Institution: University of Glasgow (UofG)		
Unit of Assessment: UoA 9 Physics		
Title of case study: Validating the integrity of nuclear waste containers for assured long-term safe storage		
Period when the underpinning research was undertaken: 2009–present		
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:**
Prof Ralf Kaiser	Professor	2001–present
Prof David Ireland	Professor	1994–present
Dr Guangliang Yang	Research Associate	2003–present
Period when the claimed impact occurred: 2016–present		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

Nuclear waste containers must be shielded to contain radiation, but this makes assessing container safety with traditional techniques such as X-rays impossible. To overcome this, UofG research into muon imaging (a non-destructive testing technology using naturally occurring, highly penetrating radiation), led to the formation of spin-out company, Lynkeos Technology (2016). The impacts of Lynkeos' Muon Imaging System (MIS) are improved nuclear safety and cost savings in nuclear waste storage. Lynkeos deployed the world's first MIS at Sellafield (2018), where it features in strategic planning and is estimated to save UK taxpayers >GBP100 million over 20 years. In recognition of the unique advantage of its MIS, Lynkeos have won several contracts including with the German Federal Company for Nuclear Waste Disposal.

2. Underpinning research

Research Context:
The UK hosts a major legacy of radioactive waste from various civil and defence programmes. The number of nuclear waste containers is expected to triple over the next 20 years, from about 20,000 to 60,000 packages. These containers are shielded to contain radiation and so cannot be imaged with x-rays or gamma rays. UofG's novel, hi-fidelity imaging system – the Lynkeos Muon Imaging System (MIS) – is operating successfully to assure container integrity.

Cosmic-ray muons are produced when high-energy cosmic rays hit the atmosphere. They are natural, ubiquitous and highly penetrating; muons can penetrate ~700m of rock but are part of the natural environment and pose no health risk. When muons are scattered, their average scattering angle depends on the atomic number of atoms within the material. Measurement of the transmission and scattering of muons makes it possible to construct a 3D tomographic image of the distribution of high-density nuclear waste within containers. Thus, the Lynkeos MIS enables the amount of nuclear waste in each container to be assessed and to be accurately monitored over time.

Development of the Lynkeos Muon Imaging System
Development started in 2009 as a research project between the Glasgow Nuclear Physics Group and the National Nuclear Laboratory (NNL), funded by the Nuclear Decommissioning Authority (NDA) via Sellafield Ltd. Over the course of a 7-year, GBP4.8 million research project, UofG research designed and developed a working full-scale prototype of a muon-tomography 3D-imaging system for nuclear waste containers. This system was the first of its kind worldwide that

was able to reliably detect uranium inside shielded nuclear waste containers [3.1]. Further research ensured full characterisation and optimisation of the muon imaging system [3.2–3.4]. In 2016, the associated IP was assigned to UofG spinout company, Lynkeos Technology Ltd. In 2017, Lynkeos won an Innovate UK First-Of-A-Kind contract worth GBP1.6 million to commercialise the MIS and, later that year, carried out the first commercial muon tomography measurements on nuclear waste containers. The Innovate UK-funded Lynkeos MIS was CE-certified and deployed at Sellafield in 2018. Lynkeos has received additional funding from STFC and the Royal Society to make additional refinements to the static muon tomography system.

Development of a Mobile Muon Imaging System

The Lynkeos MIS is a static system designed for indoor use. Lynkeos is collaborating with Swansea University and with the German Federal Institute for Material Science and Testing (BAM, Berlin) to develop a mobile system for applications in nuclear safety and civil engineering. The collaboration with Swansea University to develop a novel 3D-printing technology for scintillating fibre structures has led to a successful funding application under the EU ATTRACT scheme. The results of a joint study with BAM on reinforced concrete have been submitted for publication, demonstrating that muon imaging performs better than the standard techniques of ground-penetrating radar and ultrasound [3.5].

3. References to the research * = best indicators of quality

3.1. Mahon, D.F., Clarkson, A., Hamilton, D.J., Hoek, M., Ireland, D.G., Johnstone, J.R., Kaiser, R., Keri, T., Lumsden, S., McKinnon, B. and Murray, M., 2013. *A prototype scintillating-fibre tracker for the cosmic-ray muon tomography of legacy nuclear waste containers*. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 732, pp.408–411. (doi:10.1016/j.nima.2013.05.119)

3.2. Clarkson, A., Hamilton, D.J., Hoek, M., Ireland, D.G., Johnstone, J.R., Kaiser, R., Keri, T., Lumsden, S., Mahon, D.F., McKinnon, B. and Murray, M., 2014. *The design and performance of a scintillating-fibre tracker for the cosmic-ray muon tomography of legacy nuclear waste containers*. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 745, pp.138–149. (doi:10.1016/j.nima.2014.01.062)

3.3. Clarkson, A., Ireland, D.G., Al Jebali, R., Kaiser, R., Lumsden, S., Mahon, D., Mountford, D., Ryan, M., Shearer, C. and Yang, G., 2015. *Characterising encapsulated nuclear waste using cosmic-ray muon tomography*, Journal of Instrumentation, Volume 10, P03020 (doi:10.1088/1748-0221/10/03/P03020).

3.4. Mahon, D., Clarkson, A., Gardner, S., Ireland, D., Jebali, R., Kaiser, R., Ryan, M., Shearer, C. and Yang, G., 2018. *First-of-a-kind muography for nuclear waste characterization*. Philosophical Transactions of the Royal Society A, 377(2137), p.20180048. (doi:10.1098/rsta.2018.0048) *

3.5. Niederleithinger, E., Gardner, S., Kind, T., Kaiser, R., Grunwald, M., Yang, G., Redmer, B., Waske, A., Mielentz, F., Effner, U. and Köpp, C., 2020. *Muon tomography of a reinforced concrete block--first experimental proof of concept,* arXiv preprint arXiv:2008.07251 [available on request from HEI]

3.6. Simpson, A., Clarkson, A., Gardner, S., Al Jebali, R., Kaiser, R., Mahon, D., Roe, J., Ryan, M., Shearer, C. and Yang, G., 2020. *Muon tomography for the analysis of in-container vitrified products,* Applied Radiation and Isotopes, Volume 157, p109033, (doi:10.1016/j.apradiso.2019.109033) *

4. Details of the impact

UofG research developed a new, non-destructive technique, uniquely able to determine the amount of nuclear waste in containers and to assess it over time. This led to the creation of spin-out company Lynkeos Technology, which has carried out feasibility and design contracts for the deployment of a muon imaging system (MIS) to industrial partners including Sellafield and the German Federal Company for Nuclear Waste Disposal (Bundesgesellschaft für Endlagerung; BGE).

The impacts of the Lynkeos Muon Imaging System are improved nuclear safety and on cost savings in nuclear waste storage.

Commercial impacts relating to enhanced nuclear safety

Lynkeos has ongoing collaborations with the nuclear industry that demonstrate the impact arising from UofG's research and Lynkeos' commitment to improving nuclear safety.

Lynkeos is the first UK company to specialise in muography, addressing some of the most complex technical challenges facing society today. The practical availability of Lynkeos' technology affects safety cases and nuclear safety plans and has formed the basis of Lynkeos' relationship with Sellafield, which funded GBP4.8 million of UofG research between 2009 and 2016 [5.1]. Lynkeos' technology has been noted as impacting the Care, Maintenance and Inspection (CM&I) strategy for the new Box Encapsulation Plant at Sellafield (for the process and storage of legacy nuclear waste) [5.1].

> *"Sellafield is currently evaluating the deployment of Muon Tomography within the Box Encapsulation Plant (BEP) as an integral part of the CM&I (Care Maintenance and Inspection) strategy. This technology is able to provide information that no other technology can, namely the passive monitoring of the internal contents of waste storage containers. This is essential in BEP to identify safe storage limits of raw waste to feed into packing and storage strategy for the facility and to monitor this waste over time. Without this technology, new storage packages will need to be developed and storage space will need to be increased. For an additional storage facility alone it would cost between GBP100 million and GBP200 million. This technology is the only technology within the current BEP CM&I plan that has the potential to mitigate these additional costs." – Business and Technology Manager, Sellafield.* [5.1].

Demonstrating the growing interest and demand for the Lynkeos MIS, Sellafield issued Lynkeos with a conceptual design installation contract for the Box Encapsulation Plant, worth approximately GBP112,000, at the end of 2020 [5.2].

In addition to a role for the MIS at Sellafield's BEP, there is a second role for it at Sellafield's GeoMelt® vitrification plant (operated by The National Nuclear Laboratory; NNL). The UK has >300,000 tons of nuclear waste suitable for treatment with the Geomelt® process, which safely stores nuclear waste by converting it into an ultra-stable glass that is 10x stronger than concrete and lasts millennia. The Lynkeos MIS is the only non-destructive way to assure GeoMelt® process quality. The first commercial characterisations of GeoMelt® commenced in November 2017 to assure the quality of the GeoMelt® vitrification process, with imaging services continuing on-site since October 2018 [5.3]. GeoMelt® owners Veolia have included Lynkeos' technology in several bids for public contracts.

Lynkeos technology has been considered in the nuclear safety plans of other large nuclear organisations in the UK and internationally, such as EDF [5.4] and BGE (the German Federal

Company for Nuclear Waste Disposal) [5.5]. For example, Lynkeos won an approximate EUR103,000 German national tender at the end of 2020, to work with BGE [5.6, 5.7] who are legally obligated to retrieve nuclear waste from the Asse II mine in Germany. There are 125,787 nuclear waste containers stored in this unsecured mine, posing a potential threat due to concerns over an incorrect inventory of nuclear waste stored there in the 1960s and 1970s [5.8].

Economic impacts from cost savings in nuclear waste storage

The legacy of the UK's nuclear power programme places a high burden on UK taxpayers, with total clean-up costs ~GBP100 billion anticipated over the next 50 years. This concerns legacy waste, the safety assessment of new waste containers and the quality assurance for waste vitrification. The improved public safety and the estimated 20-year cost savings of >GBP100 million has resulted in Sellafield incorporating Lynkeos technology into their strategic planning [5.1]. The MIS is the only non-destructive technique to provide quality assurance of Intermediate Level Waste drums and GeoMelt® containers. Sellafield estimate the value of mitigating the containment risk for Intermediate Level Waste drums at ~GBP300 million [5.1].

Economic and commercial impacts within Lynkeos Technology Ltd.

Between 2016 and 2020, Lynkeos generated a total turnover of GBP2.5 million over 4 years, employing 6 staff. The commercial success of Lynkeos was highlighted by the NNL in 2018: "*When we first looked at this in 2009, we thought we had a 50/50 chance of turning this idea into a product that could be commercialized for the nuclear industry. But the results surpassed expectations at every stage*" [5.9]. Market research carried out by Systems Insight in 2020 involved interviews with nuclear and civil engineering professionals and showed that large potential markets exist for a new, unique mobile system [5.10]. Eighty percent of interviewees saw a high market potential for a mobile system, 73% saw applications especially in civil engineering and 77% believe that the adoption of the technology is likely [5.10].

The impact of Lynkeos has been recognised through awards including: Rushlight Nuclear Energy Award 2019; Best Collaboration (Business) UofG Knowledge Exchange Awards 2019; IOP Business Start-Up Award 2018; and Highly Commended, Best Technical Innovation, Nuclear Decommissioning Awards 2018.

UofG and Lynkeos have led outreach activities for experts (e.g. Royal Society Theo Murphy workshop in 2018) and for the general public (e.g. New Scientist Live 2018). The workshop proceedings are currently the best reference for the field of muon imaging worldwide. Lynkeos is regularly invited to activities of the International Atomic Energy Agency (IAEA), and was referenced throughout Section D and on the cover of the 2019 IAEA Nuclear Technology Review [5.11]. Kaiser was part of the UK Delegation to the IAEA General Conference 2019 and presented Lynkeos as an example of UK nuclear industry innovation. Kaiser chaired the first IAEA Technical Meeting on muon imaging (2019) and edits the IAEA Technical Document – the first step towards international standards in muon imaging.

5. Sources to corroborate the impact

5.1. Sellafield letter of support
5.2. Corroborating testimony can be obtained from Technical Lead, RVS Strategy and Technical, Sellafield (contact details provided)
5.3. Statement of Collaboration from NNL Ltd.
5.4. Letter of support from EDF

5.5.	Letter of support from Bundesgesellschaft für Endlagerung (BGE), Germany
5.6.	Signed purchase order from Bundesgesellschaft für Endlagerung (BGE), Germany
5.7.	Corroborating testimony can be obtained from Scientific Consultant, Bundesgesellschaft für Endlagerung (BGE), Germany (contact details provided)
5.8.	"Radioactive waste in Asse Mine" – BGE article
5.9.	"Scientists harness space particles to detect radioactive material" NNL press release
5.10.	Market Research Summary Report, Systems Insight, 2020
5.11.	2019 IAEA Nuclear Technology Review