Material matters

In an interesting discussion, Dr Aurélie Gentils speaks about her collaborative project that examines the joint impact of irradiation and helium gas on swelling in components of nuclear reactors.

To begin, what is your role in the Co-influence of Irradiation and Helium gas on swelling of pressurised-water nuclear reactors materials components: experimental and numerical simulations (CoIrrHeSim) project and what is its goal?

The aim of CoIrrHeSim is to study the joint action of both irradiation and helium gas on the ageing of material components of pressurised-water nuclear reactors (PWRs). By combining both experimental and numerical simulations, the project intends to increase knowledge of the mechanisms behind the ageing of materials in the wider framework of nuclear power plant lifetime extension. We are focusing our studies on reactor pressure vessel internal structures that are made of austenitic stainless steels (mainly composed of iron, chromium and nickel), as they are subjected to intense irradiation. I am in charge of the coordination of the whole project, which is funded by the French National Research Agency (ANR).

In what ways do PWRs differ from fast breeder reactors (FBRs) and why is it necessary to collect more data regarding the former’s decay?

FBRs use fast neutrons – that is, unmoderated – to breed the uranium fuel. This is in contrast to the commonly used PWRs that use thermal neutrons moderated by water. This neutron spectrum, which represents the distribution of neutrons in terms of rate or energy, is an important parameter to consider when studying the swelling of an irradiated material. Indeed, it partly determines the amount of helium gas transmuted from nickel, and to a lesser extent from boron (both elements are present in the reactor vessel material).

Swelling is a degradation mechanism in materials – and it is known to occur in FBRs operating above 400 °C. However, it is not possible to extrapolate these data to PWRs without considering the effect of helium gas because the mechanisms can be different. Up until now, the data available on PWRs have been obtained from investigations on decommissioned components, but in most cases the irradiation temperature and dose were too low to observe any swelling. The aim of our project is to investigate the role of helium on the potential swelling that may occur after a long irradiation time in PWRs, which is an important phenomenon to avoid if the life cycle of a nuclear reactor is to be extended.

Could you explain how your experiments are conducted? Why do you not perform experiments directly on PWRs?

In CoIrrHeSim, we use ion beams generated by particle accelerators to experimentally simulate the reactors’ conditions to which the material is subjected. Heavy ions in the megar electron volt (MeV) range are able to mimic the damage produced by neutrons. Helium ions are also implanted simultaneously inside the material to simulate helium gas presence coming from...
spallation reactions. The Joint Accelerators for Nano-science and Nuclear Simulation (JANNuS) facility in Orsay is the perfect tool to experimentally reproduce the reactors’ irradiation conditions: two ion beams are injected simultaneously towards the material in a transmission electron microscope, at a chosen temperature (380 °C in PWRs), allowing direct observation of material modifications.

This method is much less expensive than experiments with PWRs; without any activation of the material, results can be obtained in a few days (compared to decades in real-life reactors) and the various experimental parameters – such as quantity of helium, level of damage, temperature and flux – can easily be varied.

**What applications might the experiments in CoIrrHeSim have in other reactor decay models?**

Experiments performed within the CoIrrHeSim project could be applied to any other materials that need to be studied under extreme long-term irradiation conditions. For example, this could include materials for future fusion applications, such as in the International Thermonuclear Experimental Reactor (ITER), or materials for the next generation – Generation IV – of fission reactors. Materials for space applications could also be considered, as irradiation is an important safety concern.

**Have collaborations with public and industrial partners assisted with the advancement of CoIrrHeSim? How will you disseminate the results of the project?**

Collaboration between public and industrial partners is a key component of the project, as it relies on fundamental studies of materials while also taking into account important industrial issues. Looking ahead, our results will be disseminated at forthcoming international scientific conferences and through manuscripts in standard peer-reviewed journals.

**WITH 132 NUCLEAR reactors operating throughout the EU, nuclear power plants currently generate an impressive 30 per cent of the electricity produced on the continent. However, the average age of nuclear reactors in Europe is 29 years, meaning that many are approaching the end of their design lifetimes (usually 30-40 years). Due to financial considerations, many nuclear operators in Europe are attempting to extend the lifetimes of these reactors – dismantling and building new nuclear production units carries a price tag of tens of billions of euros, and each year the lifespan of a unit is extended, some €80 million is saved.

However, prolonging the lifetime of nuclear reactors is a considerable challenge, particularly when it comes to ensuring safety. In France, stringent inspection strategies and safety analyses have been implemented to monitor the ageing of key components of nuclear power plants. Ultimately however, extending the lifetime of nuclear installations depends upon further research into the materials of these components and how they degrade over time.

**A PIONEERING PROJECT**

The French National Research Agency (ANR) is funding an important project entitled Co-influence of irradiation and helium gas on swelling of pressurised-water nuclear reactors materials components: experimental and numerical simulations (CoIrrHeSim). Based at the Centre de Sciences Nucléaires et de Sciences de la Matière (CSNSM) joint research unit of the National Centre for Scientific Research (CNRS/IN2P3) and Université Paris-Sud, and coordinated by Dr Aurélie Gentils, this collaborative study aims to establish at the nanoscale the mechanisms and kinetics of the potential swelling that could occur in austenitic stainless steels under long-term neutron irradiation. “Some mechanisms, such as materials fatigue, stress corrosion and wear are quite conventional and are found in many other plants or industrial objects,” Gentils discloses. “Others are more specific to the nuclear industry, particularly the embrittlement and possible swelling of materials, most specifically steels under irradiation. While the individual mechanisms are varied, it is their synergistic action that contributes to the ageing of the material components of pressurised-water nuclear reactors (PWRs).”

Gentils’ team is attempting to establish the role of helium gas on the potential swelling that might occur in PWR materials during irradiation. The hope is that detailed analysis of this phenomenon will allow them to understand the nature of possible swelling mechanisms and enable them to predict the swelling-related ageing processes of the internal components of PWR vessels. Importantly, the project draws together many internationally renowned experts in the field of nuclear energy, from specialists in defect characterisation using transmission electron microscopy (TEM) to researchers with expertise in modelling of irradiated steels. Both public and industrial laboratories are involved in the study and the methodology combines experiments and numerical simulations.

As a prominent researcher in materials science, Gentils is well-placed to lead the project. She studied the effects of irradiation and the behaviour of the fission products in zirconia and magnesium-aluminate spinel during her PhD at the Université Paris-Sud, allowing her to build expertise in particle-solid interaction, ion beam analysis and in situ TEM. This was further consolidated during a two-year postdoctoral position at the University of Glasgow, UK, where she worked in the Solid State Physics Group within the Department of Physics and Astronomy, as a member of the European Research Training Network ULTRASWITCH. More recently, she has been employed as a full-time permanent researcher at CNRS where she develops studies based on ion beam synthesis and controlled modifications of materials.
CO-INFLUENCE OF IRRADIATION AND HELIUM GAS ON SWELLING OF PRESSURISED-WATER NUCLEAR REACTORS MATERIALS COMPONENTS: EXPERIMENTAL AND NUMERICAL SIMULATIONS

OBJECTIVE
To define, at the nanoscale, mechanisms of swelling occurring in austenitic stainless steels under long-term neutron irradiation.

PROJECT PARTNERS
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MAPPING THE METHODS
The CoIrrHeSim project is comprised of three main stages. The first involves characterising the microstructure of austenitic stainless steel subjected to ion beams. The researchers use high-energy heavy ion irradiation to simulate damage resulting from neutron irradiation, and helium ion implantation to mimic the helium gas produced by nuclear reactions. TEM then characterises the microstructure of the resultant material leading to any potential swelling. The experimental data obtained as a result – for example, the size and densities of defects, helium bubbles or cavities – are used to validate and adjust the parameters of the numerical simulations, which form the second stage.

Finally, the third stage involves combining the results obtained from the previous stages in order to make predictions about microstructure and mechanisms of swelling that could occur in nuclear reactor materials that have been exposed to long-term neutron irradiation. The hope is that this will lead to an improvement in the maintenance strategies and safety analyses of nuclear reactors in real life.

UNDERSTANDING SWELLING
As a complex degradation mechanism in materials, swelling is the result of a fast-kinetics process and is directly related to material and irradiation conditions. The production of helium gas by neutron irradiation of materials is an important aspect of potential swelling in PWRs. While swelling begins with an incubation stage in which there are no visible changes, the material deteriorates rapidly with higher doses of helium, possibly leading to embrittlement.

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The CoIrrHeSim experiments are conducted at the Joint Accelerators for Nano-science and Nuclear Simulation (JANNuS) facility located at the CSNSM lab in Orsay, which is a multi-ion beam irradiation platform co-managed by the French Alternative Energies and Atomic Energy Commission (CEA), CNRS (IN2P3 Institut) and SEMIRAMIS technical staff.

TEM image (magnification x29,000) of helium bubbles observed in the conditions of huge helium quantity at high temperature. All white points are helium nanobubbles.

Université Paris-Sud. These experiments explore austenitic stainless steel using megaelectron volt (MeV) heavy ion irradiation and helium ion implantation simultaneously at temperatures of 200 °C and 450 °C. Using an irradiation dose equivalent to a reactor lifetime of 30 years, the researchers observed that the behaviour of the steel concurred with previous work describing neutron irradiations in reactors. They also pinpointed the formation of nanobubbles that were approximately 1-3 nm in diameter when a huge helium quantity was used simultaneously with the irradiation, as an extreme condition case study (corresponding to seven times the estimated quantity of helium gas after 30 years in a reactor). These experiments were made possible by the state-of-the-art JANNuS facility, which enables the live observation of dual ion beam-induced modifications of a material: “JANNuS can of course be used for any kind of material with nuclear applications,” Gentils points out. “And researchers studying other applications – such as space, photovoltaics or microelectronics – could also take advantage of it.”

FUTURE DIRECTIONS
At present, Gentils and her collaborators are analysing the extensive data they have collected for varied experimental conditions. Validation of numerical simulations using the experimental data is also in progress, in order to use them to give predictions of austenitic stainless steel’s properties under long-term neutron irradiation in PWRs. Looking ahead, the results of the project will have important implications for existing, and indeed future, nuclear power plants across Europe.