/artemis-intelligent-power-launches-22-million-project-to-develop-low-carbon-off-road-vehicles-of-the-future/

[5.9] New multi-million pound investment into UK by Danfoss Power Systems into new joint manufacturing plant and new 30 new skilled jobs (Nov 2018)

https://www.bbc.co.uk/news/uk-scotland-scotland-business-46151201