ANNUAL REPORT 2022

Swedish Centre for Nuclear Technology
Svenskt Kärntekniskt Centrum

April 2023

KTH – Royal Institute of Technology
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This Is SKC

The Swedish Center for Nuclear Technology (Svenskt Kärntekniskt Centrum, SKC) secures the availability of competence and helps to solve complex problems by investing in nuclear research and education in Sweden. These are critical tasks for safe and sustainable operation of the nuclear power industry.

SKC connects the Swedish nuclear power industry, the regulator and the three Swedish universities that provide the majority of education and research opportunities within disciplines of nuclear technology by funding education and research in a way that benefits all parts.

The SKC collaboration is planned in cycles and the current contract period covers 2020-2023.

Organisation

Chalmers University of Technology
KTH – Royal Institute of Technology
Uppsala University
Swedish Radiation Safety Authority
Forsmarks Kraftgrupp AB
Oskarshamn Kraftgrupp AB
Ringhals AB
Westinghouse Electric

SKC
Swedish Centre for Nuclear Technology

Director's message

The energy prices started to rise in 2021 but 2022 was the year when everybody started to talk about the cost of electricity. This has made people more aware of the importance of a reliable and affordable energy production. Here the nuclear power industry has an important role to play, especially if we also consider the environment and want to produce energy in a fossil free and sustainable way.

Today several initiatives have been started to secures future safe operation of nuclear power. Small Modular Reactors (SMRs) is a hot topic, the Swedish government has taken the first step to change the law by submitting a proposal to remove the current restrictions that limits the total number of nuclear power plants to 10 reactors at the established sites, further power uprates are considered at Forsmark 1 and 3 and life extensions are performed for the current fleet. All these initiatives, as well as decommissioning of the plants in permanent shutdown, will require significant resources.

During 2022 SKC has contributed to the necessary development of knowledge and competences by continued funding of ongoing research projects performed by PhD and post-doctoral students and support for education within nuclear engineering and technology at the three partner universities. As customary, Sigvard Eklund's price has been rewarded to recognize outstanding work in the area and activities like "nuclear theses speed-dating" have been developed to attract new students to the nuclear sector.

Although the increased interest in nuclear power technology has resulted in a welcomed increase of the amount of available funding for nuclear research from other financiers the long-term support from SKC to securing knowledge and competence development at an academic level is still valuable. During 2023 the plans for the next program period, starting 2024, will be intensified. I look forward to being a part of this process and continuing the support of nuclear research and education, while hopefully also increasing the efforts to attract new students to the nuclear power sector.

Göteborg, April 5th 2023

Cilla Andersson

Director, SKC

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Swedish Centre for Nuclear Technology

SKC

The Swedish Centre for Nuclear Technology (Svenskt Kärntekniskt Centrum, SKC) was originally founded in 1992 at KTH Royal Institute of Technology. Later, the centre was expanded to include also Uppsala University and Chalmers university of Technology. Today the centre is a collaboration administrated at the School of engineering sciences at KTH.

SKC connects the Swedish nuclear power industry, the regulator and the three Swedish universities that provide the majority of education and research opportunities within disciplines of nuclear technology by funding education and research in a way that benefits all parts. The majority of the funding that SKC directs to the universities enables hiring new doctoral and post-doctoral researchers as well as retaining senior researchers and technical staff but efforts are also made to help new students discover this area of work and research.

Organisation

Board

The SKC's Board has a decision mandate over SKC's operations and serves the shared interests of all partnering organisations. For that reason the Board consists of one representative from each partnering organization and is chaired by an independent chairman.

The current Board members are listed below.

Karl Bergman
Chairman of the board
Head of R&D, Vattenfall AB

Johan Börjesson
Deputy Managing Director
Forsmark Kraftgrupp AB

Monika Adsten
Head of R&D
Ringhals AB & Forsmark Kraftgrupp AB

Jan Karjalainen
Head of Engineering
Oskarshamns Kraftgrupp AB

Lena Oliver
Fellow Engineer
Westinghouse Electric Sweden AB

Per Seltborg
Head of R&D
Swedish Radiation Safety Authority

Thomas Nilsson
Head of department
Chalmers University of Technology

Oscar Tjernberg
Deputy head of school
KTH Royal Institute of Technology

Jonas Fransson
Professor
Uppsala University

Operations

A director that answers to the Board, is responsible for the organisation's operations. During 2022 this position was held by Merja Pukari. The current director is **Cilla Andersson**.

Advisory Council

The Advisory Council serves as a reference group in which discussions on strategy and funding are taken place. The members are selected to give the advisory council a collective competence profile that is relevant for SKC:s ongoing and future activities. The council advises SKC:s board and director but takes no decisions.

The current members of the Advisory Council are listed below.

Michael Knochenhauer
Chairman of the Advisory Concril

Mattias Olsson
Radiochemistry expert
Forsmarks Kraftgrupp AB

Georg Lagerström
Reactor safety engineer,
Oskarshamns Kraftgrupp AB

Björn Forssgren
Senior Specialist
Ringhals AB

Anna Alvestav
Reactor technology analyst
the Swedish Radiation Safety Authority

Carl Adamsson
Principal Engineer
Westinghouse Electric Sweden AB

Henrik Sjöstrand
Associate Professor at Department of
Physics and Astronomy,
Applied Nuclear Physics
Representative of KTH, Uppsala University &
Chalmers

The Contract period 2020-2023

On the first of January 2020 the SKC collaboration entered into a new four-year contract period between eight partners. According to the agreement five partners will fund SKC and the three partner universities will benefit from the funding during the period 2020-2023.

Together the five financiers will contribute 52 million SEK to the budget of SKC over the course of the four year period. In doing so the Swedish Radiation Safety Authority, Westinghouse Electric Sweden AB and the three Swedish nuclear power plants Oskarshamns Kraftgrupp AB, Forsmarks Kraftgrupp AB and Ringhals AB confirm that they share a vision on the importance of funding of academic activities continuously over a relative long period of time.

The majority of the budget of SKC will be distributed between the three beneficiaries – Chalmers University of Technology, KTH Royal Institute of Technology and Uppsala University – to finance either specific research projects or to provide base support for the continuation or development of education within the disciplines of nuclear technology. SKC will also recognize and reward young talent that have recorded exceptional research in their academic theses by awarding the Sigvard Eklund´s prize to outstanding nominees. As per established tradition SKC will continue to hold annual symposium where the developments in research and education will be shared within and between all collaboration partners.

The overall goals of SKC have been defined for the entire contract period of 2020-2023. These goals, although adjusted for the specific period, are well in line with the original founding principles and intentions of SKC.

- SKC will contribute to making nuclear technology education visible to students of all higher education levels and in case of availability to high-school students.

- SKC will contribute to nuclear technology education in Sweden being perceived as an attractive alternative by students.

- SKC's activities will ensure that the contracting parties' recruiting needs of highly skilled staff and academicians will be satisfied by educating and training young talent via bachelor's and master's programmes and doctoral and post-doctoral research projects.

- SKC will facilitate the development of internationally recognized research groups within disciplines that are vital for the safe and sustainable nuclear operation in Sweden.

- SKC will fund research and education that is of value to the contracting parties.

Education and research that receive priority funding from SKC belong to the following disciplines:

- Reactor Physics
- Detector technology
- Nuclear chemistry
- Thermal hydraulics
- Nuclear fuel technology
- Material science, with an emphasis on ageing
- Severe accident analysis

Results and Activities during 2022

Financial Results 2022

The following financial statements concerns the payments received by SKC from the five financiers and the expenditures made to the three universities as project and base support. The SKC central organization is an additional expenditure item that cover administration, funding of activities for students, the Sigvard Eklund's prize and the annual symposium.

Payments to SKC from financiers	
Swedish Radiation Authority	4 000 000
Forsmarks Kraftgrupp AB	2 829 904
Oskarshamns Kraftgrupp AB (1)	1 581 014
Ringhals AB	2 089 082
Westinghouse Electric Sweden AB	1 500 000
Total payments 2022	**12 000 000**

Expenditures by SKC	
Project Support	-7 500 000
Base Funding	-3 999 999
SKC central organisation	-791 602
Total expenditures 2022	**-12 291 601**

Balance	
Reserves for project support	3 750 000
Resources at the start of 2022	5 322 689
Unallocated resources	1 281 088
Balance2022/2023	**5 031 088**

Symposium 2022

Each year SKC organize an annual symposium. This is an appreciated opportunity for the academia, the regulator and the industry to meet and discuss research, education and future opportunities in nuclear engineering and technology.

The 2022 symposium was held on October 17-18 at the KTH Albanova University Centre. Almost 70 participants took part in the Symposium which contained presentations of the situation and expectations for nuclear power in Sweden, panel discussions, updates about ongoing research at the three SKC partner universities, presentations of research projects funded by SKC and an announcement of the winners of the Sigvard Eklund´s prize.

Sigvard Eklund's Prize

Dr Sigvard Eklund played a key role in establishing the Swedish nuclear power industry through his various roles and assignments and during the period of 1961 and 1981 he was Director General of the IAEA. The foundation for his lifelong contributions to the research, development and application of nuclear technology originates back to both Uppsala University where he obtained his academic degrees and to KTH Royal Institute of Technology where he became a docent.

Sigvard Eklund's prize has been established by SKC to recognize outstanding academic work by bachelor students, master students and doctoral students at the three partner universities. Once a year the supervisors or teachers can nominate one or more theses to be considered as best academic level of the year. An independent jury will consider the motivations, the scientific merits and the overall quality of the submitted thesis to decide who should receive the award.

Best PhD Thesis

During 2022 the prize for best Doctoral thesis was awarded Lajos Nagy for his PhD thesis “Neutron Multiplicity Counting with the Analysis of Continuous Detector Signals”. The evaluation committee concluded that the author has made a significant contribution to improving high-intensity materials measurements and the toolbox for working with nuclear safeguards. The committee also states that the candidate has shown excellent understanding of the topic and an equally good set of skills to perform work. The result is a nice goal-oriented thesis made up of a related set of theoretical, numerical and experimental investigations and a nice set of papers in journals and at conferences.

Thesis for the degree of Doctor of Philosophy

Neutron Multiplicity Counting with the Analysis of Continuous Detector Signals

Lajos Nagy

CHALMERS
UNIVERSITY OF TECHNOLOGY

Department of Physics
Chalmers University of Technology
Gothenburg, Sweden

MŰEGYETEM 1782

Faculty of Natural Sciences
Budapest University of Technology and Economics
Budapest, Hungary

March 2021

Lojos Nagy, winner of the Sigvard Eklund’s Prize for his Phd thesis

In an interview after winning the prize Nagy Lajos Nagy states that winning the prize means a lot to him. When he was looking for a PhD position he was approached by his forms MSc thesis supervisor, associate professor Máté Szieberth, who mentioned that he was planning to co-supervise a PhD program jointly with professor Imre Pázsit from Chalmers University of Technology. At the time Lajos Nagy was hesitant to apply to the position since the topic, nuclear safeguards, was mostly unfamiliar to him but then he checked some of the recent papers of professor Pázsit and discovered that they contained complex probabilistic equations and long derivations. As a physicist with a keen interest in mathematics, especially in probability theory, he immediately knew that this was the perfect PhD programme for him.

Best MSc Thesis

The Sigvard Eklund Prize for the best Master's thesis was awarded to Georgios Zagoraios for his MSc thesis "Synthesis of uranium nitride fuel from UF4 stock". According to the evaluation committee the thesis is a manifest of excellent experimental skills and thorough theoretical understanding. The achievement of producing actual and novel nuclear fuel in laboratory scale is beyond the expectations of a master thesis.

KUNGLIGA TEKNISKA HÖGSKOLAN

EIT InnoEnergy Master in Nuclear Energy

Reactor Physics Division

Master Thesis

Synthesis of uranium nitride fuel from UF_4 stock

Georgios Zagoraios

Supervisor: Dr. Mikael Jolkkonen

Stockholm, Sweden, Spring 2022

Georgios Zagoraios, winner of the Sigvard Eklund's Prize for his Master thesis

Sigvard Eklund Prize for the best Bachelor's thesis was not awarded due to lack of nominations.

Aside from receiving recognition for outstanding research, the 2022 prize entailed a monetary reward of 50,000 SEK for the best PhD thesis, 35,000 SEK for the best Master's thesis and 25,000 SEK for the best Bachelor's thesis.

Student events during the year

Participation in career fairs at the Universities

SKC participated at career fairs at all three partner universities; CHARM at Chalmers University of Technology, and ARMADA at KTH Royal Institute of Technology and UTNARM at Uppsala University.

Nuclear Thesis Speed dating

During 2022 a new type of event called Nuclear Speed Dating was arranged by SKC for the first time. The aim was to bring students and industry representatives together to discuss opportunities for thesis writing.

The first event was held at KTH Albanova University Centre on October 27th and the second at Uppsala University on November 14th. Most participants assessed the event as useful and a third event at Chalmers University of Technology is planned during 2023.

Funding for student participation in CET2022

During 2022 SKC funded the participation of six students from Chalmers, KTH and Uppsala University in the conference Converging Energy Technologies (CET) 2022. The conference was organized at Oskarshamn September 21-23 to present new energy technologies and their system aspects at national, regional, and local level with emphasis on the convergence of SMR with renewables, hydrogen production and CO^2 capture.

Afterwards Elisabeth Walter from KTH described her experiences from the conference as follows:

The CET2022 was a valuable experience for me because it gave me a first impression of how diverse future careers in the nuclear industry can be. Furthermore, it was a great opportunity to meet and ask questions to possible prospective employers. The most surprising thing I learned was how many people, companies and organisations are involved in SMR technology worldwide. After the conference, my thoughts about a nuclear career have changed into being more optimistic about the future. Therefore, participating in the CET2022 gave me even more motivation for my current master's studies in nuclear energy at KTH.

Students from KTH and Uppsala University on the way home from CET2022

Strategy Workshop

At the end of the year discussions of the strategic orientation for SKC were initiated as a start of the preparations for the next program period 2024-2027.

The advisory council prepared a basis for the discussions and on December 15th the SKC board members held a strategy Workshop. The discussions will continue during 2023.

Use of the Base Funding

Distribution and use of the Base Funding

During 2022 the SKC base funding of 4 MSEK was distributed evenly among the three partner universities. In the next sections they describe how it has been used to promote research and education.

Chalmers University of Technology

CHALMERS

General Information

Research and education in nuclear science and technology is carried out at Chalmers University of Technology by three entities:

- The Division of Subatomic, High Energy, and Plasma Physics (Department of Physics).
- The Division of Microstructure Physics (Department of Physics).
- The Nuclear Chemistry group, Division of Energy and Materials (Department of Chemistry and Chemical Engineering).

At the **Division of Subatomic, High Energy, and Plasma Physics**, activities in reactor physics, modelling and safety are pursued along two main tracks: computational nuclear reactor physics, and safeguard and core diagnostics, with applications to commercial reactors.

At the **Division of Microstructure Physics**, structural nuclear materials are characterized using electron microscopy and atom probe tomography. The main focus areas are fuel cladding and reactor pressure vessel steel.

At the **Nuclear Chemistry group**, the properties of atom nuclei using chemical methods and chemical processes are studied. A particular focus is on topics relevant to the entire fuel cycle: innovative fuel cycles, partitioning and transmutation, new types of nuclear fuel, pollution prevention in severe accidents, reactor water chemistry, and chemistry of the disposal of nuclear waste. Research is also pursued in the production of radiopharmaceuticals for cancer treatment and radio analytical chemistry for the measurement of radioactive substances in the environment.

Chalmers is also a member of SAINT (Swedish Academic Initiative for Nuclear Technology).

Overview of base funding utilisation in 2022

The SKC base funding amounted to 1.33 MSEK for 2022 and was distributed as follows at Chalmers University of Technology:

- 0.538 MSEK to the Division of Subatomic, High Energy, and Plasma Physics.
- 0.304 MSEK to the Division of Microstructure Physics.
- 0.491 MSEK to the Nuclear Chemistry Group.

The use of the base funding at each group is detailed hereafter.

Division of Subatomic, High Energy, and Plasma Physics

The SKC base funding was mostly used for covering parts of the salary of Prof. Christophe Demazière and Assoc. Prof. Paolo Vinai.

3 PhD students, supervised by Prof. Demazière and Assoc. Prof. Vinai, worked in areas of direct interest to SKC:

- PhD student Huaiqian Yi (neutron noise modelling using transport methods, as part of the CORTEX project). Huaiqian Yi successfully defended his PhD thesis on January 28, 2022.
- PhD student Kristoffer Tofveson Pedersen (SKC-sponsored XEROM project on Reduced Order Modelling of xenon instabilities).
- PhD student Hirepan Palomares Chavez (VR-sponsored HYBRID project on hybrid neutron transport methods applied to fast reactors).

Moreover, Yi Meng Chan, PhD student at KTH working on the use of artificial neural networks in reactor physics calculations, is co-supervised by Prof. Demazière (the main supervisor being Assoc. Prof. Jan Dufek at KTH).

Research-wise, the Division is also involved in European collaborations and projects, such as the Horizon 2020 ESFR-SMART project on sodium-cooled reactors. The ESFR-SMART was successfully completed in 2022.

A joint application to the Swedish Energy Agency for establishing a competence center in nuclear technology was approved in 2021 and the work started in 2022. The competence center, called ANItA (Academic-industrial Nuclear technology Initiative to Achieve a sustainable energy future) is coordinated by Uppsala University. As part of this project, a PhD project on neutron noise in Small Modular Reactors will be carried out, for which the recruitment process started in 2022.

In the area of education, the Division has been developing innovative pedagogical methods, combining flipped classroom and active learning methods, and offered in a hybrid learning environment. Such an environment allows offering courses to both on-site and off-site students and is thus suited to distant education and life-long learning. As a result of its expertise and following the same pedagogical principles, the Division has been coordinating the Horizon 2020 project GRE@T-PIONEeR project since 2020. The project aims at developing a specialized education in reactor physics and nuclear reactor safety for PhD and postdoc students, for nuclear engineers, and taken as advanced courses for MSc students. The education encompasses both theory and hands-on training exercises, the latter heavily relying on the use of research/training reactors and of computer-based modelling environments. The aim is for the students to be able to perform nuclear reactor safety simulations understanding all the approximations on which such simulations rely. The use of pre-recorded lectures and electronic teaching resources allows students to learn at their own pace and get prepared for the hands-on training sessions. Those sessions, offered both on-site and remotely, use active learning methods under the close supervision and support of the teachers, thus promoting student learning. Two GRE@T-PIONEeR courses were offered in 2022: a course on “Nuclear data for energy and non-energy applications” (49 accepted participants) and a course on “Neutron transport at the fuel cell and assembly levels” (38 accepted participants). Chalmers was heavily involved in the teaching of the second course.

A short course on the “Modelling of nuclear reactor multi-physics” was offered in the Spring of 2022 to Vattenfall (Vattenfall Nuclear Fuel, Ringhals, and Forsmark) with 10 participants. The course was a flipped course: an asynchronous self-paced learning phase (representing 40 hours of work), followed by 7 half-day long interactive sessions focusing on discussions and small problem solving (representing 32 hours of work). The interactive sessions were first organized fully online (because of Covid-19), and were later in the Spring offered in a hybrid format (participants from Ringhals joining onsite and participants from Vattenfall Nuclear Fuel and Forsmark joining online).

Despite no master program in nuclear engineering at Chalmers, the Division is involved in parts of a master course in Computational Continuum Physics, in which the practical exercises are all based on nuclear reactor simulation examples, thus increasing the visibility of this area to the Physics master students and possibly attracting them to MSc thesis projects in this area.

The members of the Division also act as guest lecturers in various courses at the Bachelor and Master level at Chalmers presenting nuclear power.

An application for offering a new multi-disciplinary course in Chalmers titled “Modern Energy Technologies and Systems” was prepared and accepted. Prof. Demazière is the examiner of the course. Such multi-disciplinary courses are referred to as TRACKS courses in Chalmers. They offer much more flexibility (collaboration between different teachers from different departments, format, set-up, and courses offered typically to all Chalmers students and to Chalmers Alumni). The course describes various carbon-neutral energy technologies to tackle climate change, their advantages/disadvantages and their interdependencies. By following the course, the students will be able to understand how those technologies work and how they contribute to some of the United Nations Sustainable Development Goals. Preparations of the course started in 2022. The course will be first offered in the academic year 2023/2024.

The Division is actively involved in various networks in Sweden (SKC, SSM, SAINT, and a collaboration with KTH), as well as internationally (IAEA, ANS, ENEN and SNETP), and has been a contact point with SSM for discussing knowledge preservation in nuclear and radiation science.

Division of Microstructure Physics

The funding has mainly been used for the salaries of Assoc. Prof. Mattias Thuvander and Senior Professor Hans-Olof Andrén. Thuvander has been supervisor for two PhD students:

- PhD student Johan Eriksson (degradation of zirconium cladding tubes, funded by Swedish industry and EPRI). Eriksson defended his thesis in November 2022. He is now post-doc at the department of Chemistry, Chalmers, working in the ANItA project.
- PhD student Andrea Fazi (coated cladding tubes for accident tolerant fuel, funded by SSF). Fazi defended his thesis in February 2023. He is now employed at the division to work on two NKS projects, in cooperation with KTH and VTT.

Thuvander was furthermore supervisor of two post-docs:

- Dr Kristina Lindgren (reactor pressure vessel steels, funded by the EU project ENTENTE).
- Dr David Mayweg (degradation of zirconium cladding tubes, funded by SKC).

Thuvander is leading an SSF project on ATF, involving Chalmers, KTH and UU. This project deals with coated claddings, alloying of UN and development of gamma emission tomography for fuel inspection. Lindgren was partly working on aging of reactor pressure vessel steel welds, continuing a previous SKC-project within the MåBil project, now partly financed by NKS. The project is a collaboration with KTH and VTT, investigating RPV welds from one of the decommissioned Barsebäck BWRs. Lindgren was also taking part in the EU-project ENTENTE, focusing on irradiation effects in RPV steels. She further worked on corrosion of FeCrAl for liquid lead Gen-IV applications, together with Prof. Szakalos (KTH), funded by VR, and projects on irradiated stainless steel with Studsvik and EPRI.

Regarding teaching, some nuclear materials issues are included in the course "Physics of Materials".

During 2022, a new instrument for atom probe tomography was installed at Chalmers, following a 32 MSEK grant from the Swedish Research council (VR). The proposal was mainly written by Thuvander, in 2021. This tool is of importance for studying irradiation effects in claddings and RPV steel. This technique will also be used in projects together with Studsvik Nuclear, notably on stress corrosion cracking.

Thuvander is taking part in the ANItA project on SMRs, funded by the Swedish Energy Agency, where a post-doc will soon be hired. Andrén is taking part in the on-going projects on cladding tubes at the division, and he is a member of the advisory board of the MIDAS project in the UK. The division takes part in mostly Swedish networks (SAINT and SKC).

Nuclear Chemistry group

Nuclear Chemistry has several active courses (Nuclear Chemistry I and II, Solvent Extraction, Radiopharmacy) at Chalmers University at the MSc and PhD levels.

The group comprises currently 5 PhD students and 4 senior researchers in Nuclear Chemistry and 2 more PhD students and a PhD are foreseen to be employed during 2023. 3 PhD students defended their work during 2023 within the areas of severe nuclear accidents, Gen IV separation science and Accident Tolerant Fuel investigations.

During 2023, PhD students will be active in, e.g., corrosion studies of nuclear materials under irradiations, advanced manufacturing of nitride fuels, severe nuclear reactor accidents and their mitigation, separations for Gen IV, sorption of radionuclides from a final repository and fuel-coolant-cladding interactions.

The group is conducting research in several areas of the nuclear field, like safety of nuclear reactors, severe nuclear accident scenarios and advanced safety through research in Accident Tolerant Fuels as well as is involved in several EU projects (EURATOM).

It is worth noting that the nuclear chemistry group is the only group dealing with radioactive material in amounts relevant to some industrial and research uses. We are also a nuclear installation. This means that there is a significant effort spent in practical radiation protection as well as on a more theoretical level in relation to all the requirements from the radiation protection authority. Thus, our personnel and students will be amply familiar with all these procedures as the only university facility in Sweden.

The SKC funding was used to cover the activities of Professor Christian Ekberg, Professor Teodora Retegan Vollmer, Dr. Stefan Allard and Dr. Stellan Holgersson which are actively involved in teaching and research including radiation protection. More specifically, funding was used to support the coordination of a large-scale EU project in fuel cycle research as well as the national project ANITA coordinated by Uppsala University. Support has also been given in nuclear fuel manufacturing to, e.g., the KTH group and Westinghouse.

Both Prof. Ekberg and Prof. Retegan Vollmer are guest lecturers in various courses at the Bachelor and Master level, at Chalmers and also abroad.

Professor Ekberg is since 2022 coordinator of the EU project FREDMANS dealing with the recyclability of nuclear fuels with special emphasis on nitrides.

Prof. Retegan Vollmer is active in the 4th round of CINCH Project (currently called A-CINCH) standing for Cooperation in Education in Nuclear Chemistry in Europe, under EURATOM Horizon2020 program. The educational projects series have started in 2010 and aims at unifying the European curricula and teaching methodology at European level, by means of modern tools, including on-line teaching, learning and evaluation. We do have a close contact with our colleagues on physics from GRE@T-PIONEeR. She is also the Chalmers representative in ENEN+.

As our colleagues, we are active in various networks in Sweden (SKC, SAINT, and a collaboration with KTH) as well as international (ENEN, ANS, SNETP) as well as international collaborations on several EURATOM projects relevant for SKC.

During 2023, Chalmers will host the international SNETP annual meeting during the Swedish chairmanship of the EU. This is organised by Prof. Teodora Retegan Vollmer and Prof. Christian Ekberg.

KTH Royal Institute of Technology

General Information

The following divisions and departments are engaged in nuclear education and research at KTH:

- Division of Nuclear Engineering / Department of Physics
- Division of Nuclear Power Safety / Department of Physics
- Division of Nuclear Physics / Department of Physics
- Group of Nuclear Chemistry / Department of Chemistry
- Division of Solid Mechanics / Department of Engineering Mechanics

The Centre for Nuclear Engineering at KTH (CEKERT) is the platform to coordinate nuclear education and research at KTH, with the involvement of 14 faculty members (8 professors and 6 associate professors; see Appendix) in 2022.

The Master's Programme run by KTH is among one of the largest Master's Programmes for nuclear technology education in the world in terms of the number of students and courses. So far more than 250 students have been admitted to the Programme. In 2022, totally 38 students are enrolled within the Master's Programme and the associated double-degree programmes (e.g. EMINE).

Overview of base funding utilisation in 2022

The SKC base funding to KTH has been a vital component in keeping the critical activities of Nuclear Engineering education alive at KTH, since the actives are not fully supported by KTH alone.

The SKC base funding to KTH in 2022 was 1,333,000 SEK, among which 700, 000 SEK was used to pay the partial salaries of the 14 faculty members (50, 000 SEK per member), who were involved in the general education of BSc, MSc and PhD students. The remaining SKC base funding to KTH was used to pay partial salaries of the director and the deputy of the Master's Programme in Nuclear Energy Engineering for their management of the programme, and partial salaries of teachers who taught courses in the programme.

The usage of the SKC base funding is summarized as in the following table.

Areas of support	Items	Cost calculations	Costs (SEK)
Faculty members	– 9 professors – 5 associate professors	50 hours per faculty member spent on preparation of teaching materials and supervision of postgraduate students * Hourly rate of 1000 SEK	700,000
Master's programme management	– Programme director and deputy	208 hours of work for Assoc Prof Jan Dufek and Dr Vasily Arzhanov	258,000
Lab exercises on the VR-1 training reactor (covering a partial cost)	– VR-1 training fee – Hotel – Flights	10000 SEK/person	270,000
Courses	– Fees for invited speakers in the course SH2610 – License fee for the APROS code in the course SH2705	– 50,000 SEK for the invited speakers – 35,000 SEK for the license fee of the APROS code	85,000
Misc	– CEKERT:s kansli	– 20,000	20,000
Total			**1,333,000**

The faculty members that have benefitted from the SKC funding and their contributions to teaching and supervision are summarized in the following table.

Faculty member	Courses offered in 2022	Postgraduate students supervised in 2022
Prof. Anglart / Henryk	– SH2706: Sustainable energy transformation technologies – SH2701: Thermal hydraulics in nuclear energy engineering	– 1~2 MSc students
Prof. Olsson / Pär	– SH2605: Radiation damage in materials – SH2774: Numerical methods in nuclear engineering – SH3141: Multi-scale modelling of nuclear materials	– 5 PhD students – 4 MSc students
Prof. Wallenius/ Janne	– SH2613: Generation-IV reactors – SH2615: Neutron transport theory – SH2611: Small modular reactors – SH2772: Chemistry and physics of nuclear fuels – SH2614: The nuclear fuel cycle – SH3500: Non-proliferation of nuclear materials	– 2 PhD students – 2~3 MSc students
Assoc. Prof. Kudinov / Pavel	– SH2702: Nuclear reactor technology	– 4 PhD students – 1~2 MSc students
Assoc. Prof. Dufek / Jan	– SH2600/ SH2601: Reactor physics – SH2704: Monte Carlo methods and simulations in nuclear technology – SH2009: Project work in physics, smaller course	– 1 PhD student – 1~2 MSc students

Prof. Bechta / Sevostian	– SH2610: Leadership for safe nuclear power industry	– 4 PhD students
Assoc. Prof. Ma / Weimin	– SH2612: Nuclear power safety – SH2706: Sustainable energy transformation technologies – SH2705: Compact reactor simulator	– 6 PhD students
Prof. Cederwall / Bo	– SH2302: Nuclear physics – SH3301: Experimental nuclear physics	– 3 PhD students – 2~3 MSc students
Prof. Nyberg / Ayse	– SH2306: Experimental techniques for nuclear and particle physics – SH2101: Subatomic physics – SH2102: Subatomic physics, – SH2705SH3306: Detection techniques for nuclear and particle physics	– 1 PhD student – 1~2 MSc students
Assoc. Prof. Bäck / Torbjörn	– SH2603: Radiation, protection, dosimetry and detectors – SH2007: Research methodology in physics – SH204X: Degree project in physics	– 2 PhD students – 1~2 MSc students
Assoc. Prof. Qi / Chong	– SH2011: Theoretical nuclear physics – SH3311: Theoretical nuclear physics – SH3312: Symmetries in physical systems – SH3313: Quantum many body physics	– 1 PhD student – 1~2 MSc students
Prof. Jonsson / Mats	– CE2010: Nuclear chemistry – KD2370: Photo, radiation and radical chemistry	– 4~5 PhD students – 2~3 MSc students
Adj. Prof. Efsing / Pål	– SE2137: Fatigue	– 2 PhD students – 2~3 MSc students
Prof. Faleskog / Jonas	– SE2139: Fracture mechanics – SE2860: FEM modelling	– 4 PhD students – 2~3 MSc students

Uppsala University

General Information

Research and education within nuclear science and technology at the division of applied nuclear physics at Uppsala University span a wide range of topics. Current research and development are being conducted within the following areas:

- nuclear waste management, including spent fuel,
- nuclear data, including uncertainty propagation in nuclear systems,
- nuclear safeguards and non-proliferation,
- fuel performance modelling and experiments,
- design of instrumentation for studies of nuclear fuel behaviour,
- detector development for radioactivity monitoring

SKC provides an important contribution to the research listed above in the form of base funding and/or specific project funding. This funding complements faculty funding and external funding from, for example, the Swedish Research Council (VR) and the Swedish Foundation for Strategic Research (SSF). The research is performed in close collaboration with both national and international partners. International partners include IAEA, LANL, INL, SCK CEN, NEA, GANIL, JRC, Jyväskylä University, HRP, ESARDA and others.

Uppsala University provides education in nuclear science and technology on all levels, which includes teaching and supervision of students. Additionally, a substantial volume of contract education directed towards industry and authorities is provided and is available through Uppsala University's portal "Nordic Academy for Nuclear Safety and Security, NANSS".

Overview of base funding utilisation in 2022

SKC's base funding is used for supporting efforts in research, teaching courses that are in line with SKC's goals and supporting extensive outreach. For example, UU can support initiatives that are outside regular activities aiming at finding opportunities for new research projects. An overall report of the use of funds for 2022 is provided below.

Staff

During 2022 the salaries for the following individuals have to a various degree been supported by the SKC base funding.

Prof. Ane Håkansson has been devoted to outreach, teaching and supervision in parallel to the work as director of the now-established national competence centre ANItA (Academic-industrial Nuclear technology Initiative to Achieve a sustainable energy future). ANItA's mission is to provide society with adequate knowledge to implement small modular light-water reactors in Sweden.

Dr. Peter Andersson continued his work to develop novel approaches for post-irradiation examination within the framework of his starting grant from the Swedish Research Council. There has been an emphasis on the supervision of PhD students in 2022. One of his PhD students, Lorenzo Senis, earned his licentiate during 2022. Lorenzo and Dr. Andersson's other student, Vikram Rathore, are preparing to defend their PhD dissertations in June 2023.

Dr. Andersson's work has 2022 benefitted from collaboration with Studsvik Nuclear concerning the development of experimental methods. This collaboration resulted in the development and first use of a gamma-ray micro-densitometer in the Studsvik hot cell lab, which thereby added new capability for post-irradiation examination of nuclear fuel within Sweden.

Assoc. Prof. Henrik Sjöstrand and Dr. Erik Andersson Sundén have continued to work with the development of nuclear data evaluation methods for structural materials such as iron and chromium. In addition, Henrik has done some preliminary work on project B1 within ANItA: "Fuel assembly and core design optimization for SMRs".

Dr. Diego Tarrío has been working on the development of an experimental setup to study neutron-induced reactions at the new neutron facility NFS at GANIL, France. In 2022, the first experiments with neutron beams were performed, focusing on the study of differential cross-sections of light-ion emission on different materials when irradiated with neutrons. The first experiment, which studied such reactions on carbon, demonstrated the good capabilities of the system and, therefore, measurements on elements of relevance in structural materials (e.g. chromium and iron) are in preparation. Moreover, a further upgrade of the setup is currently ongoing, which will allow studies of actinide fission cross sections at NFS. As a result of the ongoing collaboration between Uppsala University and GANIL, a new joint Ph.D. student, Lucas de Arruda, started to work on this project in November 2022. Dr. Tarrío and Prof. Stephan Pomp from UU and Dr. Xavier Ledoux from GANIL are supervising this Ph.D. project. Dr. Tarrío also supervised the bachelor thesis of Ellen Hammarstedt, about the experimental characterisation of radiation detectors used in the same project.

Dr. Mattias Lantz has, together with Assoc. Prof. Cecilia Gustavsson and Dr. Erik Andersson-Sundén, used the UGGLA facility for measurements of Cs-137 in wild boar within the project ObeliCs. Two groups of high school pupils have performed projects where they have tested different kinds of dosimeters and compared the results with measurements at UGGLA. Dr. Lantz supervised the student project work of Mathilde Ragot, where metal foils irradiated at the NESSA2.5 neutron source were measured with the UGGLA facility in order to identify activation products and deduce the neutron field from NESSA2.5.

Some measurements have also been performed on lake sediments in order to determine the sedimentation rate.

Assoc. Prof. Andreas Solders has, together with his Ph.D. student Zhihao Gao, continued the research on fission yields in collaboration with the University of Jyväskylä, a project that is partly funded through a starting grant from the Swedish Research Council. In the spring of 2022, Gao defended his licentiate thesis describing detailed simulations of an ion guide for neutron induced fission to be deployed at the IGISOL facility in Jyväskylä. Once in operation, this device will facilitate the study of fission yields in neutron induced fission at IGISOL. Presently, Gao is writing up his thesis and preparing for his PhD defence which is planned for autumn 2023. This will be based on the study of the ion guide together with analysis of yield data from proton-induced fission of U-238 that he obtained at IGISOL in 2019.

Dr. Ali Al-Adili has continued to analyse fission-neutron data obtained from a fast-fission experiment on U-235. This experiment builds upon previous thermal measurements and required six weeks of beam time at the Tandem facility at JRC in Geel, Belgium. With financial support from the Swedish Research Council, Dr. Al-Adili and Ph.D. student Ana Maria Gomez Londoño have been developing the VERDI (Velocity for Direct Particle Identification) instrument for fission studies. Their primary focus has been on characterising silicon detectors for detecting fission fragments at the LOHENGRIN facility located at the ILL high-flux reactor in Grenoble, France. The preliminary data has been presented at several conferences and resulted in published proceedings. A full journal paper is currently being prepared. Dr. Al-Adili has recently spent three months as a scientific visitor at the IAEA to collaborate with Prof. Arjan Koning on implementing and benchmarking a new fission channel in the TALYS reaction code. In addition to research and PhD supervision, Dr. Al-Adili has also been involved in supervising the thesis work of André Pousette, as well as 15 ECTS projects of Augustine Pelletier and Dimitrios Papaioannou.

Staff changes

Regrettably, Dr. Peter Jansson and Dr. Zsolt Elter left our department during 2022. This, together with the fact that Prof. Ane Håkansson is half-time retired from 2022, has prompted considerable work to rearrange parts of the division's internal affairs and, in particular various teaching and supervision duties.

A major setback was the untimely passing of Dr. Michael Österlund at the end of October 2022. His engagement in management, teaching and all sorts of duties were considerable and he will be hard to replace. We have started a process for issuing a new position as a senior lecturer.

Infrastructure

The above-mentioned SKC-funded activities in the division of applied nuclear physics are heavily dependent on the availability of adequate experimental infrastructure. Besides laboratories abroad and, to some extent, Clab in Oskarshamn, significant efforts have been made to establish experimental infrastructure on-site in Uppsala. Funding for personnel working on infrastructure development comes to a small degree from SKC, and largely relies on other funding sources.

NESSA

The completion of the neutron facility NESSA has been delayed for various reasons, including the pandemic. Unfortunately Adelphi, the U.S. vendor of the neutron generator, made it clear in 2022 that they are not capable of delivering the generator according to our specifications. As this message contradicts their statement during the procurement process, we find ourselves in a formal dispute with Adelphi. This situation is very unfortunate, not the least due to the fact that the housing of the neutron source and necessary subsystems such as radiation protection and safety measures are completed and the licensing process is in its final stage. We are now in the process of finding a new vendor for the neutron generator.

BETTAN

The BETTAN facility is an experimental platform for developing measuring strategies and algorithms for tomographic applications. A unique feature of BETTAN is that irradiated fuel assemblies are simulated with pipes, filled with a radioactive substance that can be robotically arranged into various fuel geometries. Experimental activities using BETTAN have been carried out during 2022 and the results thereof are parts of the Ph.D. theses currently in preparation by Vikram Ratore and Lorenzo Senis.

UGGLA

The Uppsala Generic Gamma Laboratory (UGGLA) has been used for data taking from environmental samples during 2022. Measurements have also been performed on samples irradiated by neutrons in order to characterise the so-called NESSA2.5 neutron irradiation facility. The latter can serve as a testbench for neutron irradiation where UGGLA is used for gamma spectroscopy and student education.

Finished Diploma work

Olivia Winestedt, M.Sc. in Energy Systems: "Validering av Ecolego för modellering i enlighet med PSA nivå 3: Beräkning av markdeposition av radionuklider vid fiktiv svår härdskada vid Forsmarks kärnkraftverk"

Jonatan Hultin Rosenberg, M.Sc. in Energy Systems: "Variabla inloppsstrypningar i kokvattenreaktorer"

Gustav Södergren, M.Sc. in Energy Systems: "District heating with small modular reactors utilising an adaptive a-value"

Youcef Abdelmoumene, B.Sc. in Nuclear Power Technology: "Luftfiltermätningar av atmosfärisk radioaktivitet: Mätningar av luftfilter med gammaspektroskopi"

Staffan Fors, M.Sc. in Physics: "Nuclide content and decay heat in ARIANE sample BM1 calculated using Serpent 2: Impact from choice of nuclear data library"

Amela Mehic, M.Sc. in Physics: "Development of a computational method for determining gamma energy escape from calorimeters at CLAB"

Johannes Ekman, M.Sc. in Physics: "Modeling The Temperature of a Calorimeter at Clab: Considering a Thermodynamic Model of The Temperature Evolution of The Calorimeter System 251"

Marielle Aksér, M.Sc. in Physics: "Detections of nuclear explosions by triple coincidence"

André Pousette, B.Sc. in Physics: "Simulations of energy losses of fission fragments in Mylar foils at LOHENGRIN"

Ellen Hammarstedt, B.Sc. in Physics: "Determination of the homogeneity of the detection efficiency of silicon detectors using light ions"

Christoffer Rosendal, B.Sc. in Physics Education Research: "Svenska fysiklärares uppfattningar om elevers matematiska kunskaper i fysik"

Siri Werkelin and **Elsa Uggerud**, M.Sc. in Sociotechnical Systems Engineering: "Metodutveckling för säkerhetsskyddsanalys: Behovsanalys och kravunderlag för en generisk metod"

Matilda Tiberg, M.Sc. in Engineering Physics: "Simulation of IB-LOCA in TRACE: A semi-blind study of numerical simulations compared to the PKL test facility"

Research Projects financed by SKC

Introduction

Project funding decisions for the program period 2020-2023 were made in 2020. The projects were started during 2020 and 2021 and are described below.

Study of core stability during load follow with ROM methods (2019-1)

Research host:
Chalmers University of Technology
Department of Physics

Doctoral Student:
Kristoffer Tofveson Pedersen

Formal project start:
2020-09-01

Expected completion time:
2025-08-31

Main Supervisor:
Prof. Christophe Demazière

Co-supervisor:
Assoc. Prof. Paolo Vinai

Motivation

With the decreasing share of electricity produced by nuclear power in Sweden in the years to come and the corresponding increasing share of electricity produced by wind and solar power systems, an increasing reliance on intermittent energy sources in the Swedish grid is expected. As a result of this, the Swedish nuclear fleet will have to shift from a base load production mode to a load-follow production mode.

Adjusting the reactor power to follow the demand on the grid might nevertheless result in instabilities in the neutron flux under unfavourable core conditions, caused by the production/consumption of the xenon fission product. Such oscillations have a period of ca. 15-30 hours. Because of their relatively long period, the oscillations might remain unnoticed before they develop significantly, then requiring operator action in form of partial control rod insertion. In addition to detecting these oscillations when they develop, it is of utmost importance to determine whether a core configuration is stable or unstable with concerning xenon oscillations.

In this PhD project, Reduced-Order Model (ROM) techniques are used to study the stability properties of nuclear reactors during load follow conditions. In a ROM, the balance equations describing the time- and space-dependence of the neutron flux are projected onto a few properly chosen basis functions of space only. The main advantage of a ROM is to replace the complexity of the modelling of a nuclear reactor with a set of reduced balance equations, which adequately describe the physical phenomena being considered.

The main objective of the work is to be able to understand the parameters involved when studying the stability of a nuclear reactor concerning load-follow conditions and to be able to assess whether a core loading is stable or unstable directly from the ROM, without turning to lengthy and complex high-fidelity simulations.

Progress

The PhD project started on September 1st, 2020. Since then, a three-dimensional heterogeneous PWR core model was considered and used as a basis to construct an equivalent three-dimensional homogeneous core model. From this, the governing equations could be derived in a simple linear one-energy group form to maximise the transparency of the underlying physics. A "physics"-based ROM was developed. The spatial basis functions, on which the spatial dependence of the neutron flux is projected, were chosen as the eigenmodes of the neutron diffusion operator. From this expansion, the time dependence of each mode was derived analytically, as well as computed numerically. Both approaches led to identical results when using the same assumptions. The main advantage of the numerical approach lies in the capability to resolve the true interdependency between the modes. The analytical approach, on the other hand, allows for identifying which modes are driving any oscillatory or diverging behaviour. These results were an offset to creating a similar 3-dimensional heterogeneous model with two energy groups. The model was compared to the one-group homogeneous model to analyse the effects of increasing the spatial and energy resolution of the ROM. The two-group heterogeneous model predicted a significantly more unstable system than its simpler counterpart. The terms of the underlying equations responsible for the difference were identified. The coupling between modes was dependent on inner products between the adjoint and forward modes as well as either the equilibrium flux or the equilibrium xenon distribution. The normalised axial shape of two of these functions is shown in the figure below. The main reason for the difference in stability predictions comes from going from 1 energy group to 2 energy groups.

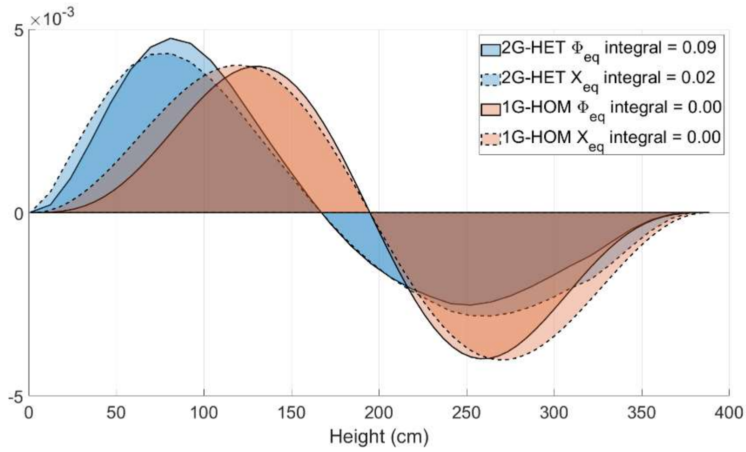

Figure 1 Comparison of the axial shape of two integrands between each of the two models along with the value of integration.

Method

The physics-based intrusive ROM was created using a linear approximation which is only valid for small deviations from the mean equilibrium values of neutron flux and xenon and iodine concentrations. The project was presented to both Ringhals and Forsmark. An exchange of data from high-fidelity simulations has started with Ringhals. In further research, this data will be used as a basis for a data-based non-intrusive ROM. The intrusive and non-intrusive approaches will be compared to each other and the simulated high-fidelity test cases.

Communications

The project was presented at the SKC annual symposium at KTH on October 17th -18th, 2022. A conference paper on the on-group homogeneous model was presented at the ANS Annual Meeting, held on June 12th -16th, 2022 in Anaheim, CA, USA. A conference paper on the two-group heterogeneous model has been accepted for the International Conference on Mathematics and Computational Methods Applied to Nuclear Science and Engineering (M&C) to be held on August 13th-17th 2023 in Niagara Falls, Canada.

Influence of ageing and radiation on ductile fracture in the DBT temperature region (2019-2)

Research host:
KTH Royal Institute of Technology
Department of Engineering Mechanics

Doctoral Student:
Shuyue Wang

Formal project start:
2020-08-17

Expected completion time:
2025-06-25

Main Supervisor:
Jonas Faleskog

Motivation

Ductile fracture involves a significant amount of plastic dissipation which increases the resistance of a material to withstand the growth of existing defects to failure. However, long-term operation at elevated temperatures may lead to a degradation of this resistance and consequently a less ductile material. If the material also is subjected to a hostile environment as found in nuclear power plants, this degradation can be accelerated.

The structural integrity of the large pressure-retaining component is vital to the continued operation of nuclear power plants beyond the initially assumed lifetime. Currently, six plants in Sweden are planning for Long Term

Operation, LTO, extending the life beyond the 40 years lifetime assumed in many of the original analyses. The process of LTO is a common tool to extend the lifetime of the plants utilized in most nuclear operating countries. Including an assessment of all systems, structures, and components relevant to, or affecting, nuclear safety.

The objective of the proposed study is to understand the influence of time-dependent ageing and degradation mechanisms on the ductile behaviour of low alloy steels at temperatures above the Ductile to Brittle transition temperature, DBTT. By understanding limitations and conservatisms, a sound basis for the assessment of the structural integrity can be obtained, and measures to improve and visualize the nuclear safety of the operating plants in a long-term operation perspective can be performed from a regulatory and operations perspective.

Specifically, the possible influence of microstructural entities and defects on the scale ranging from about ten nanometers to one millimeter combined with an overall change in plastic flow properties on ductile fracture will be investigated. The work involves the development of theory, numerical methods, and experiments. The study aims to develop a numerical tool to analyse and predict how ductile failure can be affected by aging and radiation in elevated temperatures above DBT.

Progress

The project started in August 2020 and has since focused on developing the constitutive model capable to capture crack initiation and propagation in a structure. The classical damage continuum mechanics material model is not sufficient to describe crack initiation and propagation where the numerical problem arises with strain softening and localization. Thus, a non-local approach suited for finite element analysis is essential to understand and describe the degradation of material used in the nuclear power plant where crack initiation, propagation, and material failure can lead to severe consequences.

A non-local constitutive model using two length scales associated with two different failure mechanisms – shear failure by void sheet formulation, and flat dimple rapture – has been developed and implemented into a Finite Element Method program. Numerical models for different test geometries have been developed to capture possible modes of failure in the material during degradation. Tensile geometries prone to flat dimple rupture, shear-type of geometries prone to shear failure, and a fracture test geometry with sharp crack have been investigated. Careful numerical studies have been carried out and the modelling concept has proven capable of capturing the relevant modes of failure occurring at different length scales as observed in experiments. Possible failure modes of a Single Edge Notched Bend specimen are shown as an example in Figure 1.

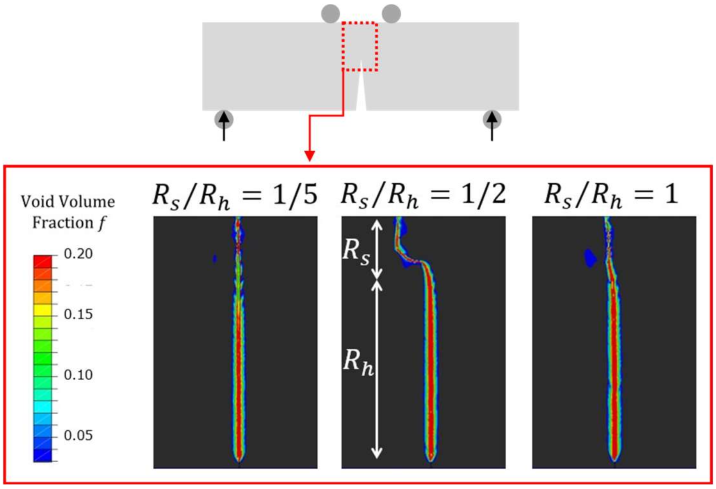

Figure 1. Possible failure modes in a Single Edge Notched Bend specimen captured by the numerical analysis.

In 2022, experiments have been carried out on low alloy steel A508 with similar ductile properties and corresponds to a forged version of A533, which is used as weld material in nuclear pressurisers. The experimental data sets are used to calibrate and validate the numerical modelling framework. The framework will be further applied to experiments to be conducted on the referential and aged weld material taken from the decommissioned pressurizer from Ringhals 2. The experimental results and numerical studies on the latter material is expected to clarify the influence of ageing and degradation mechanisms on ductile failure at elevated temperatures, and thus give a sound basis for the assessment of the structural integrity and improve nuclear safety. The calibration of the numerical model using experimental data sets from material A508 is in progress, calibrated global response from the uniaxial tensile test is shown as an example in Figure 2, and the experiments based on material A533 have been planned and are on schedule.

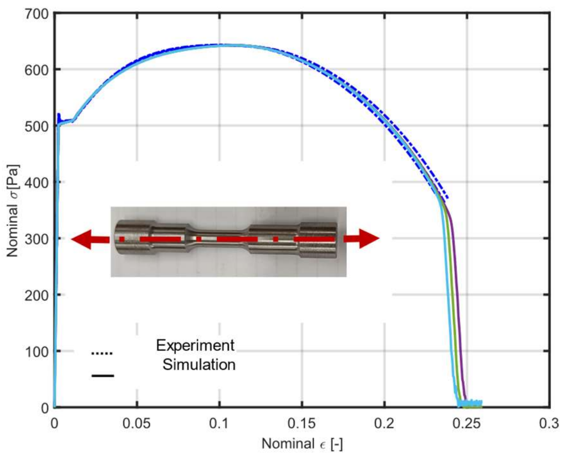

Figure 2. The global response of uniaxial tensile tests using material A508.

Methodology

The degradation of weld material used in nuclear power plants will be systematically investigated in the upper transition to the upper shelf region by experiments. The constitutive material model is based on the damage model known as the Gurson-Tvergaard-Needleman model (GTN model) modified for shear failure.

In the GTN model, damage evolution is described by a state variable f corresponding to the void volume fraction in the material and the yield condition Φ is defined by

$$\Phi = \left(\frac{\sigma_\mathrm{e}}{\sigma_\mathrm{M}}\right)^2 + 2f^* q_1 \cosh\frac{3q_2\sigma_\mathrm{h}}{2\sigma_\mathrm{M}} - (1 + q_2 f^*)^2 = 0,$$

where σ_e is the effective stress, σ_h is the hydrostatic stress, σ_M is the flow stress of the matrix material, and q_1 and q_2 are two material constants. The model assumes that plastic localization and degradation of the material involves damage mechanisms that are active in two different length scales, a deviatoric R_s and a dilatational R_h. The introduction of these length scales, rendering the constitutive description to be non-local, prevents a premature and non-physical strain localization and avoids a pathological mesh dependency. Here, an integral approach is used to for non-local treatment of evolution void volume fraction, $\dot{f}$. The non-local damage evolution can be either conducted in the referential or the spatial configuration. In the reference configuration with material volume V_0, the damage evolution at a material point $\mathbf{X}$ is obtained by

$$\dot{f} = \frac{1}{W_\mathrm{h}(\mathbf{X})}\int_{V_0} \dot{f}^h_\mathrm{local}(\widetilde{\mathbf{X}}) w \frac{\mathbf{X}-\widetilde{\mathbf{X}}}{R_\mathrm{h}} d\widetilde{V} + \frac{1}{W_\mathrm{s}(\mathbf{X})}\int_{V_0} \dot{f}^\mathrm{s}_\mathrm{local}(\widetilde{\mathbf{X}}) w \frac{\mathbf{X}-\widetilde{\mathbf{X}}}{R_s} d\widetilde{V},$$

where W_s and W_h are the deviatoric and dilatational volume integral of the weight function w, respectively.

Communication

The project was presented and is planned to be presented at the following international and national conferences and seminars:

- EMMC18 - 18th European Mechanics of Materials Conference, Oxford, United Kingdom, April 2022;
- Seminar at Vattenfall, Solna, Sweden, May 2022;
- SMD Svenska Mekanikdagar 2022, Luleå, Sweden, June 2022;
- Seminar at Kiwa, Stockholm, Sweden, November 2022;
- ICF15 -15th International Conference on Fracture, Atlanta Georgia, United States, June 2023;
- COMPLAS 2023 - XVII International Conference on Computational Plasticity, Barcelona, Spain, September 2023.

Two further publications are in preparation:

- Numerical modelling and parameter study conducted with the developed constitutive model (to be submitted);
- Calibration and verification of the numerical modelling framework based on experimental data sets (planned submission: before the end of 2023).

Corrosion fatigue in LWR environment at cyclic thermal and mechanical loads (2019-4)

Research host:
KTH Royal Institute of Technology
Department of Engineering Mechanics

Doctoral Student:
Mustafa Subasic

Formal project start:
2020-08-17

Expected completion time:
2025-08-31

Main Supervisor:
Pål Efsing

Motivation

Corrosion fatigue is a well-known degradation phenomenon in structural materials that may develop as a consequence of long-time exposure of components to cyclic thermal or mechanical loads at the presence of an aggressive environment in many industrial applications. If left unattended it will result in failures of the affected components. One such application is the piping systems in nuclear power plants where the water introduces an increased environmental risk for fatigue initiation. The existing Swedish nuclear power plants rapidly approaches the originally assumed service life of 40 years. The remaining 6 nuclear power plants in Sweden all have programs for life extension from 40 to 60 years, called Long Term Operation, LTO. The overall research objective is to add knowledge about the degradation mechanism, which can be used by the plant operators and the regulatory body during assessment of the readiness for LTO of the Swedish nuclear power plants. The objective of the project is to develop an improved risk and life prediction method for corrosion fatigue in the pipe systems.

The project results will be distributed to the engineers working at the Swedish nuclear power plants for review and dissemination. The overall goal is that the results together with other available sources of data can lead to improved assessment tools and methods against corrosion fatigue at mixing points and systems with stagnant and/or turbulent flow. It will as part of the nuclear utilities on-going LTO-programs assist in the establishment of a solid basis for in-service inspection programs and give improved data for decision on repair or replenishment of pipe joints. The knowledge on corrosion fatigue risk at Swedish nuclear power plant conditions will supply SSM with better understanding for the risk of rupture and improved judgement of safety margins. Based on these improvements SSM will be able to enhance proactive safety work at the utilities.

Progress

The project started in August 2020. During 2021, the design and manufacturing of the experimental set-up including the hollow pipe specimens was finalized. The fatigue behaviour of the suggested design, which is modified compared to the original version, have been simulated and, based on the simulations and results in the literature, it was decided that the design meets the requirements for testing the damage mode at Swedish nuclear power plant conditions. An experiment plan has been defined and discussed within the project group. Test material has been selected and acquired from the Oskarshamn nuclear power plant. The material is a vintage type 304 stainless steel plate that was recovered from the archives after construction of the Barsebäck nuclear power plant. In 2021 a fatigue design curve, i.e. a S-N curve relating the number of cycles to failure, was developed for the chosen material using standard type specimens. Cyclic tests at elevated temperature was also performed and the cyclic plasticity of the material was modelled with a combined nonlinear isotropic and kinematic hardening model in a radial return mapping algorithm. Pipe samples have been manufactured for correlation of the hollow tube samples to investigate the consistency in their behaviour at elevated temperature and pressure. In 2022, the corrosion fatigue tests with the hollow specimens commenced in the Studsvik laboratory. The tests are still running in simulated BWR water chemistry conditions. This work is sponsored by the Swedish Utilities Materials group, MG.

Parallel to the experimental program, a mechanical-electrochemical coupled crystal plasticity finite element model is being developed. The model consists of polycrystals generated from EBSD data on the material. The FE model will be used to make predictions on crack initiation during the corrosion fatigue process.

Methodology

The experimental work at the Studsvik laboratory will be the key for a successful project. The experimental work will be a collaboration between three parties, KTH Solid Mechanics where the set-up has been designed and manufactured, Studsvik where the experimental part in autoclave will be performed, and Chalmers Microstructure Physics where microscopy and damage characterization will be executed.

The ongoing simulation work for understanding and verification is running in parallel to the experimental series. It is planned for two different set-ups. One will be the multi-physical simulation of initial conditions with coupled mechanical loads and corrosion process. The second will be the crack initiation on favourable crystal planes. The plan is to use and build on the cohesive crack growth model developed by Michal Sedlak Mosesson in the recently finalized SKC funded project Mechanical Modelling of Stress Corrosion Cracking in Sensitized Stainless Steel 316.

Communication

The project was presented at the SKC Symposium 2022.

A project reference group has been established and constituted. The reference group comprise participants from all three Swedish nuclear power plants, SSM and the project parties KTH Solid Mechanics, Studsvik and Chalmers Microstructure Physics. Adjunct professor Pål Efsing from Ringhals serves as industry advisor and main supervisor. Carl Dahlberg at KTH serves as co-supervisor. Dr Jean Smith from EPRI in Chicago USA is connected to the project as expert advisor and a communication link has been established to Dr Seiji Asada at Mitsubishi Heavy Industries for the experimental work.

In July 2022, the project was presented at the “Environmental Degradation of Materials in Nuclear Power Systems” conference in Aspen, Colorado, USA. In addition, a presentation was also held in the “International Conference on Multiaxial Fatigue and Fracture” conference in November 2022 in New Orleans, Louisiana, USA. The results are also foreseen to be presented in June 2023 at the “International Conference on Fracture” conference in Atlanta, Georgia, USA, and in the “Environmental Degradation of Materials in Nuclear Power Systems” conference in Sankt Johns, Canada, in August 2023.

SEMRA: Steam Explosion Modelling and Risk Analysis for light water reactors (2019-7)

Research host:
KTH Royal Institute of Technology
Department of Physics

Doctoral Student:
Ibrahim Batayneh

Formal project start:
2021-01-15

Expected completion time:
2025-01-15

Main Supervisor:
Dmitry Grishchenko

Motivation

Steam Explosions (SE) are an inherent risk in light-water reactors (LWRs), posed by the very use of water as a coolant during accidents. There is a need to better understand these risks in currently operating and future NPPs, but state-of-the-art on steam explosions remains fragmented, with large spread in the prediction of explosion loads across modelling approaches and code users. The SEMRA project develops what is intended to be the most comprehensive modelling approach for the analysis of ex-vessel steam explosions in LWRs, and couples it with a risk analysis methodology to support decision making in modifying severe accident management (SAM) strategies. The deterministic model we develop will be applicable for any type of LWR, and any scenarios of melt release. It will be accompanied by an artificial neural network (ANN)-based surrogate model to enable fast calculations for risk assessment and uncertainty analysis.

With SEMRA's use of state-of-the-art numerical methods, comprehensive model validation, uncertainty quantification, and decision-oriented risk analysis, we will provide a flexible, generalized tool for analysing the risks of steam explosions and potentially resulting containment failure. The outcomes of this work will be relevant for the scientific community, industry, as well as regulatory/licensing bodies. The results can be directly incorporated into the current probabilistic safety analysis (PSA) used by the nuclear industry and bring the issue of steam explosion to a final resolution.

Progress

The PhD project started in January 2021. Since then, to get familiar with the topic and to see what is lacking in old steam explosion codes, 'TEXAS-5' code was used to analysis of the effects of multiple jets release on the energetics of steam explosion loads in Nordic BWRs. A full model solutions database was built from which a fast surrogate model was developed to analyse the effects of multiple melt-jets and their potential implications on the risk of containment failure. This study concluded the importance of multiple melt-jets release and the need to include it in SEMRA SE code.

The next step of SEMRA project started with the analysis of the different numerical schemes available to model the physical phenomena of steam explosion, to select the appropriate one for SEMRA SE code. A new solver for SE shock wave pressure propagation is currently being validated. The solver incorporates WENO solver with AUSM+-up and Godunov flux schemes to model pressure propagation in a multi-phase domain. The results obtained from this in-house code are compared with the experimental results from KROTOS facility and the results from TEXAS-V code.

Methodology

The calculation of a steam explosion with multiple jets was carried out by, first, computing the explosion impulse for a single jet with cell cross-section area set according to a considered jet configuration scenario; and second, the impulse resulting from a single jet calculation was multiplied by the number of jets to provide the final explosion load. A sensitivity analysis and a parametric study were carried out to confirm that the surrogate model provides physically sensible behaviour for the different input parameters. Then, the surrogate model was used in (ROAAM+) code package to analyse the failure domains as shown in the figure below.

As for SEMRA SE code, after selecting the appropriate numerical model, the code will be built gradually, starting with simple pressure and temperature calculations (1D and 2D), to including different SE phenomena such as multiple melt-jets release.

Communication

The project was presented at the SKC Symposiums 2021 & 2022. A conference paper about steam explosion in conditions of multiple jet releases was presented in the 19th international topical meeting on Nuclear Reactor Thermal Hydraulics (NURETH-19), March 2022. Two new conference papers will be presented in NURETH-20 in August 2023. One continues on SE in conditions of multiple jet releases and another on modelling of triggering and SE pressure propagation. Scientific journal articles on the same topics will be prepared as well.

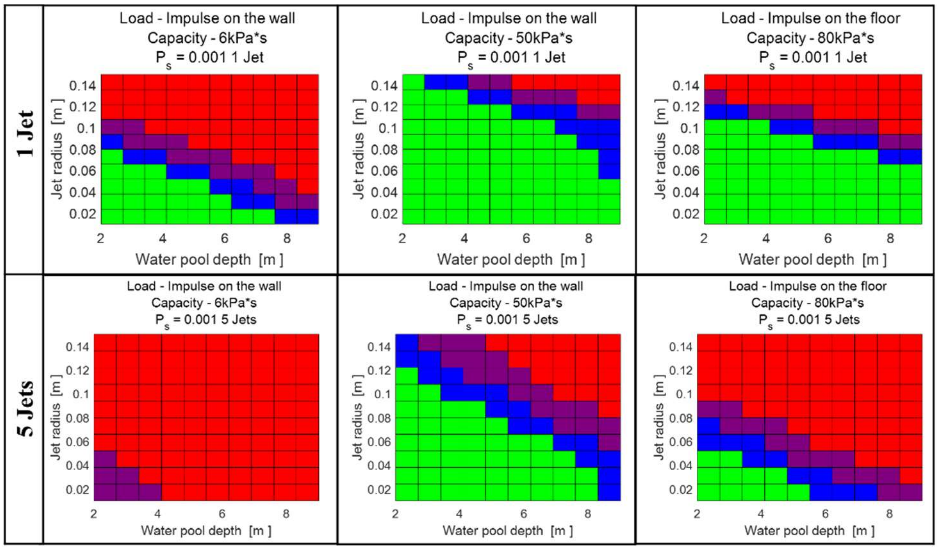

Figure 2: Failure domain for 1 vs 5 jets. (Red: failure, Green: success)

Calibration of fuel performance codes – treating model inadequacies, nuisance parameters, and unrecognized systematic uncertainties (2019-12)

Research host:
Uppsala University
Department of Physics and Astronomy

Doctoral Student:
Gustav Robertsson

Formal project start:
2020-09-01

Expected completion time:
2024-09-01

Main Supervisor:
Henrik Sjöstrand

Motivation

The proposed project addresses challenges in the calibration of fuel performance codes. These codes include models that predict thermo-mechanical behaviour of the fuel and hence, the performance and safety functions of the fuel for regular reactor operation, anticipated operational occurrences, accidents, and back-end applications.

There are several challenges with acquiring calibrated predictive models with well-founded uncertainty estimates. These challenges include handling interlinked models; integral, biased, and sparse calibration data; various types of input uncertainties; computationally costly executions; and model inadequacies. Therefore, inverse uncertainty quantification (UQ) in fuel performance modelling is particularly challenging.

Specifically, the UQ within fuel performance simulations is crucial in establishing plant operation safety limits. This manifests as conservative estimates of operation limits or an evaluation showing that the fuel cladding barrier will not be breached for a given plant operation. In addition, the fuel rod behaviour plays a central role in accident analyses, for example, in the evaluation of loss-of-coolant accidents where the cladding embrittlement is a direct safety-related parameter. In this context, calibration plays a pivotal role as it defines the uncertainties utilized when providing the conservative estimate. Inaccuracy in calibration can lead to overstepping of established failure limits, which from a safety standpoint is not acceptable. Conversely, an overly cautious and conservative treatment causes less efficient operation and fuel utilization with both cost and increased waste disposal impacts.

One of the most demanding challenges in model calibration is caused by so-called model inadequacies. A model inadequacy is when the model cannot recreate the physical reality independent of the choice of model parameters. This often has severe consequences if not accounted for properly. A simple example is shown in Figure 1, where a linear model (blue line) is used to estimate a more complex reality (orange, broken line). It is clearly seen that the resulting blue uncertainty bands of the model do not reflect the error of the model. This is the result that would be obtained if the model inadequacy is not accounted for, with significant safety implications if the model was to predict a nuclear engineering safety parameter.

Fuel performance codes are used to determine cladding oxidation, hydrogen pickup, and gas release, among other quantities. These phenomena, if not limited, can have a direct negative impact on fuel safety. For example, hydrogen uptake harms the mechanical properties of the zirconium alloy, cladding oxidation consumes the cladding, and the oxide is a much poorer heat conductor. In addition, the modelling of fission gas release is important since fission gases degrade the thermal conductivity of the gas inside the fuel rods and increase the internal pressure. Higher temperatures may also lead to negative thermal feedback since a depressed thermal conductivity will, in turn, enhance additional fission gas release. These three quantities have been the primary focus of the studies performed within the project so far.

Moreover, the project develops competence in machine learning and computational methods. This has an added advantage in that the project can cross-fertilize neighbouring nuclear technology projects in the sphere of SKC.

To summarize, the project aims to ensure safety via reliable quantification of margins simultaneously as it enables efficient use of fuel and benefits all partners of SKC. This will be achieved by improving techniques for calibration and UQ in the context of fuel rod performance simulations.

Progress

The project is executed as a Ph.D. project in collaboration between Uppsala University (UU) and Westinghouse. Active within the project are Gustav Robertson (Ph.D. student, SKC-funded), Henrik Sjöstrand (Supervisor, UU, SKC-funded), Peter Andersson (Co-supervisor, UU, SKC-funded), Paul Blair (co-supervisor, Vattenfall Nuclear Fuel AB, in-kind contribution).

During 2020 a method to address the problem related to model inadequacies in the calibration of fuel performance models has been developed and implemented. The method is designed to address model inadequacy by inflating the uncertainty of the calibration parameters to account for the discrepancies (see the yellow bands of the inflated uncertainty in figure 1 as a toy example). Initially, the Ph.D. project lacked both PIE data and a fuel performance code in contrast to previous studies such as presented in reference [1], which was performed at Westinghouse. Therefore, it was deemed meaningful at the beginning of the project to work with synthetic data since the performance of the tested methods can be more easily studied.

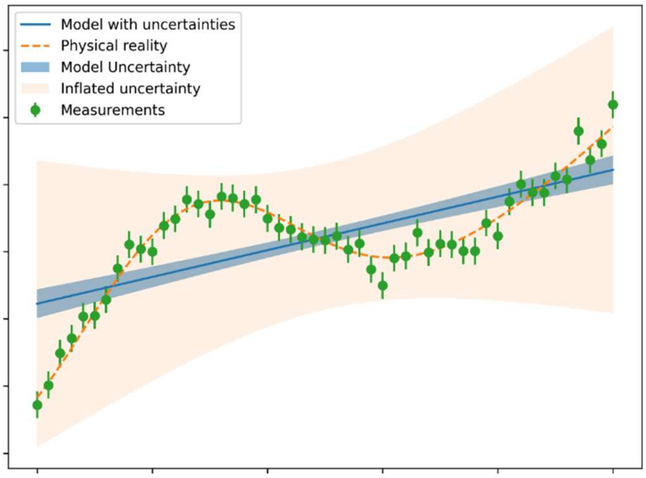

Figure 1 Showing an example of an inadequate model with uncertainty bands in a standard calibration (blue), and inflated uncertainty bands (yellow)

In 2021, the method has been further refined and completed. Quantitative metrics for the method's ability to compute well-founded uncertainties have been obtained and it has been shown that the method works well on validation data. I.e., with the new implementation, it is found that the obtained method can produce a successful joint calibration of both the oxidation and the hydrogen model where the uncertainties can explain the model error. The work has been presented at TopFuel2021 and submitted to the Annals of Nuclear Energy. The paper has been accepted after comments have been addressed during the spring of 2022 and was published in August 2022 [2].

In 2021, publicly available fission gas release data were collected to develop the proposed method further and demonstrate its applicability to more multivariate and more strongly interconnected problems using actual data and codes. For this purpose, the project has access to fuel performance code Transuranus developed by the Joint Research Center (JRC) at the European in Karlsruhe, Germany. JRC has been supportive and supplied Transuranus input files for the public experiments studied. Based on the calibration methodology, a calibration framework to calibrate Tranuranus to those experiments has been implemented. A part of the framework has been to improve surrogate modelling to support the calibration methodology with derivative predictions. This work was conducted during 2022 and published at TopFuel 2022 [3]. During 2022, additional development has been conducted on the calibration methodology to make it more robust by simplifying the relationship between model parameters and corresponding predictions by using transformations. An outcome of this development is a preliminary calibration result that is intended for publication in 2023.

During 2022, a bachelor/master project has been proposed to improve the understanding of time-dependent surrogate models in calibration. This work is expected to start in 2023 and is based on a previous bachelor work conducted in the project during 2021, "Temporal Convolutional Networks In lieu of Fuel Performance Codes" [4].

Methodology

Joint calibration using synthetic data cladding oxidation and hydrogen

The basic assumption of the method is that the calibration parameters (in this case, the oxidation rate, C, and hydrogen pickup fraction, f) vary between the experiments, in contrast to standard calibration methods that often assume one valid set of underlying parameters. The calibration parameters are considered to follow a multivariate gaussian distribution. The local experiment-specific parameters can be described by a mean vector μ and co-variance matrix Σ (mean and standard deviation for the univariate case). This results in a new formulation of the posterior distribution, as is illustrated in the equation below:

$$\log posterior \propto \sum_{i=1}^{n}\left(-\frac{1}{2}r_i^T\Lambda_i^{-1}r_i - \frac{1}{2}\log|\Lambda_i|\right) + \log prior$$

where $\Lambda_i = J_i\Sigma^{-1}J_i^T + R_i$.

Here, J is the sensitivity of the output in respect to the parameters, $J_i\Sigma^{-1}J_i^T$ is the uncertainty of the calibration parameters propagated to the model's output, r_i is the residuals evaluated at the mean of the calibration parameters and R_i is the measurement uncertainty. The resulting expression is similar to the traditional expression used in standard calibration methods, except that the term $J_i\Sigma^{-1}J_i^T$ is added and that μ and Σ are the free parameters rather than the calibration parameters directly.

The process is visually described in Figure 2

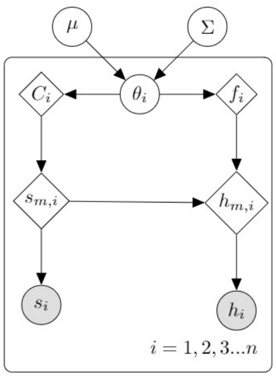

Figure 2 - Illustrates the probabilistic model developed, with the assumption of different calibration parameters (C_i, f_i) for different experiments, i. Distribution parameters (mu, sigma) describing the distribution of C_i and f_i, resulting in calculated values from the model ($s_{m,i}$, $h_{m,i}$), which are finally compared with the measured values, s_i and h_i.

The distribution parameters (μ and Σ) are sampled using Markov Chain Monte Carlo, and surrogate models are employed in place of the simulation tool to make the process computational tractable. From the obtained μ and Σ the distribution of the physical parameters can be generated and propagated in subsequent analyses.

This calibration has been thoroughly repeated 1200 times on different synthetic data sets to ensure that it produces stable and well-founded uncertainty estimates that cover the spread of the residuals regardless of source. The conclusion of the first paper published in the Annals of Nuclear Energy [2] was that: "*A repeated validation using many synthetic data sets shows that the method is robust and handles model inadequacies appropriately in most cases.*"

Calibration of fission gas release

In 2021, the above-described method has been developed, implemented, and tested using the fuel performance code Transuranus. Publicly available fission gas release data has been collected from the inter, super and overramp tests, and ITU has provided corresponding input files. To calibrate Transuranus, a specific calibration version of the code has been developed by augmenting the original code with an additional input format to read calibration parameters. Further, a python program package has been developed that executes the simulation of several experiments using Transuranus with different sets of calibration parameters, collects outputs, and generates surrogate models. Surrogate modelling techniques have been augmented to calculate various properties needed by the method, such as the Jacobi matrix with respect to the calibration parameters. A differentiated version of a standard Gaussian Process regressor has been developed to calculate the Jacobi-matrices needed in calibration. These improved surrogate models have been validated against fission gas release ramp data generated with Transuranus and this work has been published in a conference paper at TopFuel 2022 [3]. Additionally, a calibration program has been developed in which the developed calibration method has been implemented and preliminary calibration results have been obtained during 2022 that is intended for publication.

Temporal Convolutional Neural Nets In Lieu of Fuel Performance Codes

In 2021, a 15 hp bachelor project was conducted to investigate using convolutional temporal neural networks as surrogates in calibration for time-dependent models. Realistic power histories were used, and training data were generated using a simplified cladding oxidation model. The results show that temporal convolutional neural networks work to predict the outcome for an independent power history that is held back for validation. Thus, temporal convolutional networks are suitable to be deployed as surrogates for fuel performance codes. This facilitates the calibration of time-dependent parameters in the future but could also have extended use in the nuclear industry. Based on this work, a continuation bachelor/master project was proposed in 2022 to apply these techniques to more multivariate data generated with Transuranus and is expected to be conducted during 2023.

Communication during 2022

During 2022 a paper on the proposed method "Treating model inadequacy in fuel performance model calibration by uncertainty inflation" was published in the Annals of Nuclear Energy [2].

A paper "Surrogate Modeling with Derivative Prediction for Implementation in Inverse Uncertainty Quantification Methods for Fuel Performance Modeling" has been presented at Topfuel 2022.

In addition, the conference/meeting contributions [5], [6] were presented during 2022.

Miscellaneous

A solution for how the project can use proprietary fuel performance data of Westinghouse has been set up during 2022 and a non-disclosure agreement has been signed.

Since 2022, Uppsala University participates in an accelerated program to create security of supply to Russian-designed VVER reactors operating in the EU (APIS project). The project is funded by the European Commission, coordinated by Westinghouse, and includes 12 partnering organizations. From Uppsala University, Gustav Robertson and Henrik Sjöstrand will be active in the project and work with statistical development and news dissemination.

The co-supervisor Pal Blair changed position from Westinghouse to Vattenfall Nuclear Fuel in 2022, and will remain as a supervisor in the project.

In 2022, Gustav Robertson supported a master's thesis work at Westinghouse [7], mainly with insight in applying Gaussian Processes to predict critical heat flux. The collaboration led to a conference paper, "Investigation of Machine Learning Regression Techniques to Predict Critical Heat Flux over a Large Parameter Space" that was accepted for publication at the NURETH-2023 conference.

Outlook

The project is planned according to a staged approach to have an increasing complexity in both physical models and statistical techniques over the project's duration. The idea is to move between artificial test-beds and real code so that suitable methods are first investigated in controlled environments to subsequently be proved on real data. Therefore, actual data and fuel performance codes with more multivariate and strongly interconnected problems with more feedback loops etc. are used to test the already developed statistical methodology. In 2023, the plan is to access propriety data from Westinghouse. After the method has been tested on actual data and codes, the plan is to include treatment of nuisance parameters.

It is planned that the developed method and the first application will be published as a licentiate thesis during early 2023.

References

[1] J. Nyman, *Joint Calibration of a Cladding Oxidation and a Hydrogen Pick-up Model for Westinghouse Electric Sweden AB*. in UPTEC ES. 2020.

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[3] G. Robertson, H. Sjöstrand, P. Andersson, and P. Blair, "Surrogate Modeling with Derivative Prediction for Implementation in Inverse Uncertainty Quantification Methods for Fuel Performance Modeling," in *TopFuel 2022 Light Water Reactor Fuel Performance Conference*, 2022.

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[7] E. Helmryd Grosfilley, "Investigation of Machine Learning Regression Techniques to Predict Critical Heat Flux," no. 22041. in UPTEC F. Uppsala University, Division of Systems and Control, p. 39, 2022.

Impact of radiation chemistry on surface processes in LWRs (2020-18)

Research host:
KTH Royal Institute of Technology
Department of Chemisrty

Doctoral Student:
Luca Gagliani

Formal project start:
2022-01-01

Expected completion time:
2026-02-01

Main Supervisor:
Mats Jonsson

Motivation

Surface reactions such as metal corrosion, oxide deposition and oxide release/dissolution are processes that have a significant impact on the performance of and the occupational safety around nuclear reactors. These processes are largely governed by the fairly harsh conditions prevailing inside a nuclear reactor. These conditions include high temperatures, high pressures, intense neutron fluxes and intense gamma fluxes. The primary oxidative radiolysis products in gamma-irradiated water are hydrogen peroxide (H_2O_2), the hydroxyl radical (HO•) and to some extent also the hydroperoxyl radical (HOO•). Molecular oxygen (O_2) is subsequently formed project is to identify situations where the simplified approach can be sufficient and situations where this is not sufficient. The materials used in the experimental studies will include but not be restricted to cladding materials, grid spacer materials and oxide depositions

Progress

The project was started on February 2022 when the PhD-student was employed. In this first year of the project, Luca attended courses about corrosion, nuclear chemistry, and radiation chemistry, to get acquainted with the topic of the project and better understand the processes involved. Kick-off meetings with the reference group (Westinghouse, Vattenfall and OKG) were held in March and late April 2022 and a subsequent update meeting in October 2022. A second update meeting will be planned for late spring 2023. During 2022, the reference group provided some relevant cases on which further literature and experimental studies are now based. Also, significant test materials were provided and are now used for laboratory tests. Luca got first familiar with some experimental methods useful for the project's scope.

Then he defined a reliable investigation procedure to monitor and determine H_2O_2 evolution and consumption under γ-irradiation conditions in heterogeneous systems involving water and the relevant alloys provided. The project is now focusing on investigating such alloys after irradiation and pondering the exploitation of electrochemical techniques for the investigation of the interactions at the solid-liquid interface.

Methodology

So far, the techniques most used for the present project are chemical dosimetry and titration, Ultraviolet-Visible (UV-VIS) spectroscopy, Scanning Electron Microscopy (SEM), Energy-Dispersive X-ray (EDX) spectroscopy, Induced Coupled Plasma Mass-Spectroscopy (ICP-MS). Soon also X-Ray Diffraction (XRD) spectroscopy and/or X-Ray photoelectron Spectroscopy (XPS) will most probably be exploited. Furthermore, electrochemical investigation techniques, such as Electrochemical Impedance Spectroscopy (EIS), are under evaluation for analysis of the ongoing reactions at the system interface.

Communication

The project was presented for the first time at the SKC Symposium 2022 in Stockholm.

Application of artificial neural networks in reactor physics calculations (2020-19)

Research host:
KTH Royal Institute of Technology
Department of Physics

Doctoral Student:
Yi Meng Chan

Formal project start:
2021-08-16

Expected completion time:
2025-08-16

Main Supervisor:
Jan Dufek

Motivation

Nodal diffusion codes, that are used in industry for reactor simulations require spatially homogenised and energy collapsed nodal data, such as group macroscopic cross sections, microscopic cross sections for selected nuclides, diffusion coefficients, discontinuity factors, etc. The nodal data depends on both instantaneous and historic state variables, such as fuel depletion, fuel temperature, moderator density, and others. Nodal data generation is carried out by computationally expensive neutron transport codes, and it is impractical to generate nodal data on demand from these codes, therefore, it is necessary to build simplified models of the nodal data based on its state dependencies.

These dependences are usually tabulated or approximated by multivariate functions (Dufek 2011), mostly polynomials. The general problem with the table models is that tables grow exponentially with the number of state variables. The amount of data stored in the tables and the number of lattice calculations needed to fill the tables can easily become impractically large for this reason. Therefore, the table models can consider only relatively few state variables.

In this PhD project, we propose the application of Artificial Neural Networks (ANNs) to represent nodal data. The advantage of Artificial Neural Networks is its capacity to represent highly complex and non-smooth functions, which we believe may lead to more accurate nodal data representation compared to the models in the current literature. This would allow for more flexible and accurate reactor simulations than possible with existing data models. This can translate into a better optimisation of fuel load patterns and an improved reactor economy.

Progress

The PhD project started on August 2021. Since then, the project progresses according to the plan. The following points are completed or nearly completed:

- Generation of training data sets with NEWT with various initial pin enrichments and historical state parameter variations.

- Preliminary application of a model combining Principal Component Analysis (PCA) with a Deep Neural Network (DNN) to perform multi-group self-shielded cross section reconstruction shows promising results.

- The model is able to handle a large number of nuclide concentration dependencies and instantaneous state parameters.

- Analysis of model performance is currently underway and the results are expected to be published in the next few months.

Methodology

Before lattice codes output few group nodal cross sections, they first have to generate multigroup cross section libraries from continuous energy cross section libraries for each material in each fuel cell. The computational cost of these cross section processing are large. Therefore, we propose the use of a representation model to estimate lattice code multigroup cross section libraries from nuclide concentration data and state parameters.

The model combines Principal Component Analysis (PCA) and fully connected Neural Networks (NN). The model contains three sublayers in a PCA-NN-PCA configuration. The model architecture allows it to handle large multi-group cross section data sets containing cross section data for several dozen nuclides and containing upwards of 50 energy groups. A representation of a forward pass of the model is shown in Figure 1.

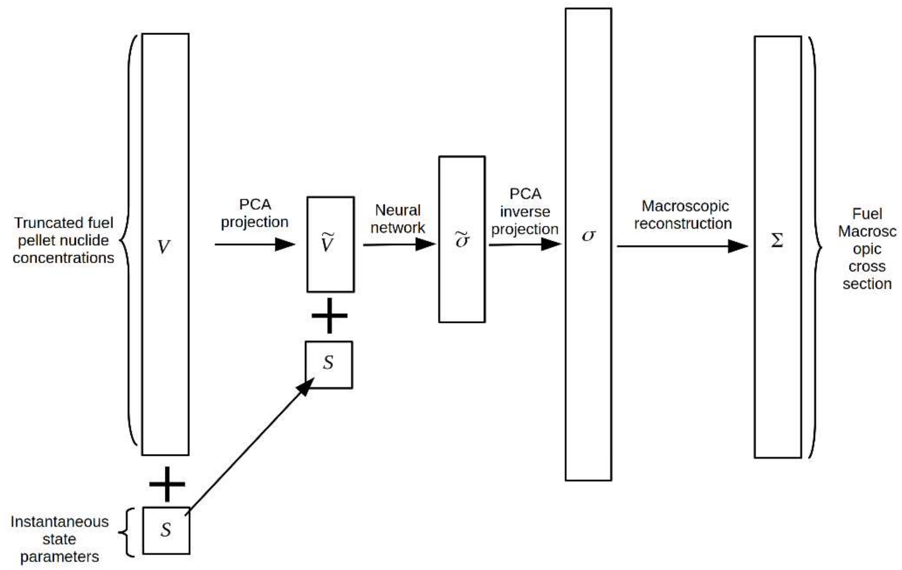

Figure 1: PCA-NN-PCA forward pass operation

The use of PCA greatly reduces the number of trainable parameters for the DNN layer and improves model performance. An illustration of the DNN utilized in the model is shown in Figure 2.

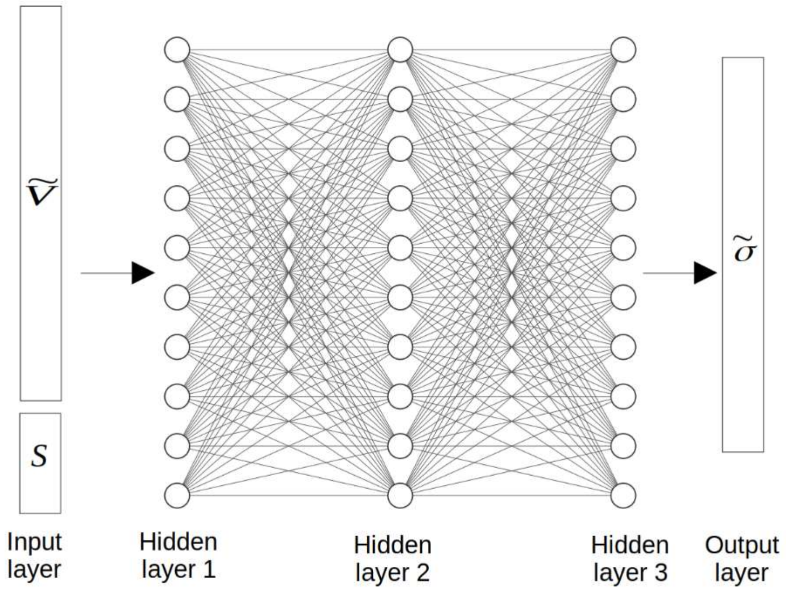

Figure 2: Fully connected neural network architecture

As proof of concept, our proposed method is trained on lattice code cross section data for the fuel pellet material in a typical light water reactor assembly. The NEWT model of quarter assembly is shown in Figure 3.

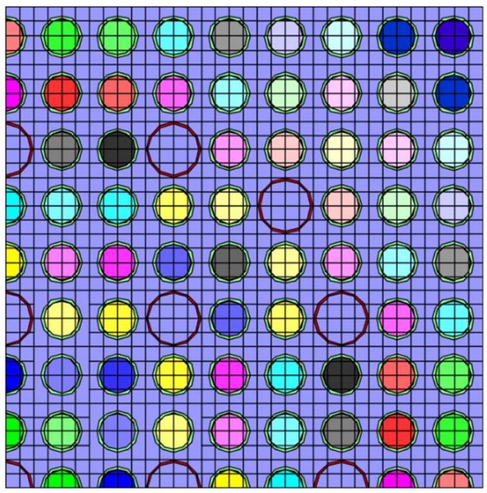

Figure 3: NEWT model of quarter 17x17 fuel assembly

The model is expected to be able to generate self shielded cross section libraries in a fraction of the time with acceptable accuracy compared to a reference self-shielding cross section processing code.

Communication

Ongoing work on this project was presented at the SKC Symposium 2022.

As part of our efforts of better understanding of how nodal data is generated and used, we have communicated with experts from Westinghouse, and with Erwin Müller and Petri Forslund Guimarães who have extensive experience in this area.

Development of a fully coupled electrochemical and micro mechanical SCC model

Research host:
KTH Royal Institute of Technology
Department of Engineering Mechanics

Doctoral Student:
Michal Sedlak Mosesson

Formal project start:
2020-11-01

Expected completion time:
2022-11-01

Main Supervisor:
Pål Efsing

Motivation

The study of Stress Corrosion Cracking has until the beginning of the 2000s mainly been associated with describing the in-the-field observations in terms of a large number of laboratory tests that address the impacts of various factors influencing the crack growth rates and cracking phenomenology. Examples of such factors include electrochemical potential, ECP, residual stresses, cold work and carbon content in the grain boundary zones understood to be sensitizated by precipitation of carbides in the grain boundaries rendering chromium mobility sluggish. Over the last 10 years, there has been a number of efforts to enhance the understanding of SCC by modelling the behaviour from both a mechanistic perspective (Shoji et al., Andresen et al., Couvant et al.) and from a local chemistry perspective (McDonald et al. Saario et al.). By combining these approaches an increased understanding of the interrelated phenomena can be achieved.

SKC has supported the work at the group of Solid Mechanics performed by Michal Sedlak with the support of Prof Bo Alfredsson and adj. Prof Pål Efsing. This work was presented and successfully defended in April 2020. The purpose of the continuations is to create a model for improved prediction of the Stress Corrosion Crack (SCC) growth rate in stainless steel in boiling and pressure water reactor environments. Primary areas of interest for this development are irradiation assisted SCC, influence of cold work on the SCC-susceptibility and SCC in replacement materials such as 316NG (low-Carbon containing stainless steel) and Alloy 690 (high Chromium containing Nickel-based material) which are considered a significant improvement to the previously utilized material but much still remains to be proven for an LTO-perspective.

Progress

The project is still ongoing under 2023 with external funding. Collaboration has been initiated with Dr Thierry Couvant from Électricité de France (EDF). Collaboration with Dr Elsiddig Elmukashfi from the University of Oxford is ongoing to develop SCC multi-physical models including hydrogen embrittlement.

The new cohesive element with moving Gauss points framework is finalized with creep and crystal plasticity. The XFEM (ghost node method) progress to create an arbitrary crack path has been developed and tested. The onset of oxide rupture due to slip planes by both an analytical solution and a finite element explicit simulation are finalized.

Methodology

In the moving Gauss points framework, oxidation module was transformed to an integration point formulation instead of node formulation, still including the duplex/mono -oxide or more complex. The oxide is now modelled with an analytical solution using Euler-Bernoulli beam theory and fracture mechanics. Creep constitutive law was used to obtain the plastic creep strain and stresses during the relaxation phase.

The next stage of the model was to replace the analytical formulation into a local FE formulation containing an oxide growth with slip-planes forming. Determining the damage process of the oxide. This could not be solved every iteration. The local solution was therefore pre-solved and mapped into the global solution.

The fracture mechanics module is enhanced with a crack path module, introducing cohesive elements in the grains with remeshing capabilities was shown to cumbersome and cost ineffective therefore the XFEM ghost node method has been introduced instead. The process introduced the possibility of branching and both inter- and transgranular stress corrosion cracking. The objective cause for the onset of branching is still ongoing research.

The electrochemical module is undergoing changes, the total energy in the model is considered with Gibbs free energy using the chemical potential. The influence from hydrogen embrittlement will also be implemented with Hydrogen enhanced plasticity (HELP) and for decohesion HEDE. The effect on the chromium mobility is also considered.

Communication

One is published. Three are being finalized. All articles are sent to high ranked international journals in their respective fields and published open-access.

Abstract was approved to the conference *21TH Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors* (August 6 -10).

Abstract was approved to the conference *15th International Conference on Fracture (ICF15) (June11-16)*.

Presented at conference 20TH Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors (June 17-21) 2022.

Publications

M. Sedlak Mosesson, B. Alfredsson and P. Efsing, Simulation of Slip-Oxidation Process by Mesh Adaptivity in a Cohesive Zone Framework , *Materials* 2021, *14*(13), 3509; https://doi.org/10.3390/ma14133509

Influence of Alloying and Neutron Flux on Irradiation Effects in Fuel Rods

Research host:
Chalmers University of Technology
Department of Physics

Doctoral Student:
David Mayweg

Formal project start:
2021-04-01

Expected completion time:
2023-03-31

Main Supervisor:
Mattias Thuvander

Motivation

The project aimed at improving the understanding of neutron irradiation effects in zirconium-based fuel cladding in a boiling water reactor (BWR) environment (see schematic in figure 1) with a focus on the microstructure evolution at the sub-µm scale. To this end we investigated two cladding tubes (Zicaloy-2 and Alloy 2 – a derivative of Zicaloy-2 with slightly higher Fe and Cr concentrations – both with heat treatment code LK3) at two fluence levels each (from a fueled segment: 38 dpa; and the plenum: 9 dpa). The samples have been used in Oskarshamn 3 from 2001-2007 for 2085 days. Although their composition differs only slightly (see Table 1) in Fe and Cr their hydrogen uptake is markedly different (Zicaloy-2: 200 ± 29 wt ppm; Alloy 2: 134 ± 9 wt ppm).

Table 1: Alloy composition of Zry-2 and Alloy 2 prior to irradiation.

Material	Fe (wt%)	Cr (wt %)	Ni (wt %)	Sn (wt%)	O (wt %)	C (wt ppm)	Si (wt ppm)
Zry-2 (LK3)	*0.18*	*0.13*	0.061	1.49	0.12	143	91
Alloy 2	*0.36*	*0.18*	0.063	1.31	0.12	120	90

This unique set of samples allows for investigation of important effects caused by the exposure to real reactor conditions (see schematic in figure 1). Three mechanisms are of interest in our investigations:

1. the waterside oxidation on the outer side of the cladding tubes,

2. the redistribution of Fe, Cr and Ni by neutron irradiation and their segregation to irradiation-induced defects (these are mainly dislocation loops that form when vacancies or interstitials rearrange; dislocation loops have a specific nature related to the crystal structure of the metal),

3. hydrogen uptake leading to formation of hydrides, which degrade the mechanical properties of the cladding tubes.

These mechanisms have been studied by various techniques used to analyse oxidation and precipitation kinetics (e.g., thermogravimetry), the microstructure (x-ray diffraction, transmission electron microscopy, etc.), composition (atom probe tomography, energy dispersive x-ray spectroscopy, etc.) and mechanical properties for a long time.

The question that connects these three mechanisms is in which manner the alloying element distribution influences oxidation and hydrogen uptake and in what way the oxidation process affects the hydrogen uptake. Since there has been a limited amount of research with respect to the nano-chemistry of fuel cladding that has been used in regular operation in an actual reactor, we try to contribute to filling this knowledge gap by employing atom probe tomography (APT).

An improved understanding of the effect that alloying elements exert on oxidation and hydride formation mechanisms can potentially aid in further optimizing alloy compositions for Zr-based fuel cladding. Such optimized alloys will allow for prolonged operation cycles and hence higher burn-up of the fuel leading to lower total fuel consumption and less down time (also with respect to reducing fuel failures). This in turn will reduce costs and the amount of highly radioactive waste.

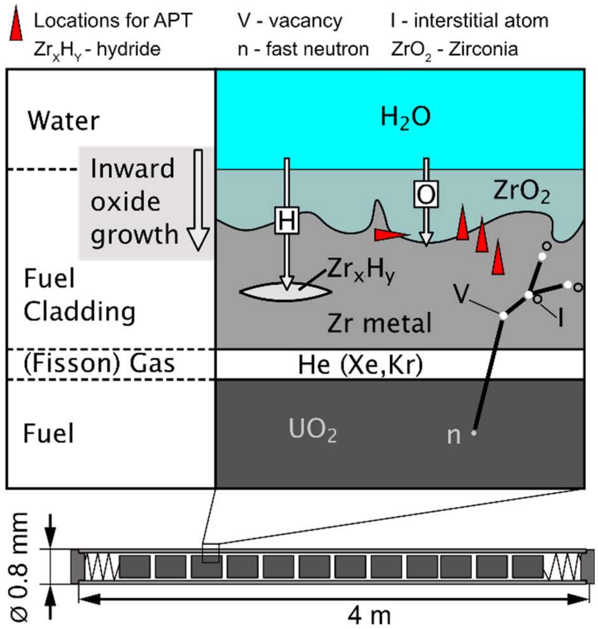

Figure 1: Schematic illustration of the arrangement of fuel pellets encapsulated in a cladding tube during reactor operation (bottom). At the top a detailed schematic of the water/fuel rod (Zr-alloy)/ fuel pellet (UO2) environment is depicted and processes of interest are illustrated: 1.

oxidation (formation of ZrO2) takes place by O transport across the oxide scale, 2. irradiation damage (vacancies and interstitial atoms) caused by fast neutrons, and 3., hydrogen uptake by the metal and leads to hydride formation. Red triangles mark positions that were targeted for specimen preparation for atom probe tomography (APT) measurements.

Methodology

The main tool employed in the present research was atom probe tomography (APT) in a combination with specimen preparation by focused ion beam (FIB) milling. APT is uniquely suitable to characterize microstructures in three dimensions with a spatial resolution of less than 1 nm and high chemical sensitivity for all elements. The technique relies on a process called field evaporation, which is used to consecutively remove atoms from a very sharp needle specimen (tip radius typically below 100 nm). These atoms are detected in ionic form by a position sensitive detector. From the mass-to-charge ratio the chemical identity of the ions can be inferred and a 3D reconstruction of the evaporated volume is created that enables chemical analysis on the near-atomic scale. Additionally, scanning and transmission electron microscopy (SEM/TEM) measurements were performed to supplement the findings with information on scales from several nm to a few µm.

Progress

The project started in April 2021. Through the first year already high-quality data could be acquired. Also notably was the progress in understanding sample preparation effects, specifically FIB-induced hydride formation and the suppression of this effect by conducting tip specimen fabrication by FIB milling at cryogenic conditions. In addition, we gained valuable insights in how to best apply atom probe analysis on these specific material, i.e., voltage pulsing had not been used much in analysing Zr alloys but turned out to work better than expected and it provides data of higher quality than laser pulsing.

Figure 2 shows two reconstructions of voltage pulsing APT runs from irradiated fuel cladding (38 dpa) in which neutron irradiation has caused the formation of a-type dislocation loops (aloops) that are known to be arranged in layers parallel to the basal plane of the HCP Zr metal. Both tips contain clusters of Fe, Ni and Cr arranged in such layers of 16-20 nm distance, which indicates that they decorate a-loops. The crystallographic information contained in these APT data aided in identifying the phases: (a) stems from a specimen prepared by FIB at – 150 °C and retained the initial α-Zr phase while (b) is an example δ-hydride formation, which took place during of FIB milling at room temperature.

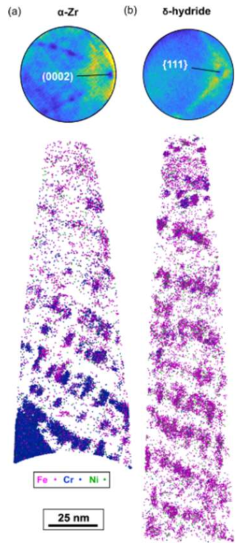

Figure 2: Reconstructions from voltage APT on irradiated fuel cladding (38 dpa). (a) shows an example of FIB sample preparation under cryogenic conditions retaining the α-Zr phase (HCP crystal structure). In contrast (b) shows the result of using FIB at room temperature, which leads to formation of δ-hydride.

The detector maps shown at the top reveal the characteristic poles that identify these two phases: (0002) proves the HCP α-Zr phase and (b) reveals a three-fold symmetry identifying the FCC structure of δ-hydride. Although cluster appearance does vary between these data sets, we did not find a noticeable effect by which the $\alpha \rightarrow \delta$ transformation altered clustering. Instead of layers being oriented parallel to (0002) planes in α-Zr they are oriented parallel to (111) planes in δ-hydride. Since these are both close packed planes the transformation is likely displacive in nature with hydrogen being the only mobile species. This means that the displacement (changing the stacking from ABABAB to ABCABC) that realizes the transformation is sufficiently small so it does not noticeably affect the cluster size, shape or composition, which after all vary strongly throughout the material. This variation is mainly dependent on the proximity of the probed volume to the reservoirs of Fe, Cr and Ni, i.e., the precipitates where these elements are located prior to irradiation (see Section 3.2)

The second year suffered from the temporary loss of experimental capabilities due to the decommissioning of the old Imago LEAP 3000X HR and the commissioning of the new local electrode atom probe instrument (Cameca LEAP 6000XR). This time was used for data analysis and advanced sample preparation so that the first experimental results from late 2022 are very promising and closed the gaps in the so far acquired data.

Oxide metal interfaces

Since the oxide (ZrO2) grows via inward O diffusion the region of interest is mainly the oxide metal interface and not the outer surface of the oxide. The oxide scales on the investigated cladding tubes were 10-12 µm thick making site-specific preparation difficult. In addition, APT measurements on the oxide metal interface are challenging since specimen fracture occurs in in many (most) cases. We had four successful runs from between 40 and 50 APT tips and (to our best knowledge) collected the first APT data sets capturing the full metal oxide interfaces that had grown under neutron irradiation inside a commercial reactor.

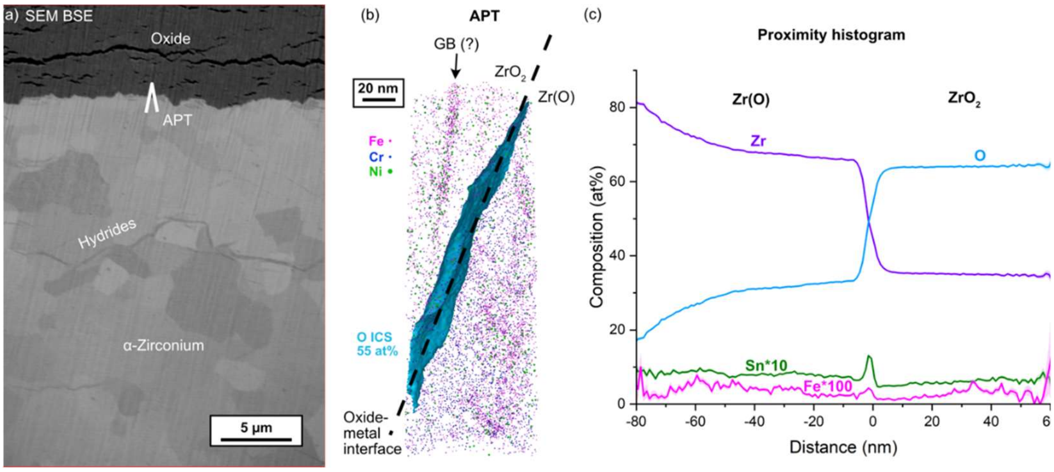

Figure 3: Oxide grown during reactor operation. Oxide metal interface captured (a) as SEM BSE micrograph and (b) by laser pulsing APT, (c) is a proximity histogram of the ICS in (b).

The SEM image (backscattered electron (BSE) signal) in figure 3 (a) provides an overview of the oxide metal interface. It shows cracking inside the oxide that is aligned parallel to the interface. Inside the bulk metal hydride platelets can be observed. These are mostly of intergranular type. Figure 3 (b) is a reconstruction of a successful laser pulsing[1] APT run capturing the oxide (ZrO2) and O-rich Zr metal. The interface is marked by a 55 at% O ICS; only Fe, Ni and Cr ions are displayed. The clustering is clearly less pronounced than seen in figure 2 and the layered arrangement is entirely absent. The feature marked by an arrow is likely a former metal grain boundary. Figure 3 (c) is a proximity histogram displaying the local composition around the interface. The "width" of the interface is an APT artifact, i.e., the transition from oxide to O saturated metal is not a gradient over approx. 10 nm but in reality, much sharper. Nevertheless, the profiles show the transition from ZrO2 to an approx. 30 nm wide plateau (Zr(O)sat with approx. 30 at%) followed by a decline in O fractions. In other data sets we have found similar composition profiles where the O fraction decreases to the nominal value of approx. 1 at%.

1 The oxide is an electrical insulator and therefore voltage pulsing APT cannot be applied.

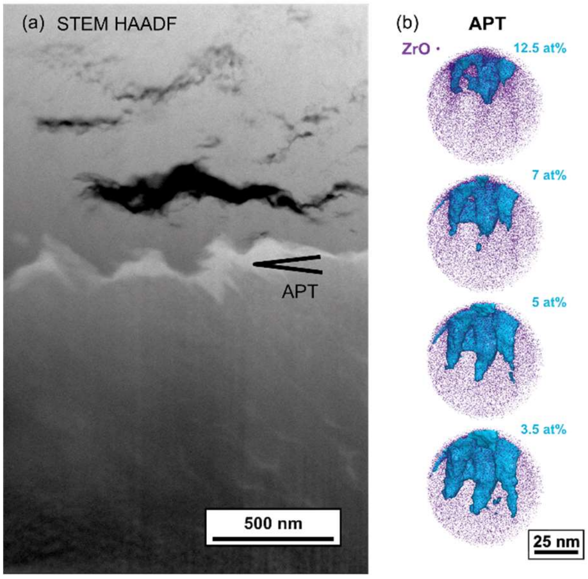

Figure 4: Detail of the oxide metal interface: (a) STEM-HAADF (b) APT illustrates the O ingress by a series of O isoconcentration surfaces; here, only ZrO ions are displayed.

The STEM-HAADF (mostly Z-contrast) image in figure 4 (a) shows the porous nature of the oxide with cracks and voids ranging from the µm range to a few nm. This porosity might be a (or the) cause for the notoriously low success rate in running APT (the stresses that are caused by the force exerted on the tips are concentrated at crack tips causing specimen fracture). In addition, there are regions of higher intensity observed at the interface that have a serrated ar "finger-like" morphology. The series of images from an APT reconstruction (horizontal lift-out like indicated in (a)) in figure 4 (b) provides strong evidence that these features are showing the oxygen ingress into the material: a series of isoconcentration surfaces (decreasing from 12.5 to 3.5 at% O) resembles the morphology seen in figure 4 (a). In autoclave corrosion, a ZrO "suboxide" with a stoichiometry of 1:1 has been observed in the pre-transition region (that is the initial oxide growth largely governed by diffusion, up to approx. 2 µm scale thickness). In later stages (when spalling and porosity change the kinetics) – the so-called post-transition or breakdown – this suboxide is not present in autoclave corroded samples. Our data did not provide evidence for the presence of a ZrO "suboxide" so the features observed in the STEM image are not a suboxide but O saturated or O enriched Zr. We conclude therefore that the oxidation behaviour under irradiation is not fundamentally different from the simulated environment in autoclave testing.

Dissolution of Secondary Phase Particles (SPPs) and clustering at irradiation induced defects

SPPs

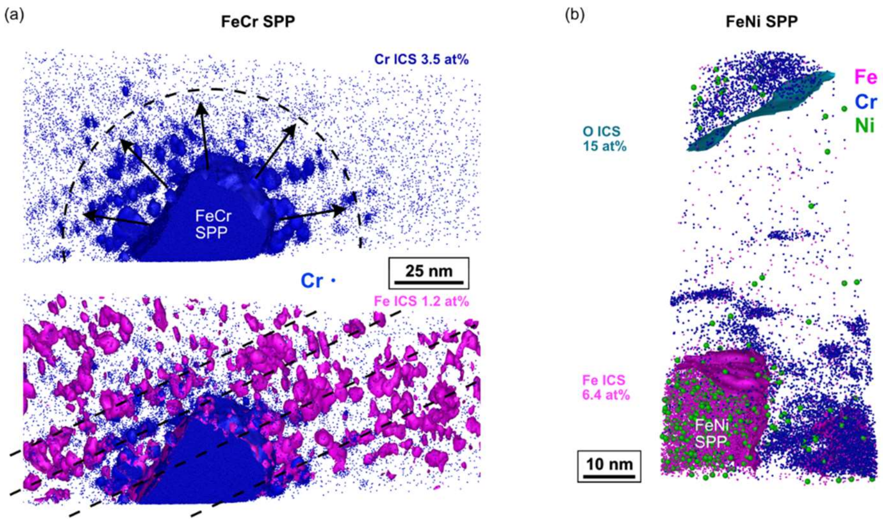

Figure 5: Reconstruction from laser pulsing APT runs showing SPPs (9 dpa materia). (a) FeCr-SPP: It is evident that the distribution of Cr is inhomogeneous due to slower Cr diffusion. (b) The SPP on the lower left is a FeNi-SPP.

Prior to irradiation sub µm-sized secondary phase particles (SPPs) of type FeCr and FeNi contain almost the entire fraction of these transition metal elements that are present in the alloys. However, as during irradiation SPPs are amorphized, temperatures are high (approx. 300 °C) and a high number of defects (manly vacancies and dislocation loops) are created Fe, Ni and Cr redistribute through the metal (albeit in a different manner). SPPs are hence the reservoirs from which clusters (as shown previously in Figure 2) are drawing their supply.

Figure 5 (a) provides an example of an FeCr-SPP (9 dpa): in the image at the top only Cr ions are depicted and the redistribution of Cr very inhomogeneous with a maximum distance of clusters from the SPP of around 50 nm (arrows and dashed line). This is in contrast with Fe (see image below), the distribution of which is shown by Fe ICSs. Fe is found through the entire volume; the layered structure again is readily apparent (see dashed lines). The reason for this difference is found in the differing diffusivities of Cr and Fe in the Zr-matrix.Figure 5 (b) shows an FeNi-SPP (highlighted by the Fe ICS) close to the oxide metal interface that does not show a significant redistribution of Fe and Ni comparable to the FeCr-SPP in (a). This might be due to its higher stability causing amorphization and dissolution only at higher damage levels.

Clustering around a-loops

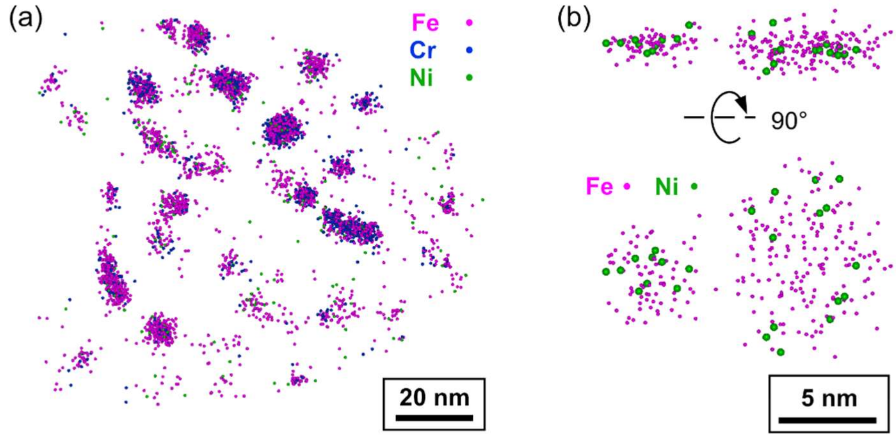

Figure 6: Results from voltage pulsing APT showing clustering around a-loops (38 dpa material): (a) one layer of FeCr-clusters (with little Ni) depicted plane view (i.e. along the [0002]-direction). (b) Two individual disk-shaped FeNi-clusters viewed edge-on and in plane view.

Figure 6 shows visualization of clusters around a-loops (size approx. 3-15 nm) on a finer scale than in the previous sections, i.e. these are sub-volumes extracted from full reconstructions to highlight small scale features. Like the SPPs, which are observed as FeCr and FeNi variants, the same is true for clusters. Figure 6 (a) depicts an individual layer of clusters that mainly contain Fe and Cr (with little Ni); these clusters have a spheroidal shape as has been observed in previous APT studies on irradiated Zr. Typical examples of FeNi clusters (with no Cr) are the two clusters displayed in (b), which are disc-shaped as the two views illustrate well. The ellipsoidal shape is in agreement with many TEM observations from the literature. Furthermore, in the larger disc-shaped cluster it can be observed that Ni ions are located away from the center. This might be related to differing segregation behaviour of Fe and Ni. To answer this question, it would be of great benefit to combine more detailed knowledge about the type of dislocation loop (vacancy or interstitial, can be in principle determined by TEM) and relate this to the nano-scale chemistry as shown here from APT data.

Clustering at c-loops

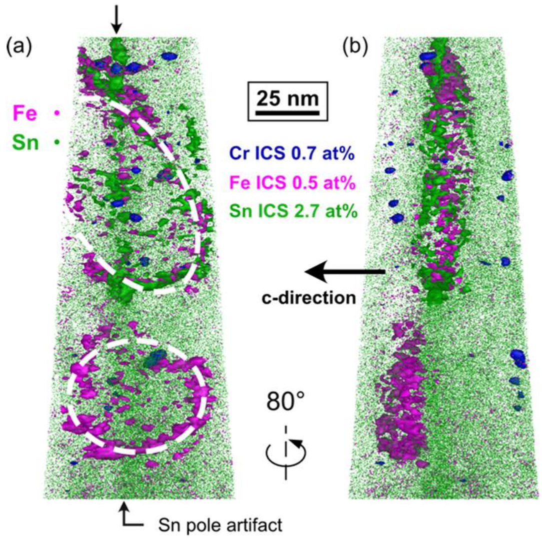

Figure 7: Segregation of Fe and Sn around c-loops in 38 dpa fuel cladding.

As shown in the previous section, a-type dislocation loops are arranged in layers parallel to the basal plane. At high damage levels however so-called c-loops form. They lie in the basal plane and are significantly larger. These loops are associated with the rod growth and the reason for this remains unknown. Figure 7(a) and (b) show two views an APT reconstruction with a relative rotation of 80° about its length axis to provide a plane and an edge-on view on the ellipsoidal features highlighted by Sn and Fe ICSs; based on the shape and the orientation these are assumed to be c-loops (see arrow indicating the c-direction). There has been very limited information about segregation behaviour around c-loops within the existing literature and further analysis with respect to potential formation mechanisms and the role of alloying elements should be pursued.

Outlook

Since quantitative analysis of clustering is not trivial and should ideally be performed using the same parameters for a large number of data sets we are working towards a pathway to make use of software that goes beyond what is currently commercially available. These efforts are ongoing work where the work flow has been established and the consistency of the analyses are currently evaluated.

Sample preparation work flows by focused ion beam milling at cryogenic temperatures should be used for analysis targeting hydrides in order to analyse the nano-scale chemistry that potentially can provide insight on hydride formation and growth mechanisms.

Communication

A joint presentation (together with Benjamin Jenkins and Megan Jones from the University of Oxford) on hydrogen analysis and clustering analysis by APT was given at the MIDAS (Mechanistic Understanding of Irradiation Damage in Fuel Assemblies) progress meeting that took place in September 2022 in Manchester.

The work on FIB-induced hydride formation and cluster analysis was presented at the SKC's annual symposium 2022.

On several occasions results were presented to industry partners (Westinghouse, Studsvik, OKG, Vattenfall).

We recently initiated a cooperation with Takashi Sawabe (CRIEPI, Central Research Institute of Electric Power Industry, Japan) to combine our APT results on SPPs from different BWR cladding materials and damage levels and publish a paper on those, working title:

D. Mayweg, T. Sawabe, M. Thuvander: *Redistribution of Fe, Cr and Ni in the vicinity of Secondary Phase Particles under different neutron fluences in Zircaloy-2 and derivative alloys*

Publications

One paper has been accepted for publication:

J. Eriksson, D. Mayweg, G. Sundell, H.-O. Andrén, M. Thuvander, Solute *Concentrations in the Matrix of Zirconium Alloys Studied by Atom Probe Tomography*, ASTM STP 1645 (2023).

One manuscript has been submitted to Journal of Nuclear Materials:

D. Mayweg, J. Eriksson, O. Bäcke, M. Thuvander: *Focused Ion Beam induced hydride formation does not affect Fe, Ni, Cr-clusters in irradiated Zircaloy-2*

Two further manuscripts are currently in preparation (titles are preliminary):

J. Eriksson, M. Kühbach, M. Rahm, M. Thuvander, D. Mayweg: *An atom probe tomography comparison of the nanoscale chemistry of two Zircaloy-2-type alloys with different iron and chromium content after boiling water reactor operation*

D. Mayweg, J. Eriksson, M. Sattari, H.-O. Andrén, M. Thuvander: *APT study of oxidization of fuel cladding in boiling water reactor operation.*