Institution: University of Strathclyde

Unit of Assessment: 14

Title of case study: Economic and environmental benefits from commercialisation of a smouldering remediation process for heavily contaminated soil

1. Summary of the impact

Research by Dr Switzer since 2009 has led to scale-up and commercialisation of a new smouldering combustion-based remediation technology: Self-sustaining Treatment for Active Remediation (STAR). STAR is sold commercially by SiREM, a division of Geosyntec Consultants, Inc. that has an exclusive worldwide licence. Since its commercial launch in 2010, STAR has [text removed for publication] and now employs 5 staff. Clean-up rates for STAR far exceed those of other methods, achieving 99.9+% destruction of contaminants in the soil and delivering cleaned soil suitable for reuse.

2. Underpinning research

Context In the UK the Environment Agency estimates there are over 100,000 contaminated industrial sites within England and Wales alone. North American environmental liability is far higher because there are much larger areas of contaminated land. Simple, non-biological, easily engineered clean-up solutions are imperative to limit environmental liability. Historically, clean-up of soils heavily contaminated with organic liquids, such as coal tar, has been of very limited success. Switzer's research played a key role in the development of a treatment process for land polluted with tar and oil, which removes a high percentage of the contaminants.

Key Findings

The treatment process, named Self-sustaining Treatment for Active Remediation (STAR), uses targeted smouldering combustion to destroy organic liquid contaminants in soil and other porous materials. The heat generated by the reaction locally supports the propagation of the smouldering front through the remaining contaminated soil. STAR very quickly becomes self-sustaining, which means that it can provide all of the energy necessary to support itself, but is completely controllable by regulating the flow of air to the process. It has achieved better than 99.9% remediation in many cases and is particularly effective on high molecular weight hydrocarbons such as coal tar and oil wastes [2], which are among the most difficult organic contaminants to treat. There are two typical field deployments of STAR. *Ex situ* STAR treats waste materials in a reactor [1,4]; these materials may or may not be soils and may or may not require mixing prior to treatment. *In situ* STAR involves the application of smouldering with purpose built hardware to contaminated soils (or "made ground") in place. Each type of deployment has key advantages that make it appealing for customers with specific waste management needs. Commercial deployment of *in situ* remediation processes requires a two-stage approach to field implementation. Once a laboratory treatability study shows that a contaminated material is well-suited to STAR, an initial field remediation (Stage 1) is carried out to evaluate the technology in a representative test area before proceeding to full-scale remediation (Stage 2). Because of the complexity of applying remediation technologies in the field, multiple *in situ* tests may be carried out at the Stage 1 scale before proceeding to Stage 2. In an *ex situ* setting, on the strength of Stage 1 testing already carried out, many waste materials can proceed directly to Stage 2.

Successful progress of the STAR technology from research papers to commercial impact has relied on a number of key findings

- 'Beaker-scale' proof of concept that organic liquids, mixed with sand, can be converted to gases through the process of smouldering combustion leaving less than 0.01% residual contaminant mass [2].
- Development of the engineered STAR system using pilot scale studies from lab/column-scale through to 3m3 scale [1,2,4],
- Demonstration of in situ field-scale treatment of 300m3 of water-saturated soil in the US, that achieved a 99.7% soil contaminant destruction, including design of the necessary emissions capture and filtration systems on site. The soil was cleaned to a standard well below the

regulatory limits and the data from this demonstration project were shared commercially as part of a Project Spotlight
- Demonstration that following STAR treatment, the *in situ* soils remain largely stable and geotechnically usable for the purposes of subsequent construction and on-site operation [3,6]. Soils experience drying ahead of the STAR process [1,2,5], aggressive chemical reactions at the soil grain surface [2,6], and subsequent re-wetting via recharge from groundwater and rainwater infiltration after remediation [4]. Despite changes to the soil, it remains suitable for reuse [3].

Key Researchers: The research is the result of an international, interdisciplinary collaboration between the Universities of Strathclyde, Edinburgh, Western Ontario (Canada), and Queensland (Australia). Dr Switzer (environmental engineer) joined the University of Strathclyde as a Lecturer in January 2009. Dr Switzer's key academic collaborators are: Prof Tarantino (geotechnical engineer) appointed to Chair at the University of Strathclyde in March 2010; Dr Jason Gerhard (contaminant hydrologist) University of Edinburgh then University of Western Ontario; and Prof José Torero (fire safety engineer) Universities of Edinburgh and Queensland.
Dr Gavin Grant, Mr Grant Scholes, and Dr David Major lead the STAR team at SiREM.

3. References to the research

References 1, 2 and 3 best indicate the quality of the underpinning research. References 2 and 3 are included in the REF2 submission UoA 14.

[1] Grant, G., D. Major, J. Gerhard, J. Torero, G. Scholes, P. Pironi, and C. Switzer. Method for volumetric reduction of organic liquids, International PCT Application PCT/US2012/035248, filing date: 26 Apr 2012.

[2] Pironi, P., C. Switzer, J.I. Gerhard, G. Rein, and J.L. Torero. (2011) Self-sustaining Smoldering for NAPL Remediation: Laboratory Evaluation of Process Sensitivity to Key Parameters. *Environmental Science & Technology* 45(7) 2987-2993.

[3] Zihms, S., C. Switzer, J. Irvine, and M. Karstunen. (2013) Effects of high temperature processes on silica sand, *Engineering Geology*. (doi: 10.1016/j.enggeo.2013.06.004).

[4] Tarantino A, Gallipoli D, Augarde CE, De Gennaro V, Gomez R, Laloui L, Mancuso C, El Mountassir G, Munoz J, Pereira J-M, Peron H, Pisoni G, Romero E, Raveendiraraj A, Rojas JC, Toll DG, Tombolato S, and Wheeler S. (2011). Benchmark of experimental techniques for measuring and controlling suction. *Géotechnique*, 61(4): 303 –312.

[5] Browder, T. Switzer C., Pironi P., Rein G., Gerhard J.I., and Torero J.L. (2010) Remediation of Oil Drilling Waste Using Smoldering Combustion. Spring Technical Meeting of the Western States Section of the Combustion Institute, Boulder, CO. Paper # 10S-55

[6] Switzer, C., Zihms, S., and Tarantino A., Effects of high temperatures on soil properties: Lessons to share from smouldering remediation experience (online 2013) *Flamma*, 6 (1), 20-22, ISSN 2171 - 665X (https://sites.google.com/site/flammafgr/texto/volumen-6-2015/6-1-2015/6-1-6)

Other evidence for quality of research (grants, patents etc.)
The quality of the research has been recognised by Lord Ezra Award for Innovation in Combustion, awarded by the Combustion Engineering Association on 8 October, 2009. It has been supported by funding:
- C. Switzer, T. Aspray and J.L. Torero. Suitability of PAS100 accredited composts as filtration media for hazardous organic vapours from high temperature processes, funded by the Waste & Resources Action Programme. April 2009 – March 2010, £41,267.42
- EPSRC Early Career Researcher Small Equipment Grant to C. Switzer for STAR hardware, £8,100 (awarded 2012)
- SiREM contribution to PhD student scholarship at Strathclyde on STAR, £21,000 (awarded 2011)

4. Details of the impact

Process/Events from Research to Impact:
The original research team developing STAR consisted of Dr Switzer (lead experimental PDRA) and Dr Rein (computational PDRA) at the University of Edinburgh under the direction of Dr Gerhard (PI), Prof Torero (Co-I). All researchers moved to other institutions beginning with Dr Gerhard's departure to University of Western Ontario in 2007. Dr Switzer, Dr Gerhard, and Prof.

Torero agreed research licences with the University of Edinburgh to continue research on STAR. In 2009, Dr Switzer joined the University of Strathclyde and continued her research to develop the engineered system. This was first achieved at $3m^3$ scale [4] and then during *in situ* and *ex situ* field studies [Source B]. After 2009 Dr Switzer supervised Ph.D researchers with Prof. Tarantino focussing on scale-up of the STAR process (Robson) and geotechnical and geochemical properties of the resulting soils (Zihms), which industrial site owners and other clients have said are key issues.

Smouldering remediation technology is delivered commercially as Self-sustaining Treatment for Active Remediation (STAR) by SiREM, a division of Geosyntec Consultants, Inc., which is a multi-national environmental consultancy that employs 1000+ individuals [Source A]. SiREM was founded in 2002 with the mission of bringing to market unique, science-based products and solutions in support of groundwater remediation.

Types of Impact from the adoption of new technology:
Economic benefits: In 2010, STAR was officially launched within SiREM as a side project of one Geosyntec employee. In 2012, the first full time STAR employees were appointed. Since that time, STAR has grown to be a department (January 2013) with 5 employees working full time and varying numbers of other employees part time as needed on STAR projects. [Text removed for publication.] SiREM has formed strategic partnerships with two large, international Fortune 500 companies (who have asked not to be named). Stage 1 remediations with STAR have been carried out on contaminated materials from the USA, Canada, Australia, and Europe. STAR projects have been highly profitable for Geosyntec, given them access to new clients, and increased revenue to other parts of the company [Source A].

A major international manufacturing company commissioned the first in situ Stage 1 implementation of STAR at the site of a former creosol manufacturing facility in the USA in 2009. Dr Switzer provided extensive consultancy support during all stages of the remediation, including advice on planning and design of initial tests; experimentation at Strathclyde to develop the ignition protocol for in situ ignition; on site support during initial tests; monitoring and data analysis during the tests; and further analysis and interpretation after the tests [Source C]. During her time on site and afterwards, Dr Switzer trained SiREM personnel how to run STAR and interpret field data. Based on the success of these initial tests, the client commissioned the design of the full Stage 2 system for implementation in 2014 to enable redevelopment of the site in 2016. [Text removed for publication.] This client demonstrated their commitment to implementing STAR by terminating the lease with the existing site tenant (waiving additional income) and clearing the site for remediation. The Stage 1 remediation was published as a Project Spotlight [Source D] and has been presented at major remediation conferences around the world since 2010.

SiREM agreed a second strategic partnership with a Fortune 500 oil and gas company to commission a prototype ex situ reactor and a series of tests on its waste materials [text removed for publication] which it paid to ship from Australia to Canada. The design of this reactor was directly influenced by research [Refs 1,2,4]. Dr Switzer provided consultancy in the form of guidance during the design of the reactor, planning of initial tests, and interpretation of data after the tests.

Environmental impacts: STAR provides significant environmental improvements to sites contaminated with heavy hydrocarbons. In both of the cases outlined previously, STAR was the only viable option for remediation. STAR destroys 99.9+% of contaminant mass in place in the soil whereas competing technologies recover some of this mass and require its disposal as hazardous waste. STAR returns visibly cleaned soil that is suitable for reuse [Reference 3 and Source A]. Sustainability analysis by SiREM in year, for the client who commissioned the first in situ Stage 1 test of STAR, showed that remediation with STAR provided significant reduction in lifecycle carbon dioxide (CO2) emissions relative to their expensive dig and dump alternative because STAR generated most of its own energy for remediation. Analysis of greenhouse gas emissions in tonnes of equivalent CO_2 emissions (eCO2) showed STAR would emit less than 10% of other potential remediation approaches: 4,400 eCO_2 from STAR compared to 41,000 eCO2 for low temperature thermal desorption and 46,000 for excavation and disposal. This analysis, which was based on the

Stage 1 remediation supported by Switzer, created further value to the client who wanted to maintain their corporate reputation for sustainability alongside their commitment to remediate the site.

Practitioners and Professional Services: Dr Switzer tested field hardware (2009) and provided field trial support on site (2009-11), directly supporting field operations, interpreting critical process data, and effectively training SiREM employees on the job for in situ and ex situ Stage 1 tests. She provided further support remotely through conference calls, emails, and file sharing (monthly or more frequent engagement, (2009-present). Her interpretations were based on experience gained during the research, particularly scale-up and emissions interpretation [1,4]. The United States Environmental Protection Agency (USEPA) began including STAR in their training materials for remediation practitioners in 2012 [Source E]. USEPA is the main environmental regulator in the USA and the precedents that it sets have global implications for the uptake of STAR technology, as it meets these widely accepted standards. USEPA has conducted independent evaluations (2012-2013) of the technology and continues to advocate for STAR to USEPA project managers [Source A].

Reach and Significance:
SiREM and Geosyntec [text removed for publication] benefitted from the development of highly-skilled employees, and increased the potential to gain access to new sites and commercial clients. SiREM's clients are supporting the development of STAR because they see benefits from early access to this remediation technology, substantial cost savings, carbon footprint reduction, and reduction of their environmental liabilities. In many cases, STAR will be the only viable remediation option for their contaminated soil or waste. In three years of commercial activity, SiREM has formed strategic development partnerships with two major international Fortune 500 companies, each with unique waste management needs. Their investment activity has been key to demonstrate STAR in Stage 1 tests in both *in situ* and *ex situ* settings for contamination issues of worldwide relevance. One client has requested that Geosyntec develop a full-scale design of *in situ* remediation and that the potential application be staged to allow further evaluation of STAR to meet their remedial objectives. The USEPA now includes STAR in its training materials [Source E]. Further, rapid escalation of STAR is expected to follow these significant, initial developments.

5. Sources to corroborate the impact
A. Senior Engineer (SiREM) will support all commercial claims including generation of investment, employment, site operation, and remediation success. Consultancy of Dr Switzer, including conference calls, site visits, training of employees, and other engagement, was essential to their commercial development of STAR.
B. Head of School, School of Civil Engineering, University of Queensland will support Dr Switzer's research leadership, particularly with scale-up of the process (from lab, to in situ Stage 1 test, to full scale operation).
C. http://star.siremlab.com/publications.php shows references to Switzer's published research used by SIREM since 2009
D. http://star.siremlab.com/pdf/STAR%20Project%20Spotlight.pdf).
E. USEPA online presentation to the National Association of Remedial Project Managers Annual Training Program http://narpm.trainex.org/materials/724/DNAPL_CummingsPart1.pdf
will support the claim(s) that USEPA has incorporated information on STAR into their training materials for remediation practitioners. US EPA is aware in situ Stage 1 site is proceeding to Stage 2 full-scale remediation.