Understanding the mechanisms of Pellet Cladding Interaction in Zr alloys and their influence on the degradation of light water reactor fuel assemblies

Supervisors (lead first): Dr. Philipp Frankel, Prof. Michael Preuss

Industrial partners: EDF & Rolls Royce

Host Institution and School: University of Manchester, School of Materials

Summary
The level of energy extracted from a fuel assembly in a given cycle for a nuclear reactor is not only limited by the fuel, but also the material that contains the pellet, i.e. the Zr alloy cladding. One of the most important factors that affect the structural integrity of fuel cladding during normal operating conditions is its performance during pellet-cladding interaction (PCI). PCI is a phenomenon, which results from the dimensional changes experienced by the UO₂ pellet and Zr cladding during in-reactor operation. When stresses build up between the UO₂ fuel pellets and the Zr rod in which they are contained, in the presence of aggressive fission products (e.g. iodine), stress corrosion cracking (SCC) can occur leading to premature failure of the fuel rods. Furthermore, irradiation experienced during service is known to enhance the susceptibility of the Zr rods to SCC. Gaining a better understanding of the mechanisms that lead to PCI is therefore vital to improving the efficiency of nuclear reactors while maintaining stringent safety standards.

Iodine-induced stress corrosion cracking (I-SCC) in Zr alloys has been studied for many years, however the combination of state-of-the-art characterisation tools now available across a range of length scales is expected to provide new insight into this important phenomenon. The proposed project will aim to develop a better understanding of PCI by combining proton irradiation at the new Dalton Cumbrian Facility (DCF) with state-of-the-art characterisation techniques to investigate relationship between critical iodine concentrations and the onset of trans- vs. inter-granular (IG vs. TG) fracture.

Introduction
The most commonly proposed mechanism for PCI involves the release of fission products from the fuel during low/moderate power conditions, with iodine believed to be the most detrimental. The iodine is thought to react with the Zr at the inner surface of the clad, resulting in a series of iodides, of which ZrI₄ is the most aggressive and likely to promote SCC. In the presence of ZrI₄, the increased stress state that arises during a ramp in power leads to the initiation of cracks. Inter-granular (IG) cracking may dominate initially until enough ZrI₄ is generated to permit trans-granular (TG) crack propagation [1]. There is also some evidence that the presence of second phase particles at grain boundaries may lead to increased levels of IG cracking [4]. However, it remains unclear what critical ZrI₄ concentration is required for initiation, whether the IG cracks are always formed initially and how the microstructure of the Zr affects the role of iodine in PCI. In addition, the influence on I-SCC of crystallographic texture and the role of recently observed Fe segregation to grain boundaries [3] (figure 2) require further investigation. Undertaking mechanical experiments on neutron irradiated Zr is prohibitively expensive and laboratories with hot cells also usually lack the type of state-of-the-art characterisation facilities that are now available to universities. DCF provides a way to overcome this issue by using proton irradiation to introduce similar damage in much less time and without activation of samples.

Student Specific Training
NGN studentships include 6 months of student specific training from months 5-11. Describe the training specific to this project. This can be a mix of academic, technical and professional training and can be delivered in any partner university, or an external organisation, as required. Please indicate where the training is to be delivered. The training is assessed, through production of two short written reports, one at half time and one at the end, one poster presentation, and one short oral presentation. Please bear these requirements in mind when developing the training package.
The student specific training may be tailored to the background of the particular student, but the initial 3 months will involve a detailed literature review of the subject area of the project, with a report due at the end of this period. During this time the student will also attend two 4th Year undergraduate Materials Science modules relevant to the project, Advanced Structural Materials and Energy Materials (both run at Manchester in academic weeks 19-24). These will cover some of the background needed for the project.

In addition, a more detailed 1-week course on "Metallurgy and Properties of Zr Alloys for Nuclear Applications" is run every summer by INSTN and CEA (with input from EDF) in Saclay, France. This course will provide a great opportunity to meet very knowledgeable researchers, gain a deeper insight into the ongoing work in the Zr field and provide a sound foundation for the student to start their own research. On their return the student will be expected to provide a presentation to the rest of the Zr group on the most relevant topics covered at the course.

Attendance at the Diamond Light Source (Didcot) summer school will give the student an insight into what experiments may be possible at this facility, allowing them to independently design experiments later in the project and apply for beam-time where appropriate. This will also give the student a better understanding of the planned 3DXRD experiments, to be carried out later in the project.

In addition to the structured courses, the student specific training will involve a mini project during which the student will begin to learn some of the skills, e.g. electron microscopy (EM), required for the rest of the project. Following their completed literature review, the student will be expected to provide input into the topic of the mini-project. It is proposed that this will cover EBSD analysis Zr samples with ex-situ loading to investigate stress localisations related to crystallographic orientations that are likely to influence the PCI behavior in the presence of iodine. The mini-project will be concluded with a final report and a poster explaining how this work will follow on to the subsequent PhD project.

References: