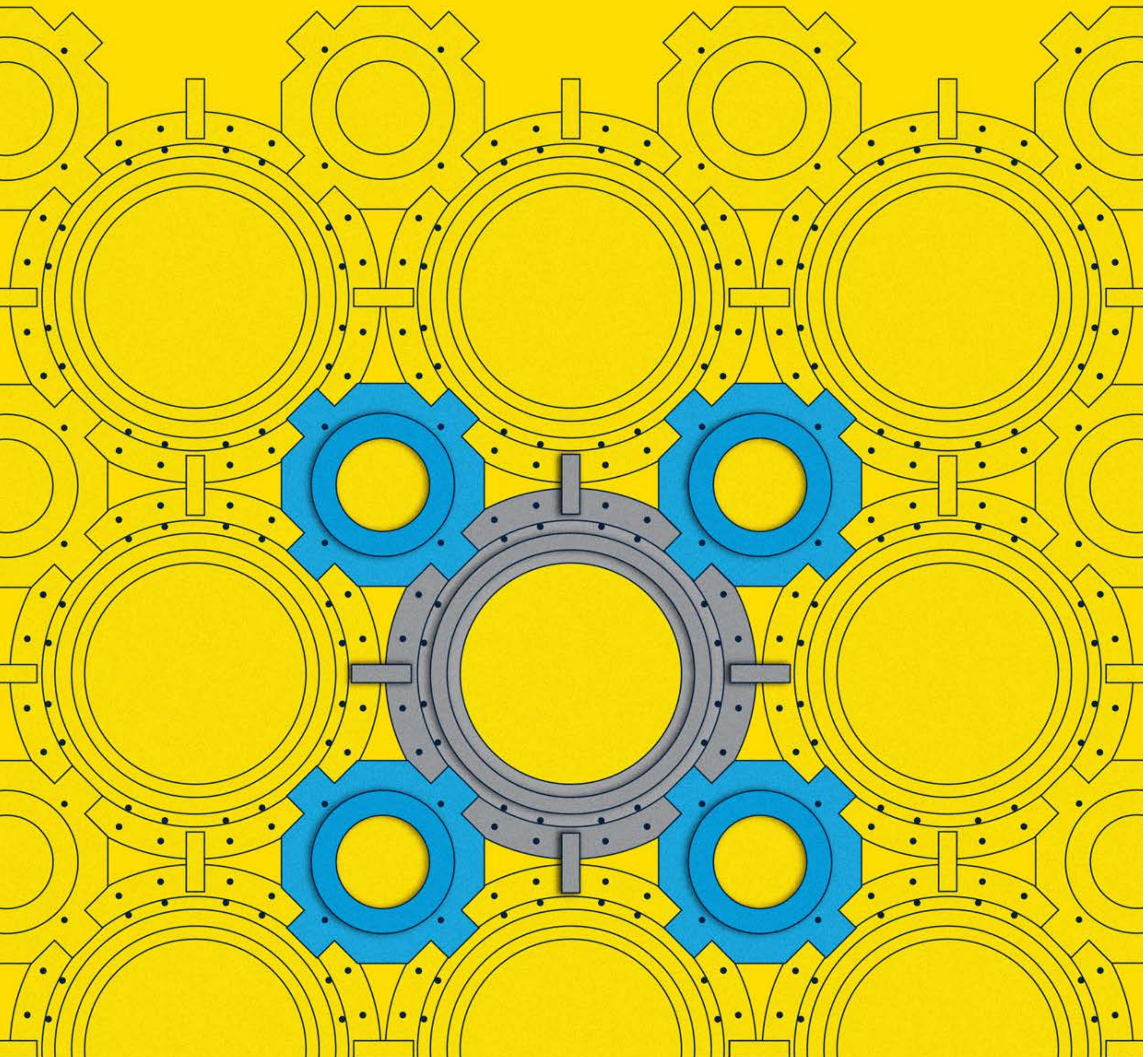
6 | Core science

Materials science enabling a **low-carbon future**



Materials science is integral to modern life and draws on a fundamental understanding of matter to develop advanced materials.

Many of the reactors that contribute to the UK's current low-carbon energy mix are safely operating well beyond their original design lifetimes because of improvements in our understanding of how materials change during service.

Based on this understanding, new reactors are currently being designed to operate for longer.

These new designs mean that components could need to withstand higher temperatures, pressures and radiation fields. A longer reactor operating lifetime is underpinned by robust standards which are maintained by highly regarded international bodies. The standards are developed by panels of experts, including our experts at NNL.

These standards, which support international regulations, are regularly reviewed and updated to reflect new understanding as well as new developments in methods to assess material properties. These developments are a result of high-quality research. At NNL, we have a long history of developing this knowledge.

Post-irradiation examination takes place at our Windscale Laboratory.

Quality

In-depth understanding of materials performance sets the highest standards and assures performance

Graphite is a key component of the designs of existing and some future reactors. This material acts as a moderator, helping to control the nuclear fission reactions, and is the main structural component of the reactor core. For this reason, before they are placed in the reactor, graphite components undergo extensive qualification using materials specifications, test methods and practices maintained by American Society for Testing and Materials (ASTM) International via a committee of world experts.

At NNL, we have pioneered new testing methods which can produce a wealth of detailed information relevant to reactor operations. Carried out at our Windscale Laboratory, the tests analyse the fracture properties of the graphite as well as changes in density and porosity. The results are compared with model predictions and confirm that any changes in the graphite do not affect the performance of the reactor. It is, therefore, very important that the data from these small samples are accurate and representative of the large graphite components in the reactors. Based on our 50 years of experience, we have developed an ASTM guide to support other laboratories in ensuring that data from small graphite samples, taken from the reactor or from separate irradiation experiments, can meet these criteria.

Future reactor technology, such as the high-temperature gas-cooled reactor (HTGR), will require new materials that can perform well in the high temperatures and radiation fields found in the reactor core. New graphite grades and metallic structural materials are being developed, which must be proven to meet these high standards. This year we published our research into new grades of graphite using a novel method that can determine the porosity of the material. With unparalleled experience in this area for the UK, we are also supporting The American Society of Mechanical Engineers (ASME) to develop the design code for HTGR graphite components.

The standards and journal publications include:

- ***Behavior and Use of Nuclear Structural Materials***
  The American Standards and Testing (ASTM) International.
- ***Graphite Testing for Nuclear Applications: The Validity and Extension of Test Methods for Material Exposed to Operating Reactor Environments***
  Editor(s): Athanasia Tzelepi, Martin Metcalfe, DOI: 10.1520/STP1639-EB
- ***Graphite Testing for Nuclear Applications: The Significance of Test Specimen Volume and Geometry and the Statistical Significance of Test Specimen Population***
  DOI: 10.1520/STP1578-EB. ISBN-EB: 978-0-8031-7602-7. ISBN-13: 978-0-8031-7601-0 STP1639-EB
- ***Boiler and Pressure Vessel Code (BPVC)***
  The American Society of Mechanical Engineers (ASME).
- ***Research on new grades of graphite is reported in***
  A. Tzelepi, J. McGladdery, I-H. Lo and G. Copeland, Nuclear Engineering and Design, (2023) 411 , 112421

View the research article on the Nuclear Engineering and Design journal's website.

Talent

Upskilling our researchers to develop advanced nuclear materials

Analysis and understanding of the behaviour of irradiated material is vital for the nuclear industry and will help develop the next generation of nuclear technologies. This is made possible when highly skilled researchers perform the analysis and interpret the results.

Working across our wider materials science portfolio are more than 30 scientists and technicians. Many elements of the work are led by early or mid-career scientists to support their growth as technical leaders. We also support 14 PhD students across 8 universities to develop vital skills and expertise in materials science. Many of these students have accessed our facilities at our Central and Windscale Laboratories, which has afforded them unique opportunities to work with material in actual nuclear settings. These experts of the future will continue to make new discoveries of materials that can last for longer, widening the possibilities for nuclear technology.

NNL's Core Science Themes, such as materials performance, led by Dr Paul Styman, push the boundaries of many aspects of nuclear science. Dr Styman originally worked on a PhD project supervised by NNL and joining NNL enabled him to continue working with internationally recognised experts in the field of nuclear materials and further develop his skills. He is now a recognised expert in his own right, holding a visiting position at the University of Oxford and participating in the OECD-NEA Expert Group on Structural Materials. Within this group, he leads the development of best practices for an advanced analytical technique, atom probe tomography, that can explore materials at the atomic scale. This type of analysis enables the effect of minute changes in composition to be determined, thereby helping to inform the manufacture of future materials for nuclear applications.

To further build future capability, this year we are actively participating in an exciting UK/US programme: the Neutron Irradiation as a Function of Temperature (NiFTE) irradiation campaign. This campaign, between the UK's National Nuclear User Facility (NNUF) and the US Nuclear Science User Facilities (NSUF), brings together experienced and early career scientists from NNL, The University of Manchester, UK Atomic Energy Authority and Idaho National Laboratory, to look at a wide variety of materials including stainless steels, nuclear graphite and novel materials.

For the first time in the UK, we have characterised the pyrocarbon layer of advanced fuel particles, which will have a significant impact on refining the fuel's performance. Continued research into the effects of radiation on materials is essential for developing and licensing nuclear technology and will help build skills.

> "The NSUF/NNUF NiFTE irradiation campaign planned to start in 2025 is the first major US/UK materials damage study in many years and involves a carefully planned campaign with partners from several national laboratories and universities on both sides. We have been very pleased to include NNL staff both in the management of the project and in the selection and provision of some of the sample sets for this ambitious programme of work."

Dr Brenden Heidrich
Director, Nuclear Science User Facilities, Idaho National Laboratory

Prof. Chris Grovenor
Oxford University

> "During my PhD at University of Liverpool, I was very fortunate to be supervised by some of the world experts that work for NNL. The opportunity to work on graphite post-irradiation examination (PIE) analysis at Central Laboratory was crucial to develop my skills. I feel that my work is really making a difference to the industry and I'm excited to keep challenging myself and maybe be recognised as a world expert myself one day."

Dr Chloe McElvaney
Graphite Scientist for NNL

Partnerships

Far-reaching research delivers vital insights

Science moves forwards rapidly when researchers come together to work on common interests. Our materials scientists are involved in numerous collaborations with universities and other national laboratories around the globe. This in-depth research improves our understanding of materials behaviour, which in turn leads to advancements in the standards that support high-quality materials and testing methods. Some of the international collaborative projects our researchers are working on are detailed below.

The Horizon 2020 project Il Trovatore will develop innovative cladding materials for advanced reactors. These materials will be more robust and so able to withstand a wider variety of conditions compared with previous materials. Many candidate materials are tested in the Belgian research reactor, BR2, and we are leading on the post-irradiation examination to understand their stability under irradiation. To date, we have characterised materials using state-of-the-art techniques which will serve as a benchmark for the irradiated materials.

The collaborative EU Horizon Europe project, FRACTESUS, takes a detailed look at the steel used in reactor pressure vessels using small-scale samples. This vital component of a reactor can measure several metres across and is 10–20 cm thick. The pressure vessel contains the fuel and the coolant which is under high pressure. It is designed to last for the entire life of the reactor and so must meet incredibly high standards to ensure continued safe operation over its lifetime. Our collaborative work has helped develop new techniques to test small specimens, thereby optimising the use of resources while maintaining scientific accuracy.

Small samples, which replicate the materials used to make the entire pressure vessel, are put inside the reactor. The results of tests to understand strength and fracture toughness are fed into increasingly advanced computer models to predict the performance of the pressure vessel as accurately as possible. Small-scale samples provide a wealth of high-quality data to ensure this impressive level of accuracy. These models are used to validate the operational lifetime of current reactors and will help predict the lifetime of future planned reactors.

We are involved in a European collaboration to create a database which collates data obtained from multiple projects where the effects of radiation on reactor pressure vessels was researched. This project, called ENTENTE, is significant as it draws together data collected by diverse, specialist characterisation techniques, which require careful consideration by experts. In this collaboration, NNL leads on the specialist atom probe tomography technique.

In another European collaboration, JHOP, we are contributing to the Jules Horowitz Materials Test Reactor which will be built in France and will allow UK-based materials researchers access to this ultramodern facility. During the current development phase, we are influencing roadmaps for essential materials and nuclear fuel research.

Read more about FRACTESUS at www.fractesus-h2020.eu and Il Trovatore at www.iltrovatore-h2020.eu

Read about ENTENTE and JHOP at the EU research and development information website: cordis.europa.eu

Impact

Developing high-quality materials for a sustainable future

The UK's gas-cooled and pressurised water reactors have supplied clean, safe power to the national grid for decades. New, advanced reactors will supply the UK with clean, safe power for generations to come, thereby contributing to a net-zero energy economy that minimises resource use while providing job security for a highly skilled workforce. These advances are supported by in-depth materials research.

NNL's materials performance Core Science Theme has been reviewed as being world-leading by a panel of international experts. In addition to publishing over 100 articles in scientific journals, our experts are involved in international steering groups and committees which place them at the heart of international programmes pushing the boundaries of materials science.

We have pioneered methods to analyse the microstructure of materials that have become the de facto standards worldwide to investigate irradiation-induced nanometre-scale clusters of atoms in steels and relate these to changes in the properties of the material. The resulting mechanistic understanding has influenced regulators and materials standards in the UK and internationally.

Key member of the materials performance community

Since 2018, Jonathan Hyde, Senior Fellow for materials, has represented the UK on the Board of Management for the Halden Reactor Project. He was appointed chair in 2023. Over the last year, the board has ensured that more than 50 years of operational experience on material irradiations has been captured and made available to the international community.

Nassia Tzelepi's work on the international standards for graphite has influenced regulators in the UK and internationally.

Susan Ortner, Principal Materials Scientist at NNL, is the UK representative on a sub-group of the Generation IV International Forum, where she is helping to define the specifications for metals used in very-high-temperature reactors.

Advanced analytical techniques can look at the structure of materials with nanometre accuracy.