SKC

Swedish Centre for Nuclear Technology

ANNUAL REPORT 2021

This is SKC

SKC secures the availability of competence and helps solve complex problems - both of which are critical for the safe and sustainable operations of the nuclear power industry - by investing in nuclear research and education in Sweden.

The Swedish Centre for Nuclear Technology or Svenskt Kärntekniskt Centrum was originally founded in 1992 at KTH. Later, the centre was expanded to also include Uppsala University and Chalmers. The centre is a collaboration administrated at the School of Engineering Sciences at KTH.

Today, SKC connects the Swedish nuclear power industry and the three Swedish universities that provide the majority of education and research opportunities within disciplines of nuclear technology.

SKC funds education and research within these disciplines because it has direct benefits for the industry, the universities and for the students. The majority of the funding that SKC directs to the universities enables hiring new doctoral and post-doctoral researchers as well as attracting and retaining senior researchers and teaching staff.

SKC funds research and education cyclically; both the budget and operational plans are unique to each cycle. However, no matter the size of the budget, SKC's investment, rather than an expense.

Swedish Centre for Nuclear Technology

Swedish Centre for Nuclear Technology
Svenskt Kärntekniskt Centrum

106 91 Stockholm
Albanova Universitetscentrum
Roslagstullsbacken 21

www.swedishnuclear.se
skc@kth.se
+46 7612 5 7612

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A YEAR
IN REVIEW

Director's message

Dr. Merja Pukari
Director

Let me start with the obvious - 2021 was not the year of making up for missed opportunities to meet, work and share with each other face to face. Quite the opposite. This year had me, along with many others, nailed to my laptop's screen for days on end. I admit that some of SKC's activities planned for the year had to be put on a back burner. Working remotly is indeed a solution that works in a multidue of scenarios during hard times. But it cannot truly replace meeting one another in person. There is something magical about the planned and serendipitous physical meetings and the way they lead to building new relationships, sharing insights and piecing together bigger pictures from spontaneous ideas.

But I've come to see 2021 not as a year of missed opportunities, but as a springboard for coming years. I believe that our collective isolation has made us more humble, tolerant and cooperative. I notice that we are eager to work together instead of competing. We work towards a better future rather than put out daily fires. And I see how ideas and plans, big and small, have been maturing during this year of isolation - waiting to be put into practice.

In more ways than not, 2021 was a good year for SKC. All our project proposals were matched with suitable recruits. Doctoral and post-doctoral students at KTH, Chalmers and UU were making great strides in both studies and research and had the opportunity to present their work at SKC's annual symposium for the first time. The three universities partnering with SKC continued to develop and maintain high level coursework at all levels of education, which is crucial for preparing young talent for working with nuclear power. Even picking out the winners for the Sigvard Eklund's prize has (thankfully so) been difficult for the expert committees due to the high quality of nominated works.

Of course, new and resumed funding of nuclear research for future applications, from organisations other than SKC, has been a necessary boost for morale. And I believe that the substantial grants that have been awarded in 2021 are vital for driving the entire field forward. I imagine that this change in funding landscape will also influence the principles for SKC's next contracting period.

Finally, let me say that I am truly proud to be working with the students and teachers, experts and novices in this field. So much good work was done in 2021 while labouring in dress shirts and pyjama bottoms, from couches and behind kitchen tables. By boldly extrapolating I claim that 2022 can only get better!

See you soon,

Merja Pukari
Director

Organisation

Board

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

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

Peter Wedin
Head of R&D, Forsmarks Kraftgrupp AB

Lena Oliver
Fellow Engineer,
Westinghouse Electric Sweden AB

Henric Lidberg
R&D manager, Vattenfall AB

Jan Karjalainen
Head of Engineering,
Oskarshamns Kraftgrupp AB

Per Seltborg
Head of R&D, Strålsäkerhetsmyndigheten

Anna Delin
Deputy head of school
KTH Royal Institute of Technology

Thomas Nilsson
Head of department
Chalmers University of Technology

Gabriella Andersson
Section dean Physics,
Uppsala University

Operations

The director of SKC is responsbile for the organisation's operations and answers to the Board.

Merja Pukari
Director

Advisory Council

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

Gustaf Löwenhielm
Chairman of the Advisory Councril

Mattias Olsson
Radiochemistry expert,
Forsmarks Kraftgrupp AB

Georg Lagerström
Reactor safety engineer,
Oskarshamns Kraftgrupp AB

Björn Forssgren
Senior Expert, Ringhals AB

Anna Alvestav
Reactor technology analyst,
Strålsäkerhetsmyndigheten

Ingemar Jansson
Principal Engineer,
Westinghouse Electric Sweden AB

Contract period 2020-2023

SKC was founded with the intention to stimulate and develop education at all higher education levels and to promote research collaboration between universities, governmental authorities and the industry within strategic and cross-functional disciplines of nuclear technology. In addition, SKC aims to help develop the skillset of young professionals and thereby increase the number of potential candidates to be recruited by the industry, the governmental authorities or the academia. Together, all parties that participate in the collaboration of SKC see to that these goals shall be met even in the period of 2020 to 2023.

On the 1st of January 2020, SKC collaboration entered into a new four-year contract period between eight partners. After a brief hiatus, SKC was glad to welcome back the Swedish Radiation Safety Authority as one of the financiers. According to the agreement, five partners will fund SKC and the three partner universities will benefit from said funding during the period of 2020 to 2023.

Together, the five financiers will contribute 52 million SEK to SKC's budget over the course of four years. In doing so, the Swedish Radiation Safety Authority, Westinghouse Electric Sweden AB, and the three Swedish nuclear power plants Oskarshamns Kraftgrupp AB, and the Vattenfall majority-owned Forsmarks Kraftgrupp AB and Ringhals AB confirm that they share a vision on the importance of funding academic activities and that such funded is provided continuously over a relatively long period of time.

The majority of SKC's budget 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 recognise 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 the 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 the 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 recognised research groups within disciplines that are vital for the safe and sustainable nuclear operations in Sweden.
- SKC will fund research and education that is of value to its 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

Financial results

2021 payments to SKC from financiers	**12,000,000**
Strålsäkerhetsmyndigheten	4,000,000
Forsmarks Kraftgrupp AB	2,829,904
Ringhals AB	2,089,082
Oskarshamns Kraftgrupp AB	1,581,014
Westinghouse Electric Sweden AB	1,500,000
2020 expenditures by SKC	**11,810,285**
Project Support	7,000,000
Project 2019-1 (1)	-
Project 2019-2	1,000,000
Project 2019-4	1,000,000
Project 2019-7	1,000,000
Project 2019-12	1,000,000
Project 2020-2	1,000,000
Project 2020-12	1,000,000
Project 2020-18 (2)	-
Project 2020-19	1,000,000
Base Funding	4,000,000
Chalmers	1,333,333
KTH	1,333,334
UU	1,333,333
Centre administration	810,285
Balance 2021/2022	**5,322,687**
Reserved for project support (3)	4,250,000
Unallocated resources	1,072,687

(1) Project is financed directly by SSM
(2) Formal project start in 2022, no financing requested from SKC during 2021.
(3) Reserves for continued financing of projects according to the payout scheme, quarterly during 2 (post-doc) or 4 (PhD) years from the formal project start. .

Research project portfolio 2020-2023

SKC ID	PROJECT TITLE	PROJECT MANAGER	HOST	LENGTH
2019-1	Study of core stability during load follow with ROM methods	Christophe Demaziére	Chalmers	4 y
2019-2	Influence of aging and radiation on ductile failure in the DBT temperature region	Jonas Faleskog	KTH	4 y
2019-4	Corrosion fatigue in PWR environment at cyclic thermal and mechanical loads	Pål Efsing	KTH	4 y
2019-7	SEMRA: Steam explosion modelling and Risk Analysis for Light Water Reactors	Dmitry Grishchenko	KTH	4 y
2019-12	Calibration of fuel performance codes – treating model inadequacies, nuisance parameters, and unrecognized systematic uncertainties	Henrik Sjöstrand	UU	4 y
2020-2	Development of a fully coupled electrochemical and micro mechanical SCC model	Michal Sedlak	KTH	2 y
2020-12	Influence of Alloying and Neutron Flux on Irradiation Effects in Fuel Rods	Mattias Thuvander	Chalmers	2 y
2020-18	Impact of Radiation Chemistry on surface processes in LWRs	Mats Jonsson	KTH	4 y
2020-19	Application of Artificial Neural Networks in Reactor Physics Calculations	Jan Dufek	KTH	4 y

Funding 2021

Base funding

SKC's programme for this contract period foresees that a total of 4 MSEK per year will be allocated to the three partnering universities, with intention to advnance and promote education within nuclear engineering and technology. SKC is not overly restrictive on how the base funding ought to be utilized by the universities. SKC presumes that the distinguished academicians applying for base funding have full understanding of the overall goals of SKC and intend to put the funds to best possible use.

Base funding has historically been used to pay out salaries and thereby retaining existing teaching staff or attracting new research and teaching talents. The funding is also used to develop in-classroom or digital courses, to provide practical lab-work experiences nationally or internationally, to compile study materials, or to guarantee that universities have in-kind contribution available for applying for funding from larger research funding platforms. All and each of these applications for the base funding are not only acceptable but prioritised by SKC. A specification on the appropriate utilisation of the base funding has been made during 2021, underlying that the funds should not be used for operation and maintenance costs of multipurpose infrastructure at respective universities.

Historically, SKC's base funding has proven to be a relevant leg-up for partner universities, amplifying greatly their capacity to develop and maintain high quality nuclear technology education and key staff. Indubitably, allocating base funding to universities will continue to serve that purpose even during this contracting period.

The universities were invited to submit an application for base funding, declaring the intentions for how the base funding would be used, what the long-term effect of such application is expected to be, and specifiying the costs. Universities proposed unanimously to distribute the base funding equally, given that the total budget did not merit a competition. The funding was also distributed euqally in 2020, on the recommendation of the Council. The utilization of the base funding during 2021 is described in the next section. The Advisory Council has evaluated universities' reports and concluded that the base funding has been utilized in accordance with SKC's principles and guidelines.

Project funding

Project funding decisions, to the full extent of the budget, were made in 2020. In 2021, SKC has been financing these projects through quarterly payments. Due to the time-consuming recruiting process, several projects were not formally started until 2021. Therefore, payments for several projects were also initated first in 2021.

SKC will be financin all projects in full despite projects running past 2023. This applies even in the event of SKC not entering into a new contracting period in 2024.

Symposium 2021

As customary, SKC held its annual symposium where the academia and the industry are brought together to discuss research, education and future opportunities in nuclear engineering and technology. Similarly to the year before, the two-day symposium had unfortunately to be held digitally, at the end of October. The symposium had just over 80 registered and several (very welcome) unregistered participants over these two days.

Much of the first year of this contract period was spent by supervisors at the universities on recruiting researchers and kicking the projects in gear. And so, the symposium in 2021 gave the opportunity for sharing the early progress of all SKC-funded projects for the first time. The high quality of presentations made by doctoral and post-doctoral students at the symposium was particularly noteworthy.

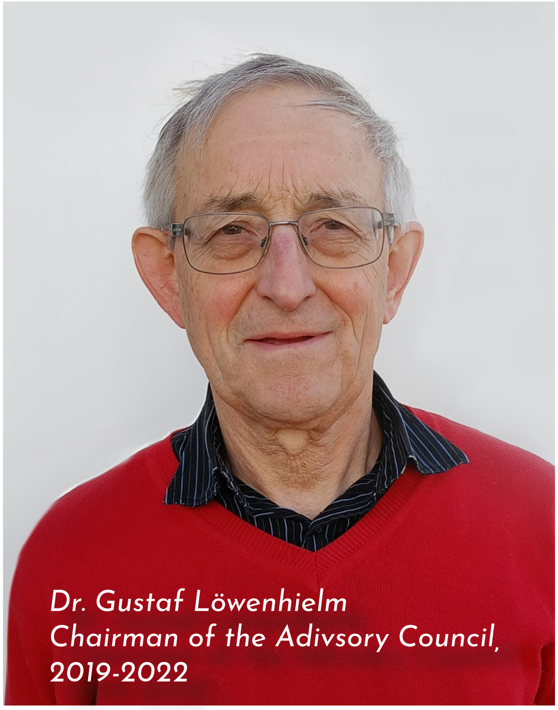
SKC also had the pleasure of announcing the winners of Sigvard Eklund's prize for the best doctoral and master's thesis at the symposium, both of whom gave an illuminating presentation over their theses. The prize for best bachelor's thesis could unfortunately not be awarded due to no applictions having been sent in.

The symposium was rounded up by inviting representatives from Chalmers, KTH and UU to share their perspectives on improved methods for teaching and research and the funding of it. Many of the thoughts shared during that session will also be considered in the preparation for SKC's next contract period.

Speakers

Desirée Comstedt (Vattenfall), Kristoffer Tofvesson Pedersen (Chalmers), Shuyue Wang (KTH), Mustafa Subasic (KTH), Ibrahim Batayneh (KTH), Gustav Robertsson (UU), Michal Sedlak Mosesson (KTH), David Mayweg (Chalmers), Yi Meng Chan (KTH), Mats Jonsson (KTH), Emma Ekberg Berry (UU/FKA), Magnus Boåsen (KTH), Kyle Johnson (Studsvik), Christophe Demaziére (Chalmers), Janne Wallenius (KTH), Stephan Pomp (UU), Christian Ekberg (Chalmers), Merja Pukari (SKC)

Gustaf Löwenhielm passes the baton



Dr. Gustaf Löwenhielm
Chairman of the Adivsory Council, 2019-2022

SKC's Advisory council has been chaired by Gustaf Löwenhielm, SSM's former head of research, since May 2019. As of 2022, Gustaf is passing the responsibilities over to another capable pair of hands. As his last contribution to the organization, SKC has asked Gustaf to share his thoughts on the role he has had and on nuclear power in general.

What does an Advisory Council do?

SKC is directed by the Board that consists of representatives from the financiers and universities. The Advisory Council - as the name indicates - is an advisory body to the Board. It consists of the Chair, experts from the financiers and one representative for all three universities.

The Advisory Council has had three distinct phases of operation since I started working with SKC. The first phase and the Council's first challenge was to prepare a strategic plan for SKC's contract period 2020-2023. In fact, SSM's decision to rejoin SKC after some years' break was vital for SKC to continue. In preparing for the contract period, we proposed to extend the period from three to four years, negotiated the total budget, considered the ratios of base funding with respect to project funding and administration but also which research areas should be included in the program. Other aspects, such as collaboration between universities and with the industry, also became central in the discussions. And so, SKC's strategic plan was approved in 2019 and the first call for research projects was announced.

The most challenging tasks for the Advisory Council came in what I call the second phase, i.e. identifying which research projects SKC should finance. The competition between applications from both calls in 2019 and 2020 was tough and choosing the final 9 projects was not an easy task. Luckily, the Advisory Council consists of experts who are pragmatic, systematic and have the capability to compromise when necessary. Aside from project funding, the appropriate distribution of base funding also had to be decided upon. But compared to project funding, this is a much simpler task.

The workload during the third phase, as of 2021, has been considerably lower since the Advisory Council has mainly had to study the annual applications for base funding and later revise whether the funding was spent towards realizing SKC's overall goal of developing nuclear competence in Sweden.

How come you chose to accpet this responsibility, while retired none the less?

Good question. I was 73 years old when I accepted the role of the Chair. And although I had retired, I was still consulting at a comfortable rate for myself, no more than a hundred or so working hours a year. More importantly, though, I have always been interested in education, training and research. I had previously represented both SKI and SSM in SKC's Board. SKC was a very important instrument of retaining nuclear education and research in Sweden when I joined SKI in 1999. But most importantly - it was a matter of survival, since universities made it clear that the professor chairs within nuclear technology after retirement would not be reinstalled, unless the industry and the regulatory body started to support this competence.

What do you see in the future for SKC?

I think that it is very important that SKC's Board, prior to the next contract period, develops a long-term strategic plan for sustainably maintaining and developing competence in the various areas of nuclear engineering and technology. Sweden has recently experienced massive changes in SKC's areas of interest. In 2019, both the Research Council and the Swedish Foundation for Strategic Research decided to invest in advanced reactor technologies. More recently, the Swedish Energy Agency has decided to support building a research reactor at Oskarshamn's nuclear site for investigating the safety concepts of small modular reactors (SMR). Of course, this reactor would be heated electrically, with mock-up fuel. But I think that one has to analyze what the consequences of these changes are for the "nuclear" universities in Sweden.

SSM has also recently submitted an analysis to the government regarding how nuclear safety competence in Sweden will be maintained. In the future, should we look for Finland's approach to research (SAFIR) as inspiration? It's clear to me that there are many dimensions to investigate when developing the program for the next contract period. It will no longer be my task to figure out how SKC should strategize, but I believe it is important for the organization to keep its focus and make sure that there is a vital education and research environment at KTH, Chalmers and UU. Conditions for achieving that are there.

And nuclear power in Sweden, what do you predict for its future?

This is definitely not an easy question to answer to. And it is a question that is very political. However, it is interesting that heavy-profile research organizations such as the Research Council and Swedish Foundation for Strategic Research are investing in advanced reactors and that the Swedish Energy Agency has given 99 MSEK for building a research reactor. Perhaps, this research will lead to reactors of this type will be built in Sweden but it also requires for the law restricting the number of reactors in operation in Sweden to be changed. For now, 10 reactors on 3 existing sites are allowed and that does not align with the idea of SMRs of ca 100 MW each.

What now, what awaits you post-SKC?

SKC was my last nuclear assignment. I have worked with nuclear power for over 50 years, since I started my PhD at the institute of reactor physics. Even though the work with SKC hasn't been a full-time job, it still required some effort. I will also spend less time in other associations, where I have been active, to be able to spend more time with family. I have a very close relationship with my 2 kids and 7 grandkids that all live close to us. But I have no intention of slowing down. I am currently learning Spanish, even if the progress is somewhat slow, in the hopes of achieving one of my long- time dreams of going to Machu Picchu.

Dr. Sigvard Eklund
19 June 1911 - 30 January 2000

Sigvard Eklund's prize

Sigvard Eklund's price has been established by SKC to recognise and reward outstanding academic work by bachelor's, master's and doctoral students at the three partner universities.

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

Sigvard Eklund's price has been established by SKC to recognise and reward outstanding academic work by bachelor's, master's and doctoral students at the three partner universities. Once a year, the supervisors or teachers can nominate one more theses to be considered as the best of its academic level of the year. An independent jury will consider the motivation for nomination, the scientific merit and the overall quality of all the submitted theses in deciding to whom the award should be given.

Every year, one young talent per academic level can be awarded the prize. In addition to the honour and recognition, the winner is rewarded with SEK 50 000 for the best doctoral thesis, SEK 35 000 for the best master's thesis and SEK 25 000 for the best bachelor's thesis.

	Doctoral thesis	Master's thesis	Bachelor's thesis
2021	Magnus Boåsen, KTH	Emma Ekberg Berry, UU	
2020	Kristina Lindgren, Chalmers	Govatsa Acharya, KTH Fredrik Dehlin, KTH	
2019	Mattia Bergagio, KTH		Daniel Fransén, KTH
2018	Klas Jareteg, Chalmers	Anna Benarosch, KTH	Daniel Karlsson, KTH Amanda Rasmussen, KTH
2017	Zsolt Elter, Chalmers	Mimmi Bäck, KTH	
2016	Luca Messina, KTH	Alicia Marie Raftery, KTH	Fredrik Höök UU Adam Bruce, UU
2015	Cheuk Wah Lau, Chalmers Klara Insulander Björk, Chalmers	Giulio Imbalzano, KTH	Johan Larsson, UU
2014	Victor Dykin, Chalmers	Kaur Tuttelberg, KTH	
2013	Cláudio Miguel Lousada Patrício, KTH	Claudio Torregrosa Martin, KTH	Johan Erlandsson, UU Patrik Berg, UU
2012	Anders Puranen, KTH	Antoine Claisse, KTH	Azur Bajramovic, UU
2011	Chi Thanh Tran, KTH	Martin Lundgren, Chalmers	Katja Göller, UU
2010	Andreas Enqvist, Chalmers	Paul Bramson, KTH	
2009	Åsa Henning, LU	Petty Bernitt Cartemo, Chalmers	
2008	Olivia Roth, KTH	Andreas Carlson, KTH	
2007	Carl Sunde, Chalmers		
2006	Marcus Eriksson, KTH	Simon Walve, KTH	
2005	Staffan Jacobsson Svärd, UU	Henrik Lindgren, KTH	
2004	Christophe Demazière, Chalmers	Dereje Shiferaw, KTH	

*M*agnus Boåsen *w*as a*w*arded Sig*v*ard Eklund's prize for the best doctoral thesis 2021

The exemplary work conducted by Magnus Boåsen was recognized by SKC in Octber 2021 by awarding Magnus with Sigvard Eklund's prize for the best doctoral thesis of the year. The thesis, Modeling of structural integrity of aged low alloy steels using non-local mechanics, was written at KTH under the supervision of Pål Efsing.

An indepentent international committe responsible for selecting this year' winner pointed out that World-wide, more and more nuclear power plants enter life-time extension to continue to produce CO_2 free electricity at a competitive price. Nuclear safety is always leading and an accurate assessment of the status of the integrity of nuclear power plant components is key to this. A good understanding of the ageing of steels, both due to irradiation effects and thermal ageing, is extremely important to judge the status of nuclear power plants.

The committee found that the thesis presented theoretical and numerical models which had been developed to better describe material properties of aged low alloy steels, and for understanding the mechanisms of thermal ageing of these steels better. The author shows an excellent understanding of the topic, and an equally good set of skills to perform the work. The research has resulted in a good thesis made up of a related set of theoretical, numerical, and experimental investigations. Furthermore, the academic papers that made up a part of the thesis were a pure pleasure to read.

Dr. Magnus Boåsen, 2021 winner of Sigvard Eklund's prize for the best doctoral thesis

Magnus, how come you become interested in this field?

Solid mechanics and especially fracture mechanics in conjunction with ageing of nuclear materials was not my first choice of field of study.

During my bachelor level studies I was highly motivated to learn mechanical design engineering with an intent of going towards the vehicle industry. However, I always came to the question of whether or not something

I was thinking about would work and more specifically if it would hold up under load. This lead me to specialize in solid mechanics after my bachelor degree, a field that also fuelled my interest for materials science. When the opportunity to enroll as a PhD-student within the field of nuclear materials came, I was naturally interested.

How did your work develop over time?

The purpose of the project was always to study ageing effects in low alloy steels used in nuclear applications. In the beginning of the project, my supervisor and I were inspired to look at ageing due to both neutron irradiation and thermal ageing. As the project progressed it became more inclined towards thermal ageing due to availability of material for experimental investigation and ease of handling non-irradiated material.

The research questions related to my project were initially sown as seeds by my supervisor and developed together with me, and towards the end of my period as a PhD-student they were developed in their entirety by me and approved by my supervisor.

Did you come accross any hurdles during this journey?

The largest difficulty that I met during my project was related to the uncertainty of material availibility for experimental investigations.

Aside from becomin an expert in the field, did you gain any other skill-sets doing this work?

In my project, I was quite independent in my day-to-day work. Later on in the project, this also grew to encompass the planning of the project so that I, to a large extent, planned and managed the project. This has given me some very valuable insights into planning, managing and executing research projects.

And now what - what will you be working with next?

As of early 2022 I will be working as a solid mechanics and fracture mechanics expert at a Swedish steel company. I am hoping to develop there as an engineer and to gain further insight into the connections of fracture mechanics and its connection to materials science and how those fields can interconnect to create better steels and metallic materials in general.

Modeling of structural integrity of aged low alloy steels using non-local mechanics

Master's thesis written by
Magnus Boåsen

supervised by
Pål Efsing

KTH, School of Engineering Sciences (SCI), Engineering Mechanics, Vehicle Engineering and Solid Mechanics, Solid Mechanics.

Abstract

Ageing of low alloy steels affects the structural integrity assessment as it most commonly causes embrittlement and a hardening of the material. This is due to theevolution of the microstructure during operation in the specific application. In nuclear applications, the most common causes of ageing of low alloy steels areirradiation and thermal ageing. Embrittlement in this type of materials is generally divided into hardening and non-hardening embrittlement. The formation of clusters or precipitates of solute atoms typically cause the former, and the weakening of grain boundaries generally cause the latter. This thesis is devoted to thedevelopment of models that can be used to describe the material properties of aged low alloy steels in terms of plastic properties and fracture toughness, and to thestudy of the effects of thermal ageing on the mechanical properties of a low alloy steel.

In Paper I, a strain gradient plasticity framework is applied in order to capture length scale effects. The constitutive length scale is assumed to be related to the dislocation mean free path and the changes it undergoes during plastic deformation. Several evolution laws for the length scale were developed and implemented in a FEM-code. This was used to solve a test problem in order to probe the effects of the length scale evolution. All length scale evolution laws considered in this study results in a decreasing length scale, which causes an overall softening in cases where the strain gradient dominates the solution. The results are in tentative agreement with phenomena of strain localization that occurs in highly irradiated materials.

In Paper II, a scalar stress measure for cleavage fracture is developed and generalized, here called the effective normal stress measure. This is used in a nonlocal weakest link model which is applied to two datasets from literature in order to study the effects of the effective normal stress measure, as well as to experiments considering four-point bending of specimens containing a semi-elliptical surface crack. The model is shown to reproduce the failure probability of all considered datasets, i.e. well capable of transferring toughness information between different geometries.

In Paper III, a thermally aged weld from the Ringhals nuclear power plant is studied experimentally and compared to a reference material using fracture toughness testing. The main objective of the study was to investigate the effect of thermal ageing on the cleavage or brittle fracture toughness, with a specific focus on the effect of crack tip constraint. The testing showed that thermal ageing had enabled brittle fracture initiation from grain boundaries, resulting in a bimodal toughness distribution due to multiple mechanisms for brittle fracture initiation.

In Paper IV, the non-local weakest link model in Paper II is further developed to account for multiple mechanism brittle fracture. The model is developed for brittle fracture initiation from grain boundaries and second phase particles. The grain boundary mechanism is inferred from simulations of polycrystalline aggregates using crystal plasticity. When applied to the experimental results of Paper III, the model is able to describe the fracture toughness distribution with a remarkable accuracy

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Emma Ekberg Berry was awarded Sigvard Eklund's prize for the best master's thesis 2021

In October 2021, SKC recognized the outstanding work of Emma Ekberg Berry with Sigvard Eklund's prize for the best master's thesis of the year. Emma's thesis, Analysis of wear in control rod drives at Forsmark´s nuclear power plant, was written at Uppsala University, the work was done in close collaboration with Forsmark Kraftgrupp.

An independent committe admitted that selecting the winning work from those submitted was challenging due to the overall high level of the theses. However, Emma's thesis was unanimously identified as the best.

The thesis is, in the opinion of the committee, an excellent example of historical data analyzed in a new manner to find optimized maintenance schemes for improved continued operations. The work is a valuable contribution to the development of so-called condition-based maintenance, which is a developing field of uttermost importance for competitive and long-term operations of existing nuclear power plants. The committee also states that the thesis is very well written and is a good example of fresh engineering skills and analytics applied to real industrial challenges.

Emma Ekberg Berry, 2021 winner of Sigvard Eklund's prize for the best maste's thesis.

Emma, what made you interested in this particular field?

I started to get interested in the nuclear field when I studied for my master's degree at Uppsala university, specializing in energy systems. One of the fields which I considered most interesting was nuclear power. I therefore chose to take several courses in nuclear power during my master's studies and in my last semester I got the chance to do my master's thesis work at Forsmark nuclear power plant.

The one thing which I believe made me most interested in the nuclear field is the huge amount of energy which can be produced due to nuclear power, and the great impact which this energy source has on the power system today. My great interest in the nuclear field made me interested in working at Forsmark nuclear power plant, where I am currently working today.

How did your work develop over time?

In the beginning of writing my thesis, the work mainly consisted of literature studies and historical research of the maintenance of the control rod drives which had been implemented at Forsmark one and two throughout the previous years. Thereafter I started looking deeper into the potential of condition-based maintenance for the control rod drives, to investigate if there was any chance to improve the current maintenance of the control rod drives at Forsmark.

What difficulties did you encounter during the project?

In the project I encountered some difficulties mainly regarding the gathering of historical information of the maintenance of the control rod drives, specially of the information from the early years of the reactors which were more difficult to find.

What do you think are the most valuable competences and skill-sets you gained by doing this work?

By doing this work I believe the most valuable competence I gained was the knowledge of the great potential and possibilities of development that comes with condition-based maintenance. Also I learned what possibilities this might have for the maintenance in the nuclear industry in the future, not only for the control rod drives, but for the whole industry.

In the future I would like to keep working in the nuclear sector, as I do today. In my work at Forsmark nuclear power plant I get the advantage of combining the maintenance and the engineering work at the nuclear power plant, which gives me the perfect opportunity to get a bigger perspective of the work at the power plant. My future career plans are to develop my experiences in the nuclear sector and I look forward to being in a position where I will be able to have an impact and to contribute to the nuclear industry in the future.

Analysis of wear in control rod drives at Forsmark´s nuclear power plant

Master's thesis written by
Emma Ekberg Berry

supervised and reviewed by
Caroline Bohlin och Mikael Seppälä
Mattias Lantz

Faculty of Science and Technology
Uppsala University

UPPSALA
UNIVERSITET

Abstract

This master thesis is done within the Energy Systems Engineering program at Uppsala University and performed for Forsmarks Kraftgrupp, Vattenfall. Forsmark is a nuclear power plant that consists of three BWR units and is an important component for the Swedish power system. An important part of the system inside the nuclear power plant is the control rod drives, which controls the motion of the control rods inside the core to adjust the power production of the plant. Currrently the wear of the control rod drives has increased thus the economic costs due to the wear increases.

The aim of this thesis is to analyse the current wear of the control rod drives at Forsmark 1 and Forsmark 2. Moreover the thesis presents possible reasons for the origin of the wear together with derived methods for possible identifications of wear in the control rod drives at an early stage, which is analysed in the simulation program MATLAB. Furthermore the report presents a new maintenance plan for the control rod drives at Forsmark 1 and Forsmark 2 based on the evaluation of the current wear together with knowledgement from other nuclear power plants regarding an optimal maintenance plan for the control rod drives.

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BASE FUNDING

Chalmers

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, 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).

The SKC base funding amounted to 1.33 MSEK for 2021 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.**

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 and 1 Post-Doc researcher, 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 – see below).
- 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).
- Post-Doc researcher Antonios Mylonakis (neutron noise modelling and unfolding in commercial nuclear reactors, as part of the CORTEX project – see below).

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).

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

Research-wise, the Division is heavily involved in various European collaborations and projects: the Horizon 2020 CORTEX project (also led by the Division) on core monitoring and diagnostics, the Horizon 2020 ESFR-SMART project on sodium-cooled reactors, the Eurostars-2/Vinnova SEALION project on molten-salt reactors. The CORTEX and SEALION projects were successfully completed in 2021.

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. 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.

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. One student from this course, Erik Andersson, did his MSc thesis project on the numerical modelling of neutron noise in Molten Salt Reactors, with his thesis titled "Static and dynamic modelling of 1D heterogeneous Molten Salt Reactors".

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

The Division was also heavily involved in lecturing in various specialized schools and webinars in 2021, such as: the seminar on "Multiphysics Modelling of Advanced Nuclear Reactors" held online on March 17, 2021 (organized by the IAEA), the Spring School on Sodium Cooled Fast Reactors held online on March 29-31, 2021 (organized as part of the ESFR-SMART project), the VI International Summer School on Engineering Computing in Nuclear Technology held online on June 28-July 9, 2021 (organized by MEPhI and the Western Norway University of Applied Sciences), and the Frederic Joliot/Otto Hahn Summer School on high-fidelity modelling and simulation of nuclear reactors held online on August 25-September 3, 2021 (organized by CEA and KIT).

The SKC funding was also used to prepare a project proposal as Coordinator to the European Commission for a follow-up of CORTEX, as well as two other project proposals as participant. Moreover, the group participated to a project proposal on a competence centre submitted to the Swedish Energy Agency, together with other groups at Chalmers, other Swedish universities, and the Swedish nuclear industry.

Division of Microstructure Physics

The funding has mainly been used for the salary of **Assoc. Prof. Mattias Thuvander** and **Senior Professor Hans-Olof Andrén.**

Assic. Prof. Thuvander is supervisor for two PhD students and two post-docs working on nuclear materials, and has been taking part in meetings and seminars of SAINT, SKC and SSM.

The post-doc Kristina Lindgren is partly working on aging of reactor pressure vessel steel welds, continuing an SKC-project within the MåBil project, now partly financed by NKS. The project is a collaboration with KTH and VTT. Lindgren is also taking part in the EU-project ENTENTE, focussing on irradiation effects in steels. She further works on corrosion of FeCrAl for liquid lead Gen-IV applications, together with Prof. Szakalos (KTH), and projects on irradiated stainless steel with Studsvik and EPRI.

PhD-student Andrea Fazi is working on coatings on Zr-alloy cladding tubes, where Thuvander is leading an SSF project on ATF, involving Chalmers, KTH and UU. PhD-student Johan Eriksson is working on irradiation effects on traditional cladding tubes, a project funded by Westinghouse, Vattenfall, OKG and EPRI, which is also a part of MUZIC-3. He is partly supervised by Andrén. Since April 2021, the post-doc David Mayweg, financed by SKC, is working together with Eriksson, with focus on cladding tubes irradiated in O3.

Regarding teaching, some nuclear materials issues are included in the course Physics of Materials. Moreover, the group participated to a project proposal on a competence centre submitted to the Swedish Energy Agency, together with other groups at Chalmers, other Swedish universities, and the Swedish nuclear industry.

Nuclear Chemistry group

Nuclear Chemistry has several active courses (Nuclear Chemistry I and II, Solvent Extraction, Radiopharmacy) at Chalmers University at MSc and PhD level. The group comprises currently of 7 PhD students and 4 senior researchers in Nuclear Chemistry and 2 more PhD students and a PhD are foreseen to be employed during 2022, while 3 persons will defend their thesis during 2022.

The group is conducting research in several areas of 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. The Nuclear Chemistry group 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, the personnel and students will be amply familiar with all these procedures as the only university facility in Sweden.

The funding was used to cover the activities of **Prof. Christian Ekberg, Assoc.. Prof. Teodora Retegan Vollmer, Dr. Stefan Allard** and **Dr. Stellan Holgersson** who are actively involved in teaching and research including radiation protection. More specifically, funding was used to prepare participation in several EU projects of which 2 were successful (one failed). Moreover, the group participated in a project proposal on a competence centre submitted to the Swedish Energy Agency, together with other groups at Chalmers, other Swedish universities, and the Swedish nuclear industry.

Both Prof. Ekberg and Bitr. 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. Assoc. 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 online teaching, learning and evaluation. We do have a close contact with our colleagues on physics from GRE@T-PIONEeR.
The group is active in various networks in Sweden (SKC, SAINT, and a collaboration with KTH) as well as internationally (ENEN, ANS, SNETP). The group is involved in several EURATOM projects relevant for SKC.

KTH Royal Institute of Technology

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**
- **Department of Solid Mechanics**

The Centre for Nuclear Engineering at KTH (CEKERT) is the platform to coordinate nuclear education and research at KTH, with the involvement of 15 faculty members (9 professors and 6 associate professors) in 2021.

In addition to general education of BSc, MSc and PhD students, KTH is running the Master's Programme in Nuclear Energy Engineering, which 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.

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 2021 was 1,333,000 SEK, among which 750, 000 SEK was used to pay the partial salaries of the 15 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 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 2021, totally 27 students are enrolled within the Master's Programme and the associated double-degree programmes (e.g. EMINE).

Areas of support	**Items**	**Cost calculations**	**Costs (SEK)**
Faculty members	9 professors 6 associate professors	50 hours per faculty member spent on preparation of teaching materials and supervision of postgraduate students at the hourly rate of 1000 SEK/h	750,000
Master's programme management	Programme director and deputy	208 hours of work for Assoc. Prof. Jan Dufek and Dr. Vasily Arzhanov	208,000
Lab exercises on the VR-1 training reactor	VR-1 training fee Hotel Flights	27 students at 10,000 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

Uppsala University

The nuclear technology research and education at Uppsala University covers a broad range of areas. Currently, research and development work is being conducted within the following areas:

· **nuclear waste management, including spent fuel**

· **nuclear data, including uncertainty propagation in nuclear systems**

· **nuclear safeguards**

· **fuel performance modeling and experiments**

· **design of instrumentation for studies of nuclear fuel behavior**

· **detector development for radioactivity monitoring**

To augment the research and aiming for the future, a high- intensity neutron irradiation research facility, NESSA, is currently under construction. This facility is planned to be used for nuclear technology research such as fuel development, materials research, and education.

Complementing the funding from faculty funding and external sources such as VR and SFF, these research areas are funded by SKC either through base funding and/or specific project funding. The research is conducted in close collaboration with partners nationally and internationally. International partners include IAEA, LANL, INL, SCK CEN, NEA, NFS, JRC, Jyväskylä University, HRP, ESARDA to mention a few.

In addition to the research activities, Uppsala University's nuclear technology education comprises teaching and supervision on all levels and includes a substantial volume of contract education directed towards industry and authorities through Uppsala University's portal: "Nordic Academy for Nuclear Safety and Security, NANSS"

SKC's basic support is used for supporting efforts in research, teaching courses that are in line with SKC's goals and supportint 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 2021 is provided below.

Staff

During 2021, 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, work connected to the infrastructures (see below) and work connected with an application to the Swedish Energy Agency. The application regarded the creation of a national competence centre, ANItA, to provide society with adequate knowledge to enable the implementation of small modular light-water reactors in Sweden. The application was approved and work to formally establish ANItA is now underway. A part of prof. Håkansson´s salary was also covered by SKC to free faculty funding for Dr. Zsolt Elter and Dr. Erik Branger who, for formal reasons, could not receive support from SKC.

Dr. Peter Andersson continued his work to develop novel approaches for PIE within the framework of his establishing grant from the Swedish Research Agency. One of his Ph.D. students, Vikram Ratore, earned his licentiate during 2021. His other students, Lorenzo Senis, is preparing for his licentiate during spring 2022. Peter's work has during 2021 been augmented by establishing a collaboration with Studsvik Nuclear concerning development of experimental methods. Peter has also supervised two Diploma works, see below.

Dr. Ali Al-Adili continued developing fission measurement techniques to measure neutron emission in fast-fission of 235U(n,f). This extends previous corresponding measurements for thermal fission of 235U. For this, 6 beam time weeks were delivered at the Tandem facility of the Joint Research Centre of the European Commission in Geel, Belgium. Within his establishing grant from the Swedish Research Agency, and together with his Ph.D. student Ana Maria Gomez Londoño, continued developing the VERDI (Velocity for Direct Particle Identification) instrument for fission studies. Main efforts concerned characterization of the Silicon detectors for detection of fission fragments. This was carried out the LOHENGRIN facility located at the ILL high-flux reactor in Grenoble, France. Furthermore, Dr. Al-Adili supervised the thesis works of Daniela Romero, Ivar Wikander and Elizaveta Yakovleva.

Assoc. Prof. Andreas Solders continued developing methods for measuring fission yields in a fast reactor spectrum at IGISOL in Jyväskylä, Finland. This work is carried out as part of his establishing grant from the Swedish Research Agency and together with his Ph.D. student Zhihao Gao. The focus during 2021 was finishing the benchmarking of fission fragment transport calculations using several modelling codes, with experimental data. The code package will then be used to design a fission fragment ion guide with increased efficiency to allow for the planned fission yield measurements.

Dr. Zsolt Elter has been teaching the summer course "Reactor physics with Python" that he had developed previously. The course was popular and attracted 56 participants. Based on the good reviews the course received, UU has decided to give the course also in the summer of 2022. Dr. Zsolt was also co-supervising William Lindberg on his Diploma work (see below).

Dr. Erik Branger was involved in the summer course Introduction to Nuclear Power and supervised one Diploma work.

Dr. Erik Andersson Sundén has been working with developing the NESSA facility, especially the licensing process.

Dr. Mattias Lantz and **Assoc. Prof. Cecilia Gustavsson** have continued developing the UGGLA facility. During 2021, several high school pupils have been involved in measuring Cs-137 in environmental samples. Several student projects where performed that contribute to characterization of UGGLA, especially gaining an improved understanding of geometrical effects on measurement uncertainties. Dr. Lantz and Assoc. Prof. Gustavsson supervised the thesis of Sofia Tynelius and Hjalmar Andersson, and the student project work of Marielle Aksér.

The summer school "BEST" for students interested in nuclear power originally planned for summer 2021 had to be cancelled due to the pandemic.

Staff changes

Regrettably, Dr. Peter Jansson and Dr. Zsolt Elters announced to leave the business from 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. This manpower must be replaced, and UU intends to use part of the SKC base funding to support new positions.

Infrastructures

The experimental work within Applied nuclear physics is heavily dependent on the availability of adequate experimental infrastructures. Besides laboratories abroad and, to some extent, CLAB, UU has made considerable efforts for establishing infrastructures on-site. In 2021, work on the infrastructures below has been carried out, partly using base funding from SKC.

NESSA

The completion of the neutron facility NESSA has been delayed for various reasons e.g. due to the pandemic situation. The housing of the neutron source and necessary subsystems such as radiation protection and safety measures are almost completed while the licensing process is in the last stages. The neutron generator is expected to be delivered autumn 2022 and the first experiments could be carried out spring 2023.

BETTAN

The BETTAN facility is an experimental platform for developing measuring strategies and algorithms for tomographic applications. BETTAN was originally intended for testing the tomographic methodology developed at UU for validating core simulators by measuring newly irradiated fuel assemblies. A unique feature of BETTAN is that irradiated fuel assemblies are simulated with pipes, filled with a radioactive substance, that can be robotically arranged in various fuel geometries.

BETTAN has during 2021 been refurbished to fit the ongoing development work of new PIE methodologies at UU. An important part of this work has been to adapt BETTAN for accepting the new segmented Ge detector that is expected to be delivered during March 2022. Experimental activities using BETTAN are planned to start during spring 2022 as a part of two Ph.D. projects supervised by Peter Andersson.

UGGLA

The Uppsala Generic Gamma Laboratory UGGLA was further developed and characterized during 2021. Currently the main use of the facility is measuring radioactivity in environmental samples and eventually from air filtering. In the future, UGGLA will be used to measure activity in samples irradiated at the NESSA facility. This then serves mainly two purposes; characterization of NESSA, and student education within measurement techniques for nuclear reaction studies.

Finished Diploma work

Erik Gustafsson, M.Sc. in Energy Systems: "Verification of the fluid dynamics modules of the multiphysics simulation framework MOOSE."

William Lindberg, M.Sc. in Physics: "Monte-Carlo response for mobile gamma spectroscopy in fallout affected residential areas."
Viktor Nerlander, M.Sc. in Energy Systems: "Power Increase Limits To Prevent Pellet Cladding Interaction - Calculation of Strain-And Fission Gas Release Margins."

Daniela Romero, M.Sc. in Physics: "Comparison of digital signal processing routines in nuclear experiments."

Lars Vikström, B.Sc. in Nuclear Power Technology: "Vibrationsmätningar: Uppföljning av negativa trender."

Ivar Wikander and **Elizaveta Yakovleva**, B.Sc. in Engineering Physics: "Investigation of the Plasma delay time in PIPS detectors using the LOHENGRIN spectrometer."

Sofia Tynelius and **Hjalmar Andersson**, B.Sc. in Engineering Physics: "Analys över strategi för kvalitetsäkring av produktion av radioaktiva nuklider för PET."

PROJECT PORTFOLIO

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


Kristoffer Tofveson Pedersen

Research host
Chalmers University of Technology
Department of Physics
Division of Subatomic, High Energy and Plasma Physics

Research done by doctoral student
Kristoffer Tofveson Pedersen

Formal project start
2020-09-01

Expected time of completion
2025-08-31

Main supervisor
Prof. Christophe Demazière

Co-supervisor
Assoc. Prof Paolo Vinai

Discipline
Reactor Physics

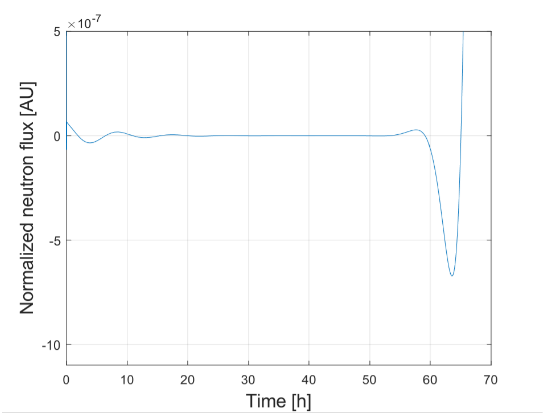
Keywords
Reactor modelling; high-fidelity simulations; Reduced Order Modelling; xenon oscillations; xenon instabilities

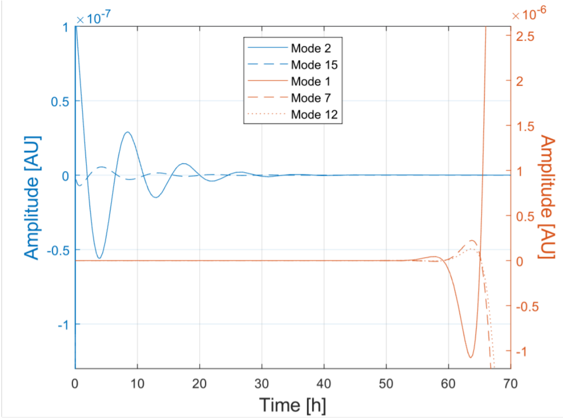
Motivation

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 time period, the oscillations might remain unnoticed before they develop significantly, then requiring operator action in form of partial control rod insertion. In addition to detect these oscillations when they develop, it is of utmost importance to determine whether a core configuration is stable or unstable with respect to Xenon oscillations.

In this PhD project, Reduced-Order Model (ROM) techniques are used to study the stability properties of nuclear reactors during





(Left) *Simulated neutron flux at a point in the reactor* **(Right)** *Time dependence of the amplitudes of the governing eigenmodes computed by the numerical ROM.*

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 by 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 with respect to 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 likewise simple linear one-energy group form to maximise 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 individual mode has been derived analytically, as well as computed numerically. Both approaches led to identical results when using the same assumptions. The main advantage in the numerical approach lies with the capability to resolve the true interdependency between the modes, as illustrated in the figure below. The analytical approach, on the other hand, allows identifying which modes are driving any oscillatory or diverging behaviour.

Methodology

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. In further research, an attempt will be made to include the nonlinear terms in the governing equations as well as the creation of a more realistic heterogenous multigroup model.

Thereafter, high-fidelity simulation data from Ringhals and Forsmark will be acquired and used as a basis for a data based non-intrusive ROM. The intrusive and non-intrusive approaches will be compared to each other and to the simulated high-fidelity test cases.

Communications

The project was presented at the SKC annual symposium on October 20th-21st, 2021. A conference paper has been submitted to the ANS Annual Meeting, to be held on June 12th-16th, 2022. The project was presented to and discussed with stakeholders at Ringhals and Forsmark to initialise the data acquisition process.

2019-2: Influence of aging and radiation on ductile failure in the DBT temperature region

Research host
KTH Royal Institute of Technology, Department of Engineering Mechanics, Unit of Solid Mechanics

Research done by doctoral student
Shuyue Wang

Formal project start
2020-08-17

Expected time of completion
2025-06-25

Main supervisor
Jonas Faleskog

Discipline
Solid Mechanics

Keywords
ductile fracture, length scales, aging degradation, long-term structural integrity, material inhomogeneities

Motivation

TDuctile fracture involves a significant amount of plastic dissipation which increase the resistance of a material to withstand 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 are vital to the continued operation of the Nuclear Power Plants beyond the initially assumed lifetime. Currently 6 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 of the 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 both 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 development of theory, numerical methods, and experiments.

Progress

The doctoral student, Wang, since the start in late August 2020, focused on developing the constitutive model capable to capture the crack initiation and propagation. The classical damage continuum mechanics material model is not sufficient to describe crack initiation and propagation where 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 FEM 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 cracked geometry 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. A large existing experimental data sets performed on a nuclear pressure vessel steel has been acquired and will be used to calibrate and verify the modelling framework. Furthermore, the framework will be applied to experiments to be conducted using the aged weld material taken from the decommissioned pressurizer from Ringhals 2. These experiments have been planned and are on schedule.

Methodology

The degradation of weld material used in nuclear powerplants will be systematically investigated in the upper transition to the upper shelf region by experiments. Physical understanding of the failure mechanisms suffering from aging and degradation will be provided by numerical analysis of a relevant constitutive damage material model.

Communication

:
The project was presented at the SKC symposium 2021 and will be presented at the EMMC18 international conference, Oxford, April 2022. The plan is to publish the progress described above in international scientific journals.

2019-4: Corrosion fatigue in PWR environment at cyclic thermal and mechanical loads

Mustafa Subasic

Research host
KTH Royal Institute of Technology, Department of Engineering Mechanics, Unit of Solid Mechanics

Research done by doctoral student
Mustafa Subasic

Formal project start
2020-08-17

Expected time of completion
2025-08-31

Main supervisor
Pål Efsing

Discipline
Solid mechanics

Keywords
Corrosion fatigue; Environmental degradation; Fatigue initiation; Hollow pipe specimen; Cyclic thermal and mechanical loads

Motivation

Corrosion fatigue is a well-known degradation phe¬nomenon 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 are 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 programmes 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 behavior 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. Samples have been manufactured for correlation of the hollow tube samples that they are consistent in their behavior at elevated temperature and pressure. The test rig has been transported from the Solid mechanics laboratory to the Studsvik laboratory where tests will be performed using relevant water chemistry conditions in an autoclave. This work is sponsored by the Swedish Utilities Materials group, MG.

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 planned simulation work for understanding and verification will start 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 favorable crystal planes. The plan is to use and build on the cohesive crack growth model developed by Michal Sedlak Mosesson in the recently finalised SKC funded project Mechanical Modelling of Stress Corrosion Cracking in Sensitized Stainless Steel 316.

Communication

The project was presented shortly at the SKC Symposium 2021.

A project reference group has been established and constituted. The reference group comprise participants from all three Swedish nuclear pow¬er plants, SSM and the project parties KTH Solid Mechanics, Studsvik and Chalmers Microstructure Physics. Adjunct professor Pål Efsing from Ringhals serves as industry advisor. 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.

Due to the pandemic situation, the planned participation with a presentation at the "Environmental Degradation of materials in Light water reactor conditions conference", originally scheduled for the fall of 2021, was postponed. This meeting will now occur in the summer of 2022. In addition to this, the results are foreseen to be presented at the ASTM multi-axial fatigue seminar in May 2022.

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

Ibrahim Batayneh

Research host
KTH, Physics, Nuclear Engineering

Research done by doctoral student
Ibrahim Batayneh

Formal project start
2021-01-15

Expected time of completion
2025-01-15

Main supervisor
Dmitry Grishchenko

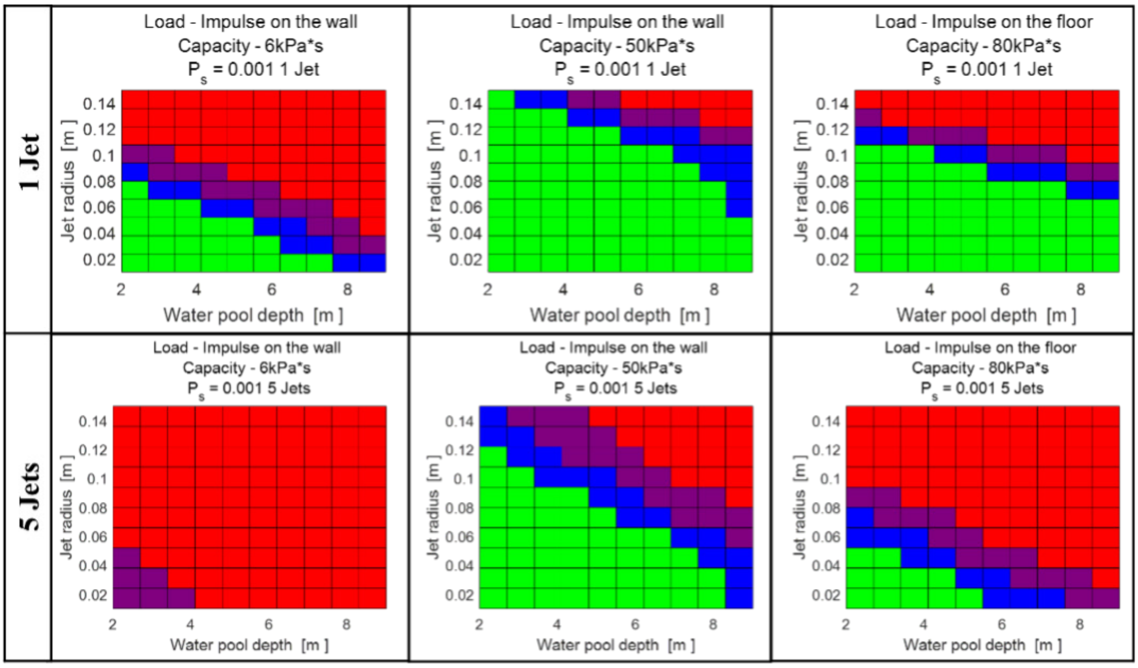
Discipline
Thermal hydraulics, safety

Keywords
Steam explosion, numerical methods, uncertainty quantification, model validation, risk informed decision making, surrogate model

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



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

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 was 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 for the 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 analyze 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 steam explosion code. The results of the study have been reported on several conferences. The next step of SEMRA project started with the analysis and testing of different numerical schemes available to model the physical phenomena of steam explosion, to select the appropriate one for SEMRA 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 multi-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 behavior for different input parameters. Then, the surrogate model was used in (ROAAM+) code package to analyze the failure domains as shown in the figure.

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 Symposium 2021. Two conference papers about steam explosion in conditions of multiple jet releases were submitted and will be presented. One for the 19th international Topical Meeting on Nuclear Reactor Thermal Hydraulics, held in Belgium, in March 2022 and the other for the 10th European Review Meeting on Severe Accidents Research held in Germany, May 2022. A scientific journal article on the same topic is being prepared as well.

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

Gustav Robertson

Research host
Uppsala University, Department of Physics and Astronomy, Applied Nuclear Physics, Nuclear reaction group, and Fission diagnostics group

Research done by doctoral student
Gustav Robertson

Formal project start
2020-09-01

Expected time of completion
2024-09-01

Main supervisor
Henrik Sjöstrand

Discipline
Fuel Performance Modeling. Statistics.

Keywords
Nuclear Fuel, Cladding Oxidation, Machine Learning, Calibration, Inverse-UQ, Data Assimilation

Motivation

The proposed project addresses challenges in the calibration of fuel performance codes. These codes include models that predict thermo-mechanical behavior 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 modeling 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 behavior 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 modeling 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 neighboring 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, Westinghouse, 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

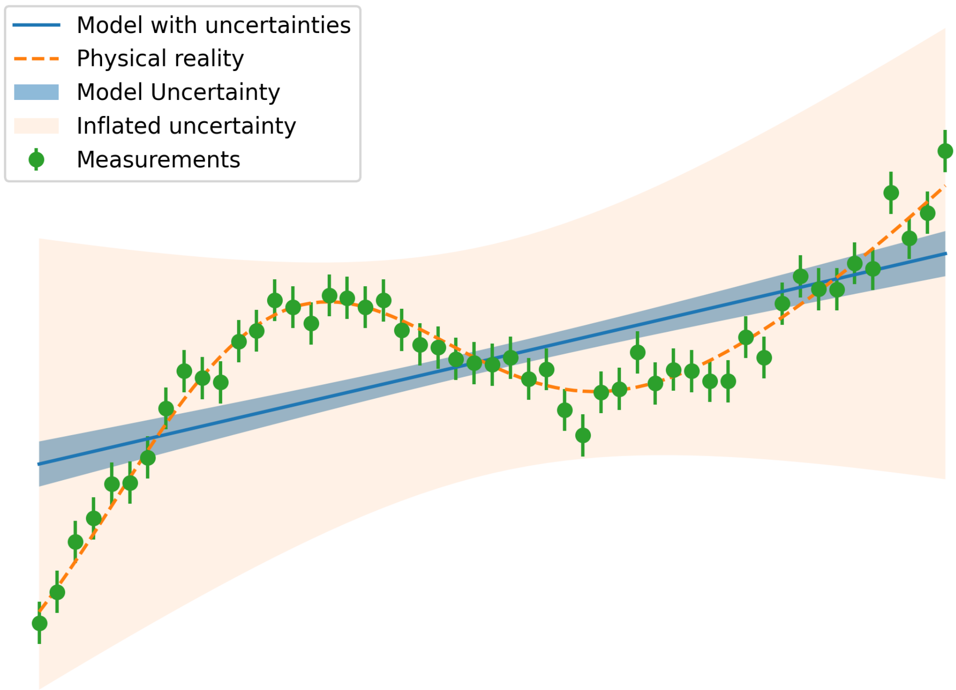


Figure 1. *Showing an example of an inadequate model with uncertainty bands in a standard calibration (blue), and inflated uncertainty bands (yellow).*

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.

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 Annals of Nuclear Energy.

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 Institute for Transuranus Elements (ITU) at the European Commission Joint Research Center in Karlsruhe, Germany. ITU has been supportive and supplied Transuranus input files for the public experiments studied. Based on the calibration methodology developed during 2020 and 2021, a calibration framework to calibrate Tranuranus to those experiments has been implemented, and initial calibration results have been obtained.

Additionally, during summer 2021, A 15 hp bachelor project, "Temporal Convolutional Networks In lieu of Fuel Performance Codes", was conducted within the project (supervised by Gustav Robertson) to improve understating of time-dependent surrogate models needed in calibration [2].

In early 2021, the Transuranus code was acquired from Joint Research Center (JRC). This has been more difficult than expected by the fact that Uppsala university works under the principle of openness (offentlighetspricipen), whereas JRC contracts require non-disclosure. A process has started on how the project can use proprietary fuel performance data of Westinghouse and some minor legal and practical issues are still to be solved. A non-disclosure agreement is expected to be finalized in early 2022.

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 2022, 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 2022. In addition, it is planned to deliver a literature report to ITU-JRC, as it is a part of the Transuranus license agreement. This report will also be used for the licentiate thesis.

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.

The distribution parameters (μ and **Σ**) are sampled using Markov Chain Monte

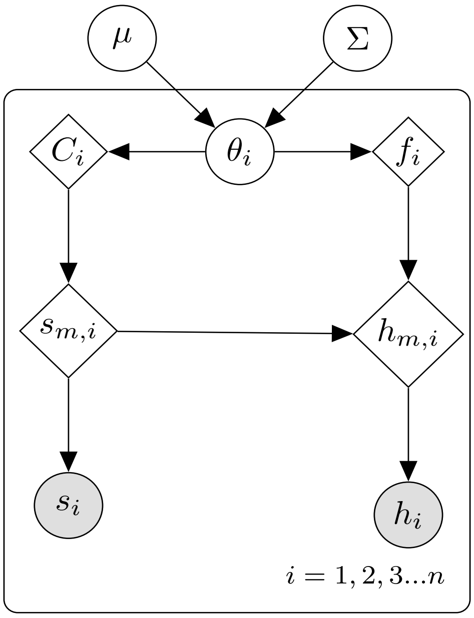


Figure 2. *Illustrates the probabilistic model developed, with the assumption of different calibration parameters (C_i, f_i) for different experiments, i. Distribution parameters (mu, sigma) describing the distribution of C_i and f_i, resulting in calculated values from the model ($s_{m,i}$, $h_{m,i}$),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

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 submitted to Annals of Nuclear Energy [3] 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 modeling 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. Additionally, a calibration program has been developed in which the developed calibration method has been implemented.

Temporal Convolutional Neural Nets In Lieu of Fuel Performance Codes

During summer 2021, a 15 hp bachelor project was conducted to investigate the use of convolutional temporal neural networks as surrogates in calibration for time-dependent models. Realistic power histories were used, and training data were generated using Transuranus. 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.

Communication

A paper on the proposed method has been accepted and presented at TopFuel-2021 [4]. A paper "Treating model inadequacy in fuel performance model calibration by uncertainty inflation" has been submitted to Annals of Nuclear Energy.

A student project was supervised, presented, and published [2].

An abstract is submitted to and accepted by the SIAM UQ22 conference in Georgia.
In addition, the conference/meeting contributions [4]–[9] have been performed during 2021.

Gustav has also participated as a guest lecture at the course Nuclear Technology and Systems, where he has presented Westinghouse and the project to the students.

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2020-2: Development of a fully coupled electro-chemical and micro mechanical SCC model


Michal Sedlak Mosesson

Research host
KTH Royal Institute of Technology, Department of Engineering Mechanics, Unit of Solid Mechanics

Research done by post-doctoral student
Michal Sedlak Mosesson

Formal project start
2020-11-01

Expected time of completion
2022-11-01

Main supervisor
Pål Efsing

Discipline
Solid mechanics

Keywords
Intergranular stress corrosion cracking; Environmental degradation; Crack growth; Cohesive elements

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 sensitizatized 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 Michel 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.

Motivation

A research plan has been established with the student and supervisor. The collaboration has been initiated with Dr Thierry Couvant from Électricité de France (EDF). Code implementation for the collaborative work has begun. Also, collaboration with Dr Elsiddig Elmukashfi from the University of Oxford is ongoing to develop SCC multi-physical models including hydrogen embrittlement. A reference group is planted to be initiated containing "Svenska Materialgruppen". We are in the process of finalizing the cohesive element with moving Gauss points framework. The XFEM (ghost node method) progress to create an arbitrary crack path has been developed and tested. Ongoing work is on slip plane forming during oxide growth in FE to determine the onset of oxide damage.

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 modeled more realistic with a brittle material law (Columb Mohr md law) instead of the cohesive law. Creep constitutive law was used to obtain the plastic creep strain and stresses during the relaxation phase.
Stage II of the model has been to replace the one element Colum Mohr 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 with deep machine learning (Tensorflow).
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 will introduce the possibility of branching and both inter- and transgranular stress corrosion cracking. For both 2D and 3D.
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. All articles are sent to high ranked international journals in their respective fields and published open-access.

Abstract was approved to the conference 20TH Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors (June 17-21).

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

2020-12: Influence of alloying and neutron flux on irradiation effects in fuel rods

Research host
Chalmers, Department of Physics, Microstructure Physics

Research done by post-doctoral researcher
David Mayweg

Formal project start
2021-04-01

Expected time of completion
2023-03-31

Main supervisor
Mattias Thuvander

Discipline
Nuclear Materials (Fuel)

Keywords
Zircaloy, irradiation effects, corrosion

Motivation

The project aims to improve the understanding of neutron irradiation effects in fuel rods in a boiling water reactor environment (see schematic in Figure 1). To this aim we investigate two different alloys (Zicaloy-2 heat treatment code LK3 and Alloy 2) at two fluence levels each (from a fueled region referred to as high fluence and the plenum region referred to as low fluence), which have been used in Oskarshamn 3 from 2001-2007. Although their composition differs only slightly (see Table 1) in Fe and Cr their hydrogen uptake is markedly different (LK3: 200 ± 29 wt ppm; Alloy 2: 134 ± 9 wt ppm).

Table 1: Alloy composition of Zry-2 (LK3) and Alloy 2.

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

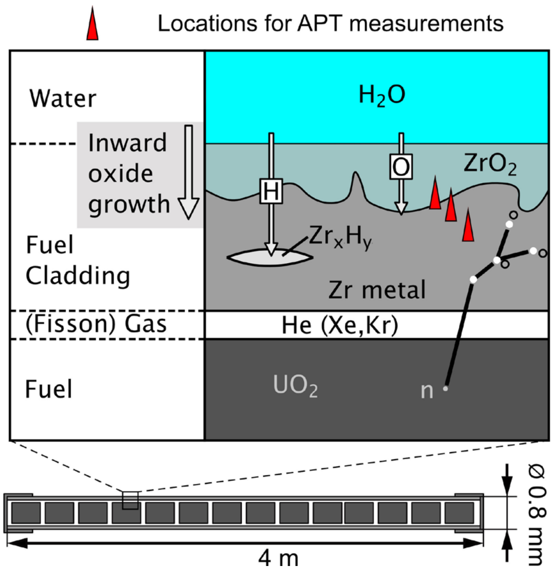


***Figure 1**: Schematic section illustrating the arrangement of fuel pellets encapsulated in a rod during reactor operation (bottom). At the top a detailed view of the water/fuel rod (Zr-alloy)/ fuel pellet (UO_2) environment is depicted and processes of interest are illustrated: irradiation damage is caused by neutrons originating in the fuel; oxidation (formation of ZrO_2) takes place by O transport across the oxide scale. H originating from the water diffuses into the metal and leads to hydride formation (δ-hydride - $ZrH_{1.6}$ at operation conditions/temperature). Red triangles mark the positions aimed at for atom probe tomography (APT) measurements.*

This unique set of samples allows for comparative investigation of important effects caused by the exposure to real reactor conditions (see schematic in Figure 1). Of main interest are the redistribution of Fe, Cr and Ni by neutron irradiation and their segregation to defects and the oxidation behavior in this environment. What is especially important to notice is that the mentioned effects cannot be studied sufficiently in materials that have "only" been exposed to emulated reactor conditions by, e.g., ion irradiation or in autoclave corrosion tests.

An improved understanding of irradiation effects and oxidation behavior is needed in order to further optimize 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. This in turn will reduce costs and the amount of highly radioactive waste.

Methodology

The main tool employed in the present research is atom probe tomography (APT) in a combination with specimen preparation by focused ion beam milling. This technique 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. Additionally, scanning and transmission electron microscopy are performed for supplementing the findings with information on scales from several nm to a few µm.

Progress

The project started in April 2021. So far successful atom probe tomography measurements of oxide grown on Alloy-2, oxide metal interfaces as well a (many) of the metal (from both alloys and fluences) were performed.

Accurate APT measurements of the oxide are challenging since overlaps in the mass spectra hinder fully quantitative analyses. Since the metal oxide interface with its abrupt change in (evaporation) properties is comparatively weak this often leads to early fractures especially when the interface is perpendicular to the analysis direction (i.e., horizontal in the depictions in Figure 2). As the current (thirteen-year-old) APT system (LEAP 3000X HR) is replaced by a model of the newest generation (LEAP 6000XR) before summer and new capabilities will be

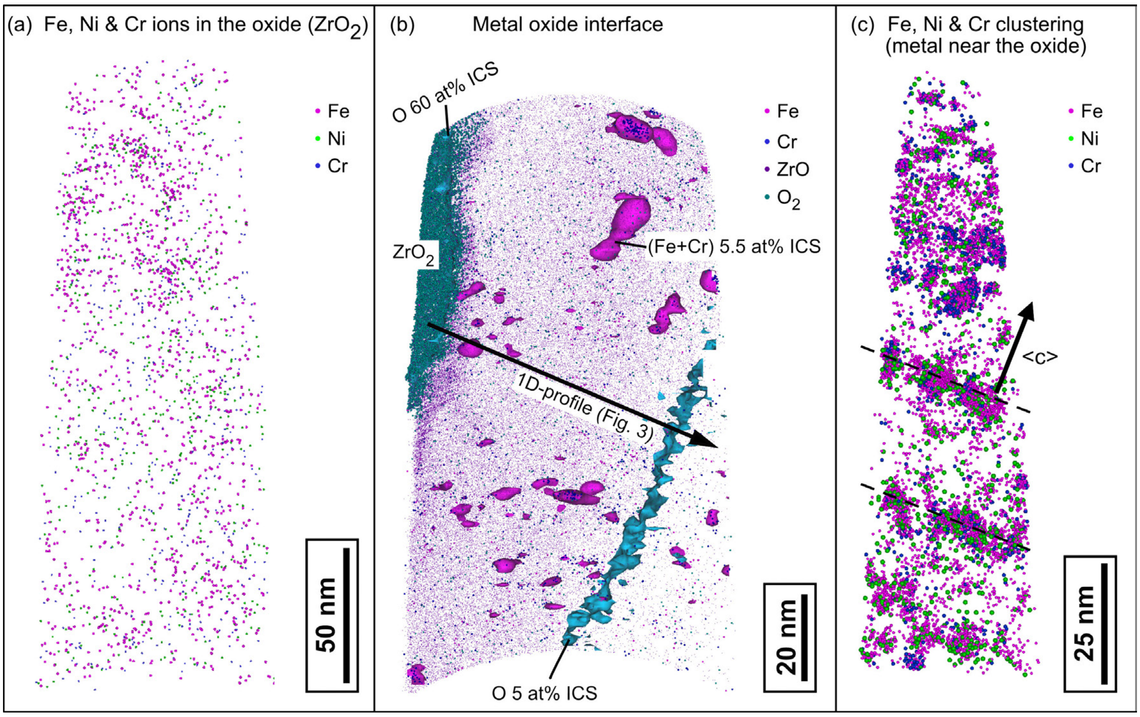


Figure 2: *Examples of 3D reconstructions from atom probe tomography experiments. Only elements/ions of interest are displayed. (a) Displays Fe, Ni and Cr ions detected in a measurement of the oxide scale (Alloy 2) from a distance of 100-200 nm away from the metal oxide interface; ions are not randomly distributed; however, now strong clustering is found either. (b) Slice of APT reconstruction capturing the metal-oxide interface (LK3). On the upper left the captured oxide (ZrO_2) marked by characteristic O_2 ions. In the region below the oxide ZrO ions (violet) are prevalent and their density decreases towards the lower right. (c) Alloy 2: This APT reconstruction exhibits clearly visible clustering of Fe, Cr and Ni in layers parallel to the basal plane.*

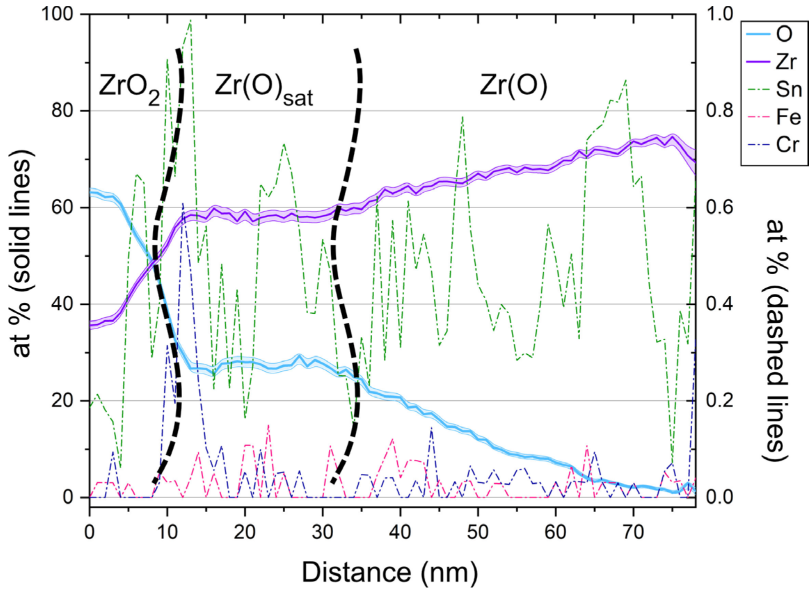


Figure 3: *1D composition profile along the arrow depicted in Figure 2 (b). The solid lines represent Zr and O while the dashed lines represent the Sn, Fe and Cr contents. The latter have been multiplied by a factor of 100 for increased visibility (scale on the right-hand side).*

available it is likely that new measurements with even better data quality (and quantity) can be obtained.

Figure 2 showcases three APT reconstructions from (a) an oxide, (b) a metal oxide interface and (c) the base metal. The 3D ion map in (a) shows that clustering caused by segregation to dislocation loops in the metal is much less pronounced in the oxide indicating dissolution of clusters during oxidation. A slice of a successful measurement of the metal oxide interface is shown in Figure 2 (b). ZrO_2 is located on the upper left. The region to the lower right is visually separated by a 5 at% O iso composition surface (ICS) and also shows a lower density of ZrO ions (purple). The O ICS shows that the bulk diffusion front is roughly parallel to the metal oxide interface. There are few Fe and Cr regions highlighted by pink ICSs. Figure 2 (c) is a reconstruction of the Zr metal in a few hundred nm below the metal oxide interface. It contains clusters of different compositions aligned in layers parallel to the basal planes (traces marked by dashed lines) the normal of which is indicated by an arrow. In the upper third spherical Fe-Cr-clusters are observed while in the lower part mostly disc-shaped Fe-Ni-clusters are present.

Figure 3 depicts a 1D composition profile along the arrow shown in Figure 2 (b). The solid blue line shows the measured O profile, which starts at an O content >60 at% (nominal 66.7 at%). Due to experimental artifacts the drop to a plateau in the region of around 28 at% O spans across about 10 nm. Within the plateau region of a width of around 20 nm, Zr is saturated in O and the O content then decreases roughly linearly towards the bulk composition. From this measurement the diffusion profile can be estimated to be shorter than 100 nm. It is noteworthy that no ZrO phase/layer (sub-oxide), which has been observed in autoclaved Zry-2, is present between the oxide and the O saturated Zr metal. While Fe and Cr do not show any partitioning tendency the Sn composition profile exhibits a maximum in the metal near the interface. This indicates that Sn mobility might play a role in the oxidation process.
Data analysis with respect to the clusters' number density, shape, size and composition is ongoing. Sample preparation work flows by focused ion beam milling at cryogenic temperatures, which will allow for more reliable H quantification by APT, are under way. Furthermore, there will be further measurements with the new instrument in order to have a larger basis esp. for cluster analysis and improve the understanding of the oxidation mechanism.

Communication

Some data have been included in a paper recently submitted for presentation at Zirconium in the Nuclear Industry 2022. It is concerned with the matrix compositions of Zry-2 with differently heat treatments and matrix composition before and after irradiation of Zry-2 LK3 and Alloy 2.

Currently, three further publications are in preparation. Those are concerned with:

- hydrogen and hydride analysis by APT (submission planned before summer),
- detailed analysis of clustering in the two alloys in both high and low fluence samples (submission planned before the end of the year), and
- the oxidation behavior, oxygen diffusion paths (submission planned before the end of the year).

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

Luca Gagliani

Research host
KTH, Department of Chemistry, Division of Applied Physical Chemistry

Research done by doctoral student
Luca Gagliani

Formal project start
2022-02-1

Expected time of completion
2026-02-01

Main supervisor
Mats Jonsson

Discipline
Nuclear chemistry / Radiation chemistry

Keywords
Nuclear chemistry, light water reactors, surface processes

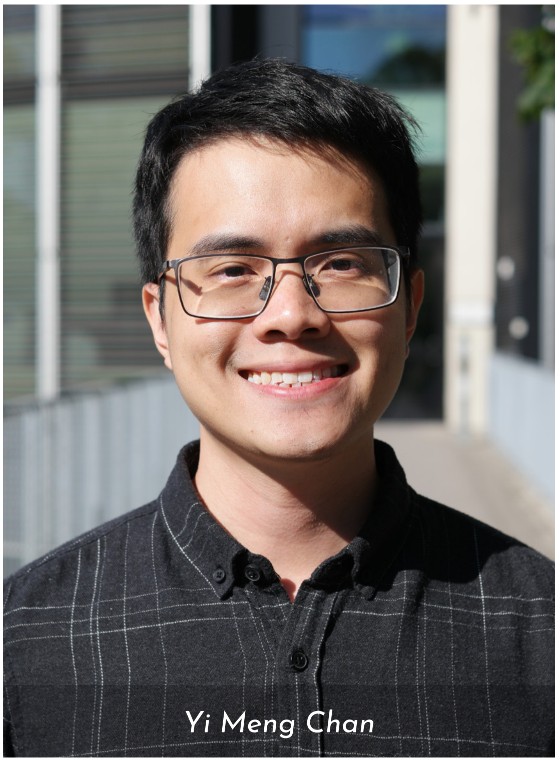
Motivation

Surface reactions such as metal corrosion, oxide deposition and oxide release/dissolution are processes that have significant impact on the performance of and 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 as a secondary oxidative radiolysis product. These products may react with metal and metal oxide surfaces either by redox reactions or via surface catalyzed decomposition. In the present project, the mechanisms behind corrosion, oxide deposition and oxide release will be studied with particular emphasis on the role of water radiolysis. Corrosion and release of activity are often simulated in setups where the impact of water radiolysis is simulated by adding H_2O_2 to the water. In some cases, this could be sufficient to mimic the in-reactor conditions while in other situations, the involvement of other radiolysis products cannot be omitted. The aim of this 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 initiated on 1 February 2022 when the PhD-student was employed. So far, Luca has been going through safety courses to be allowed access to the laboratories at Chalmers. After receiving access he has started to get familiar with some of the experimental methods to be used in the project. In parallel with this, he has been attending a PhD-course in corrosion. A first meeting with the reference group for the project was held on 15 March. It was decided that the reference group will provide some relevant cases for further literature and experimental studies at the next meeting at the end of April.

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



Research host
KTH, Department of Physics, Division of Nuclear Engineering

Research done by doctoral student
Yi Meng Chan

Formal project start
2021-08-16

Expected time of completion
2025-08-16

Main supervisor
Jan Dufek

Discipline
Reactor Physics

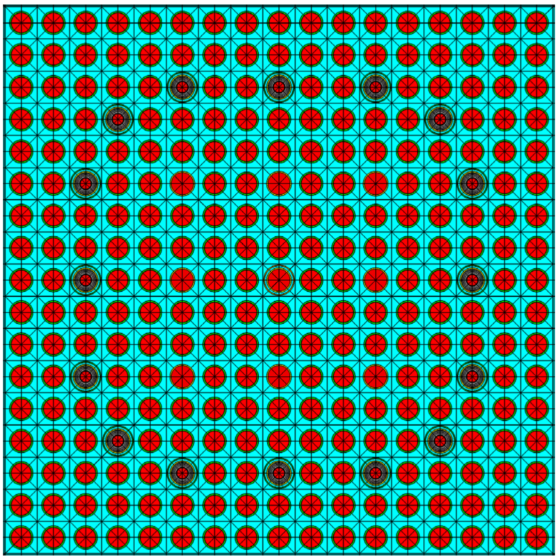
Keywords
Reactor physics, artificial intelligence, artificial neural networks

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



Fuel assembly model in POLARIS with burnable absorber rods

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:

- reviewing the current state-of-the-art methods of nodal data representation,
- getting familiar the general theory of machine learning and theory of ANNs,
- getting familiar with Tensorflow Python package (Tensorflow has a large user-base with many online resources detailing its usage with examples, and performs relatively fast with a very convenient API implementation),
- getting familiar with nodal data generation code POLARIS from the SCALE code package (see the figure below) and Monte Carlo codes SERPENT and OpenMC (we are planning to investigate also other codes for this purpose),
- preliminary testing of simple ANN-based nodal data models.

Methodology

ANNs are a suit of algorithms in the machine learning field and are often used to solve problems with a high degree of dimensionality dealing with complex underlying physical phenomona. ANNs comprises of a network of neurons with synapses connecting them. The inputs to a neuron is multiplied by a synaptic weight and summed. This summed value is then put through the neuron's activation function and the resulting value is the output of the neuron. By choosing appropriate activation functions and network architecture, neural networks can capture complex non-linearities in the data, and are offer a greater degree of flexibility due to the modularity of the network structure. ANNs can be used for time-series forcasting, autoencoding and even regression in a Baysesian framework. The training of neural networks is typically performed using the back propogation algorithm with a weight-update function.

Communication

This project was presented at the SKC Symposium 2021. 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.

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