Institution: University of Bristol		
Unit of Assessment: 14) Geography and Environmental Studies		
Title of case study: Novel approaches to improve nuclear safety in Europe and Japan		
Period when the underpinning research was undertaken: 2012-2020		
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:**
Professor David Richards	Professor of Physical Geography	01/2000 to present
Professor Dan Lunt	Professor of Climate Science	08/2003 to present
Professor Andy Ridgwell	Professorial Research Fellow	11/2006 to 04/2019
Professor Thomas Scott	Professor in Materials	01/2006 to present
Dr Peter Martin	Senior Research Associate	04/2019 to present
Period when the claimed impact occurred: 2014- 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

University of Bristol researchers have provided the nuclear power sector with critical evidence to strengthen public and environmental safety. Using novel methodologies, they have accurately mapped and characterised environmental radioactivity, and, using climate models, they have simulated the effects of long-term climate change on the safety of nuclear waste disposal. The resulting impacts include:

- Reduced costly delays for dredging operations for a UK nuclear new-build at Hinkley Point C.
- Provided evidence supporting the expedited and safe return of tens of thousands of evacuated citizens to their homes after the disaster at the Fukushima Daiichi Nuclear Power Plant, Japan.
- Improved clean-up operations in the Fukushima catchment to prevent radiation leaks.
- Strengthened regulatory assessments by the Swedish and Finnish nuclear waste authorities (Posiva, SKB) concerning the safe storage of high-level radioactive waste over the next 1 million years.

2. Underpinning research

The University of Bristol (UoB) team have a uniquely broad skill set encompassing isotope geochemistry, material characterisation and environmental surveying **[1-4],** and climate modelling **[5, 6],** covering a wide range of spatial scales from local to global, and temporal scales from years to millions of years. Their research has direct relevance to key issues associated with the nuclear industry, primarily *mapping of environmental radioactivity* and *modelling long-term future climate and environmental change for the safety of geological nuclear waste disposal.*

1. Novel techniques for mapping environmental radioactivity for risk assessment

The UoB research directly addresses the problem of low-level radioactive contamination of coasts and rivers, which is crucial in assessing post-accident, new-build and decommissioning safety. Traditionally, mapping in this field relies on radioactive decay counting methods which do not provide the sensitivity (higher detection limits) and specificity (limited range of isotopes) required to attribute the source of material at ultra-trace levels (sub parts per trillion) and cannot provide the necessary confidence to support effective decision making. The UoB research optimised chemical separation and multi-collector mass spectrometry protocols to focus on low abundance isotopes of Pu, Cs and U for challenging environmental samples, such as coastal sediments and organic materials **[1]**. The team recognised that interdisciplinary collaboration, at the intersection of physics, geography, and chemistry, was needed to develop nuclear forensic tools for effective post-accident mapping. Following the disaster in Fukushima in 2011, they designed survey methods and sampling schemes to assess the spatial pattern of radioactivity in the fallout zone, focussing on inaccessible areas that are challenging to survey with traditional approaches, such as hand-held gamma detectors. The key innovation was the design and deployment of autonomous unmanned aerial vehicles (UAVs) with miniaturised radiation detectors for field campaigns from 2014-2016 **[2]**, which enabled the rapid production of contamination maps, in higher resolution than is possible using manned vehicles. The maps facilitated assessment of the factors influencing contaminant transport and efficacy of clean-up operations. In addition, UoB developed a unique combination of nano-scale synchrotron analysis **[3]** and high-precision mass-spectrometry (Pu, Cs and U) **[4]** to establish the specific reactor from which the highly radioactive particulates had originated.

2. Novel process-based modelling of long-term future climate for nuclear safety

Geological nuclear waste repositories represent a considerable risk to future generations. The risk is due to the potential for the impacts of environmental change, such as substantial changes in sub-surface hydrology or erosion caused by ice sheets, to compromise the integrity of a repository hosting long-lived radionuclides. This represents a considerable scientific and numerical challenge to be addressed at the global scale, and on timescales of up to one million years into the future to cover the timescales of radioactive decay.

Previously, the standard research practice in this field was to approximate the future evolution of atmospheric CO_2 using simple empirical functions, and to use models to provide ‘snapshots’ in time of possible future extreme climate states. These methods are inadequate because the assumptions underlying the empirical functions may break down under future climate states, and do not simulate the continuous evolution of climate. The UoB team recognised this failing and, through their combination of world-leading expertise in biogeochemical and physical paleoclimate modelling (evidenced through Lunt’s role as a Lead Author in the current IPCC report), proceeded in 2011 to develop a novel and integrated process-based approach, consisting of:

- an efficient methodology for calculating the time-evolution of anthropogenic CO_2 concentrations based on a coupled climate-carbon cycle model **[5]**;
- a statistical emulator, calibrated using ensembles of climate model simulations, that can be used to rapidly simulate the continuous long-term evolution of climate at high spatial resolution with relatively low computational cost, and evaluated against paleoclimate records over the same timescales **[6]**; and
- a workflow that includes a combination of statistical downscaling and landscape modelling to provide reference futures for use in waste repository safety assessments (developed through commissioned work for the International Atomic Energy Agency, see **[g]** and Section 4.3).

3. References to the research

[1] Dunne JA, **Richards DA**, Chen H-W (2017). Procedures for precise measurements of $^{135}Cs/^{137}Cs$ atom ratios in environmental samples at extreme dynamic ranges and ultra-trace levels by thermal ionization mass spectrometry, *Talanta*, **174**, pp.347-356 doi.org/10.1016/j.talanta.2017.06.033

[2] **Martin PG**, Payton OD, Fardoulis JS, **Richards DA**, Yamashiki, Y, **Scott TB** (2016). Low altitude unmanned aerial vehicle for characterising remediation effectiveness following the FDNPP accident, *Journal of Environmental Radioactivity*, **151(1)**, pp.58-63 doi.org/10.1016/j.jenvrad.2015.09.007

[3] **Martin PG**, Louvel M, Cipiccia S, Jones CP, Batey DJ, Hallam KR, Yang IAX, Satou Y, Rau C; Mosselmans JFW, **Richards DA**, **Scott TB** (2019). Provenance of uranium particulate contained within Fukushima Daiichi Nuclear Power Plant Unit 1 ejecta material, *Nature Communications*, **10(2801)**, doi.org/10.1038/s41467-019-10937-z

[4] Dunne JA, **Martin PG**, Yamashiki Y, Ang IXY, **Scott TB**, **Richards DA** (2018). Spatial pattern of plutonium and radiocaesium contamination released during the Fukushima Daiichi nuclear power plant disaster, *Scientific Reports*, **8(1)**, [16799], doi.org/10.1038/s41598-018-34302-0

[5] Lord NS**, Ridgwell A**, Thorne MC and **Lunt DJ** (2016). An impulse response function for the “long tail” of excess atmospheric CO_2 in an Earth system model, *Global Biogeochemical Cycles*, **30(1)**, pp.2-17, doi.org/10.1002/2014GB005074

[6] Lord NS, Crucifix M, **Lunt DJ**, Thorne MC, Bounceur N, Dowsett, O'Brien CL, **Ridgwell A** (2017). Emulation of long-term changes in global climate: application to the late Pliocene and future, *Climate of the Past,* **13**, pp.1539–1571, doi.org/10.5194/cp-13-1539-2017

Grant evidence

[i] **Scott TB (PI)**, **Richards DA (CI),** *Environmental behaviour and management of U-containing fuel debris particles,* EPSRC UK-Japan Civil Nuclear Research Programme Phase 5, 31/10/18-30/03/21, Bristol team share: GBP261,000

[ii] **Scott TB**, **Richards DA,** *Aerial and in-situ mapping of fallout in Fukushima prefecture,* University of Bristol International Strategic Fund (Bristol-Kyoto), 1/4/14-30/6/14, Bristol team share: GBP8,000

[iii] **Lunt DJ**, **Ridgwell A**, *Long-term climate projections for the storage of nuclear waste,* RWM through Amec Foster Wheeler and Quintessa commissioned research, 1/10/13-30/9/16, Bristol team share: GBP80,000

[iv] **Lunt DJ,** *Long-term future prediction for the nuclear industry.* Posiva and SKB commissioned research, 15/2/17-14/12/18, Bristol team share: GBP240,000

4. Details of the impact

The UoB research has delivered impact in three arenas of risk assessment: for new nuclear reactors, following nuclear disasters, and for future nuclear waste repositories; all using UoB's novel methods and models, in the UK and internationally.

1. Risk assessment for new nuclear reactors: Hinkley Point C

In 2014, as part of the development of Hinkley Point C nuclear power station, NNB Genco (a subsidiary of EDF Energy) obtained a license from National Resources Wales to dredge 300,000 tonnes of sediment from the Somerset coastline and dispose of it in the Severn Estuary, at a site near Cardiff. This activity was part of the preparation for the installation of six vertical shafts that form part of the reactor cooling water system. Once this operation became public knowledge, there was significant concern about the release of radioactive material into the environment and its potential health hazard **[a]**. In response to a public petition calling for a suspension of the marine licence, a motion was debated in the Welsh Assembly in October 2018. UoB provided supporting evidence to EDF for their case **[a]**, based on newly-developed mass-spectrometric ultra-trace methods **[1]** that detailed the very low abundance of the radioactive elements caesium (Cs) and plutonium (Pu) in Severn Estuary sediments and the insignificant threat to public health. The disposal license was not suspended, and dredging continued without further costly delays **[a]**.

2. Risk assessment post-nuclear disasters: Fukushima Daiichi Nuclear Power Plant

Return of evacuated residents. In 2011, the catastrophic release of radiation during the Fukushima disaster led to the evacuation of over 110,000 local citizens from 'required to leave' areas and an additional 49,000 from surrounding areas. In 2014, the UoB team joined forces with Kyoto University to assess the distribution of contamination and its transfer in the environment in the Fukushima prefecture with their newly-developed aerial radiation survey equipment **[2]** and high-precision isotopic analysis of Pu and Cs **[4]**. The mapping work *"moved beyond proof-of-principle to offer practical advice to local administrators"* with Kyoto University **[b]**. This evidence was used by local governments and municipalities to either delay or expedite repopulation activities. For example, the results informed influential decisions by a Senator for Minamisōma City, pop. 54,000, who declared that UoB researchers *"provided independent evidence that helped us consider the safety of our district, before and after clean-up*" and that the "*health of our citizens is of our foremost concern and [the] data was extremely helpful as we made difficult decisions*" **[b]**. Also, in Kawamata Town, which had a displaced population of 15,300, UoB analysis showed "that concentration of dangerous radionuclides such as plutonium was low in the soil captured in Yamakiya zone". The Town Council were "*reassured by results, collected independently of the decommissioning agency*," that supported re-opening Yamakiya Junior High School in 2017 **[b]**.

Informing remediation efforts. UoB's new aerial radiation methods **[3]** were used to provide surveys to ATOX Co. Ltd, who work alongside Japan's Ministry of Environment as one of the sub-contractors responsible for clean-up operations across the contaminated area. A first survey by UoB in Oct 2016 identified that there had been a "*radioactivity leak…from a number of the store's* *waste bags"* in ATOX Co. Ltd's site in Kawamata Town **[c]**. ATOX Co. Ltd were able to "*sort out the radioactive leak*" and UoB's "*second survey* [June 2017] *informed our office that the fixing of the leak was good*" **[c]**. As a result of the surveys, ATOX Co. Ltd "*now undertake routine monitoring every 3 months of all of the sites to see if the same radiation leaks happen anyway else. Our office has found four sites that have leaked and required cleaning up*" (Backend Technology Department, ATOX Co. Ltd) **[c].**

Decommissioning activity. Tokyo Electric Power Company (TEPCO), the operators of Fukushima Daiichi Nuclear Power Plant (FDNPP), were made aware of UoB's research related to the particle composition of fuel material debris using synchrotron methods **[2]**. TEPCO are responsible for the safe decommissioning of the multiple damaged reactors. Writing in 2019, TEPCO report that the research provided "*valuable information on the state of the fuel debris material and …allowed* [simulation] *of the conditions that we are likely to encounter when we enter the fuel retrieval phase*". They further note that the *"results will influence how we plan our unit 1 core retrievals"* (Manager-Safety Engineering & Assessment Group, TEPCO) **[d]**.

The Japan Atomic Energy Agency (JAEA) is responsible for both nuclear research and providing underpinning guidance on plant/facility decommissioning activities in Japan. The UoB team has actively collaborated with JAEA since 2016 (now formalised with a Memorandum of Understanding). Through the unique portfolio of analyses on emitted particles, UoB directly influenced hazard reduction and decommissioning activities at the FDNPP. JAEA notes, in 2019, that "*this analysis confirmed that the current low levels of residual radioactive particles in most areas and their environmental changes have not affected local people*" (translation from Japanese) (Researcher – Spent Fuel Analysis, JAEA) **[e]**. This work has enabled JAEA to: better establish the sequence of events that occurred in the reactors; estimate the state, properties, and chemistry of the fuel – crucial to its future mechanical removal; inform local citizens of its environmental hazard; and validate estimates as to the condition of the internal reactor pressure vessel/primary containment vessel, which together house the damaged fuel assemblies **[e]**.

3. Future safety of geological nuclear waste repositories

The International Atomic Energy Agency (IAEA) deems it necessary for its Member States to identify and comprehensively evaluate the impact of climate and environmental change on the robustness nuclear waste repositories, on timescales relevant to each specific repository. Given the lifetime of the radionuclides concerned, this requires accurate climate prediction from 100,000 years into the future for low- and intermediate-level waste, to 1,000,000 years for high-level waste. To ensure safe and internationally-calibrated standards, the IAEA commissions international programmes to summarise recent developments and provide best-practice guidelines, such as MODARIA (MOdelling and DAta for Radiological Impact Assessments, 2012-2015).

UoB, through commission from the UK Radioactive Waste Management (RWM) and in conjunction with AMEC Foster Wheeler and Quintessa (see grant **[iii]**), were lead contributors to Working Group 6 of the IAEA MODARIA programme – "Common framework for addressing environmental change in long term safety assessments of radioactive waste disposal facilities*"* **[g, pp.36-60].** The approaches developed by UoB **[5, 6, g]** were praised by the RWM because they *"…have strongly benefitted both the UK and overseas radioactive waste management programmes"* **[f, p.vii]** and that the work had made a *"substantial contribution, both at a national and an international level, to the approach to be adopted and the techniques to be used in projecting future changes in climatic and landscape characteristics for use in post-closure performance assessments of geological facilities for the disposal of solid radioactive wastes"* **[f, p.viii]**.

Importantly, following this work the IAEA strongly encouraged its Member States to use the UoB approach for waste disposal programmes, noting in a technical report (2020) that *"an overall methodology for taking climate change and landscape development into account in post-closure radiological impact assessments of disposal facilities for solid radioactive wastes has been set out. It is intended to be applicable to a wide range of disposal facility types and provide a common and scientifically supported basis for addressing these complex issues in assessments carried out by Member States"* **[g, p.116]**.

A summary of the work can also be found in the interim report of the IAEA BIOMASS programme (published 2018), which states that *"These global results could be used in any safety assessment* *programme worldwide in which the focus was on radiological impacts during the current interglacial episode"* **[h, p.61]**.

Indeed, this methodology was adopted, including further funded development for its application by UoB (see grant **[iv]**) by two specific Member States, Finland and Sweden.

Adoption by Finland. Finland, through its national radioactive waste management organisation, Posiva Oy, is highly advanced in terms of implementing a long-term geological disposal facility. In December 2012, Posiva Oy submitted a Construction Licence application for their proposed repository in Olkiluoto. As part of the Operational Licence Application for the repository, due to be submitted in December 2021, a Safety Case is required which is underpinned by "*prediction of the climate and ice age cycles of the next 1,000,000 years."* A key consideration in the long-term safety of the repository is the *"number and duration of future ice ages during which ice sheets overlay the site of Olkiluoto."* **[i]**. Posiva Oy identified that "*the Bristol group were best placed to carry out this* [climate modelling] *work"* **[i]**. The data provided by Bristol was published as a Posiva Oy report in 2020 **[i]** and is fundamental evidence that is required for approval of their Safety Case. Posiva Oy state that "w*ithout this report and the work underpinning it, we would not be able to submit a complete case"* (Safety Case Programme Manager) **[i]**.

Adoption by Sweden. The national radioactive waste management organisation in Sweden, Svensk Kärnbränslehantering AB (SKB), have been developing a preliminary safety analysis report for a proposed spent fuel repository at Forsmark, Sweden. SKB identified the "*unique knowledge and expertise at Bristol University*" **[j]**, enabling them to fulfil their obligation to "*demonstrate that the repository fulfils the assessments of long-term repository safety*" through "*scenarios for future changes in climate*" **[j]**, as mandated by the regulating authorities. SKB state that the results "*are now being used in ongoing safety assessments, and will also be included in future assessments*" and that they "*proved paramount for improving the description of climate variability*" (Scientific Coordinator, SKB) **[j]**. As such, UoB's work has strengthened SKB's safety analysis report, which will enable them to progress to the next stages of the repository licence application, and ultimately its safe operation.

Overall, the team's expertise in long-term climate modelling, their research findings, and their engagement with the nuclear industry, has directly led to international improvements in the safe storage of radioactive materials, safeguarding the health of countless future generations.

5. Sources to corroborate the impact

[a] EDF Hinkley Point C Letter of Support (2020), Senior Manager-Community Relations; BBC article (2017) Hinkley Point's Cardiff Bay toxic mud claim 'alarmist' [Accessed 16/2/21]

[b] Kyoto University – Letter of Support (2020), Former Vice Dean, Graduate School of Advanced Integrated Studies in Human Survivability (GSAIS); City Council of Minamisōma, Fukushima – Letter of Support (2020), Senator; Kawamata Town Council – Letter of support (2020), Vice Chair, Nuclear Disaster Countermeasures Division

[c] ATOX Co. Ltd – Letter of Support (2019), Backend Technology Department

[d] TEPCO – Letter of Support (2019), Manager, Safety Engineering & Assessment Group

[e] JAEA – Letter of Support (2019), Researcher, Spent Fuel Analysis

[f] Thorne M and Walke R (2017), *Summary of the Output of an International Collaboration on Climate and Landscape Change Modelling and its Application to the UK*, Quintessa and AMEC Report to RWM, AMEC/200041/004, QRS-1667A-4, 13 March 2017

[g] IAEA – Report (2020), *Development of a Common Framework for Addressing Climate Change in Post-Closure Radiological Assessment of Solid Radioactive Waste Disposal*, MODARIA Working Group 6, IAEA-TECDOC-1904

[h] SKB – BIOPROTA report (2018) *BIOMASS 2020: Interim Report*, produced in association with IAEA MODARIA II Working Group 6, Report R-18-02, March 2018

[i] Posiva Oy – Letter of Support (2020), Safety Case Programme Manager; Posiva Oy Report (2020) *Modelling Changes in Climate over the Next 1 Million Years*, POSIVA 2019-04

[j] SKB – Letter of Support (2020), Scientific Coordinator Climate Research Programme; SKB Report (2018), *Post-closure safety for the final repository for spent nuclear fuel at Forsmark – Climate and climate related issues*, PSAR version, SKB Technical Report TR-18-05