Institution:	**University of Manchester (UoM)**
Unit of Assessment (UoA):	**B10 (Mathematical Sciences)**

Title of case study:
Oilfield Reservoir Souring Research and Development

1. Summary of the impact

Accurate forecasting of oilfield souring is vital for the oil industry. Souring (an increase in concentration of toxic hydrogen sulphide) increases the cost of maintenance and repairs four-fold, and reduces the value of crude oil by up to 20%. Our research led to development of the World's first predictive models for the souring of oil-wells. The implementation of the models in software, commercialised by Rawwater Engineering Limited, provides accurate forecasts and has been validated by major Operators, including BP, Shell and Chevron. Since 2008, twelve different Operators have used the models in souring management, which has led to an estimated cost saving of US$360m since 2008.

2. Underpinning research

The impact is based on research conducted in the unit of assessment in partnership with the industrial company CAPCIS (a spin-out from UMIST). The key researcher was

Professor Patrick Laycock (Professor 1993 - 2001)

The research was initiated via the UK Oilfield Reservoir Souring Programme and a primary statistical analysis of a set of large databases supplied by the contributing oil companies was conducted before the assessment period. The research involved the development, in conjunction with biologists and chemists, of a biogenic souring model that describes the down-hole microbiological generation of hydrogen sulphide from sulphate, and dispersal of that hydrogen sulphide. The crucial insight was that the origin of the hydrogen sulphide is biological and dependent on the 'water flood' ('seawater injection for secondary recovery', which forces additional oil from the reservoir). The model development took place within the REF qualifying period (1993-1994) and initial models were published in 1993 [1] and 1994 [2].

Applied research into the practical control of souring continued at UMIST (now The University of Manchester) in collaboration with Rawwater Engineering Company Limited resulting in the sour gas forecasting model DynamicTVS© [3]. This complex mathematical model combines physical balance laws and data-derived descriptions of the biology. In general, it describes the cooling of an oil reservoir due to water flooding, the opportunity for growth of sulphate-reducing bacteria (SRB) in the cooled zone, the transport of the hydrogen sulphide produced by the SRB to the production well and finally the partitioning of the sulphide at specified pressure and temperature in the production facilities.

3. References to the research

The research was published as a report [1] for the Health and Safety Executive, London, which was peer reviewed by international senior scientists working in the Oil Industry; and in a peer-reviewed conference proceedings [2] of the fifth international symposium on chemistry in the oil industry, organised by the Industrial Division of the Royal Society of Chemistry. Citations are shown for

Google Scholar (GS) as of 30-9-13.

1. *Oilfield Reservoir Souring*, R.D. Eden, P.J. Laycock & M. Fielder, HMSO, OTH series: London, September 1993. [GS: 23]. http://www.hse.gov.uk/research/othpdf/200-399/oth385.pdf
2. Oilfield Reservoir Souring - Model Building and Pitfalls, R.D. Eden, P.J. Laycock & G. Wilson, pp 179-188, in Recent Advances in Oilfield Chemistry, pub Royal Society of Chemistry, London, 1994. [GS: 3] ISBN: 0851869416 / 0-85186-941-6
3. Dynamic TVS© Software Package, available through Rawwater Engineering Company Ltd, http://www.rawwater.com/souring

4. Details of the impact

Context

An oilfield reservoir has soured when an increased concentration of hydrogen sulphide H2S is observed in production fluids. This foul smelling and corrosive 'sour gas' is toxic to life and liable to cause cracking and pitting of susceptible steels [S1], leading to the failure of hydrocarbon pipelines both on land and subsea which can have a catastrophic impact upon both the environment and the Operators' (oil companies) public reputation. Reservoirs are categorised as either 'sweet' or 'sour', and the origin of H2S from an erstwhile sweet reservoir is linked to secondary oil recovery, in which (sea)water is injected into the reservoir to maintain pressure.

Prior to our mathematical modelling the phenomenon of souring was not understood and, accordingly, remediation measures were poorly targeted, expensive and usually ineffective. Only after the advent of our robust physical and numerical model was it possible for the Operator to identify the appropriate, targeted, prevention methodology and/or remediation treatment.

By 1993, the results of a previous statistical analysis of Oilfield Reservoir Souring had demonstrated strong correlations between seawater injection parameters and subsequent souring; more specifically those conditions which created a 'downhole' environment in which anaerobic sulphate-reducing bacteria could live. This was reinforced by field evidence. Based on these data, our research led to the development of a biogenic souring model to explain unexpected increasing concentrations of H2S in produced fluids.

Pathways to Impact

The initial modelling work was carried out as part of the UK Oilfield Reservoir Souring Programme at CAPCIS (Dr Robert Eden) and UMIST (Prof Patrick Laycock) and funded by the oil and gas industry. The very nature of the project ensured a swift introduction of the souring prediction algorithms based on our models into the industry. The early model forecasts were subsequently validated through field evidence and lead to the model's wider dissemination and use.

In 2000 Rawwater Engineering Company Limited was established and the originators of the DynamicTVS© model, Laycock and Eden were granted title to commercialise it. The research has followed a continuous development line funded by Operator money initially through the multiclient programmes and the UK Department of Energy, and then by single client studies.

The sponsors are now well represented in the Forbes 500 companies, and beyond, including BP, BG Energy Holdings Limited, Braspetro Petrobras Internacional S.A., ConocoPhillips, Chevron Corporation, Hoang Long JOC, Ithaca Energy UK Ltd, Lundin ASA, Mærsk Olie og Gas AS, Nexen Inc, Petro-Canada Inc., Rhodia UK Ltd, Saudi Aramco, Statoil ASA, Tullow Oil UK (Ltd) and Yara

International ASA.

Much of the work is necessarily confidential and so has unfortunately not been available for publication. However, the track record and positive reputation of the model and the technology has enabled Rawwater Engineering Company Limited to market the model's on-going development and exploitation through industry contacts and its internet presence [S2].

Reach and Significance of the Impact

The founding of Rawwater was a direct consequence of the understanding gained from our research. The company has built and operates the World's largest facility to study biogenic souring under simulated reservoir conditions using a suite of pressurised, flowing, sand-packed bioreactors, whose design was directly influenced by the research.

The only two souring forecasting models in common usage in the Oil Industry today are Rawwater's DynamicTVS©, a direct consequence of our research, and a more recent model SourSim©, released in 2006, which uses many of the ideas that we developed, and data from Rawwater's bioreactor suite. SourSim© is only available to a restricted set of Operators for incorporation in their existing reservoir simulation packages, but DynamicTVS© is commercially available to the entire global community (and therefore all potential beneficiaries of the research).

The research has had impact in the period 2008 – 2013 by providing revenue for Rawwater, with 10 associated jobs, and also by providing the Operators with assistance in souring management. One of the 'big five' Operators reports that today the cost of souring and its control consumes 1/3 of the production budget, and this same company has set aside $50M for souring research over the next ten years [S3].

With respect to impact of the DynamicTVS© model upon the Operators, the figure is difficult to calculate. For example, the specification of sour service materials, which resist cracking, will add 10% to the pipeline inventory costs (typically an additional US$1m per well). Since 2008, DynamicTVS© has been used by 12 Operators to either save costs against unnecessary treatments or to identify appropriate mechanisms to control souring (costs can be in the range of US$1M - US$10m per annum per 'typical' reservoir). This, in turn, has a direct impact upon 'lifting costs', oil quality and profit margin, but the precise details are commercially sensitive and not available for public scrutiny. Nonetheless an approximate calculation gives a net saving over the REF period of 12 operators x 6 years x US$5m /year = US$360m.

We can also describe an illustrative case study: in 2012 the output of the model was used to demonstrate that an Operator should not take delivery of a US$100m sulphate-removal plant allocated to the field for biologenic souring control. The model forecast that the field would not go sour and hence this sulphate-removal technology was inappropriate, despite the Contractor's insistence to the contrary. At a high level internal Operator meeting, the results of the model were endorsed by Contractor representatives and the sulphate-removal plant remained unsold [S2, S3].

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

S1] https://www.osha.gov/SLTC/etools/oilandgas/general_safety/h2s_monitoring.html
(Supports claim that sour gas is toxic and can damage metals)
[S2] www.rawwater.com/souring
(Demonstrates web presence of Rawwater and marketing of DynamicTVS)
[S3] Letter from Managing Director of Rawwater

(Supports all financial claims, details of Rawwater Engineering Company Ltd and further specific details of the impact)