Institution: University of Strathclyde

Unit of Assessment: 12

Title of case study: Commercial impact of innovative design of a new oil and gas well service pump range

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

Economic impact was achieved through transfer of research (2010-2012) to the design of a new fluid-end for *Weir SPM* oil & gas well service pumps. Field tests have demonstrated the new Duralast™ design, based on Strathclyde research, gives double the working life of previous designs. The new pump features have now been introduced across the entire SPM fluid-end range. These robust new pumps enable hydraulic fracturing and recovery of extensive unconventional oil and gas resources, delivering a major impact on global energy supply. Duralast™ has provided market differentiation and increased market share to Weir SPM, generating [text removed for publication] since October 2012.

2. Underpinning research (indicative maximum 500 words)

Context:

The hydraulic fracturing process, or *fracking*, uses high down-hole fluid pressures to create fissures in the rock that enhance or enable recovery of hydrocarbon resources. The required fracking pressure developed by the pump depends on reservoir geology. Development of formerly inaccessible hard-shale natural gas resources has seen a significant increase in the required operating pressure of frack pumps. The Vice President of Engineering Weir Oil & Gas (Source 1) has noted: "*As unconventional drilling became more prevalent, pumping pressures trended upward. This had a detrimental effect on the service life of our equipment. At Weir SPM, we recognised we needed a step change in frack pump technology to significantly improve durability and reliability*". Weir SPM consequently engaged with Strathclyde researchers to design a fluid-end with enhanced structural integrity and improved operating life. This project drew on key research findings from Strathclyde research, from 2002 onwards, in pressure vessel design by analysis, specifically: global failure mechanisms, the effect of local geometry on stress concentration at structural discontinuities, and optimisation of the autofrettage process for maximum fatigue life.

Key Findings:

Six journal papers detailing the main research outputs utilised in the Case Study are identified in Section 3.The relevant research findings fall into three categories:

1. Development of new finite element analysis methodologies and criteria to determine the plastic collapse load of complex 3D structures [Refs 1, 4, and 5]. This includes investigation of the effects of material strain hardening and large structural deformations on static ductile failure of pressurised components. This work was used in the case study to establish safe maximum working pressures for the fluid-end design.
2. Identification and quantification of the effect of local structural discontinuity (design detail) on elastic stress concentration at cross-bores in thick cylindrical pressure vessels [Refs 2, 3]. Research showed that features reducing stress at one specific region could cause increased stress at other locations: a global rather than local approach is required to ensure overall stress reduction. Detailed computer analysis provided quantitative information on reducing stress concentration through off-setting cross-bores in thick cylindrical vessels. This research informed design of the internal fluid-end geometry in the case study and led directly to the new, patented offset cross-bore design.
3. A methodology to optimise the autofrettage process for maximum fatigue life of complex pressurised vessels was proposed. The location of the maximum alternating stress, which limits the fatigue life of the vessel, was found to change with the degree of the plastic deformation/residual stress induced by the autofrettage process. This new methodology [Refs 3, 6] tracks changes in the location of the limiting alternating stress range with increasing autofrettage pressure. This procedure was used in the case study to determine the optimum autofrettage pressure for the fluid-end designs developed.

Key Researchers at University of Strathclyde:
The research was carried out from 2002 onwards. The Principal Investigator was Prof D Mackenzie, (then a Senior Lecturer/Reader), working with Strathclyde academics Dr T Comlekci (Lecturer) and Dr J Wood (Senior Lecturer) in the Department of Mechanical Engineering.

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

References 1, 3 and 5 exemplify the underpinning research quality, and reference 5 in included in REF2, UoA 12 submisison:

1. Muscat M, Mackenzie D and Hamilton R, "A work criterion for plastic collapse," Int. J. Pres. Ves. & Piping, 80, 49-58, 2003.
2. Makulsawatudom P, Mackenzie D & Hamilton R, "Stress Concentration at Crossholes in Thick Cylindrical Vessels," J. Strain Analysis for Engineering Design, 39, 471-481, 2005.
3. Comlekci T, Mackenzie D, Hamilton R, & Wood J, "Elastic stress concentration at radial crossholes in pressurized thick cylinders," J. Strain Analysis, 42, 6, 461-468, 2007.
4. Camilleri D, Mackenzie D, & Hamilton R, "Evaluating plastic loads in torispherical heads using a new criterion of collapse," ASME J. Pres. Ves. Tech., 130, no.1, 2008.
5. Naruse T & Mackenzie D, "Design analysis of ductile failure in dovetail connections," J. Strain Analysis, 43(5), 295-306, 2008.
6. Li H, Johnston R & Mackenzie D, "Effect of Autofrettage in the thick-walled cylinder with a radial cross-bore," ASME J. Pres. Ves. Tech., 132, p. 011205, 2010. (Journal version of 2007 ASME Pressure Vessel & Piping Conference paper).

Other evidence for quality of research:
The research leading to Reference 4 was supported by EPSRC project: "*Development of Plastic Collapse Criteria for Pressurised Components*" D Mackenzie, R Hamilton & JT Boyle, EPSRC GR/81841/01, 2004-06: £98k.

4. Details of the impact (indicative maximum 750 words)
Process from Research to Impact
The project arose from discussions between the University and the Weir Group plc in 2009, in which Weir SPM identified improving the durability of well service pump fluid-ends as an immediate Research and Development priority.
The Vice President of Engineering Weir Oil & Gas (Source 1) has commented: "*Our first investment in new fracking pump technology was an 18 month collaborative research project with the University of Strathclyde to develop a new frack pump design that would meet market demands*".

Detailed technical discussions were held between Weir SPM and University researchers during March 2010. An 18 month R&D project investigating structural, material and flow aspects of fluid-end design was launched in April 2010 (£396k, funded by Weir SPM, Fort Worth, Texas, PI Prof D Mackenzie). The project objective was to design and develop a new high performance Oil & Gas Well Service Pump fluid-end that would:

- Extend product life under conventional well hydraulic fracturing conditions.
- Enable development of hard shale resources, which require significantly greater fracking pressures than conventional wells.

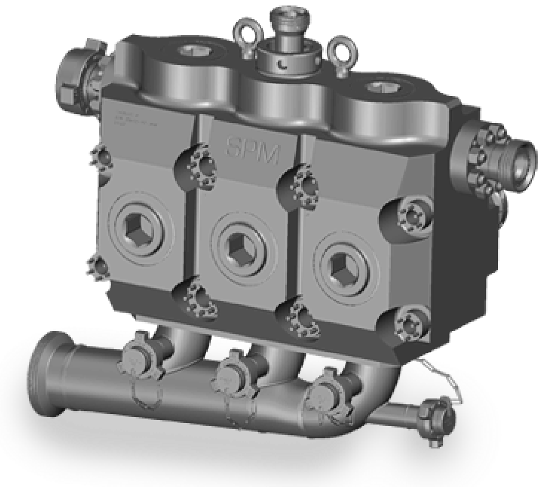
The gross static (ductile) strength of the fluid-end was assessed by employing the non-linear Finite Element Analysis methodology proposed in references 1, 4, and 5. The fatigue life was improved through detailed analysis of the pump internal geometry. A novel aspect of the new design was to off-set the intersection between the horizontal and vertical bores of the fluid-end, which results in lower intersection stresses than an in-plane intersection. This effect had been researched for cross-bores in cylindrical pressure vessels in Reference 3, but this is the first time the concept has been applied to a fluid end configuration. Two patents are pending for this novel design feature (*United States Patent Application Publications US 2010/0144995* and *2010/0183424*, July 2012). Further reduction in stress concentration was achieved through design by analysis of the valve

seat and valve seat deck, resulting in a new, long life, patent-pending configuration (World Intellectual Property Organisation, International Publication Number: WO 2013/116488 A1).
A further major improvement in fatigue life was achieved through specification of a new fluid end autofrettage procedure based on the methodology proposed in Reference 6. This procedure ensures that the optimum residual compressive stress is established in each individual fluid-end cylinder, reducing local mean stress at highly loaded locations and hence enhancing fatigue life. During the R&D project, the Strathclyde researchers worked closely with a Weir SPM design team in Fort Worth, USA. Weekly transatlantic “Webex” meetings were held to discuss design issues and transfer information throughout the project.

Types of impact from the research: The research has rapidly translated into benefits for Weir Oil and Gas as follows

Impact on Weir SPM Products:
A new fluid-end model based on the configuration and autofrettage specification proposed by Strathclyde researchers was finalised by Weir SPM towards the end of 2011.
Prototype fluid-ends were manufactured for test-bed and field testing in the first half of 2012. These tests demonstrated that:

- The new fluid-end design has significantly greater durability than the previous design, demonstrating double the field life of its conventional predecessor under standard operating conditions.
- The new design can accommodate greater fracking pressures than previous designs.



The new fluid-end design was launched by Weir SPM in October 2012 under the product name Duralast™ (see illustration). The new Duralast™ technology has now been incorporated in every Weir SPM pump product family (Source 2).

The Vice President of Engineering Weir Oil & Gas (Source 1) has stated: “*Having established the superior performance of the new Duralast design through testing and field trials, we took the decision to introduce the new technology across the entire Weir SPM fluid-end model range. This required a significant financial investment by Weir SPM - establishing a new design team to implement the design changes, adapting the manufacture process and introducing new testing procedures*.”

The company has also reported (Source 3): “*Fluid ends are a key aftermarket pressure pumping component used in shale oil and gas drilling operations. When a SPM® frac pump uses Duralast™, we project that it can have up to double the life of existing SPM® fluid ends. Using existing materials, Duralast™ can deliver operational cost savings while the technology can also be applied to fluid ends made with stainless steel and other alloys. Duralast™ fluid end technology will be initially launched for our Destiny™ frac pump range in the third quarter of 2012, before being applied across the full SPM® fluid end range*.”

Commercial Impact on Weir Group:
The main commercial beneficiary of the impact reported in this case study is the Weir Group PLC, a multinational FTE 100 business serving the Oil & Gas, Minerals and Power & Industry sectors. The introduction of the innovative new Duralast™ range of fluid-ends has resulted in substantial commercial advantage to Weir SPM over its competitors, delivering market differentiation and increased market share. The Vice President Engineering Weir Oil & Gas (Source 1) has stated: [text removed for publication].

Other Impacts:
The enhanced operating life of Duralast™ fluid ends at higher operating pressures will have a

direct impact on and benefit to fracking operators using Weir SPM equipment to develop unconventional oil and natural gas resources. The new products enable recovery of known extensive resources in hard shales, which require higher fracking pressures, and will have a major impact on global energy supply.

The International Energy Agency (Source 4: Golden Rules for a Golden Age of Gas, 2012) has proposed that unconventional gas resources, such as shale gas, could account for 32% of gas supply by 2035, leading to greater energy diversity, more secure supply in those countries that rely on imports to meet their gas needs, and reduced energy costs.

The success of the Duralast™ project led directly to the Weir Group establishing the Weir Advanced Research Centre at the University of Strathclyde in 2011, under the leadership of Centre Director Prof D Mackenzie. Fully funded by the Weir Group, (£1.95M in 2011-2013, and continuation funding 2014-2015 of £1.95M), the Centre carries out research in all aspects of pumping and flow control technology, which directly benefits Weir products and processes.

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

1. Vice President Engineering, Weir Oil and Gas, has provided statements to support the claim that the outcomes of Mackenzie's research delivered significant financial impact to Weir Group/SPM.
2. Weir Oil and Gas webpage http://www.weirinaction.com/innovation/spm-duralast-fluid-end-technology will support the claim that the research has transferred through to a new Weir fluid-end product range: Duralast design.
3. Press release http://www.prnewswire.com/news-releases/weir-oil--gas-launches-new-products-for-upstream-oil-and-gas-markets-149469565.html will support the claim that the Duralast product range has been launched in the fluid-end market, including specific products targetted at hard shale (high pressure) applications.
4. The International Energy Agency, Golden Rules for a Golden Age of Gas, 2012. http://www.worldenergyoutlook.org/media/weowebsite/2012/goldenrules/weo2012_goldenrulesreport.pdf will support the claim(s) that recovery of unconventional gas will have a major impact on global energy supply.