Institution: Edinburgh Research Partnership in Engineering

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

Unit of Assessment: UoA12 Engineering

Title of case study: Autonomous intelligent control valves enhance oil recovery and environmental sustainability

Period when the underpinning research was undertaken: 2001 – July 2015

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:
David Davies Khafiz Muradov Ivan Grebenkin	Professor Associate Professor PDRA	1996-2017 2011- present 2013-2014

Period when the claimed impact occurred: August 2015 – December 2020

Is this case study continued from a case study submitted in 2014? No

1. Summary of the impact

Global environmental pressures are increasing to avoid the opening of new oil wells and to optimise outputs from existing wells. Existing technologies can only recover less than one third of the reserves that they reach due to ingress of water or gas. ERPE researchers at Heriot-Watt University investigated and modelled an innovative intelligent Autonomous Inflow Control Valve technology (AICV®) within a multi-partner industry consortium, led by the Norwegian limited company InflowControl AS (InflowControl). Impacts arising include:

(A) – AICV technology is now mass-manufactured in multi-country supply chains including the UK and has been installed in over 100 petroleum industry wells worldwide;

(B) – InflowControl, a start-up company in Norway, now with a USD 17 Million turnover;

(C) – Oil recovery has been enhanced, where AICV is deployed, by an average of 38% with consequent increases in revenue and savings in production costs;

(D) – New knowledge and practice across the international industry sector deriving from the ERPE parametric approach to optimising AICV deployment; and

(E) - Water ingress and co-produced waste can be reduced by up to 89% with consequent positive environmental impact.

2. Underpinning research

Enhancing oil recovery (EOR) from existing wells is a strategic aim of the UK Government Oil and Gas Authority, the European Union and international bodies, and a key imperative for multi-national and national oil companies and their supporting supply chains, including many Small to Medium Enterprises (SMEs). Environmental pressures require production companies to increase and optimise outputs from existing wells rather than open new ones. Around the world, however, only 32% of the available reserves are extracted from existing oil fields, leaving 68% behind. A major challenge in oil production is to enhance and maximise the total oil recovery from the reservoir. Such low oil recovery rates are mostly due to ingress of water or gas into the well. In the early 1990s, the oil industry introduced Inflow Control Devices (ICDs) to passively control the influx of fluids into a well. Multiple ICDs restrict flow inside a petroleum production well to improve its productivity. Field experience demonstrated that ICDs could only balance the well influx initially but, being passive, could not adapt to the changes in the inflow conditions as the well matured over its production life. To reduce water and gas ingress, known as ‘breakthrough’,

on an ongoing basis over the lifetime of the well required the development of active, rather than passive, control.

This led to the development of Autonomous Inflow Control Valve (AICV) technology that would require pioneering ERPE complex modelling of the geo-statistical features of different reservoir geologies and production inflows to ensure that their deployment was effective.

Development of this new AICV technology was enabled by a collaborative, interdisciplinary effort. The EU Framework 7 REVIVAL project [P1] (2013-2015) was completed by a European consortium of four SMEs, one large company and three research and technology developers (RTDs), with Heriot-Watt University (HWU) as the lead university. The consortium was led by InflowControl, a Norwegian company that was the primary inventor of AICV technology.

As one of the world leaders in inflow control technology research, ERPE prior studies (2001-2013) underpinned the research in REVIVAL. An ERPE Joint Industry Project (JIP) 'Added value from Intelligent Well Technology' started in 2001, supported by an international consortium of petroleum operator and service companies. By 2013 this project and its multiple successors, funded by over 20 oil companies, produced over 40 publications on inflow control technology. Notable contributions, relevant to the subsequent REVIVAL's AICVs studies, included:

[3.1], 2005 – was the first research to relate the geostatistical features of different geology reservoirs to their suitability for the flow control device technology. The REVIVAL project's AICV suitability for various oil field geologies was informed by this research.

[3.2], 2007 – this research thoroughly reviewed the application, modelling, and evaluation of the types of inflow control device technology in oil and gas fields. This technology assessment framework was later extended to include REVIVAL's AICV studies.

[3.3], 2010 – these studies developed comprehensive analysis, assessment, application, modelling, and screening of all the inflow control device technology types commercially available at the time. This work was a fundamental enabler of ERPE REVIVAL studies that compared the performance of AICVs to other earlier ICDs and demonstrated the AICVs' potential advantages, leading to their adoption by the industry.

ERPE contribution to REVIVAL (2013-2015):

ERPE modelled the long-term, oil recovery benefit of the AICV technology and defined and quantified the criteria that determined the suitability of an oil-field for AICV deployment. The ERPE team led the development of a reservoir recovery model for AICVs that assessed their necessary flow performance, evaluated their application envelope and quantified their long-term benefits at oil-field scale. This was vital to assess the potential of AICV for improving oil recovery and thereupon in justifying the investment in AICV technology. The stages of the work were as follows:

In Stage 1, comprehensive research delivered the first collected appraisal of all available types of flow control devices in use and identified where an AICV was best-suited and most economically able to increase yield.

In Stage 2, AICV performance modelling approaches were critically analysed and a parametric basis developed to determine how they could immediately be used in several leading, commercial, reservoir simulators. The parametrised AICV flow model that ERPE developed also enabled optimisation of AICV performance to achieve a required reservoir response (later related to the quantity of its 'good' and 'bad' water or gas flows (as explained below).

In Stage 3, the approach was also applied to multiple generic reservoir models to demonstrate the potential benefit and application envelope of the AICV technology, and to provide appropriate guidelines on its assessment and adoption [3.5].

The ERPE modelling of a wide range of possible generic oil fields, geologies, fluid properties, and production scenarios informed the engineering design and optimisation of AICV technologies within the REVIVAL consortium.

In Stage 4, the above work was extended to derive and produce a novel, generalised approach to modelling, evaluation and fast optimisation of flow performance of any type of AICV. This used 3D mapping of a parametrised response to a given reservoir and was illustrated for AICVs in heavy oil reservoirs [3.6].

The ERPE team showed that the AICV technology would promote the flow of 'good water' (i.e. the level of unwanted fluid acceptable in the efficient oil production in wells) while restricting the 'bad water' (i.e. the level of unwanted fluid adversely affecting the oil production performance in wells), and how the AICV flow performance should behave to achieve this [3.4, 3.5, 3.6]. This informed the AICV engineering design of the REVIVAL consortium that was able to achieve the optimal AICV flow performance.

3. References to the research

[3.1] **Conference**: Ebadi, F., Davies, D., Reynolds, M. and Corbett P. (2005) 'Screening of Reservoir Types for Optimisation of Intelligent Well Design', Society of Petroleum Engineers Conference. Paper SPE-94053-MS. https://onepetro.org/SPEEURO/proceedings-abstract/05EURO/All-05EURO/SPE-94053-MS/74591

[3.2] **Conference**: Al-Khelaiwi, F. and Davies, D. (2007) 'Inflow Control Devices: Application and Value Quantification of a Developing Technology', Society of Petroleum Engineers Conference, Paper SPE-108700-MS. DOI: 10.2118/108700-MS https://onepetro.org/SPEIOCEM/proceedings-abstract/07IOCEM/All-07IOCEM/SPE-108700-MS/142623

[3.3] **Journal**: Al-Khelaiwi, F., Birchenko, V., Davies, D. and Konopczynski, M. (2010) (WellDynamics), 'Advanced Wells: A Comprehensive Approach to the Selection Between Passive and Active Inflow-Control Completions', Paper SPE-108700-PA, Journal of SPE Production and Operations, Vol. 25 (Issue 3), pp305-326.

https://doi.org/10.2118/132976-PA

[3.4] **Report**: REVIVAL deliverable D5.1 'AICV Reservoir Module'. (2014) Khalid Eltaher, E., Muradov, K. and Davies, D. (reviewed and approved by InflowControl) **– confidential.**

[3.5] **Conference**: Khalid Eltaher, E., Muradov, K., Davies, D. and Grebenkin, I. (2014) 'Autonomous Inflow Control Valves - their Modelling and "Added Value"', Society of Petroleum Engineers Conference, Paper SPE-170780-MS https://doi.org/10.2118/170780-MS

[3.6] **Conference**: Khalid Eltaher, E., Haghighat Sefat, M., Muradov, K. and Davies, D. (2014) 'Performance of Autonomous Inflow Control Completion in Heavy Oil Reservoirs', International Petroleum Technology Conference. Paper IPTC-17977-MS https://onepetro.org/IPTCONF/proceedings-abstract/14IPTC/All-14IPTC/IPTC-17977-MS/153425

Related Research Project Funding:

P1 – Davies (PI): REVIVAL, EU FP-7-SME grant 605701, (EUR1,498,683), Aug,2013- Jul,2015

4. Details of the impact

Lift, processing, transportation, storage and disposal of unwanted fluids (i.e. trapped water and gas in the geological reservoirs) co-produced with oil is one of the most expensive, energy consuming and environmentally unfriendly activities in petroleum production. It is also a key factor limiting the quantity of oil recovered during production. The range of impacts resulting from the ERPE research resulted in not only in a **world-first new technology** that significantly reduced this co-produced residue but also delivered a **series of multi-partner country economic, business and environmental impacts** as follows.

(A) Development of a multi-country partnership supply chain for AICVs

The primary objective of the REVIVAL project was to develop an innovative low-cost, high-performance Autonomous Inflow Control Valve to enable increased recovery of oil by preventing breakthrough of water and gas into the oil well. ERPE research [3.4-3.6] underpinned this

development and led to a multi country partnership to manufacture and commercially test the AICV technology including: InflowControl (Norway), HP Etch (Sweden), International Syalons (UK), Seal Engineering (Norway), RT Filter Technike (Germany), Norner (Norway) [5.1]. Today, '*InflowControl sources the AICV parts from suppliers in Norway, Sweden, France, Germany, the UK and Switzerland, and assembles these parts in Norway to produce the AICV*' [5.2].

(B) World First Installation and Company Growth

InflowControl was a new start-up company in Norway. As a result of the ERPE modelling, the benefits of the technology were quantified, the technology was adopted and the world's first installation of the AICV occurred in August 2015 [5.3]. InflowControl confirmed that, by November 2020, AICVs had been '*installed in over 100 wells worldwide'* [5.4] and the 2019-20 turnover for InflowControl from AICV technology and deployment had been circa USD17,000,000 [5.1].

(C) Economic Impact with International Reach

Each oil field may typically require 100 valves [5.2] and the AICV modelling designed and developed by the ERPE team demonstrated [3.4] the positive impact of the AICV on the oil production and recovery rates, allowing full economic justification and payback to be clearly provided for different reservoirs/customers [5.1, 5.5].

Provision of quantifiable evidence from the ERPE reservoir simulation model assisted in overcoming a major marketing barrier by allowing customers to model the additional cost/benefits offered by the novel AICV system for their oil fields [5.1]. The CEO of InflowControl has stated that the '*research helped to identify and develop the best approach to model the performance of a well completed with AICVs in one or more reservoir simulator(s).*' [5.1]. The modelling also demonstrated the ability of the AICV technology to improve the production and recovery rates, enabling more complete economic appraisal of reservoirs to a wider customer base [5.1]. This enabled InflowControl to grow substantial global reach:

- By late 2020 inflow client companies were installing the AICV in '*Canada, Saudi Arabia, Russia, Oman, Norway, Bahrain and China. The AICV® wells cover a large number of applications, onshore and offshore, carbonate and sand stone, new and retrofit, ultra-light, light, medium, heavy and extra heavy oil for gas, steam, CO_2 and/or water choking/shut-off*' [5.6]. Further, the technology has demonstrated significant increase in oil production of 38% on average [5.4]. In some cases, depending on the geology and other characteristics of the oil field the AICV can increase oil recovery from 50% to 80% [5.2].

- InflowControl reported operational cost savings for a client in the Middle East in 2020, for one field alone in the 'first year' of operation, of USD2,000,000, with a 'water cut' reduction of 68%, (due to reduced water handling costs). Oil recovery from the existing wells as a result of the AICV deployment was enhanced by 18% [5.7].

- Another major operator with one of the largest fields in the world had areas of the field that could not be recovered, due to an excessively high Gas Oil Ratio (GOR). After fitting AICVs in a well, the GOR *'reduced by over 85%'*, resulting in significantly enhanced oil recovery [5.8].

- In a Middle East AICV deployment, '*within the first 12 months of the well having been brought on line with the AICV retrofit completion, the operator earned a net gain of over 51 times the cost of the retrofit completion, including rig costs'* [5.9]

(D) Optimisation Modelling and Knowledge Exchange for AICV Deployment

The ERPE underpinning research [3.4-3.6] showed how the AICV technology and modelling could be deployed successfully while also 'adding value' when compared to existing passive valve control technologies and approaches. This evidence through reservoir simulation models supported the InflowControl marketing strategy and the additional cost/benefits offered by the novel AICV system. With [3.4-3.6] and an early consultancy project for Woodside Energy by ERPE [5.5], to assess the future potential of the AICV, the engineering design process was informed across the consortium partners, which was previously stated by the CEO of

InflowControl as '*helping to identify and develop the best approach to model the performance of a well completed with AICVs in one or more reservoir simulator(s)*.' [5.1]. The ERPE findings and partnership with InflowControl has also been disseminated widely through the international network called the 'InflowControl Forum' supporting knowledge exchange involving major oil and engineering companies such as Total, Chevron, Shell & Halliburton [5.10]

(E) Positive Environmental Impact

Water and gas trapped in the geological reservoirs, co-produced with oil, is one of the most expensive, energy consuming and environmentally unfriendly activities in the petroleum business. Over 75% of fluid produced from oil reservoirs today is dirty water. ERPE researchers were the first to quantify the long-term potential of AICV technology to restrict inflow of unwanted fluids (improving environmental outcomes) and enhance oil recovery. Based on the results from the REVIVAL project, the performance and the functionality of the AICV were compared to competing technologies. The significant advantage of this AICV compared to the passively controlled valves is that it can operate actively and, if necessary, close completely to prevent breakthrough of unwanted fluids. Enhancing oil recovery and reducing co-produced waste reduces significantly the direct environmental impacts and importantly also reduces the operational carbon footprint [5.1] through reduced unwanted water/gas handling with consequent economic cost savings. InflowControl reported in 2020 that, across the range of client projects with AICV installations, *'the gas oil ratio (GOR) and/or water cut (WC) had been reduced significantly'* (by 89% on average) [5.4]. This has supported the environmental marketing aspects for InflowControl to their clients "*Environmental benefits are achieved by reducing gas and water production, which supports companies goals of being less carbon intensive within their total production operations"* [5.11].

5. Sources to corroborate the impact

[5.1] InflowControl, CEO; (Named individual who can be contacted to corroborate impact)

[5.2] EU Commission website outlining some of the AICV technology benefits. New valve increases oil recovery for better fuel security (2017) https://ec.europa.eu/research/infocentre/article_en.cfm?id=/research/headlines/news/article_17_02_08_en.html&artid=&caller=AllHeadlines

[5.3] World-first deployment of the AICV valve and system (August 2015).

https://www.inflowcontrol.no/news/five-years-since-first-global-aicv-installation/

[5.4] InflowControl technology success overview – detailing 100 wells, average increase in oil output 38% and 'water decrease 89%'(2020) https://www.inflowcontrol.no/aicv-technology/used-in-over-100-wells/

[5.5] Woodside Energy Ltd, Chief Reservoir Engineer; (Named individual who can be contacted to corroborate impact – of the first assessment on deployment impacts and return)

[5.6] Applications to diverse oil field types, new and retrofit and range of countries. https://www.inflowcontrol.no/aicv-technology/retrofittable/

[5.7] InflowControl case study, '68% Water Cut Reduction: 6 AICV® Wells Within a Mature Heavy Oil Field', (2020). https://www.inflowcontrol.no/case-studies/case-study-3-68-water-cut-reduction-in-6-mature-heavy-oil-wells/

[5.8] InflowControl case study, 85% Gas Shut-off in Mature Carbonate Reservoir with Ultra-Light Oil', (2020).https://www.inflowcontrol.no/case-studies/case-study-1-85-gas-shut-off/

[5.9] JPE short paper by InflowControl – Demonstrating significant benefits within first year and also 51:1 ratio revenue return on install costs (May, 2020).

https://jpt.spe.org/autonomous-valve-controls-excess-water-gas-production-increase-oil-recovery

[5.10] InflowControl Forum (2017) where ERPE experts were 3 of the 15 presenters at the international knowledge exchange event, demonstrating the novel AICV technology and modelling optimisation capabilities to major oil and engineering companies. (Event Programme)

[5.11] InflowControl website. 'About us, leading the way'. https://www.inflowcontrol.no/about-us/