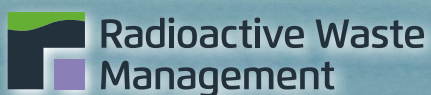




RATE

Radioactivity and the Environment Programme Impacts and Legacy

January 2018



A research programme funded by the Natural Environment Research Council, Radioactive Waste Management and the Environment Agency with support from the Science and Technology Facilities Council.
The RATE programme was five years in duration 2013–2018.



Intended audience

RATE brought together policymakers, business, scientists and research funders to improve the knowledge base and to develop skills and capability to help address strategic issues concerned with the management and development of nuclear energy in the UK. The audience for this action is broad and includes those undertaking research with interests in the energy and environment domain and those interested in the implementation of the findings (including national regulators, industry and key international organisations). It also targets those capable of forming effective and lasting partnerships to influence research and innovation funding arrangements.

Acknowledgements

Lead author: Jim Wharfe (Independent Consultant)

This programme overview would not have been possible without the helpful comments of a number of experts. Contributions are acknowledged from the funding organisations: Jon Martin (Radioactive Waste Management), Andrew Pynn and David Bennett, (Environment Agency), Blanche Wynn-Jones and Elizabeth Garratt (Natural Environment Research Council), and Kevin Smith (Science Technology Facilities Council); and from the investigators: Nicholas Beresford and Catherine Barnett (Centre for Ecology & Hydrology), David Copplestone (University of Stirling), Jim Smith (University of Portsmouth), Francis Livens and Gareth Law (University of Manchester) and Robert Zimmerman (Imperial College). Particular thanks go to Joanna Wragg (British Geological Survey), for her patience and support in helping deliver the final document.

Disclaimer

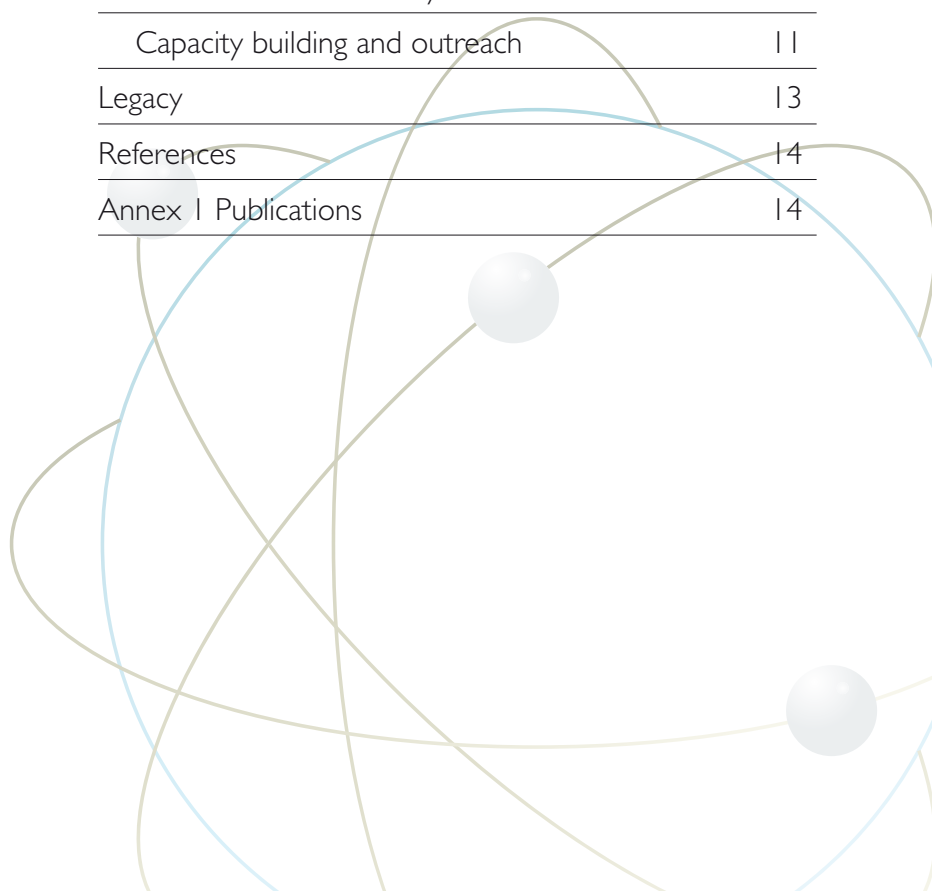
This report was commissioned by the British Geological Survey providing the science coordination for the RATE research programme and acting on behalf of the funding organisations. The information and views expressed by contributors to this report are as individuals and do not necessarily represent the views of their organisations.

January 2018

Front cover: The Chernobyl Exclusion Zone, the natural laboratory for the TREE project (image courtesy of www.lmasseyimages.com).

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Introduction

In recent years compelling evidence, based on a wealth of measures that include a rise in average surface temperatures, increasing atmospheric carbon dioxide levels, thinning of Arctic sea ice and a rise in global sea levels, shows a warming trend that is unprecedented in history with most of it attributable to human activity⁽¹⁾.

Our reliance on fossil fuels for energy is changing with the recognition of a low carbon future that will likely depend more on a mix of renewable, nuclear and bioenergy sources. Delivering affordable energy and clean growth is one of the ten pillars set out in the Governments Green paper 'Building our Industrial Strategy'⁽²⁾ but the transition to low-carbon is not without serious challenge requiring security of supply and done in a way that is affordable to business and domestic consumers. Furthermore, the UK adopted nuclear programmes at an early stage for civil and military purposes and has a substantial legacy of contaminated sites that have the potential to release radiation to the environment, decommissioning and safe disposal of materials is a major challenge.

Chernobyl green space at Prypiat.



RATE in context

There is large uncertainty around the balance of our energy mix by 2050 with widely differing options to achieve the two-degree scenario to meet the Government commitment to the Paris Agreement that came into force in November 2016. Nuclear is part of all of the 2017 (FES³) energy scenarios with a gap predicted between the decommissioning of old plants and new plants coming on-line.

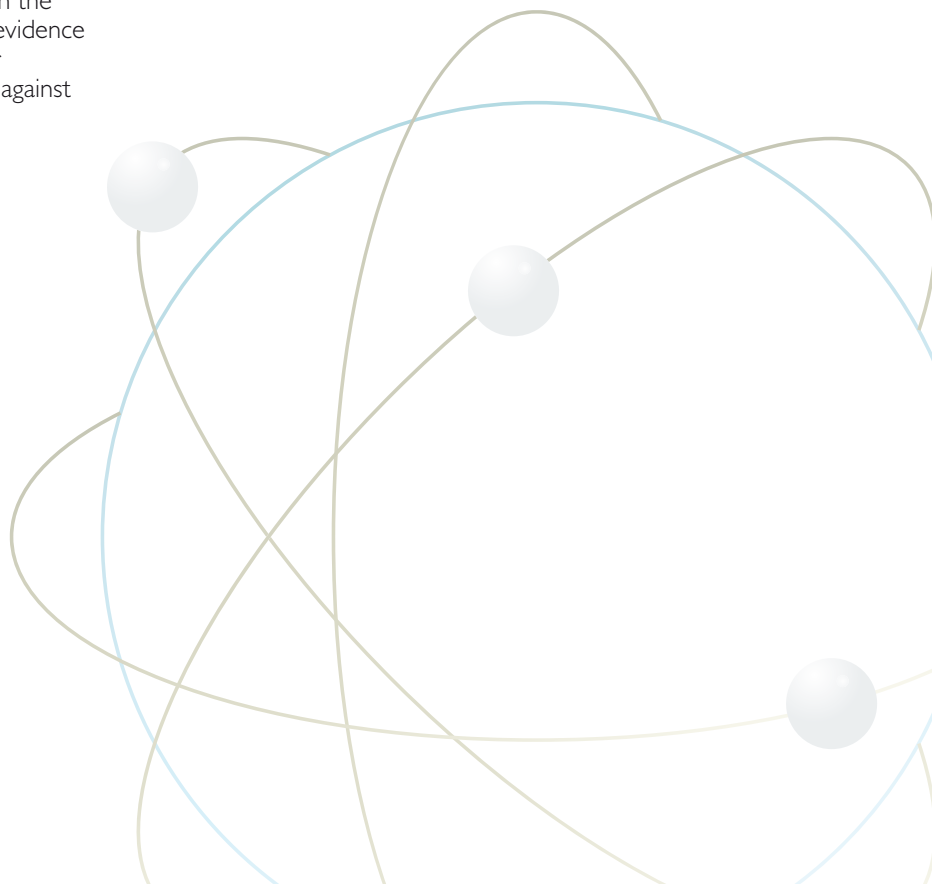
Nuclear energy has had an eventful history since it first came in to the UK in the mid 1950s. Incidents such as Chernobyl in 1986 and Fukushima in 2011 have raised a social debate on the threat posed to the environment and people. However, many contend that nuclear power is safe and projections indicate a significant increase in world nuclear power generation by 2040.

Footnote: Throughout this document GDF and repository are synonymous.



Image courtesy of www.lmasseyimages.com

The RATE programme was developed in recognition of the need within the UK to develop and maintain an agile and flexible R&D capability to stimulate high quality, interdisciplinary research and be seen as a credible international partner. Growth of the nuclear sector in the UK is a complex issue. Government policy, the relative cost of nuclear power, technology development and public opinion, will all influence the speed and direction of growth in the decades to come. It is important that decisions are evidence based and scientifically sound, so that nuclear power production can be impartially and robustly assessed against other energy options.

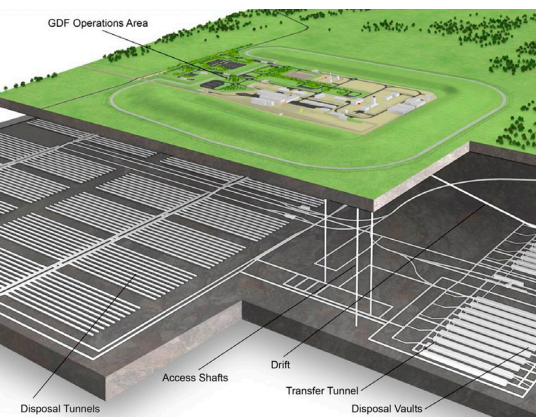




Genesis of the RATE programme

In December 2009 NERC received a commissioned report⁽⁴⁾ that considered the priority research needs relating to radioactivity in the environment over the 10 years ahead, taking account of likely UK developments in the nuclear power industry, nuclear decommissioning, and the disposal of radioactive waste. The recommendations informed an investment of £5M by NERC for the RATE programme. Partnership engagement with Radioactive Waste Management and the Environment Agency increased funding to £8M. The programme received further support from the Science and Technology Facilities Council through the funding of Research Networks (EnvRadNet and GeoRepNet) that enabled scientists to gain access to world-leading research facilities.

Geological disposal facility—key elements.



- A suitable site with a willing host community
- Waste packaged in a form suitable for permanent disposal
- A robust safety case and design

The funding partners and their challenges

The **Natural Environment Research Council (NERC)** is the leading public funder of environmental science and the primary funder of the RATE programme. NERC's vision is to place environmental science at the heart of the responsible management of our planet. The RATE programme has contributed to addressing the 'Benefitting from Natural Resources' challenge as outlined in the NERC strategy.

Radioactive Waste Management Limited (RWM) is nominated by the UK Government for implementing the delivery of a Geological Disposal Facility (GDF) for the UK's higher activity radioactive wastes. RWM works with a wide range of stakeholders including regulators, industry and academics to consider the permanent disposal of the UK's most radioactive waste. An analysis of the nature and timing of RWM's future generic research and development activities is provided in their Science and Technology Plan⁽⁶⁾.

The **Environment Agency (EA)** regulates nuclear power stations and other nuclear sites in England for the disposal of radioactive waste. The EA consults on

permit applications and draft decisions for proposed new nuclear sites, supported by technical assessments to ensure that any new power stations and radioactive waste disposal sites meet high standards of safety, security, environmental protection and waste management.

The **Science and Technology Facilities Council (STFC)** has contributed to the RATE programme through the commissioning of two network arrangements. The EnvRadNet⁽⁷⁾, set up in November 2012 to initiate an Environmental Radioactivity Network to develop and promote the use of STFC facilities in environmental radioactivity research, and the Geological Repository Network (GeoRepNet 2013⁽⁸⁾) to bring together a wide diversity of scientists, policy makers and instrument designers to consider and prioritise the key scientific and technical challenges in understanding the geochemical, geophysical and biological processes that influence the establishment, operation and monitoring of geological repositories

The early engagement and commitment from RWM and the EA helped shape the portfolio of RATE research projects to help meet **end-user challenges**,

These challenges included:

The change in paradigm from radiation protection centered solely on human species to understanding the adverse effects of radiation exposure that considers doses and biological effects in a wide range of organisms including Representative Animals and Plants (RAPs⁹). In addition to current and new build, the UK has a substantial legacy of contaminated sites that could release radiation into the environment, leading to exposure to humans and non-human biota. There are considerable weaknesses in our knowledge of the pathways and transfer of radionuclides in terrestrial and aquatic systems and the effects of radiation releases on organisms.

Plans to develop a repository for deep geological disposal of intermediate-level and high-level wastes. Potential sites for a repository may have relatively complex geological formations and detailed studies will require techniques for non-intrusive characterisation of the geosphere, developing understanding of the temporal evolution of the geosphere on gas production and migration, pathways of contaminated groundwater, and solution-solid interactions of radionuclides. To meet regulatory permits for disposal RWM will need to understand the impacts of the very low levels of radioactivity that will eventually, on timescales of many millennia, return to the environment. The health effects of these low levels of radioactivity on humans and non-human biota both need to be adequately understood.

A programme of new build nuclear power plants that will require detailed environmental assessments, including evaluation of impacts as mandated by environmental regulations. There is a need to secure new data sets and to improve our current modelling capability to help inform environmental assessments with the knowledge that nuclear energy will likely play some part in a world where global population levels continue to increase.

Additionally, a high level goal of the RATE programme was to **rebuild UK capacity** in radioactivity and the environment, such that in the future a major scientific contribution to the enhancement of environmental protection and safeguarding of human health from releases of radioactivity from nuclear power plants, waste repositories and legacy-contaminated sites can be made. The programme directly addressed this critical issue by recruiting young scientists and developing early career researchers to secure the next generation of experts in radiation protection and nuclear crisis management.

RATE research consortia

Three research consortia were funded under the RATE programme:

1. TTransfer-Exposure—Effects (TREE⁽¹⁰⁾). Integrating the science needed to underpin radioactivity assessments for humans and wildlife.

Principal Investigator—Nicholas Beresford (Centre for Ecology & Hydrology)



The overall objective of TREE was to reduce uncertainty in estimating the risk to humans and wildlife associated with exposure to radioactivity and to ionising radiation. This was achieved through interlinked science components beginning with improving understanding of the biogeochemical behaviour of radionuclides in soils through to studying the transgenerational effects of ionising radiation exposure on wildlife.

The studies combined controlled laboratory experiments with fieldwork, most of which took place in the Chernobyl Exclusion Zone (CEZ). The investigation involved: short-term measurements of bioavailability in soils to test model predictions of the long-term availability of radionuclides in CEZ soils; characterizing radionuclide uptake by plants and other organisms to develop more robust alternative modeling approaches; improving quantification of radiation exposure and gaining a mechanistic understanding of resultant biological effects (including comparing laboratory findings with field reality).

2. Long-lived radionuclides in the surface environment (LO-RISE⁽¹¹⁾): mechanistic studies of speciation, environmental transport and transfer. Principal Investigator—Francis Livens, University of Manchester



LO-RISE characterised biogeochemical, biological and radiological conditions at 'natural laboratories' that contain elevated levels of radionuclides from man-made and natural sources, spanning both onshore and offshore locations in the UK.

This included the occurrence and movement of radioactivity through soils, waters, plants and animals, and how biological

processes control this movement. A series of natural laboratories (South Terras (Cornwall), Needle's Eye (Scotland), the Ravenglass Estuary (Cumbria), and various UK marine/coastal locations) were used to conduct experiments, to investigate the way soil/sediment conditions influence the radionuclide concentrations in solution, the form of the radionuclides, and the way radionuclides are taken up and distributed in the tissues of selected biota. The results from field and laboratory studies were used to develop and test mathematical models of radionuclide transport and transfer processes. The resulting models can be used in assessing environmental impacts, cleaning up contaminated land and predicting the long-term impact of radioactive waste disposal.

3. Hydromechanical and biogeochemical processes in fractured rock masses in the vicinity of a geological disposal facility for radioactive waste (HydroFrame⁽¹²⁾). Principal Investigator—Robert Zimmerman, Imperial College

HydroFRAME

Hydroframe investigated technological innovation for rock mass characterisation at a range of spatial scales and biogeochemical coupling. The study addressed the development of improved methods for estimating the repository-scale hydraulic conductivity of a fractured rock

mass, based on geologically realistic fracture network geometries. It explored and evaluated suitable seismic monitoring strategies for the characterisation of potential repository sites and examined the key seismic attributes for identifying fracture properties that play a critical role in repository performance. Coupled thermo-hydro-mechanical models for the behaviour of fractured rock masses were developed with modelling of colloid and tracer transport experiments. The importance of biogeochemical processes involving microbes and natural organic matter on actinide mobility in the near-field environment of a radioactive waste repository were also investigated.





RATE achievements

RATE has made a significant addition to our knowledge, providing new data sets, surveillance techniques and modelling capability. It has provided training and enhanced our skill capacity following a period of relatively low research investment in this field of research in the UK. This section provides an insight to some of the key findings and how they have helped address the end-user challenges, together with details of the important capacity building elements of the programme. Peer reviewed publications continue to emerge from the programme, a list of those published to date is provided in Annex 1.

Meeting end-user challenges

From the start, RATE research was shaped by end-user commitment that greatly helped integration and the translation of the programme outputs to achieve impact.

Challenge 1: Environmental radioactivity in plants and animals: uptake and effects

Many physical, chemical and biological processes influence radionuclide transport through the environment. RATE has improved understanding of the mechanisms governing radionuclide speciation and the subsequent impact on mobility and uptake by humans and wildlife reducing uncertainty associated with the modelling of these complex environments.

New, species diverse (80 plus species) datasets, focused on current and possible future flora of the British Isles, have been generated for plant uptake of iodine, technetium and selenium radioisotopes under controlled conditions. Plant uptake of these radionuclides reflects the relative solubility of the elements seen in soil incubation studies. Bioavailability followed the sequence $Tc > Se > I$. In the case of technetium, the soluble form (pertechnetate, TcO_4^-) was highly bioavailable but once fixed by sorption in the soil, technetium was not available for further plant uptake. Plant uptake behaviour was found to be channelled down branches of the plant phylogeny, it is not randomly distributed between species and has not been subject to significant adaptation by any group tested.

Models based on taxonomic groupings have been developed for the transfer of caesium, strontium, uranium, selenium and lead to terrestrial wildlife. These take

Red Forest area in the CEZ
courtesy of the RED FIRE project:
<https://www.ceh.ac.uk/redfire>



into account site effects that can contribute to the often orders of magnitude variation observed for any organism-radionuclide combination in commonly used concentration ratios. The studies have provided new transfer values specifically for species falling within the taxonomic families defined for the RAPs included in ICRP's framework, data for these organisms are often sparse. These outputs have contributed to the developing International Commission on Radiological Protection (ICRP) documentation on environmental protection.

More than 30 years after the Chernobyl accident there is **no consensus on the longer-term impact of chronic exposure to radiation on wildlife in the Chernobyl Exclusion Zone (CEZ)**. Reconciling this lack of consensus is one of the main challenges for radioecology.

Some of the findings from current research on chronic radiation effects from laboratory and CEZ field studies include: greater radiosensitivity of bumble bees than expected; no effects on fish embryonic development, although at the highest concentration tested in the laboratory (10mGy/d) hatching was delayed; no indication of radiation effects on fish health in the field although the gonads in some female perch were underdeveloped in two of the three most contaminated lakes; and no relationship between radiation exposure and soil biological activity. A significant increase in DNA damage in the sperm of marine crustaceans was observed with subsequent effects on offspring in the laboratory, although field studies showed no significant difference in brood sizes of freshwater crustaceans. **Importantly, for all species considered, any effects observed were at dose rates higher than those for permitted/anticipated releases in the UK from nuclear power plants, waste repositories and other sources.** Studies on the effects of radiation on birds, small mammals, *Daphnia pulex* and *Drosophila melanogaster*, and marine and freshwater mussels are on going.

Other studies conducted in the UK have shown that some of the ^{14}C discharged into the Irish Sea becomes incorporated into shellfish and transfers through the food chain, accumulating in predator species (seals, porpoises etc.). Predators sampled closer to the Sellafield site showed higher ^{14}C activities. Whilst all the commercially important fish, crustaceans and molluscs sampled showed ^{14}C enrichments above background levels, **the radiation dose that would come from their consumption was found to be extremely low and radiologically insignificant.** However, ^{14}C still remains as a significant issue in terms of its collective effective dose and hence requires a detailed understanding of its ultimate fate.

Challenge 2: Biogeochemical impacts on transport processes and repository development

Examination of the biogeochemistry, transport and distribution of Sellafield derived radionuclides (^{99}Tc , ^{137}Cs , ^{236}U , ^{237}Np , ^{241}Am ,) in marine and estuarine environments has shown that these **radionuclides are still being transported to Welsh and Scottish coastal sites** despite the fact that contemporary waste discharges from Sellafield are minor compared with those released between 1950-1970. Current work in the Ravensglass Estuary and

the Irish Sea indicates that accumulated radionuclides from historical discharges in a band of silt on the Irish Sea floor continues to act as a source of anthropogenic radionuclides to UK coastal waters.

Terrestrial studies focussed on uranium and radium biogeochemistry and uranium and technetium behaviour in microcosms systems representative of contaminated aquifers. Weathering of a local pitchblende vein at Needles Eye and high concentrations of organic matter in the soil produce anoxic conditions and solid phase uranium enrichment ($> 1600 \text{ mg kg}^{-1}$). Uranium enrichment at the site is largely controlled by U(VI) complexation with organic matter and appears to limit trophic transfer into indigenous plants. In contrast, at South Terras (a former uranium/radium mining site) where soils are more mineralogical in nature, uranium and radium transfer into plants is much higher.

Studies on technetium (^{99}Tc) and neptunium (^{237}Np) show that repeated redox cycling (fluctuating between oxic and anoxic conditions) plays an important role in limiting redox active radionuclide solubility in aquifer systems. However, a small but significant proportion of radionuclide-Fe-bearing colloids can form in redox cycled sediment systems and may provide an important radionuclide transport vector in aquifers.

The uptake of radionuclides on rocks surrounding a Geological Disposal Facility (GDF) is an important safety function in many concepts and is influenced by such factors as rock composition and groundwater geochemistry. Significant progress has been made in the fundamental understanding of the thermal, hydraulic, mechanical and chemical processes that interact in these complex natural systems that impact on the safety functions of the GDF.

The presence of a GDF will affect the surrounding geosphere during construction, operations and the post closure although **detailed investigation cannot take place until site-specific and concept-specific information are available.** In many host rock formations that are possible locations of a GDF interconnected networks of fractures may form the main potential pathways for the transport of radionuclides from the repository to the biosphere

Key soil properties governing the fate of radionuclides relevant to GDFs have been determined for iodine, technetium, uranium and selenium. Organic matter content, pH and soil texture were key, indicating that reduction and subsequent bonding to organic carbon are the dominant fixation processes. Uranium is very rapidly distributed into three distinct fractions, electrostatically adsorbed, isotopically exchangeable and 'fixed' (non-reactive). The distribution of uranium between these fractions changes only slowly with time. Extractions from highly contaminated Chernobyl soils confirmed the presence of some enriched uranium (^{235}U) in an electrostatically adsorbed form 30 years after the accident.

Experiments conducted over 2.5 years show incomplete mixing of added isotopes and native pools, underlining the need for decadal term measurements under realistic environmental conditions to establish the longer term mixing

of native and introduced isotopes in soils. Investigation of isotopic interaction of selenium and iodine with humic acid has shown the importance of iron (Fe^{2+} and Fe^{3+}) as bridging cations in organic soils and the roles of temperature and pH on carbon bonding reactions.

Other studies on biogeochemical processes in fractured rock masses have used a combination of laboratory experiments and numerical computations to study uranium mobility in saline and alkaline aqueous solutions, representative of the near field of a GDF. In batch experiments, variations in pH, uranium concentration, type of geomaterial, and bicarbonate content, affect uranium removal from solution. Quartz, sandstone, and volcanic rock adsorb uranium onto their surfaces between pH 4 and 8 in sufficient concentrations to be efficient at retaining radioactive uranium after the failure of a low-level waste or intermediate level waste repository. They are also efficient at retaining uranium at pH 10–12, where concentrations are ≥ 10 ppm, mainly through precipitation as sodium precipitates. The presence of bicarbonate, a common ion in groundwater, reduces uranium retention only in the pH range 8–10, but enhances it at pH 10–12 when uranium ≥ 10 ppm. These results are important for the understanding of how uranium may interact and be immobilised in areas where it may escape into environments with similar lithology, and predicting the fate of this contaminant.

Challenge 3: Monitoring and modelling improvement for reduction of uncertainty

Monitoring and surveillance capability has been enhanced by a new live-measurement detector system designed to allow quantification of both gamma and beta emitting radionuclides in wildlife (e.g. small mammals, birds). The detector can be deployed in the field, allowing capture, measurement and release of animals within a short time frame. In-situ monitoring has helped map the spatial extent and depth profiles for gamma emitting radionuclides in the CEZ.

A range of dosimeter types, in combination with GPS-tracking collars, have been successfully used to assess how animal movement affects exposure and to test the assumptions commonly used in assessment models. This research was conducted in collaboration with a UN International Atomic Energy Agency (IAEA) working group. Important dose contributors and exposure pathways for a number of organisms show that the common use of ambient dose rate in field radiation effects studies will underestimate the actual total absorbed dose rate (for example in the CEZ by up to one-order of magnitude).

A network of motion-activated camera traps (>240 positions over a 12-month period) demonstrated similar medium-large mammal species composition across all radiation levels in the CEZ. Census data showed that the relative abundance of mammals within the CEZ was unrelated to radiation levels with mammal populations around Chernobyl similar to those found in nature reserves in the region.

Alternative models to the commonly used yet highly variable concentration ratio approach for both human foodstuffs and wildlife have been developed. The research has

identified a significant predictable component in the transfer of a range of elements to biota (including food crops).

New and improved methodologies, codes and protocols for analysing various processes that occur during the lifetime of a GDF have been developed. Interconnected networks of fractures may form the main potential pathways for the transport of radionuclides from the repository to the biosphere. Two different approaches have been taken to model the flow of fluids through networks of rock fractures: effective medium theories (in which the fractured rock mass is 'replaced' by an unfractured porous continuum that has the same macroscopic permeability as the actual fractured rock mass) and discrete fracture models.

Effective medium theories proposed in the literature were used to compare their predictions to the 'exact' permeabilities, as computed by detailed finite element calculations. Input includes matrix permeability, fracture apertures, lengths, orientations, and number densities. Studies found that extremely accurate permeability estimates could be obtained demonstrating that classical effective medium theories, properly applied, can be used to model the permeability of the fractured rock in the vicinity of a GDF.

Modelling efforts focussed on the generation of geologically realistic fracture networks have generated the first simulations of dense fracture networks that are based on the rigorous computation of stress intensity factors, and the accepted principles of fracture mechanics. A finite element method is used to compute the displacements and stresses around the various fractures, the fractures are then allowed to grow based on whether or not the computed stress intensity factors reach a critical value that depends on rock type. This methodology promises to yield much more realistic fracture geometries than can currently be created using discrete element methods, or heuristic semi-analytical approaches.

Colloid formation and tracer migration experiments were carried out at Nagra's (the Swiss nuclear waste management organisation) underground rock laboratory in Grimsel. Tracers injected into the rock mass via boreholes that intersect the fractures are recovered at extraction wells allowing tracer breakthrough curves at the various extraction wells to be modelled. Hydrological models have been created, with heterogeneous distributions of transmissivity and storativity to help predict colloid and radionuclide migration for americium and plutonium. The results show excellent matches to the measured breakthrough curves.

Capacity building and outreach

A key goal of the RATE programme was the **strengthening of skills sets and capacity in the UK**. This has been achieved through a number of initiatives.

During the course of the programme each of the research consortia provided multi-disciplinary training at summer/winter schools and opportunities through laboratory and field investigation for the development of **31 PhD students** and a number of **Post Doctoral Researchers**.

RATE capacity building—learning about the radioecology of Chernobyl during the TREE Summer School.

To date there have been **over 40 peer reviewed publications in more than 20 journals** with other papers in progress (Annex 1). The TREE project was **awarded the Times Higher Education Project of the Year 2016** and many students have received individual awards for their research. RATE has attracted considerable interest from other research groups during the course of the programme, both nationally and internationally, allowing significant leverage in both financial terms and academic engagement.

Recognising the excellence of RATE science – the TREE project is named the Times Higher Education Project of the Year 2016.

New UK research networks have been supported through Research Council sponsored initiatives, the Environmental Radioactivity Network and the Geological Repository Network. These networks have helped researchers to make advances by introducing them to research facilities. An example being the training of students in the use of analytical capability at the Diamond Light Source, enabling them to probe deep into the basic structure of matter and materials and understand physical processes at atomic and molecular scales.

Comprehensive **stakeholder engagement and outreach** through a range of events:

Examples include:

- Stakeholder engagement at the Museum of Science and Industry (July 2015; >500 visitors) and the Manchester Science Museum;
- Stakeholder engagement at the Manchester Science Festival (2015, 2016 and 2017; c. 2000 visitors per year);



The Manchester Science Festival— one of the many RATE public outreach events.

- Stakeholder engagement at a public 'Nature Live' presentation at the Natural History Museum in London, 24 February 2017;
- Contributions to an environmental protection course to Environment Agency staff (July 2015);
- Sponsored networks, opening up the benefits of STFC analytical capability for RWM through collaboration with academia;
- Environmental radiation protection capacity building workshops, based around TREE research, for Japanese Government (Feb 2015), South African Government (Sept 2016) and European Commission International Atomic Energy Agency IAEA (Sept 2015);
- Attendance at national and international conferences (International Conference on the Biogeochemistry of Trace Elements, International Conference on Radioecology & Environmental Radioactivity, Society for Environmental Toxicology and Chemistry workshops, and European Radiation Protection Week);
- Discussions with the Food Standards Agency concerning impacts of ^{14}C in the UK food chain and discussions with Sellafield Ltd. concerning potential future work in this area;
- Inputs to ICRP Task Groups and UN IAEA Working Groups.

The Manchester Science Festival— one of the many RATE public outreach events.

Wide **media interest**:

Examples include:

- International TV news (ITN for Channel 4, BBC, Sky News, YTV South Korea) and radio coverage (Swiss National Radio, ABC Australia, BBC Radio4, Radio X Digital Radio, talkRADIO) and print/on-line media (New Scientist, BBC Earth, BBC on-line, Der Spiegel);
- Boosts to the TREE profile tweets (including @drmdwood and @radioecology) largely associated with work in the CEZ which has resulted in social media based discussions about the research.



Image courtesy of www.lmasseyimages.com

Legacy

The RATE programme has provided important new data sets and increased our knowledge and fundamental understanding of how radionuclides enter and move through the natural environment, how they change in the environment and how they might affect plant and animal health. The research has shown relationships between radionuclide physicochemical properties and their effects on organisms in the environment.

Models have been developed to describe geological features and environmental pathways and impacts to help determine the siting of a radioactive waste repository. The complex behaviour of radionuclides and their interactions and effects in the environment presents an on-going challenge. Many questions remain and there is still a pressing need for high-quality data to ensure that these models are applicable and can be translated into specific contexts of use.

RATE has allowed scientists to work together across borders to understand these complexities taking a robust, systematic approach that pools strengths and expertise across disciplines. The networks and research it has supported, and the publications produced have been of the highest quality, building capability and ensuring that the UK remains a credible global partner.

To help build on this legacy, it is the funders intention to support a Knowledge Exchange Fellow to facilitate the application of the science delivered from the RATE research programme in both core and wider disciplines to a variety of users and stakeholders, including policy makers, government agencies and industry.

Early consideration, taking into account the wider context of the Industrial Strategy and EU exit, needs to be given to some of the pressing research questions that remain and which will be critical to the decision-making process as the future role and size of the nuclear energy option in the UK becomes clear.

RATE capacity building— learning about the radioecology of Chernobyl during the TREE Summer School.



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Annex I RATE publications

TREE publications to date

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