Institution:	Imperial College London
Unit of Assessment:	12 Engineering
Title of case study:	Corrosion Monitoring
Period when the underpinning research was undertaken:	January 2000 to December 2020

Details of staff conducting the underpinning research from the submitting unit

Name(s):	Role(s) (e.g. job title):	Period(s) employed:
Peter Cawley	Professor and Associate Dean for Enterprise	1981 to present
Frederic Cegla	Reader in Mechanical Engineering	2008 to present

Period when the claimed impact occurred: 1 Aug 2013 to 31 Dec 2020

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

1. Summary of the impact

Corrosion costs the oil and gas industry USD8,000,000,000 per annum in the USA alone. Concern about its impact on plant-life limits the operator's ability to take advantage of lower cost feedstocks because they are more corrosive. Our research solved this problem by monitoring corrosion in real time and in harsh conditions, with data transmitted directly to the plant control room. We invented two novel monitoring systems, one for high temperatures up to 600^{0}C and another for temperatures up to 300^{0}C with the ability to operate through coatings. The impact of our research is:

1. We founded a spinout company, Permasense Ltd, to commercialise the research. The company was sold to Emerson for GBP32,400,000 in 2016 and now employs 52 staff in the UK.
2. Over 20,000 corrosion sensors have been deployed in over 200 sites world-wide, generating revenues exceeding USD72,000,000 for the company over the current REF period.
3. Providing economic benefits and enhanced safety to companies in many industrial sectors including oil and gas, power generation and material processing companies, resulting in economic benefits estimated to be in several USD100,000,000 per annum.

2. Underpinning research

Corrosion costs developed countries 3.4% of GDP (Source A from Section 5) and the annual cost of corrosion to the US oil and gas industry alone has been estimated to be about USD8,000,000,000 (Source B from Section 5). Wall loss is usually detected from ultrasonic thickness measurements but a particular problem is monitoring the progress of wall loss at high temperatures that are beyond the operational range of most piezoelectric materials from which ultrasonic transducers are made. Following conversations with industry this issue was investigated by Cawley and Cegla in the mid 2000's. They used a waveguide as an 'acoustic cable' to transmit ultrasonic waves from a conventional transducer positioned outside the insulation to interrogate the hot structure. Previous work had looked at longitudinal modes in rod-like waveguides for this purpose but they suffer from dispersion if the waveguide is thick, and transmit most of their energy into surface waves if it is thin. They recognised that shear horizontal waves in a strip-like waveguide are essentially non-dispersive and will couple via a dry contact into a cylindrically spreading wavefield in the test piece. This was a significant breakthrough. The concept was patented [R1] and published in [R2] and [R3]. This work was commercialised through their spinout company Permasense as discussed later.

While the first generation of corrosion monitoring sensors resulting from their research can operate up to 600^{0}C, many potential applications require sensors that operate at lower temperature up to 300^{0}C, but with the added complication that the pipes are often coated, e.g. with fusion bonded epoxy. Clamping the waveguides onto this surface tended to damage the coating so it was necessary to remove it, leading to corrosion susceptibility at the interface. Electromagnetic acoustic transducers (EMATs) can potentially operate through coatings but they suffer from poor signal to noise ratio (SNR) and are generally excited with drive pulses of >100V and this is not allowed in a typical petrochemical plant where intrinsically safe operation is required. Cegla solved the signal-to-noise ratio problem by introducing two new ideas: flux concentrators [R4] and coded excitation [R5]. The research on flux concentrators showed that the ultrasonic signal is proportional to the square of the magnetic flux and a new compact magnetic circuit design was conceived that tripled the magnetic flux and improved the overall measurement SNR by roughly 20dB. This led to a further patent [R6] and an additional range of corrosion monitoring sensors that can penetrate pipe coatings. The research on coded excitation addressed the constraint that the maximum power of signals needs to be limited to avoid the potential of producing sparks in a hazardous environment and achieve safety (ATEX) certification for the sensors. Coded excitation achieves this by spreading out the energy over a longer time period and then pulse compressing the signal at the receiver. Conventional coded excitation could not be used in pulse echo mode (sending and receiving on the same transducer); the research led to a new coding scheme that enabled the use of very long excitation codes in pulse echo mode, improving the SNR of the measurement system by a further 20dB.

3. References to the research

R1. Cawley, P. and Cegla, F.B., 'Ultrasonic non-destructive testing', patent EP 1 954 413 B1, 2006 (priority date 4-11-2005).

R2. Cegla, F.B., ‘Energy concentration at the centre of large aspect ratio rectangular waveguides at high frequencies’, *Journal of the Acoustical Society of America*, Vol. 123, No. 6, pages 4218-4226, Jun. 2008. https://doi.org/10.1121/1.2908273

R3. Cegla, F.B., Cawley, P., Allin, J. and Davies, J., 'High-Temperature (>500°C) Wall Thickness Monitoring Using Dry-Coupled Ultrasonic Waveguide Transducers', *IEEE Trans UFFC*, Vol 58, pp156-167, 2011. https://doi.org/10.1109/TUFFC.2011.1782

R4. Isla J., Cegla F., 2016, ‘Optimization of the Bias Magnetic Field of Shear Wave EMATs’*, IEEE Trans UFFC,* Vol: 63, pp 1148-1160, ISSN: 0885-3010. https://doi.org/10.1109/TUFFC.2016.2558467

R5. Isla J., Cegla F., 2017, ‘Coded Excitation for Pulse-Echo Systems’, *IEEE Trans UFFC*, Vol: 64, pp 736-748, ISSN: 0885-3010. http://dx.doi.org/10.1109/TUFFC.2017.2661383

R6. Cegla, F. and Isla, J. ‘Electromagnetic Acoustic Transducer’, patent EP3213063A1, 2015 (priority date 29-10-2014).

4. Details of the impact

Context and history of impact

Corrosion in pipes is a serious problem in many industrial sectors, particularly in oil and gas. It is estimated that such corrosion problems cost developed countries 3.4% of GDP (Source

A). It has also been reported that in the US oil and gas industry alone, the annual cost is estimated to be about USD8,000,000,000 (Source B).

BP contacted Cawley in 2006 wanting a method that would allow them to monitor internal wall loss due to corrosion or erosion in pipes and vessels operating at high (>400^{0}C) temperatures during operation. The waveguide concept had recently been patented [R1] and BP funded a trial deployment of waveguide sensors at Gelsenkirchen refinery in Germany. At this stage they were deployed on hot plant, but readings were taken manually by plugging in a standard ultrasonic test set. This was successful and BP then funded the Imperial team to develop a wireless system that involved installing custom electronics and a battery on the cold end of the waveguide, measurements typically taken every 12 hours being transmitted to a base station via a low power mesh network, so providing ‘data to desk’. This concept worked very well and intrinsic safety certification was obtained, enabling it to be operated on refineries and other plant.

The IP was owned by Imperial Innovations and following the success of the trial, they agreed to the formation of a spinout company, Permasense Ltd, to market the technology, initially to BP who had exclusive rights to use it in return for funding the development work. Cawley was chairman of the company, Cegla was a director and two of the original employees had been involved in the development work. BP placed an initial order for 3000 sensors to be delivered in 2010 and this enabled the company to ‘bootstrap’ without requiring capital funding. In 2011 an agreement was reached with BP for the technology to be marketed worldwide to other companies in both the oil and gas and other sectors.

Impact in the current REF period

1. Further developing a successful spinout company Permasense Ltd

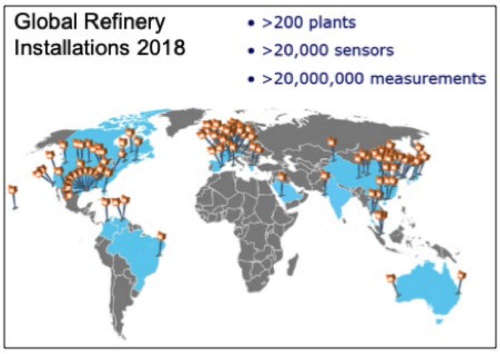
During the current REF period, Permasense Ltd has “… *achieved global success and its technology has become the market leader and a global standard.*” (Source C). In 2015, Permasense featured as one of the 10 ‘Ones to Watch’ in the Sunday Times Tech Track 100 list. The success of this spinout company, whose technology is derived entirely from the research from Cawley and Cegla, is clearly evidenced when in September 2016, Emerson, a Fortune 500 company, purchased the company for GBP32,400,000 (Source D). This synergetic acquisition provides Permasense (and the impact of our research) the opportunity to extend its reach by integration into the sales force and distribution channels of a large multinational company.

The pipeline for translation from research to impactful industrial applications between our team and Permasense continued over the current REF period. Before the publication of Cegla’s research [R4] and [R5], the original waveguide sensors were sometimes applied on lower temperature plant, but it became clear that sales in this market were restricted by the difficulty of installing over a coating such as fusion bonded epoxy as the waveguide tips tended to damage the coating and so create a potential corrosion site. This led Permasense to license the patent [R6] and adopt the EMAT system based on Cegla’s underpinning research described in Section 2 above.

Magnetically attached EMAT sensor ET-200

2. **Generating revenue and employment in the UK**

Over 20,000 corrosion sensors have been deployed in over 200 installations including 135 refineries, 33 upstream sites and other industrial plants worldwide (Source E, see figure). Most of these sales and deployments happened since 2014. The sales value of sensors and associated services exceeded USD72,000,000 over the current REF period (Source F). The company now employs over 50 highly qualified staff at its Crawley site including 3 PhD graduates from the Imperial College group.



3. **Providing economic benefits and enhanced safety to companies**

In addition to economic impact from direct sales of the monitoring system by Permasense, deployment of our technology has also enabled refineries to optimise their feedstock and to reduce the use of corrosion inhibitor chemicals. Higher TAN (acidic) crude oil is more corrosive than 'sweet' crudes and so if processed without appropriate corrosion inhibition and/or monitoring could lead to plant failure with huge human safety and economic implications. Our technology has become a major tool in BP's strategy for corrosion prevention (Source G). As an example, the installation of the system at BP's Gelsenkirchen refinery enabled the operator to reduce feedstock costs and process low cost but high TAN acidic crude without the risk of corroding through their pipework. This resulted in additional profit of EUR100,000,000 over a 2.5-year period, i.e. EUR40,000,000 per year (Source H).

Another example is the PTT Global Chemical Company Rayong refinery in Thailand where savings of USD300,000 per annum in inhibitor chemicals by installing a Permasense monitoring system have been achieved (Source I).

Deployed high temperature waveguide sensor WT-100 (in orange)

A further advantage of the permanently installed monitoring system is that it enables improved equipment life management. This is beneficial because it reduces the number of unplanned outages and enables better scheduling of remediation work. This leads to shorter outages and hence less lost production and lower costs for the remediation work as components can be ordered in advance at better prices. Depending on the application, the installation of a small (~25) sensor network can result in savings of EUR1,500,000 to EUR4,000,000 per installation. (Source H).

The monitoring system also leads to major savings in the upstream oil industry. For example, Shell Brunei had a well that was prone to producing sand, leading to severe erosion problems. Installing a Permasense monitoring system meant the well no longer had to be classified as high risk and an extra 80 m^3/day (~500 barrels/day) of oil could be produced at a value of USD11,000,000 per annum; a similar volume of gas was also produced. (Source J).

The four example applications discussed above are drawn from over 200 installations at customer sites. These four cases to date led to savings or increased production benefits of over USD50,000,000 per annum. Therefore, while it is not possible to compile an exact figure, it is not unreasonable to estimate that the overall financial benefit to industries from the 200 total installations is in the region of hundreds of millions of US dollars per annum. Additionally, the deployed systems have resulted in enhanced safety assurance and reduced the need for human personnel to enter hazardous environments.

5. Sources to corroborate the impact

A. GH Koch et al, NACE International Impact study, International Measures of Prevention, Application, and Economics of Corrosion Technologies, 2016. PDF available here.

B. I Haggan, Oilfield Technol. 1, 43–5, 2014. PDF available here.

C. "Pipework monitor spin-out sold for over £30 million" EPSRC Case Studies, 21 June 2018. https://epsrc.ukri.org/newsevents/casestudies/pipework-monitor-spin-out-sold-for-over-30-million Link archived here.

D. Letter from Head of Investment, IP group (previously Imperial Innovations Ltd) confirming the sale price for Permasense Ltd.

E. "Rosemount Wireless Corrosion & Erosion Monitoring", https://www.emerson.com/en-us/automation/permasense. Link archived here.

F. Letter from CTO, Permasense division of Emerson Automation Solutions.

G. BP Annual Report and Form 20F, 2014, page 17. PDF available here.

H. Email evidence from BP Gelsenkirchen inspection superintendent (until 2017) on impact of corrosion sensors on BP's Gelsenkirchen Refinery.

I. Email evidence from Materials and Corrosion Engineer, PTT Global Chemical Company, PTTGC6 refinery, Rayong, Thailand.

J. Email evidence from Production Technologist, Brunei Shell Petroleum.