Institution: University of Manchester		
Unit of Assessment: 12 (Engineering)		
Title of case study: New industrial electromagnetic sensor systems improve safety processes and optimise capabilities in the UK's energy, rail and manufacturing sectors		
Period when the underpinning research was undertaken: 1 Dec 2004 – 1 Dec 2020		
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:**
Anthony Peyton Wuliang Yin William Lionheart Liam Marsh Michael O'Toole Adam Fletcher	Professor Senior Lecturer Professor Lecturer Lecturer PDRA	2004 – present 2012 – present 1999 – present 2011 – present 2011 – present 2019 – present
Period when the claimed impact occurred: 1 August 2013 to 31 July 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Sensor systems based on electromagnetic induction (EMI) inspection techniques have wide-ranging industrial applications including rail inspection, steel production and food safety. Historically these techniques have been empirical, with limited theoretical understanding restricting their performance. University of Manchester research has delivered ***theoretically-based, quantitative*** electromagnetic inspection systems, pioneering the development of revolutionary EMI tomography and spectroscopy techniques. This has optimised industrial processes, resulting in cost savings, and improving confidence and accuracy of important safety processes in UK rail, energy and steel production:

1) **Rail** – introduction of a new EM track inspection system [text removed for publication];
2) **Energy** – introduction of a new graphite inspection technique for the UK fleet of gas cooled nuclear reactors for EDF Energy, broadening the base of the safety case;
3) **Steel production** – creation of the first micro structure inspection technology – EMspec^{TM} – enabling Tata Steel to inspect over 30Mtonnes of strip steel;
4) **Metal detection** – development of innovative technologies resulting in the introduction of new metal detection products [text removed for publication]

2. Underpinning research

Since 2004, Peyton has led a body of work at The University of Manchester (UoM), to improve the performance of electromagnetic inspection systems across a range of applications. Drawing on tomographic approaches for solving inverse electromagnetic problems, key research findings cover three broad areas:

2.1. Magnetic Induction Spectroscopy (MIS)

UoM research has shown that the spectroscopic response of conducting magnetic objects such as metal components can be used to characterise the object and quantify particular parameters of interest. The use of these multi-frequency techniques has been central to the UoM research. This research was initiated on simple plane objects such as plate and strip material and is now applied in the metal production industry. The seminal paper [1] shows that a plate has a particular phase spectra, which is used to monitor the microstructural properties of the metal during hot processing and reject interfering process parameters such as the distance between the sensor and plate. This work was funded through a series of EPSRC projects (GBP939,000) and two major EU projects (PUC, RFSR-CT-2013, EUR8,050,000).

Since 2011, the use of spectroscopy was extended to more complex shaped conducting objects, such as small objects for metal detection / classification applications, engineering components and even in biology for items of fruit and vegetables. This has included the inspection of graphite moderating bricks, demonstrating the suitability of MIS to quantifying the depth profile of conductivity within the brick [2]. This work has been funded through four doctoral projects and an EPSRC Impact Accelerator Award (GBP158,000) in partnership with EDF-Energy.

2.2. Tensor theory

UoM research has shown how tensor representation (the electromagnetic polarisability tensor) can describe the effect that the shape of a conducting object has on the response of an electromagnetic sensor. Furthermore, if the object is sufficiently small that the tensor is a fundamental property of the object, this enables the response of metal detector systems to be fully described [3]. Since 2012, this has been applied across the metal detection industry.

The tensor also has a spectroscopic response, underlining the synergy with the multi-frequency MIS work described above [4]. The tensor representation can optimise sensor performance and provide enhanced discrimination of threat objects by taking into account the effects of the shape and material composition of the object. This research on the application of tensor theory was initiated in 2008 with an RCUK project in partnership with Rapiscan Systems (DT/F002467, GBP594,000, 2008 – 2011). A series of projects followed in partnership with Rapiscan (for security scanners), Safeline (for industrial metal detectors) and the Sir Bobby Charlton Charity (for humanitarian demining), with research contracts valued at over GBP5,000,000 since 2012, including two funded lectureships for Yin and O'Toole.

2.3. Advanced modelling and analytical techniques

Building on the research into tensors and spectroscopy [1-4], further research demonstrated that advanced modelling and analytical techniques can be used to represent defects in metal components with sufficient accuracy for practical application in non-destructing testing. Since 2010,UoM has used these techniques for quantitative inspection of rail properties [5-6], supporting on-going research with partners in the rail industry.

3. References to the research

Citation counts are from Web of Science (October 2020).

[1] **W. Yin**, X.J. Hao, **A.J. Peyton**, M. Strangwood, and C.L. Davis (2009) Measurement of permeability and ferrite/austenite phase fraction using a multi-frequency electromagnetic sensor, *NDT&E International*, **42**(1), p64-68, DOI:10.1016/j.ndteint.2008.01.009 (31 cites)

[2] B. Dekdouk, R. Chapman, M. Brown, **A.J. Peyton** (2012) Evaluating the conductivity distribution in isotropic polycrystalline graphite using spectroscopic eddy current technique for monitoring weight loss in advanced gas cooled reactors, *NDT & E International*, **51**, p150–159, DOI:10.1016/j.ndteint.2012.06.011 (10 cites)

[3] **L.A. Marsh**, C. Ktistis, A. Jarvi, D.W. Armitage and **A.J. Peyton** (2013) Three-dimensional object location and inversion of the magnetic polarizability tensor at a single frequency using a walk-through metal detector, *Measurement Science and Tchnology*. **24** (4), 045102, DOI: 10.1088/0957-0233/24/4/045102 (37 cites)

[4] O.A. Abdel-Rehim, J.L. Davidson, **L.A. Marsh**, **M.D. O'Toole**, and **A.J. Peyton** (2016) Magnetic polarizability tensor spectroscopy for low metal anti-personnel mine surrogates, *IEEE Sensors Journal*, **16** (10) p3775-83, DOI:/10.1109/JSEN.2016.2535346 (16 cites)

[5] Q. Zhao, J. Hao, and **W. Yin** (2013) A simulation study of flaw detection for rail sections based on high frequency magnetic induction sensing using the boundary element method, *Progress In Electromagnetics Research*, **141**, p309-325 DOI: 10.2528/PIER13042702, (4 cites)

[6] W. Zhu, W. Yin, S. Dewey, P. Hunt, C.L. Davis, **A.J. Peyton** (2017) Modeling and experimental study of a multi-frequency electromagnetic sensor system for rail decarburisation measurement, *NDT&E International*, **86**, p1–6, DOI:10.1016/j.ndteint.2016.11.004, (9 cites)

4. Details of the impact

The underpinning research has been used in several industrial applications, as follows:

4.1 Improving safety management within the energy sector

Nuclear power contributes approximately 19% of the UK's electricity supply, with this largely generated by Advanced Gas-Cooled Reactors (AGRs) all operated by EDF Energy. AGR cores are constructed from graphite moderator bricks, which degrade due to the harsh radioactive and oxidising environment. This leads to brick cracking and a reduction in graphite density (weight loss), which consequently limits the nuclear-station lifetime. In order to ensure the continued safe operation and life extension of the AGR fleet, thorough understanding of the number and nature of cracked bricks, as well as the state of weight loss within the graphite core is vital. Prior to the UoM research, the only means of crack detection was through visual inspection (via deployed video camera), where (prior to EMI methods) the only means of gaining weight loss information was to destructively remove radioactive samples (trepan) from the reactor and analyse these at the National Nuclear Laboratory [A].

UoM research [2] informed the design and development of EDF Energy's electromagnetic (eddy current) inspection tools (brought into service between 2013 and 2018). Improved simulation of the tool's electromagnetic characteristics allowed UoM to design new sensor heads (building on the work in [2]) which are significantly more sensitive to subsurface defects. This has increased the quality of information available on cracked bricks, and improved the equipment's ability to provide through brick weight loss, further improving understanding of graphite weight loss.

The research [2] informed how eddy current data is used in weight loss safety cases. Eddy current methods provide complementary information to trepanned samples. Trepanned samples provide very precise, but highly localised information at one point within a brick, allowing the through wall weight loss profile to be accurately measured. However, this approach requires destructively removing radioactive samples from the core, which has safety implications, and furthermore, cannot be undertaken in bricks that have cracked.

Eddy current inspections provide close to 100% coverage of the brick bore albeit with a reduced level of depth penetration but with the possibility of gaining information on cracked bricks. Since 2018, EDF Energy have supplemented trepanned samples with eddy current inspections, to improve the information on the state of the reactor core, which has [A]:

- increased confidence in predictions of future core behaviour through reduction in uncertainty margins on material properties;
- increased safety through increasing the information on the sub-population of cracked bricks which cannot otherwise be ascertained; and
- provided a diverse information source to weight loss prediction methods (FEAT-DIFFUSE finite element software) allowing improvements to the physical models they use. This has increased understanding of graphite behaviour and hence improved the quality of predictions and increased confidence in the models.

The information now produced from eddy current tools forms part of the safety case across the UK's AGR fleet (all 14 reactors) [A]. Since 2013, eddy current methods have been used to characterise defects and cracks that are on the limits of visual inspection techniques and provide information of the properties of bricks which have already cracked, which would be unavailable by other methods (trepanning) [A].

These benefits support graphite-core safety cases, which in turn support the return to service of reactors from outages and underpin plant life-extension safety cases. As confirmed by EDF, the UoM research is therefore "*important in ensuring the UK's AGR fleet remain operating safely and continue to make up a significant part of the UK's low carbon power generation capability*" [A].

4.2 Improved monitoring of steel production quality
In the steel industry, advanced high strength steels (AHSS) are developed in pursuit of lighter, stronger steel. AHSS's favourable strength properties result from well-engineered combinations of thermal and mechanical treatments of selected chemical compositions of the steel. The final microstructure is highly sensitive to both the thermal manufacturing process conditions and to the incoming state of the material, with any resulting reductions in yield being extremely costly to steel manufacturers.

To help monitor production, using the spectroscopic techniques described in [1], UoM (with Tata Steel and Primetals) invented a new electromagnetic sensor system, EMspec™. EMspec™ is internationally protected by two patent families (GB2481482B and GB2490393B), and was awarded the 2015 Institute of Materials, Minerals and Mining IOM3 Williams prize [B]. EMspec™ uses multi-frequency operation to record changes in the magnetic permeability of the steel during the harsh process conditions, whilst simultaneously rejecting the effects of unwanted process parameters. This enables the evolution of the steel microstructure to be monitored in a non-contact, non-destructive fashion, and real-time calibrations made to maximise yield.

Tata Steel, one of Europe's leading steel producers, has confirmed the UoM research *"has resulted in the world's first and only commercially available system for phase transformation monitoring for use in hot rolling mills*" [B]. Tata Steel, has three EMspec™ sensors installed on their hot strip mill in IJmuiden in the Netherlands [B]. Since 2014, this has enabled:

- over 30 Mtonnes of strip steel to be inspected, valued at EUR500 per tonne [B], equating to a cumulative product value of EUR15,000,000,000;
- acceleration of new products, due to EMspec™ transformation monitoring system improving the product development process [B];
- control models for existing steel grades to be fine-tuned, resulting in improvements in product homogeneity and quality consistency [B];
- inline product uniformity sensing to be undertaken, with corresponding annual benefits to the EU steel industry estimated between EUR60,000,000 to EUR70,000,000 [C];

AHSS are used in the automotive and transport industries, to construct lightweight vehicles, with improved energy efficiency and CO_2 intensity. For a modern family car, this is estimated to save 170 to 270kg, compared to conventional steel [C]. Tata have confirmed that per vehicle, this reduces CO_2 emissions by 3 to 4.5 tonnes over the vehicle life cycle, which is more than the total CO_2 emitted during production of all the steel in the vehicle [C]. The usage of AHSS in vehicle structures has drastically increased from 10% in 2010 to 40% in 2020 [C], reflecting the industrial benefit to improving this process.

4.3. Improved metal detection within the food safety industry
Protection against metallic contamination of food is a legal requirement in most countries. In 2010, UoM started a partnership with the industrial metal detector division of Mettler-Toledo (MT) Safeline to transfer the spectroscopy [1-2] and tensor modelling [3-4] research into product development. MT Safeline is the global brand leader in the supply of highly sensitive in-line radio frequency metal detectors, primarily for the food and pharmaceutical industries. Safeline Ltd, is a subsidiary division of the larger Mettler Toledo Company, and in 2019, Safeline Ltd's annual turnover exceed GBP45,000,000 [D]. [Text removed for publication].

This research [1-4] has improved the metal detection capabilities of Safeline Ltd, through new multi-frequency signal processing techniques, which has significantly improved the accuracy of food metal detection. [Text removed for publication].

4.4 Improved rail safety

The Hatfield rail crash in 2000 brought increased attention on rail inspection and management. The derailment was attributed to a distributed surface defect, Gauge Corner Cracking (GCC), arising from Rolling Contact Fatigue (RCF). RCF is found worldwide on most high speed, high tonnage railway. Since 2010, Sperry Rail (the largest global rail inspection company) collaborated with UoM to research and develop electromagnetic non-destructive testing techniques for the inspection of rail surfaces [5-6].

[Text removed for publication].

5. Sources to corroborate the impact

- [A] Letter of Support from Graphite Materials Inspection Engineer, EDF Energy, September 2020
- [B] Letter of Support from Director Programmes, Tata Steel Research and Development, January 2021
- [C] Letter of Support from Principal Scientist at Tata Steel Research and Development, January 2021
- [D] Mettler Toledo Annual Report 2020
- [E] Letter of Support from Safeline, January 2021
- [F] Letter of Support from Director Innovations, Sperry Rail, October 2020