SKC

Swedish Centre for Nuclear Technology

ANNUAL REPORT 2020

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

SKC helps solve research problems and secures the availability of competence, 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

Contents

This is SKC

The Swedish Centre for Nuclear Technology, Svenskt Kärntekniskt Centrum, was originally founded in 1992 under the name of KTC, Kärntekniskt Centrum, at KTH. Later, the centre was expanded to include also 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 vast 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 vast majority of the funding that SKC directs to the universities enables hiring new doctoral and post-doctoral researchers as well as attract and retain senior researchers and teaching staff.

SKC funds research and education cyclically and the budget is unique to each cycle. However, no matter the size of the budget, every crown that SKC spends is considered and investment, rather than an expense.

Director's message

The year 2020 has been anything but ordinary. For SKC, business has been far from usual in more ways than one. Although not widely known, it was for some time unclear how and if the centre should continue its work. Fortunately, the eight partners benefitting from SKC reached an agreement to renew the contracting period at the end of 2019. And so, on January 1st 2020, SKC entered into the ongoing four-year contract period with a new budget, a new mission and a new director.

SKC has committed to allocating a total of MSEK 32 during this contracting period to research projects. This decision allows Swedish universities to create multiple doctoral and post-doctoral positions, meaning that some of the most curious and brightest individuals will get to solve problems that to date go unanswered. But perhaps more importantly, it allows these young researchers to grow - to push their boundaries and to become irreplaceable experts within their fields along the way. By the end of 2020, SKC had allocated the entire research project budget, financing a total of 7 doctoral and 2 post-doctoral positions. At the time of writing, the majority of these positions had already been filled and the research is, to varying degree, in progress. And so, SKC is already looking forward to learning what these newly appointed researchers, with the help from their supervisors and supporting experts, will discover, develop and dissect.

SKC is also witnessing the incredible value that universities are creating from the so-called base funding that amounts to MSEK 4 a year. Looking at the universities' reports, it becomes clear that SKC's funding plays a significant role in the development and continuation of nuclear education in Sweden. In fact, Oxford Research AB's report on nuclear energy research and innovation, commissioned by the Swedish Energy Agency and issued in October 2020, concludes that SSM and SKC have for a long time been the most significant and reliable financiers of nuclear research in Sweden.

The same report also discusses the frankly concerningly low levels of investments in nuclear research and innovation in Sweden. The vast majority of research funding is currently directed to projects that are of relatively immediate value for the existing nuclear fleet. SKC, too, is funding these kinds of projects, in alignment with the centre's agreed-upon principles and purpose. Looking at the bigger picture, it is nevertheless crucial that other organisations invigorate the research arena by also supporting research and innovation of advanced materials, systems and technology. The decision of Swedish Foundation for Strategic Research to fund the development and qualification of an advanced reactor, i.e. the SUNRISE project, is a particularly noteworthy one from the year that passed.

I would like to conclude by saying that SKC has had, much due to the contributions from the industry and the academia alike, a trouble-free and successful year. I am very proud to have led SKC through 2020 and am truly looking forward to a much more ordinary 2021.

All the best,

Merja Pukari
Director SKC

Organisation

Board

SKC's Board has a decision mandate over SKC's operations and serves to represent the shared interests of all partner organisations. For that reason, the Board consist of one representative from each partner organisation and is chaired by an independent chairman of the board.

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 operational activities and answers to the Board.

Merja Pukari
Director of SKC

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 their professional backgrounds cover the areas of nuclear technology that is considered relevant to the financers during the present contract period. The council provides advice to the SKC board and the 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

Ingmar Jansson
Principal Engineer,
Westinghouse Electric Sweden AB

A YEAR IN REVIEW

Hindsight is 2020

01 New director

SKC starts the year, and the new contract cycle, with a new director.

01 Funding decision

Five PhD projects for a total value of 20 MSEK receive funding from SKC. Base funding of further 4 MSEK for 2020 is distributed to universities.

03 Annual report 2019

Annual report and progress reports on relevant research projects within the disciplines of nuclear technology is released.

04 Call for research project proposals

SKC announces the second call for PhD and post-doc research projects, to be funded from SKC's 2020-2023 budget.

09 Funding decision

Further 2 PhD and 2 post-doc projects, for a total of 12 MSEK, are awarded funding. SKC has thereby fully distributed its budget for research projects.

10 Annual symposium

SKC hosts its annual 2-day symposium digitally.

10 Sigvard Eklund prize

Prize winners for the Sigvard Eklund's prize for Ph.D and M.Sc theses are announced.

11 Career Fair

SKC and several partner organisations participate in the digital Utnarm and Armada career fairs.

11 Energy Dialogues

SKC is invited to introdue its activities at the conference Energy Dialogues organised by KTH.

12 Call for base funding proposals

SKC calls for base funding proposals for 2021. A total of 4 MSEK per year will be distributed

Financial results

Balance 2019/2020	**303,363**
2020 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	**7,170,390**
Project Support (1)	2,750,000
Project 2019-1 (2)	-
Project 2019-2	500,000
Project 2019-4	500,000
Project 2019-7	500,000
Project 2019-12	500,000
Project 2020-2	250,000
Project 2020-12	250,000
Project 2020-18 (3)	-
Project 2020-19	250,000
Base Funding	3,999,999
Chalmers	1,333,333
KTH	1,333,333
UU	1,333,333
Centre administration (4)	420,391
Balance 2020/2021	**5,132,973**
Reserved for project support (2020 expense)	4,250,000
Reserved for base funding (2020 expense)	-
Reserved for centre admnistration (2020 exp)	171,600
Unallocated resources	711,373

(1) See reserved for project support for full expenses
(2) Project is financed directly by SSM
(3) Project has not yet requested payout from SKC
(4) See reserved for centre administration for full expenses

New contract period

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 SEK 52,000,000 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 vast majority of the SKC 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.

SKC will provide

SEK 32,000,000
for doctoral and post-doctoral research projects

and

SEK 16,000,000
as base funding to support the continuation and development of nuclear technology education in Swedish universities.

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 projects that are of value to its contracting parties.

Education and research that will 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

Funding decisions

Base funding

SKC's programme foresees that over the course of this contract period, a total of SEK 4,000,000 per year will be allocated to the three partner universities to support the continuation and advancement of education within nuclear technology education. SKC chooses not be be overly restrictive on how the base funding ought to be utilized by the universities. In other words, 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 been historically 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 2020, underlying that the funds should be used neither for operation and maintenance costs of multipurpose infrastructure with respective universities, nor to supplement specific research projects whose costs exceed the SEK 1,000,000 per year that SKC already has allocated.

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.

By the end of 2019, each partner university was 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 what the costs covered from the base funding budget would amount to. An application from each university was received and the outlined proposal evaluated by the Advisory Council. On the recommendation of the Council, the Board decided to distribute the base funding equally between partner universities for during the first of the four contracting period years. The utilization of the base funding during 2020 is described on the following pages. It has been agreed that SKC would re-evaluate how the base funding is distributed between the partner universities, annually, relying both on how optimally the base funding has been used the year before and what the intentions of its application are for the upcoming year.

A call for applying for the base funding in 2021 was announced by SKC in December 2020.

Project funding

SKC's budget for financing research projects in the current contract period amounts to SEK 32,000,000 in total. In more tangible terms, that corresponds to financing 8 new doctoral positions, i.e. the salary costs of 8 doctoral students over their full anticipated research period of 4 years, excluding additional teaching and administrative duties that young researchers might take on.

Relevant to this contracting period, two calls for research project proposals have been announced by SKC - the first in the autumn of 2019 and the second in the spring of 2020. Measured in the number of submitted proposals, both calls have been met with considerable interest from the partner universities. A total of 18 proposals were submitted for the first call, the second call resulted in 20 proposals. It should be noted that researchers whose proposals did not receive a positive funding decision from the first call were in many cases offered feedback specific to their submission and were urged to re-submit their reworked proposals for the second call. Let it also be pointed out that many of these improved proposals did end up receiving a positive funding decision from the second round. In general, the quality of proposals increased from the first to the second round, arguably due to SKC clarifying the evaluation criteria along with announcing the second call.

All proposals have been evaluated against the following criteria, which are all weighted equally:

Potential to apply research results

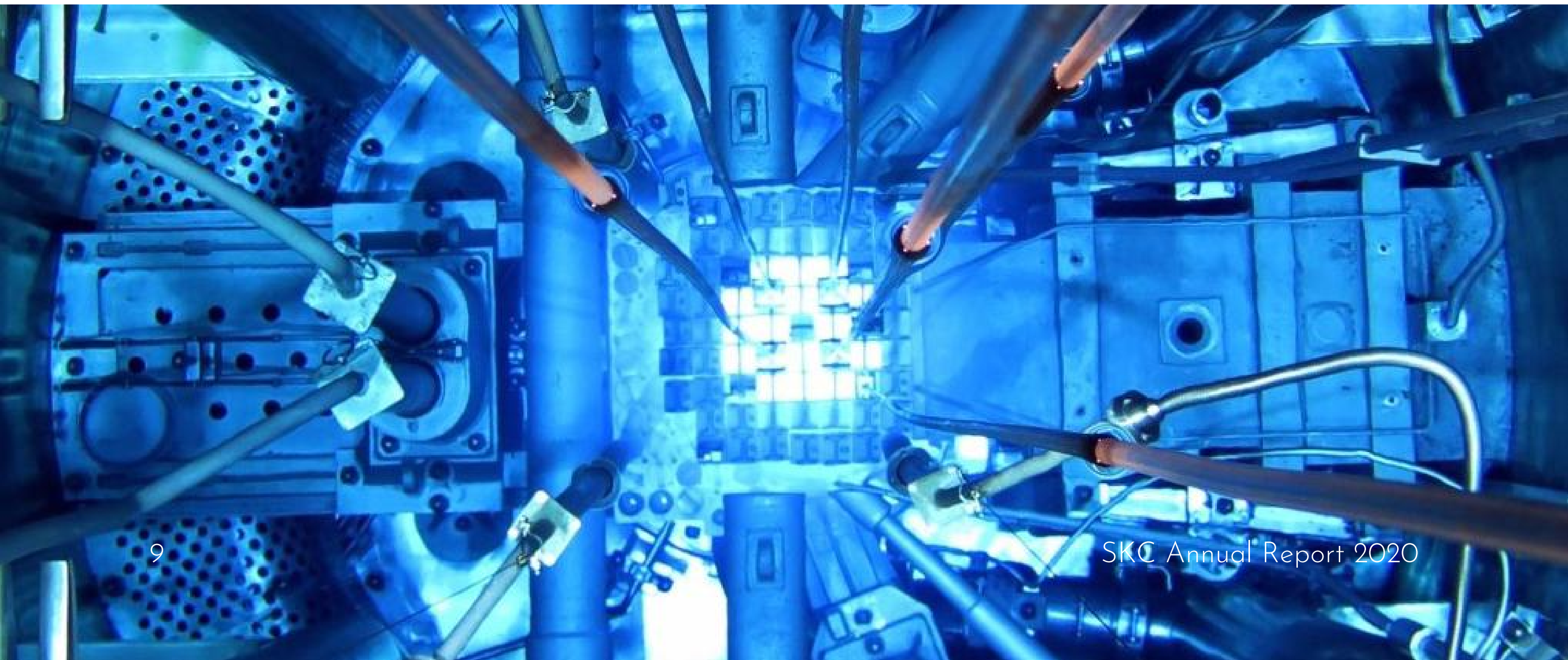
SKC's financiers prioritize, in line with the guidelines for this contracting period, projects whose results can benefit the financiers' operations in some form or another on a relatively short time scale. Therefore, the projects are evaluated based on the potential to apply the obtained results.

Potential to apply gained competence

One of the intended outcomes from financing research projects is to ensure that, as a consequence of having carried out research of a multi-year period, key competence for the Swedish nuclear power industry is developed. Project proposals are therefore evaluated against the probability for these projects yielding skill-sets that are necessary for the industry in the short and long term. This does not imply that the specific topic of a project has to be relevant, as many competences are transferrable within a specific discipline.

Academic merit

It is vital that the projects funded by SKC are of a high academic value and that any recruited researcher, i.e. doctoral or post-doctoral researchers, is in a position to realize her potential to the fullest.



Including academic merit of a project as one of the criteria also lowers the probability of SKC only receiving applied research proposals.

Collaboration

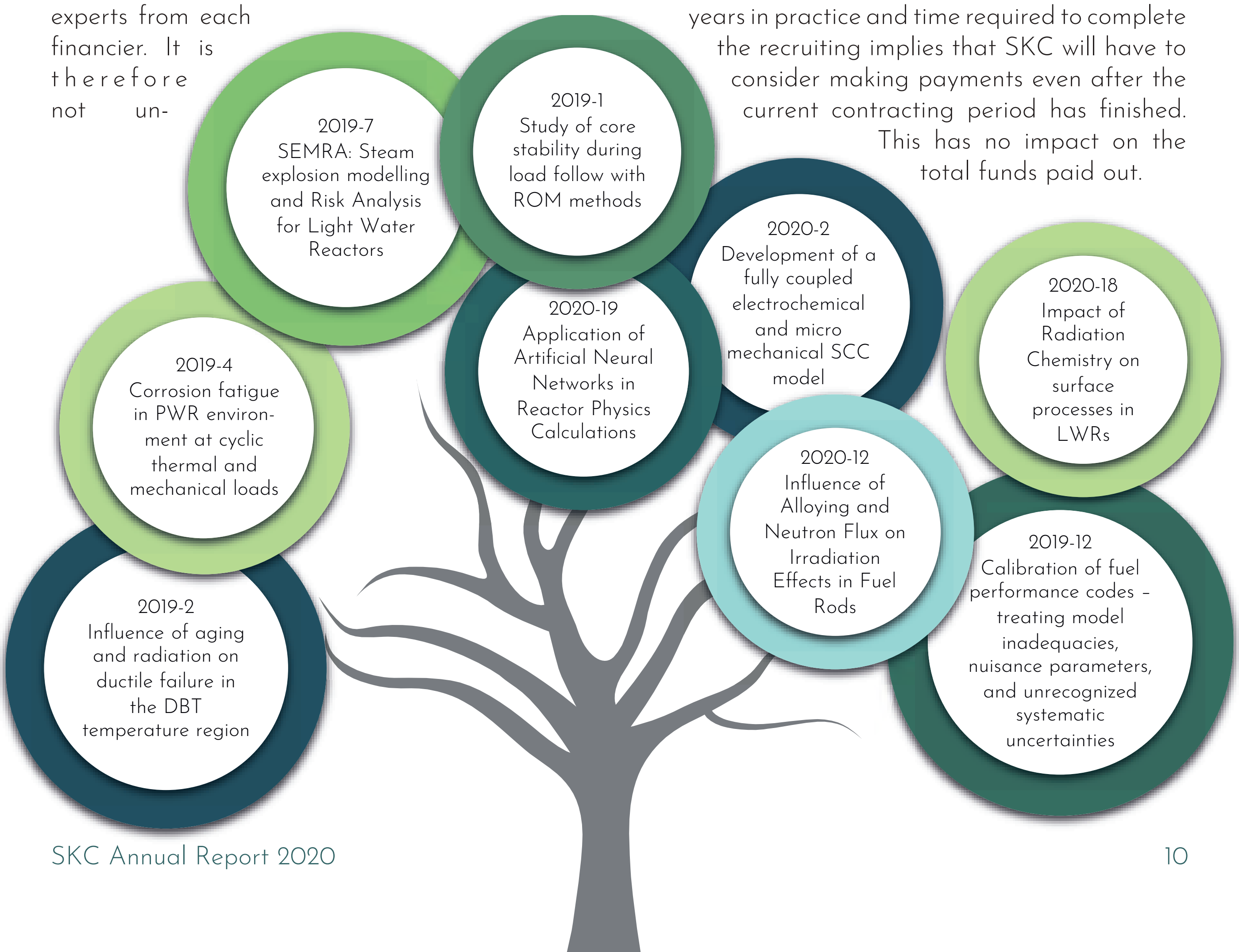
SKC values collaboration in research as it has proven not only to yield work of higher quality but has a high probability of serving as non-technical support for the researcher and will greatly develop the professional network of all involved. Therefore, project proposals are evaluated against the foreseen collaboration between the hosting university and other academic institutions, the regulatory body or the nuclear power industry.

The Advisory Council has been tasked with evaluating the proposals against these criteria from both calls. It has been the responsibility of the Chairman of the Advisory Council to lead the evaluation process and to prepare a joined recommendation to the Board. The recommendations include the number and type of projects to finance from each call and suggest specific proposals to award with a positive funding decision. It is worth noting that, although the recommendations were finalized by the six members of the advisory council, each project proposal has been discussed by a number of experts from each financier. It is therefore not unreasonable to assume that each project proposal has been evaluated by tens of qualified experts.

The quality of a proposal and its overall ranking against the four considered criteria has been a priority. However, the Advisory Council's recommendations consider the interests of all financiers and is therefore naturally a compromise between the varying interests of the financiers. Aside from considering a variation in research topics to fund, the recommendation also aims to achieve a healthy distribution of project funding between universities and research teams, if reasonably justified.

The recommendations made by the Advisory Council have been accepted in full by the Board and the financing decisions have been made in line with the recommendations. Financing decisions were made in January and September 2020, following the autumn 2019 and spring 2020 calls, respectively.

A total of 9 research projects are funded by SKC in the period of 2020-2023, 7 of which are doctoral 2 are post-doctoral research projects. The projects will continue for 4 and 2 years, respectively. It is customary for doctoral projects to last for over 4 years in practice and time required to complete the recruiting implies that SKC will have to consider making payments even after the current contracting period has finished. This has no impact on the total funds paid out.



Research projects funded by SKC in the period of 2020-2023

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

Symposium

As customary, SKC held its annual symposium during the autumn to provide an opportunity for the academia and the industry to meet over brand new and though-provoking research and discuss the opportunities in both realms. Due the constraints posed by the global pandemic, the two-day symposium was held digitally at the end of October. Traditionally, a shared dinner is one of the highlights of the symposium, offering a real opportunity for the curious to converse. Despite the entertainment unfortunately having been left to one's own devices, the symposium attracted over 120 registered participants and a few more that joined without formal registration.

The session on research highlights on Day 1 was appreciated by many as it provided a birds-eye view on all the fascinating and challenging research carried out in Sweden. The session introducing current and future opportunities in Swedish nuclear power industry on the same day proved particularly useful to the participants planning for their future. For the same reason, the presentation of SUNRISE project gained a lot of traction.

Of the speakers on Day 2, participants valued doctoral students Magnus Boåsen, Gustav Robertson and Luis Gonzalez as well as Fredrik Dehlin, one of the winners of Sigvard Eklund's prize, for presenting their work in a structured, engaging and pedagogic manner. Researcher Peter Anderssons presentation on his work at Uppsala University was also mentioned as very educational. Machine learning applications in particular gained interest amongst the participants.

Day 1
20 October

10:30–11:00 **Welcome!**

11:00–12:00 **Advances in higher education**
Uppsala University, Chalmers & KTH

Time for lunch
Lunch not coordinated by SKC

13:00–15:00 **You are wanted by the Swedish nuclear power industry**
Students, PhD students, post-docs and young researchers are invited to learn about their options in Sweden.

Quick break!

15:15–16:15 **Research highlights 2019-2020**
Uppsala University, Chalmers & KTH

Quick break!

16:30–17:00 **Project overview**
Goals, plans & successes

Day 2
21 October

8:30–9:30 **Nuclear power safety**
Research project presentations

Quick break!

9:45–10:45 **Computational tools development**
Research project presentations

Quick break!

11:05–12:20 **Sigvard Eklunds prize**
Announcing the winners and learning about their work

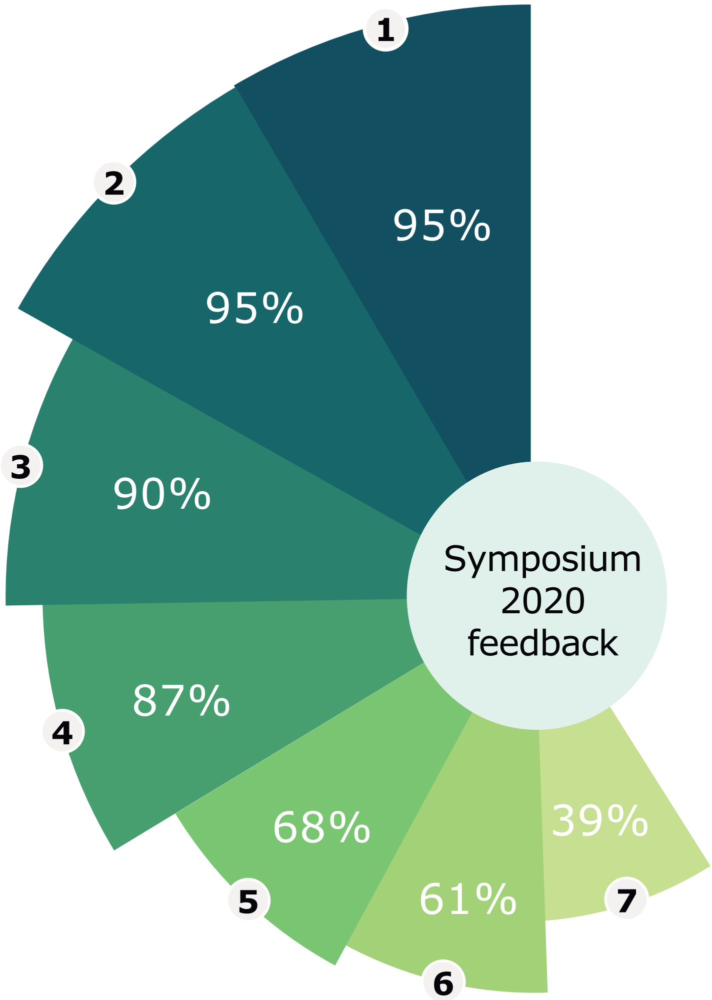
Time for lunch
Lunch not coordinated by SKC

13:20–14:40 **Nuclear materials**
Research project presentations

Quick break!

14:55–16:15 **Nuclear fuel**
Research project presentations

Farewell!



1 95%

thought that the symposium was very well or extremely well organized.

2 95%

received all or most of the information they needed prior to the conference

3 90%

thought that this year's symposium was either good, very good or excellent.

4 87%

thought that the lenght of the symposium was just right

5 68%

thought the most valuable aspect of the symposium was getting an overview of the research done in Sweden

6 61%

could attend all or most of the symposium

7 39%

of the participants were from the industry or the regulatory body

To be proud of and to improve on

Freedom

While a virtual meeting has definite drawbacks, participants also value the flexibility it provides. Many participants, including speakers, would not have been able to or had the interest in devoting two full days to the symposium. The fact that the symposium attracted 110 registered participants was considered a definite positive. A virtual meeting also reduces demands on travelling, which is appreciated. It is therefore suggested that next year's symposium take place both in person and virtually.

Focus on SKC

On the one hand, some participants considered it a positive that even projects that were not funded by SKC were presented and would have liked to see even more speakers and more diversity in speakers. However, it has been pointed out that a clear distinction between SKC-funded projects and other research would have been appreciated. In connection to that, a more thorough presentation of SKC, its activities and financing options would be appreciated by those who are not familiar with SKC.

Content

The content of the symposium - the technical presentations, an overview of training and education opportunities, an overview of the research conducted in Sweden and the introduction to potential employers - was valued by participants. The programme also provided sufficient variation for participants. Particularly appreciated were these presentations where speakers showed equal mastery of technical details and the ability to relate their research to real life applications.

Physical presence

The dominant drawback of this year's symposium was the need to organize it virtually. This leaves participants without the opportunity to organically learn about each other's work and to network, which usually happens over breaks or meals. A virtual meeting also makes it challenging for participants to focus on presentations and to engage in fruitful discussions afterwards. Break-out rooms for discussing specific presentations in smaller groups could have been created, despite it potentially drawing participants away from ongoing sessions.

Organising

Participants also appreciated that the symposium was well organized. The fact that sufficient information was received beforehand made it possible for the symposium to run smoothly. Despite the length and the number of participants, the technology worked unexpectedly smoothly. That, plus the speakers generally respecting their time allowance, made it possible to stick to the schedule. A reliable schedule-keeping was particularly appreciated by

Complexity

Additionally, participants reflect that speakers should consider that the symposium has a broad audience. For best impact, speakers could consider making their presentations easy-to-understand and providing context for their work, rather than present the specifics. More technical details could then be left for post-presentation discussions between those with relevant experience in the field.

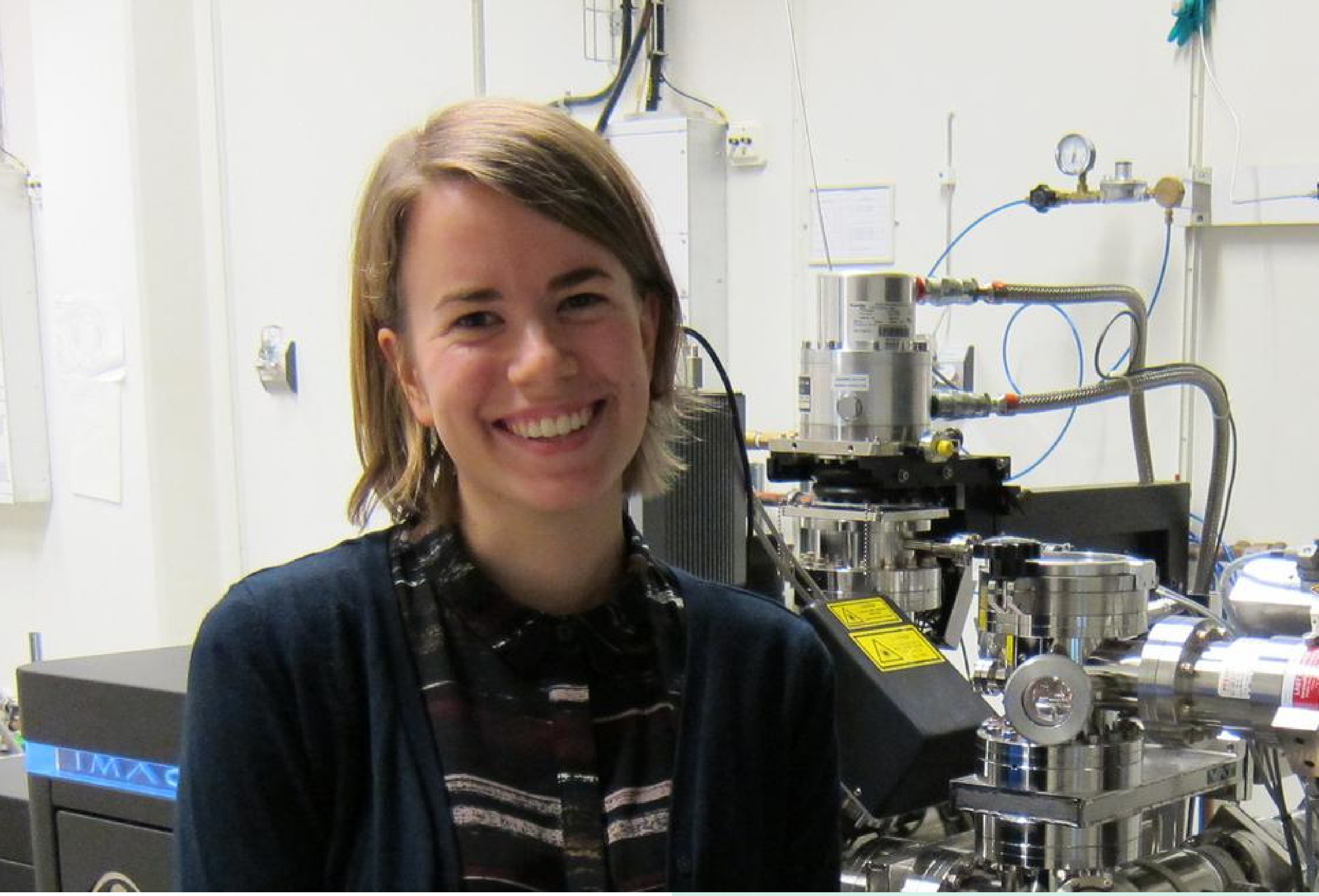
Dr. Sigvard Eklund
19 June 1911 - 30 January 2000

Sigvard Eklund's prize

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.



Best doctoral thesis 2020

Kristina Lindgren

The independent jury evaluating nominations has unanimously recommended that Kristina Lindgren be awarded the Sigvard Eklund's prize for her doctoral thesis.

In the jury's opinion, the nominated thesis is a good collection of systematic experimental investigations. The topic of the dissertation fits well into the scope of the prize and aligns well with the disciplines that SKC prioritises, as a deep understanding of the evolution of structural materials is vital to safe and sustainable long-term operation of any nuclear reactor. Furthermore, the author has displayed excellent understanding of her research topic and the experimental techniques used throughout the thesis.

"I feel very honoured to win the Sigvard Eklund prize. I would like to stress the importance of finding a research project that is interesting and challenging, a supervisor that you work well with, and a research group that supports you and with whom you can have a good time. If you find that, chances are higher that you will enjoy your years as a doctoral student, which in then end affects the quality of the work! I have also had the benefit of having a close contact with both the industry and a doctoral student at KTH, which really helped me with the understanding of the topic."

Effects of Irradiation and Thermal Ageing on the Nanoscale Chemistry of Steel Welds

Doctoral thesis written by
Kristina Lindgren

and supervised by
Prof Mattias Thuvander

Department of Physics
Chalmers University of Technology

Abstract

Structural materials of nuclear power plants degrade during operation due to thermal ageing and irradiation from the reactor core. Effects on the materials are an increase in hardness and tensile strength, and a decrease in ductility and fracture toughness, i. e. embrittlement. The degradation of the mechanical properties stems from changes in the microstructure. In this thesis, the effects of thermal ageing and irradiation on the nanoscale chemistry has been studied using atom probe tomography (APT).

During irradiation, nanometre sized clusters are formed in the reactor pressure vessel (RPV) welds. As the RPV is a life-limiting part of a nuclear power plant, neutron irradiation with high flux is attractive for accelerated studies. Here, the effect of high flux is found to result in a higher number density of smaller NiMnSi-rich clusters for the high Ni and Mn - low Cu welds from Ringhals R4, resulting in similar hardening compared to surveillance material. It is also found that there are some stable matrix defects formed in the high flux material, contributing to the embrittlement. The cluster evolution showed no signs of late blooming phases (an accelerated degradation at high fluences). Furthermore, thermal ageing during operation for 28 years of a weld from the former Ringhals R4 pressurizer with similar composition is found to result in clusters forming mainly on dislocations, hardening the weld metal.

In ferrite with higher Cr-content, such as the ferritic parts of the mainly austenitic welds from the core barrel of the decommissioned Spanish reactor Jos´e Cabrera, spinodal decomposition occurs as well as G-phase ($Ni_{16}Si_7Mn_6$) precipitation. Weld metals irradiated up to 2 dpa are compared with thermally aged welds, confirming that the irradiation is considerably contributing to the changes in the microstructure. After 0.15 dpa, the spinodal decomposition was well developed, and the Cr concentration in the ferrite was found to influence the wavelength more than the difference in irradiation (0.15 to 2 dpa). The G-phase precipitates were more well-developed after 1 dpa neutron irradiation, but no difference could be distinguished between the material irradiated to 1 and 2 dpa.

ISBN 978-91-7597-825-3
Doktorsavhandlingar vid
Chalmers tekniska högskola

Ny serie nr 4506
ISSN 0346-718X

Fredrik Dehlin

I am deeply honoured to be a co-winner of the Sigvard Eklund prize for the best master's thesis 2020 and I can't even begin to describe how happy I am for my work to be recognized by the committee.

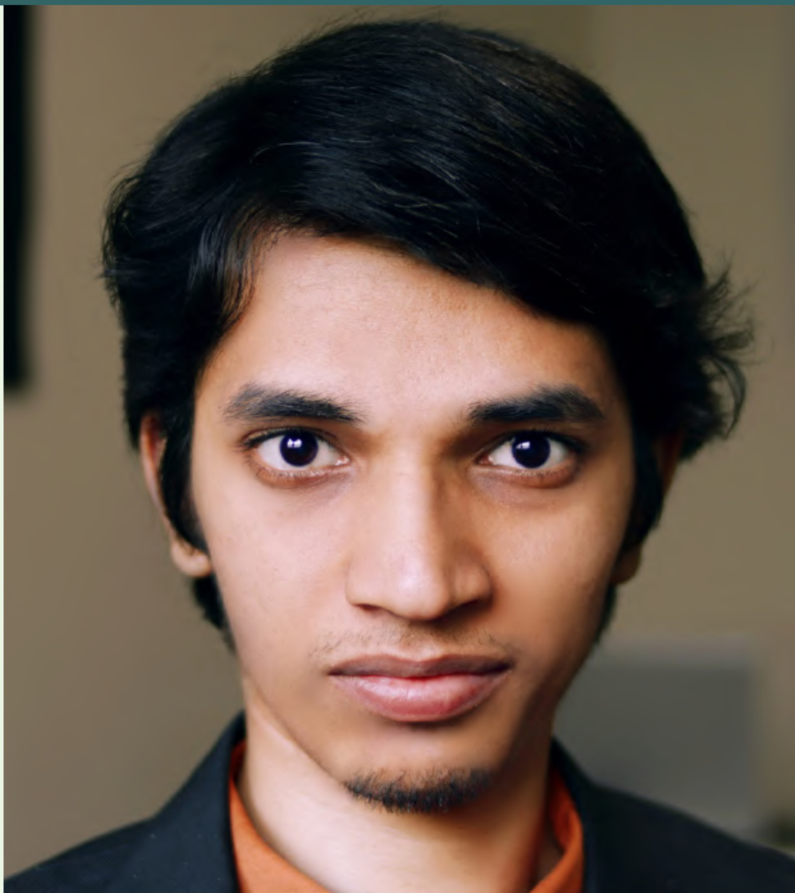
This win proves how important it is to work hard and to be meticulous in everything I do, and it also gives me a large boost of self-confidence which I can bring with me when I start my doctoral studies.

Best master's theses 2020

Contrary to common practice, SKC has decided to award the prize for the best master's thesis to two young talents. The prize is awarded to Fredrik Dehlin and Govatsa Acharya jointly. In the words of the jury, both authors demonstrate excellent examples of crucial development in a technology field where the scientific development for decades has not managed to keep pace with the urgency of humankind and society regarding durable low-carbon power technologies. The authors also make it clear that the emerging generation of engineers and scientists is capable of turning their recently gained engineering skills into practical solutions of high value to the society. Moreover, the authors show an excellent example of cooperation that strengthens the results of the individuals.

Govatsa Acharya

I believe in acquiring knowledge as a foundation where one can contribute to discovering new knowledge and expanding the boundaries of what we know. Having a focused mindset dedicated to analysing complex issues, my master's studies at KTH culminated in a very interesting thesis. It is an honour that this piece of work was co-awarded the Sigvard Eklund Prize 2020. This recognition only goes to show that with passion and persistence in the field of work, right guidance and a bit of ingenuity, one can contribute to advancement in science. With this win, I am super motivated and look forward to an exciting future in research.



Implementation of an Autonomous Reactivity Control (ARC) system in a small lead-cooled fast reactor

Master's thesis written by
Fredrik Dehlin

and supervised by
Dr Sara Bortot

School of Engineering Sciences
KTH Royal Institute of Technology

Abstract

The Autonomous Reactivity Control (ARC) is a state-of-the-art, innovative safety system, proposed to be implemented as a self-actuated passive safety system in Generation IV liquid metal cooled fast reactors. It is intended to address one of the safety objectives staked out by the Generation IV International Forum; Generation IV nuclear energy systems operations will excel in safety and reliability. This master's thesis studies the design, implementation and characterisation of an ARC system in a small lead-cooled fast reactor and intends to demonstrate the contribution to reactor safety during an anticipated transient without SCRAM.

A hot-state model of the core was developed, and the neutronic characteristics were studied using the Serpent2 Monte Carlo code. A model of the ARC system was developed and implemented in the BELLA multipoint dynamics code, in which analyses of transients were performed. It was shown that the ARC system provides stringent negative reactivity feedback during a transient. The steady-state temperatures were reduced by almost 300 K, compared to an identical transient without the ARC system.

Future investigation and development of the ARC system are of great interest to the development of reactors cooled by liquid metals. It can be of particular relevance to developers of sodium reactors currently facing issues with sodium boiling during transients.

TRITA-SCI-GRU ; 2019:128

DiVA, id: diva2:1330701

Investigating the Application of Self-Actuated Passive Shutdown System in a Small Lead-Cooled Reactor

Master's thesis written by
Govatsa Acharya

and supervised by
Dr Sara Bortot

School of Engineering Sciences
KTH Royal Institute of Technology

Abstract

The application of passively or self-actuated passive safety systems in nuclear reactors allow to simplify the overall plant design, besides improving economics and reliability, which are among the high-level goals set out by the Generation IV International Forum. This thesis focuses on investigating the application of a self-actuated, passive shutdown system for a small, modular lead-cooled fast reactor, and on its implications on the dynamic response to an initiating event.

The application of passive shutdown systems for a lead-cooled reactor is not studied extensively, due to the general consensus that lead as a coolant, is too dense to achieve any passive shutdown by gravity. On the contrary, dense liquid lead as a coolant is viewed to be extremely efficient in buoyancy-driven passive shutdown. Initially neutronic parameters were determined using a combination of Monte Carlo codes, OpenMC and Serpent, by carrying out sensitivity analyses on a critical, hot-state core at middle of life. The reactivity worths of the intended shutdown assemblies and control assemblies were then determined. According to a first-order approximation approach, the passive insertion of shutdown rods was assumed to be influenced by gravity, pressure drag and viscous drag due to flow against the assembly and finally the buoyant force.

Sensitivity analyses were performed for a spectrum of models with varied drag coefficients, in addition to determining the effect of addition of ballast to the assembly and finally to assess the effect of changing coolant flow rate. The time of insertion of the shutdown assembly from its parking position in the core was determined for each of these scenarios. An optimised shutdown foot profile was designed to allow the quickest passive insertion and then implemented in BELLA multi-point dynamics code, in order to perform dynamic analyses of a transient overpower scenario. This study provides evidence for the viability and reliability of gravity-driven shutdown systems in a heavy liquid metal cooled reactor, and also providing specific data for buoyancy-driven insertion.

Further studies could be carried out to investigate the application of such systems in different reactors cooled by, for instance, lead-bismuth or mercury, and also to improve the efficiency of safety systems in sodium cooled reactors.

TRITA-SCI-GRU ; 2019:127

DiVA, id: diva2:1330700

Doctoral thesis

- 2020 Kristina Lindgren, Chalmers
- 2019 Mattia Bergagio, KTH
- 2018 Klas Jareteg, Chalmers
- 2017 Zsolt Elter, Chalmers
- 2016 Luca Messina, KTH
- 2015 Cheuk Wah Lau, Chalmers
- 2015 Klara Insulander Björk, Chalmers
- 2014 Victor Dykin, Chalmers
- 2013 Cláudio Miguel Lousada Patrício, KTH
- 2012 Anders Puranen, KTH
- 2011 Chi Thanh Tran, KTH
- 2010 Andreas Enqvist, Chalmers
- 2009 Åsa Henning, LU
- 2008 Olivia Roth, KTH
- 2007 Carl Sunde, Chalmers
- 2006 Marcus Eriksson, KTH
- 2005 Staffan Jacobsson Svärd, UU
- 2004 Christophe Demazière, Chalmers

Master's thesis

- 2020 Govatsa Acharya, KTH
- 2020 Fredrik Dehlin, KTH
- 2018 Anna Benarosch, KTH
- 2017 Mimmi Bäck, KTH
- 2016 Alicia Marie Raftery, KTH
- 2015 Giulio Imbalzano, KTH
- 2014 Kaur Tuttelberg, KTH
- 2013 Claudio Torregrosa Martin, KTH
- 2012 Antoine Claisse, KTH
- 2011 Martin Lundgren, Chalmers
- 2010 Paul Bramson, KTH
- 2009 Petty Bernitt Cartemo, Chalmers
- 2008 Andreas Carlson, KTH
- 2006 Simon Walve, KTH
- 2005 Henrik Lindgren, KTH
- 2004 Dereje Shiferaw, KTH

Bachelor's thesis

- 2019 Daniel Fransén, KTH
- 2018 Daniel Karlsson, KTH
- 2018 Amanda Rasmussen, KTH
- 2016 Fredrik Höök UU
- 2016 Adam Bruce, UU
- 2015 Johan Larsson, UU
- 2013 Johan Erlandsson, UU
- 2013 Patrik Berg, UU
- 2012 Azur Bajramovic, UU
- 2011 Katja Göller, UU

Student engagement

Every year, the three Swedish universities that stand for the majority of nuclear technology education hold career fairs. It is the purpose of these career fairs to connect students on the brink of their career with prospective employers. Despite SKC not offering available positions, the centre has nevertheless participated in the career fairs - to assist in guiding job-seekers towards the multitude of employers in the Swedish nuclear energy sector, whether they are or are not represented in the career fairs.

In 2020, SKC's booth was set up at two fairs. As most other activities in 2020, the career fairs held in the autumn were influenced by the Covid-19 induced restrictions. Consequently, the venues of the events were digital and the booths of all participants were hosted online by a service provider Graduateland. The benefit of the format proved to be the convenience of attendance for the students and the team members alike. It also significantly reduced the carbon footprint of the booth, since marketing material did not need to be printed or prepared. On the other side, communication restricted to the chat function of the platform eliminated the opportunity to casually attract the attention of students. It also lowered the threshold for students' engagement and inviting many to phish for available positions with identical sales pitches, in essence eliminating the need for a booth at a career fair. The overall impression is that virtual career fairs in particular have a low benefit to cost ratio for SKC and SKC's financiers.

Uppsala University held its annual career fair Utnarm on the 5th of November 2020. During this one-day event, over 40 students from the university were assisted, coached and advised by a team of professors and researchers from Uppsala University, from Forsmark's HR and by SKC. The vast majority of students that initiated a conversation with SKC were fluent in Swedish, had a Swedish citizenship, and were enrolled in a programme or courses related to nuclear technology. Many had already personal ties or information on potential employers in their region, with Forsmark being the most popular. The team also organised a questionnaire to engage students. Those who received most points were later awarded with SKC takeaways, which were very positively received.

The annual career fair Armada, organized by the Royal Institute of Technology, was held on the 17th and the 18th of November 2020. The booth was manned with dedicated representatives from SKC, KTH, Ringhals and Forsmark who assisted over 40 students with advice on potential employers and career tracks. The vast majority of students that approached the booth had an international background with no or very limited Swedish language skills and a non-Swedish citizenship, which significantly limits their employability. The majority of students that engaged with SKC had no nuclear background. During the two days, no student from KTH's Nuclear Energy Engineering Master's programme engaged in a conversation with SKC.

Communications

Nuclear research status

In the spring of 2020, the Swedish Energy Agency commissioned Oxford Research to map Swedish resources, investments and gaps in research and innovation related to nuclear power research. SKC has contributed to this work through documentation and interviews. The issued report, Kunskapssammanställning om forskning och innovation på kärnkraftsområdet i Sverige, illustrates that total funding of nuclear R&D in Sweden has been steadily decreasing for over a decade. The report also highlights the relevance of SKC in the continuation of nuclear research and education in Sweden.

Social media

SKC's primary means of communication to date, excluding personal meetings in pairs or groups, has been arranged via the centre's website and targeted emails. Although these means of communication serve their purpose, none are ideal for communicating news to a broader audience and enabling the organic spread of information.

As of autumn 2020, SKC maintains social media accounts on LinkedIn and Facebook. The communication via these channels has been kept infrequent but relevant, posting information on the symposiu, the Sigvard Eklund's prize winners and the Energy Dialogue symposium. The intention is to slowly ramp up the rate of posting, but the ensure that the information exchanged will be kept relevant to SKC. A detailed communication strategy for SKC will be developed during 2021.

Despite the limited posting, both platforms are gaining followers. Drawing attention to the profiles of Sigvard Eklund's prize winners in particular has led to an organic growth of interest towards SKC and the winners profiles. A comparison of social media posting dates with theses download rates also confirms that posts on social media have a significant impact on the dissemination of research.

In addition, SKC has been profiled via Forsmark's social media channels. Forsmark's communication experts have also contributed to SKCs visibility by recording and editing video material introducing SKC to students.

Energy Dialogue

In November 2010, the conference KTH Energy Dialogue was held as a live digital broadcast with special focus on the country's energy competence centres. SKC was invited to present its goals, the current research project portfolio and the impact of the centre to an audience engaged in the energy sector. All SKC-funded projects were also invited to record and submit a 3-minute overview of their project, to be uploaded to a virtual gallery. Many researches captured the opportunity to share their work and thereby also raise the profile of nuclear technology research.

Media

SKC's annual symposium has increased the centre's visibility within KTH, resulting in a news article about the symposium and SKC. The article, titled A hub for nuclear technology knowledge and competence, can be accessed at KTH's website.

BASE FUNDING

Chalmers University of Technolgoy

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.

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).

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, work in areas of direct interest to SKC: PhD student Huaiqian Yi, PhD student Kristoffer Tofveson Pedersen, PhD student Hirepan Palomares Chavez, and Post-Doc researcher Antonios Mylonakis.

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 Division is also driving research projects with national funding: the VR-sponsored HYBRID project on hybrid neutron transport methods applied to fast reactors and the SKC-sponsored XEROM project on Reduced Order Modelling of nuclear reactors.

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 perfectly suited to distant education and life-long learning. As a result of its expertise and following the same pedagogical principles, the Division is coordinating a newly launched Horizon 2020 project called GRE@T-PIONEeR. 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 newly started master course in Computational Continuum Physics course, 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 (1 student will actually do his MSc thesis project in 2021 on reactor physics).

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.
Finally, Prof. Demazière is one of the recipients of the 2020 Chalmers pedagogical prize.

Division of Microstructure Physics for 2020

The funding has mainly been used for the salary of Assoc. Prof. Mattias Thuvander. He is a supervisor for two PhD students and one post-doc 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 received the Sigvard Eklunds price for best PhD-thesis in 2020. 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.

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 partly working on ATF and partly on irradiation effects on traditional cladding tubes, a project funded by Westinghouse, Vattenfall, OKG and EPRI, which is also a part of MUZIC-3.

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

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 3 more PhD students and a PhD are foreseen to be employed in the beginning of 2021.

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). The funding will be used to cover the activities of Professor Christian Ekberg, Assoc. Professor Teodora Retegan Vollmer, Dr. Stefan Allard and Dr. Stellan Holgersson which are actively involved in teaching and research.

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

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 on-line teaching, learning and evaluation. We do have a close contact with our colleagues on physics from GRE@T-PIONEeR.

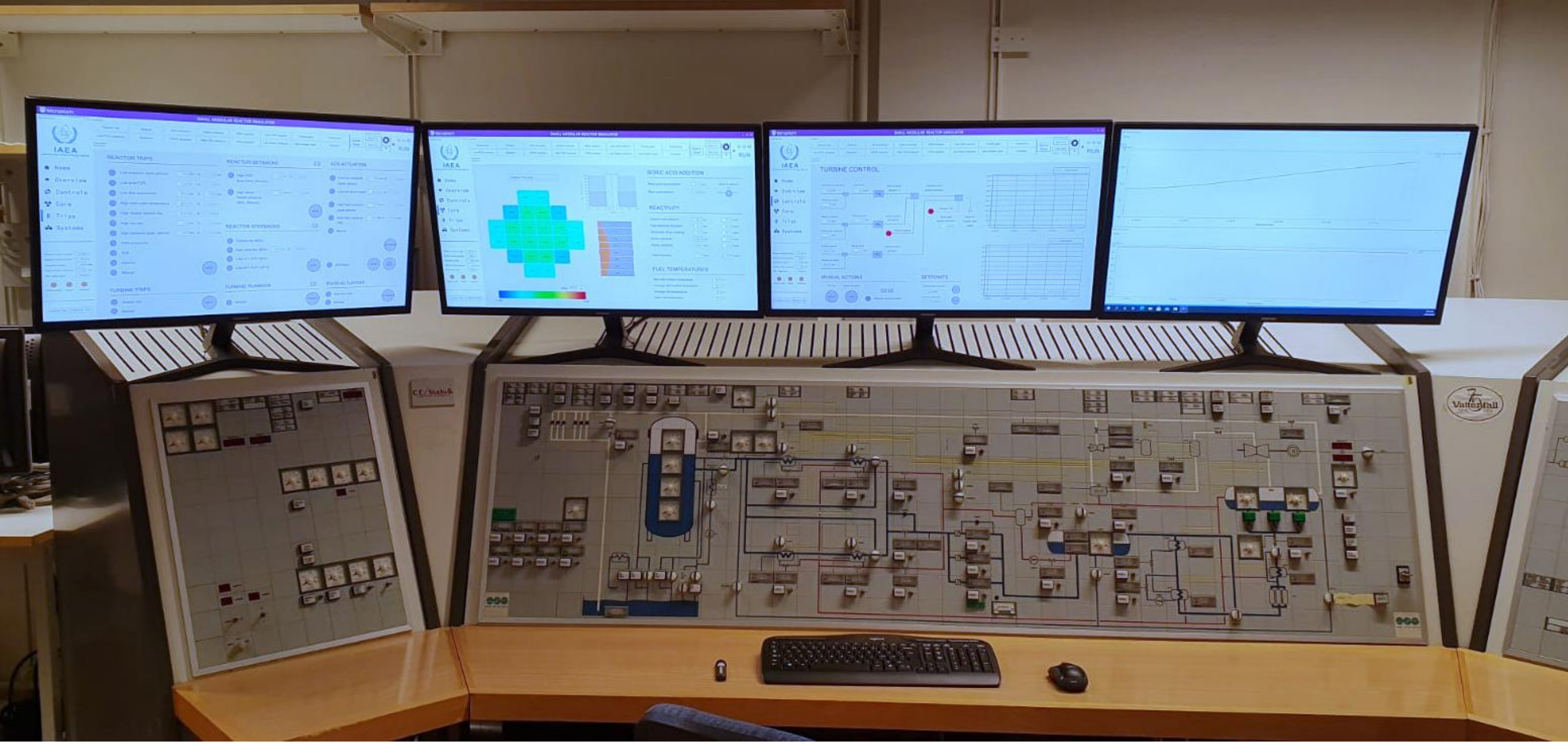
As our colleagues, we are active in various networks in Sweden (SKC, SAINT, and a collaboration with KTH) as well as international (ENEN, ANS, SNETP) as well as international collaboration on several EURATOM projects relevant for SKC.

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 2020. 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 200 students have been admitted to the Programme. In 2020 the number of enrolled students was 23. The SKC base funding to KTH in 2020 was used to pay partial salaries of the director and the deputy of the Master's programme for their management of the programme and development of education tools, and partial salaries of teachers who taught courses in the programme (see details below).



With the development of technology, it is only natural that the laboratory equipment at universities gets an update. The analog control panel of Forsmark 3, once used as a simulator for student exercises, no longer works. It now serves a new purpose as a stand for the new, server-run IAEA simulator at KTH.

SKC base funding

The SKC base funding to KTH has been a vital component in keeping the critical activities of Nuclear Engineering education alive at KTH, since they are not fully supported by KTH alone, following the historical decision to phase out nuclear power in Sweden.

The SKC base funding to KTH in 2020 went to the critical functions, such as the partial coverage of salaries of the faculty and staff who are heavily involved in teaching courses and management of the Nuclear Energy Engineering Master's programme (TNEEM, EMINE, Dual diplomas). Apart from the strong mandatory courses, the Master's programme has a wide variety of high-quality elective courses. The use of internal KTH funds alone is hard to maintain such an educational programme attractive and competitive, since some courses are simply too small in the KTH educational economy model, but still provide critical components supporting the programme. The SKC base funding helps support the Master's programme as a whole and is most probably one of the main reasons the Master's programme achieved the highest grade by UKÄ in their last evaluation (one of only five such grades at KTH out of the fifty Master's programmes).

Teaching in Nuclear Energy Engineering Master's programme

This incurs the costs of Profs. Pär Olsson, Henryk Anglart and Janne Wallenius as well as Assoc. Prof. Jan Dufek and Dr. Vasily Arzhanov who spent times on preparation of teaching materials for the courses in the Master's programme, and on supervision of postgraduate students (see the table below).

Management of Nuclear Energy Engineering Master's programme

This incurs the costs of the director and the deputy of the Master's programme: Prof. Jan Dufek and Dr. Vasily Arzhanov who spent times to manage the Master programme at KTH.

Development of Möbius problems for Nuclear Reactor Physics course

The most effective way of learning reactor physics comes via solving a large and varied set of problems. For the past several years, the Möbius electronic platform have been employed for this purpose. This platform allows setting unique problem parameters for each student. Students also get immediate feedback on their results and the complete derivation of the correct solution.

The specific usage of the SKC base funding to KTH in 2020

Person	Teaching courses / other educational activities	Costs [SEK]
Prof. Henryk Anglart	• SH2701 Thermal-Hydraulics in Nuclear Energy Engineering • SH2702 Nuclear Reactor Technology • SH2706 Sustainable Energy Transformation Technologies • Supervision of 1 doctoral student	200,000
Prof. Pär Olsson	• SH2605 Radiation Damage in Materials • SH2007 Research Methodology in Physics • SH2774: Numerical methods in nuclear engineering • Supervision of 6 doctoral, 3 master's and 3 bachelor's students	350,000
Prof. Janne Wallenius	• SH2611 Small Reactors • SH2613 Generation IV Reactors • SH2614 The Nuclear Fuel Cycle • Supervision of 2 doctoral and 3 master's students	200,000
Assoc. Prof. Jan Dufek	• SH2600 Nuclear Reactor Physics • SH2703 Nuclear Reactor Dynamics and Stability • SH2704 Monte Carlo Methods and Simulations in Nuclear Technology • Möbius problems for Nuclear Reactor Physics course • Virtual simulator for reactor exercises in Nuclear Reactor Physics course • Management of the Nuclear Energy Engineering master's programme at KTH • Supervision of 1 doctoral student	380,000
Dr. Vasily Arzhanov	• SH2615 Neutron Transport Theory • SH2774 Numerical Methods in Nuclear Engineering • Management of the Nuclear Energy Engineering master's programme at KTH • Supervision of 5 master's students	183,000
Misc	• CEKERT's administration	20,000
Total		1,333,000

By the end of 2019, only a rather small set of problems has been implemented in Möbius since the derivation and implementation of the problems is very time-consuming. Therefore, during 2020 a relatively heavy investment from the SKC base funding was directed to the development and implementation of a large new set of advanced reactor physics problems in Möbius. In total, 140 new problems (with derivations of their solutions) were implemented into the electronic platform and these new problems were already used during the course. This allowed us to introduce a new structure to the electronic problems: from this year, students get two sets of problems every week. The first set of problems is non-graded, and its purpose is to train students to solve advanced problems without being afraid of being graded. The second set of problems is graded students collect points that count towards their final grade. The newly implemented problems were also used during the electronic written exam.

Virtual simulator for reactor exercises in Nuclear Reactor Physics course

The Covid-19 pandemic has not allowed the traditional reactor training of the Master students on a research reactor during 2020. In summer 2020, it was therefore decided to buy and set up a new multi-monitor computer environment with virtual reactor simulators and develop instructions for two four-hour laboratory sessions (for an eight-hour laboratory exercise). The first laboratory exercise is based on the iPWR-SMR simulator licensed from IAEA. This simulator represents the complete power plant, and it allows students to practice plant start-up, load maneuvering, determination of core reactivity feedbacks, and experiencing the xenon poisoning after reactor shutdown. An original instruction manual was developed for this exercise. The second laboratory exercise is based on the TRIGA research reactor (created by Reactor Physics Division of Jozef Stefan Institute in Ljubliana, Slovenia). On this simulator, the students practice critical experiment, reactivity measurement, control rod calibration, reactor kinetics and reactor dynamics behavior. An original instruction manual was developed for this exercise as well.

Uppsala University

The nuclear technology research and education at Uppsala University cover a broad range of different 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 base funding

SKC's base support is used for supporting teaching, supervision on all levels, our rather extensive outreach, and to support various aspects of our research. The latter means, for example, that we can support initiatives that are outside our regular activities aimed at exploring opportunities for new research projects.

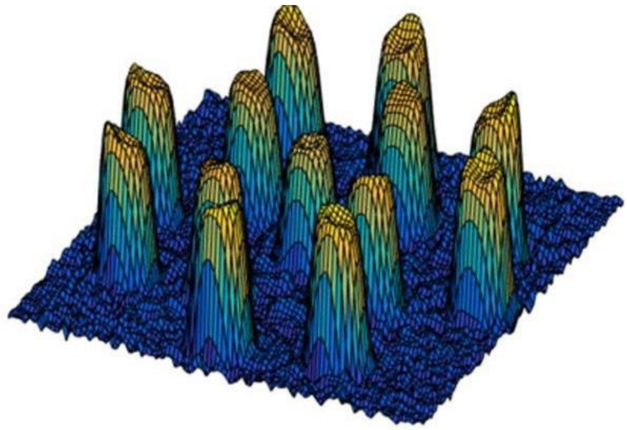
During 2020, the base funding was used to support Peter Andersson, Andreas Solders, Mattias Lantz, and Erik Andersson Sundén for their work with performing and developing teaching; supervision at various levels; development of infrastructure; and performing research. Their contributions during 2020 are listed below.

In line with last year's request, some of the fixed support has been used to support Peter Andersson's establishment grant from VR (see below) and especially the work with establishing a collaboration with INL regarding fuel development. In the same spirit, some of the funds were used to support Andreas Solders and Ali Al-Adilis establishment grants from VR (see below). All projects contain Ph.D. students and an important part of the base funding is used to provide supervision and training of these students.

Research projects partly financed from SKC base funding.

Nuclear Fuel Diagnostics, Peter Andersson

This project aims to develop non-destructive techniques, spectroscopy and tomography, for post-irradiation examination of nuclear fuel. This is particularly important for the understanding of the behavior of the fuel in accident scenarios. Using the penetrating gamma rays from the fuel, the internal properties of nuclear fuel can be examined. For example, the activity of the long-lived radionuclide 137Cs is a good indicator of local burnup in nuclear fuel, and short-lived 140La/Ba is a good indicator of the heat-rate in the last weeks of operation. Other phenomena that may be studied are the migration of radioactive cesium and iodine inside the fuel, and the release of fission gasses from the fuel to the plenum region of the nuclear fuel rods. In particular, the technique has found use in destructive fuel tests, such as in-pile LOCA transient tests, where fragmentation and relocation are of interest to study.

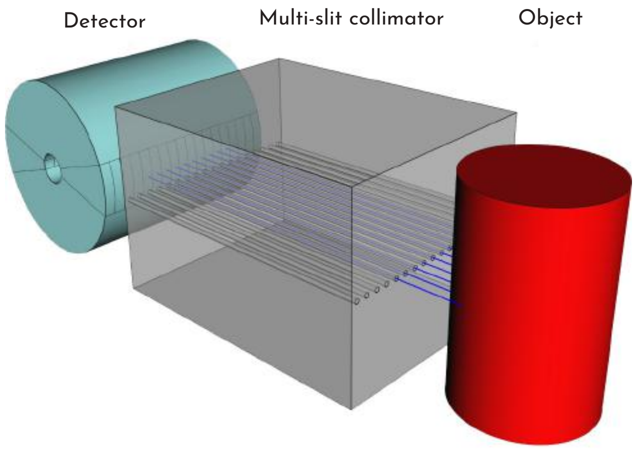


Distribution of 137Cs in 13-pin fuel bundle from the Halden reactor. Source.

The spectroscopic techniques can be applied at the reactor site (either at power or research reactors), as well as in hot-cell facilities. By complementing the destructive PIE that requires hot-cell facilities, it enables to gather more data on fuel performance with less cost. It may also contribute to faster learning and licensing in the introduction of new fuels.

The focus in 2020 has been on two topics, the development of segmented high-purity germanium detectors, in order to enable simultaneous data collection in multiple positions with a single detector. Such detectors can be used to increase data collection rate, and can thereby allow for higher position resolution in the obtained images. An optimized geometrical configuration was obtained and is shown in the figure below. Procurement of an instrument is foreseen during 2021.

In addition, a new focus in the project is the development of high position-resolution gamma-ray transmission densitometry, using strong Co-60 sources that irradiate the fuel. The attenuation is used to determine the density, and correspondingly the fuel swelling. This work is performed in collaboration with Studsvik Nuclear AB, and the expectation is to



Segmented high-purity germanium detector for simultaneous interrogation of multiple lines of sight. Small segments are used for localization of gamma-ray entrance, and large segments are used for retrieving the full energy of the incident gamma, which may scatter in several locations in the detector volume. [1]

obtain radial density measurements of irradiated fuel samples with position resolution in the 100 um range. In 2020, feasibility studies were performed in order to judge the viability of such techniques and during 2021 such an instrument is planned to be taken into active use for the examination of fuel pellets from Swedish power plants.

Two Ph.D. students, Vikram Rathore and Lorenzo Senis, are being supervised within the Nuclear Fuel Diagnostics project.

Works published in 2020

[1] V. Rathore, et al., "Geometrical Optimisation of a Segmented HPGe Detector for spectroscopic Gamma Emission Tomography – A Simulation Study", accepted in NIMA (2021)

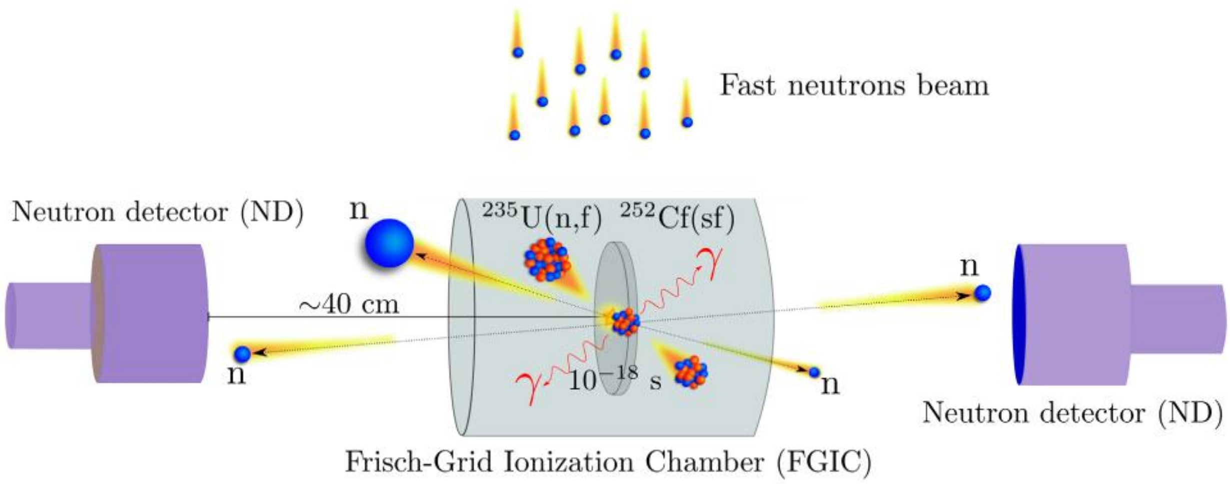
[2] P. Andersson, et al., "Simulation of the response of a segmented high-purity germanium detector for gamma emission tomography of nuclear fuel", AN Appl. Sci. 2 (2020) 271.

[3] H Atak, et al, "The degradation of gamma-ray mass attenuation of UOX and MOX fuel with nuclear burnup", Progress in Nuclear Energy 125 (2020)

Fission observables,
Ali Al-Adili

This research focuses on the physics of nuclear fission. Understanding the fission process is important for the safe operation of today's nuclear power systems since accurate fission data are pivotal in reactor criticality-, burn-up, and decay-heat calculations. However, there is a lack of accurate and conclusive description of neutron-energy dependence of most fission data in the nuclear data libraries.

The latest experimental advances in fission measurement techniques are being used to measure the number of neutrons emitted in the fast-fission of 235U(n,f). This is an important observable for



The ionization chamber (FGIC) and one neutron detector used to measure the prompt fission neutrons.

model development and for reactor calculations. Neutron detectors will be used in connection to an ionization chamber (see figure on the bottom of the previous page). Up to now, experiments on the thermal fission of 235U have been performed. The experiment was successfully performed and revealed the need for a new evaluation. With this data, the fission community can be provided with reliable and precise neutron yield data, which will be valuable in developing fission models.

Regarding fission yields, the instrument VERDI (Velocity for Direct Particle Identification) is being developed. The instrument measures the velocities and energies of the two fragments (see figure below), to allow for a precise determination of the mass yield. The instrument being developed is the spectrometer, which consists of an array of 32 Si detectors and two Micro Channel plates (MCPs). The efforts which have been put into this project have so far resulted in a major development of the setup, by including a second MCP for enhanced timing performance. The project was recently granted with a 4-year VR starting grant and the Ph.D. student Ana Maria Gomez Londono could be hired to work on this topic. First experiments are envisaged for this year, both at JRC-Geel in Belgium and at the ILL reactor in Grenoble, France.

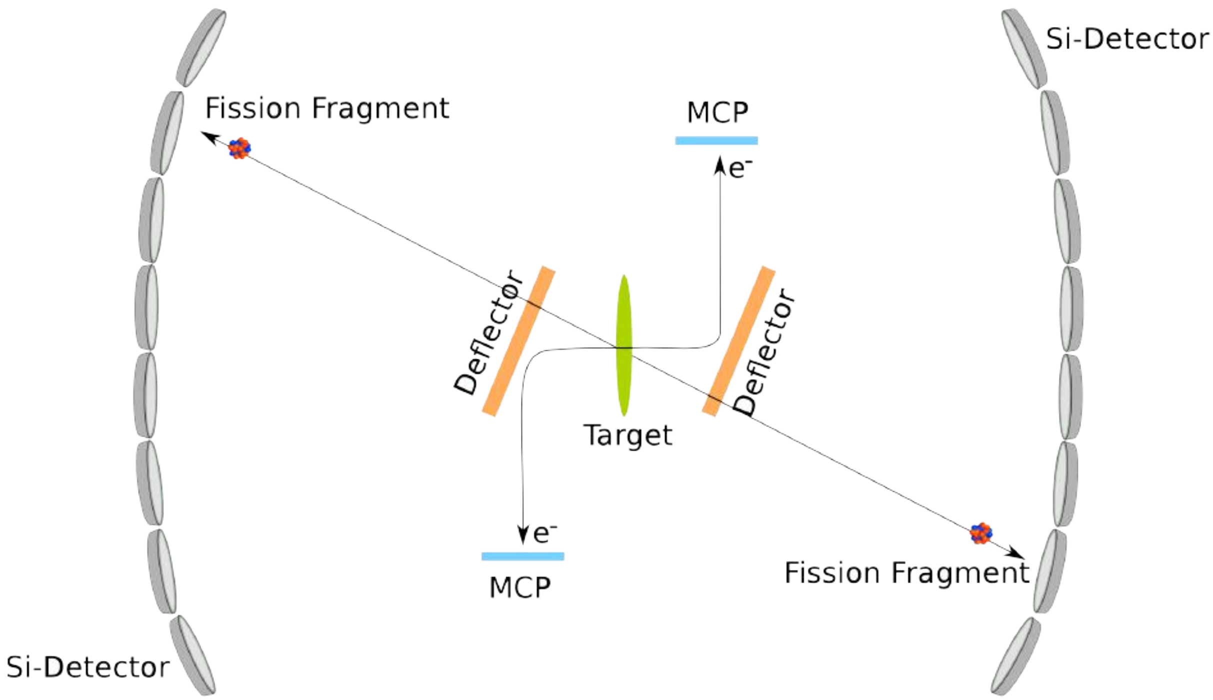
Works published in 2020

[1] Al-Adili, A., Tarrío, D., Jansson K. et al. "Prompt fission neutron yields in thermal fission of U-235 and spontaneous fission of Cf-252", Phys. Rev. C 102,064610, 2020.

[2] L. Qi, C. Schmit, et al. "Potential of prompt -ray emission studies in fast-neutron induced fission: a first step", Eur. Phys. J. A (2020) 56:98

Conferences 2020

[3] A. Al-Adili - Experiments on fission yields and neutron multiplicities, for enhanced fission modelling, IAEA CRP - coordinated research project on fission yields, (2020)



The VERDI spectrometer.

Fission yields for next-generation nuclear power, Andreas Solders

The purpose of the project is to obtain high-quality data on Independent Fission Yields (IFY), defined as the amounts of specific nuclides produced in fission. The inventory of fission products in the fuel of a nuclear reactor affects for example reactor operation (delayed neutrons, reactor poisons, burn-up monitoring), reactor safety (decay heat), and waste handling (final repository and reprocessing). With the development of Generation IV nuclear power, the change in the composition of the fuel, in combination with a different neutron spectrum, will alter the yields of fission products, which in turn will affect the inventory of the fuel during and after burn-up.

The main funding for the project comes from the Swedish Research Council through a Starting grant for New nuclear technology. The VR funding includes the salary of the Ph.D. student Zhihao Gao and parts of the supervision. The rest of the supervision, and the research done by the senior staff, comes partly from SKC Base funding. Furthermore, during 2020 two Master of Science students have been involved in the project, see the section Diploma works for more details.

So far, 19 isomeric yield ratios (IYR) from 238U(p,f) have been measured and the data is currently being analyzed. In 2020, Zhihao Gao has developed a dedicated analysis code using machine learning algorithms to deduce the yield ratios, and preliminary results have been obtained. Although proton-induced fission does not have a direct bearing on reactor applications it is important for the understanding of nuclear fission as a phenomenon and for improving contemporary fission models.

To facilitate neutron-induced measurement an intermediate goal of the project is to develop a proton-to-neutron converter and a dedicated ion guide for neutron-induced fission, to be used in experiments at the Ion-Guide Isotope-Separation-Online (IGISOL) facility at the University of Jyväskylä. For this purpose, a computer model of the converter and ion guide has been developed and benchmarked against a prototype of the setup. A preliminary report of this work was published as a conference proceeding in 2020 [1] and will form the basis of the licentiate thesis of Zhihao.

Works published in 2020

[1] Z. Gao, et al., Fission studies at IGISOL/JYFLTRAP: Simulations of the ion guide for neutron-induced fission and comparison with experimental data, EPJ Web of Conferences 239, 17019 (2020)

Infrastructure development partly financed from SKC base funding

Activities of the NESSA facility, Erik Andersson Sunden

The NESSA facility is being built by the Division of applied nuclear physics of Uppsala University. NESSA will be one of the strongest neutron generators of its kind in Europe. It is a deuterium-tritium neutron generator that delivers high-energy (14 MeV) neutrons.

The main purpose of the facility is to strengthen the experimental and teaching capabilities of the division. The work at the division that will benefit from the facility includes detector development (for current and future reactors), nuclear data measurements, studies of irradiation damages of electronic circuits, fuel development, and development of neutron tomography techniques.

In addition to the research, the facility will be used for teaching within summer schools of Ph.D. students as well as, on longer time scales, the development of neutron labs within the master and Ph.D. programs of Uppsala University.

The neutron generator will be delivered after the summer of 2021. The NESSA facility will commence operations in early 2022 after a site-acceptance test and calibration measurements of the neutron field.

The Covid-19 pandemic has impacted the finalization of the neutron facility, NESSA, since the U.S. vendor had put the production of the neutron generator on hold. This has delayed the start-up of NESSA until the autumn of 2021. However, SKC base support has been used to co-finance work on the facility's radiation protection, access control, etc.

Much of the preparatory work of the NESSA bunker has been completed, including strengthening the radiation shielding and installation of electricity and ventilation. Furthermore, the procurement of the dose monitoring system was finalized.

In addition, the Safety analysis report has been partly written. The Safety analysis report includes the calculated dose rates received by personnel as well as workers at the facility, routines for minimizing doses to workers, and a description of the security system of the facility. The safety analysis report of NESSA is the stepping stone to get authorization from the Swedish radiation authority to run the facility.

Activities with the UGGLA gamma measurement station, Mattias Lantz and Erik Andersson Sunden

The development of gamma measuring station UGGLA (Uppsala Generic Gamma LAboratory) has continued where Mattias Lantz has, among other things, supervised several diploma works. One important purpose of this project is to build up competence, primarily within the division but through the involved students also among future professionals, on environmental monitoring of radioactivity, which is of importance at, e.g., events with uncontrolled releases of radioactivity.

The UGGLA gamma measurement station is a set of High Purity Germanium (HPGe) detectors used for gamma spectroscopy on radioactive samples. A lead-shielded HPGe setup with 30% relative efficiency has since 2018 been the main workhorse for the citizen science project Strålande Jord and related studies. Other HPGe detectors are tested in temporary setups for different applications, and several students have been involved.

The main objective is to establish a reliable and well-calibrated measurement station that can be used for a number of different fields, including radio-ecology and neutron-induced activation studies.

In 2020, a set of student projects and two publications were completed. Funding was used to supervise the students and to complete the publications. The overarching goal has been to build up competence and infrastructure for gamma measurements at UU and to give students hands-on experience in radiation science and nuclear technology. In addition, a few tasks connected to public outreach have been performed (see below)

Student projects within the UGGLA project

A B.Sc project where the absolute efficiency of one of the detectors was investigated through a combination of measurements in different geometries and compared with Monte Carlo simulations. The main outcome of this project is two parallel recommendations. The first one, in order to improve a general absolute calibration, is to perform a tomographic investigation of the detector. The second is to use standardized reference samples for calibration of the measurements in the Strålande Jord project.

A B.Sc project where a thin HPGe detector was used in order to detect the Pb-210 decay from a column of sediment samples at different depths. The project, performed together with limnologists at Uppsala University, had an objective to investigate if the decay, which gives a photon with very low energy, could be distinguished from the background of higher energy photons. With appropriate shielding, this was achieved and the decay of Pb-210, with 22 years half-life, could be used as reference time in order to determine the sedimentation rate at the bottom of a lake. As a blind test, the Cs-137 signal could be used. It turned out that the peak of Cs-137 from the Chernobyl accident was positioned at the expected depth, though with a quite broad distribution.

Four high school pupils collected biological samples at two different locations and compared the results.

The main objective was to compare the difference in Cs-137 after the Chernobyl accident, but samples of certain moss species also contained Be-7 which is produced in the atmosphere through cosmic ray interactions.

Researchers in other fields, and private individuals, have asked for measurements of samples from nature. The purpose has been to find out if the samples include any relevant amounts of natural or anthropogenic radioactivity, such as K-40 in sediments from a glacier, or Cs-137 in mushrooms.

An ongoing MSc project is developing a methodology of using neutron activation analysis for accurate determination of the neutron field at the upcoming NESSA facility. Calculations and studies of standards are combined with measurements at UGGLA. In September 2020 a neutron activation experiment was performed at the neutron facility in Lund, followed by gamma spectroscopy measurements both in Lund and Uppsala of the irradiated samples.

Works published in 2020

Two articles were published [1, 2] during the year. The conference proceedings were both related to the Strålande Jord project, with one article focusing on the measurement technique and the other one on the citizen science aspects.

[1] C. Gustavsson et al., "Citizen science in radiation research", EPJ Web of Conferences, Vol. 238, 25001 (2020).

[2] M. Lantz et al., "Gamma spectroscopy methodology for large amounts of environmental samples in Sweden 30 years after the Chernobyl accident", EPJ Web of Conferences, Vol. 239, 25002 (2020).

SKC supported Education

The SKC funded teachers and researchers have worked with several SKC relevant courses. They have contributed to these courses, by teaching, examination, and developing material. In particular, due to the pandemic, substantial efforts were made to allow for remote teaching, e.g., developing and integrating video material into the courses.

Although the pandemic severely hampered activities during 2020, it also offered an opportunity in the sense that UU offered various summer courses to people who have been released due to the pandemic. In this context, part of the SKC base fund could be used to develop an "introductory course in nuclear technology" that was given online during the summer with over a hundred applying students of which sixty could be offered a place.

Besides the summer course mentioned above, a number of courses in the regular education programs are given due to the possibility to finance teachers through the SKC base fund. The reason for this is that some of these courses attract few students and would not be offered without external financing. In the three Engineering master programs (Civilingenjörsprogram), STS, F, and ES the following SKC relevant courses have been taught and developed with support the SKC funded teachers:

- Future Nuclear Energy Systems - Analyses and Simulations

- Energy Physics II with Nuclear Energy

  Here, UU wants to highlight a development project where Andreas Solders developed a course concept using Jupyter Notebook. A Jupyter Notebook is an interactive document in which a descriptive (narrative) text can be mixed with executable code, equations, and visualizations. In this way, traditional textbook content is mixed with the interactivity found in for example the "apps" of mobile phones. This concept was integrated in Energy Physics II in 2020, and is planned to be continually applied to reactor physic tought at the devision.

- Nuclear Power - Technology and Systems

- Energy System Physics
  A substantial part of the course has nuclear engineering content.

- Safety Analyses in the Energy Sector
  Though not only a nuclear engineering course

this course covers PSA and DSA, tools with high relevance for the nuclear industry. In addition, the course uses nuclear power as a common example.

- Complex Systems in Technology and Society - Technology
  Though not only a nuclear engineering course this course covers PSA and MTO, two tools with high relevance for the nuclear industry, and it uses nuclear power as a common example.

During 2020, Andreas Solders was active in the program committee of the Energy System Engineering program (ES), where he continued to develop the "Nuclear engineering track" by developing "Computational Reactor Physics with Python", which will be offered as a summer course within and outside the program.

Diploma works

Funding has been used to support supervision and subject review of eight diploma works as listed in the table below.

Student	Level	Title of diploma work	Supervisor	Subject reviewer
Dany Gabro	M.Sc	Estimating fission fragment angular momentum using TALYS	Ali Al-Adili, Andreas Solders	Henrik Sjöstrand
WIlliam Bäckström	B.Sc	Dating lake bottom sediment by searching for Pb-210 using gamma-ray spectroscopy	Mattias Lantz	Andreas Solders
Anton Lundqvist, Elias Brådenmark	M.Sc	Tillgänglighetsanalys inom svensk kärnkraft	RiskPilot	Mattias Lantz
Emma Ekberg Berry	M.Sc	Analys av drivdonsslitage vid Forsmarks kärnkraftverk: För drivdon på Forsmark 1 och 2	Caroline Bohlin, Mikael Seppälä	Mattias Lantz
Mohammad Nori	M.Sc	Derivation of the angular momentum of primary fission fragments from isomeric yield ratio by TALYS using Python	Zhihzo Gao	Andreas Solders
Axel Sjöstrand	M.Sc	BWR Fuel failure statistics - Westinghouse fuel	Clara Anghel	Peter Andersson
Felicia Lapinski	B.Sc	Experimental studies at CERN-nTOF of the 230Th(n,f) reaction	Diego Tarrío	Ali Al-Adili
Robert Nilsson	B.Sc	Analysis And Correction Of The Error In The Determination Of The Specific Activity Of Caesium-137 In The Project Radiant Earth "Strålande Jord"	Cecilia Gustavsson	Erik Andersson Sundén

Public outreach

Formalized outreach, the third task, is included in the regular duties at a Swedish university. For mainly public reasons, nuclear power technology is a subject that requires more effort than is usually set aside for this task. Typical examples are contributions to the general debate by commenting and informing but also mobilizing special efforts towards strategic target groups as politicians, journalists, and young people. Our activities are extensive in that respect; some examples where researchers financed by SKC contributed are listed below.

- Mattias Lantz organized a workshop on 21 November on nuclear power and ionizing radiation for female high school students around the country within the framework of Uptown Tech.
- Peter Andersson and Ali Al-Adil created a nuclear Advent calendar spread via social media and attracted attention through the department news channel.
- A talk with the title "En radioaktiv resa mellan himmel och jord", arranged by Forskning & Framsteg and Folkuniversitetet, was held in September 2020 by Mattias Lantz. The talk included findings from some of the student projects that have been performed at UGGLA.
- Kulturnatten 2020 in Uppsala was in digital format. Peter Andersson and Mattias Lantz had a digital study visit to the radiation lab, where the visitors, over Zoom were shown different ways to measure and identify radioactivity. The visitors could ask questions and direct Peter and Mattias to do different kinds of measurements.
- Mattias Lantz has responded to a number of debate articles with incorrect statements about radiation effects in Fukushima and the climate impact of nuclear power.
- Peter Andersson and Mattias Lantz helped in organizing and manning the SKC booth Utnarm which is the Uppsala Union of Engineering and Science Students' annual career fair.

PROJECT PORTFOLIO

2012-1

Mechanical modelling of stress corrosion cracking in sensitized stainless steel 316

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

Main supervisor
Bo Alfredsson

Discipline
Solid mechanics

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

Formal project start
2012-08-31

Time of completion
2020-04-21

Motivation

Intergranular stress corrosion cracking is a degradation phenomenon that may develop at long time usage with primary (service induced) and/or secondary (generally manufacturing induced) static tensile loads on susceptible materials in the presence of an aggressive environment. If unattended, it may eventually lead to leakages and in its worst consequence, component or systems failures. One such application is piping systems in nuclear power plants where the water comprises the environment and the stainless steel in the pipes can be sensitized by heat-treatment, for instance welding, or cold work, such as grinding.

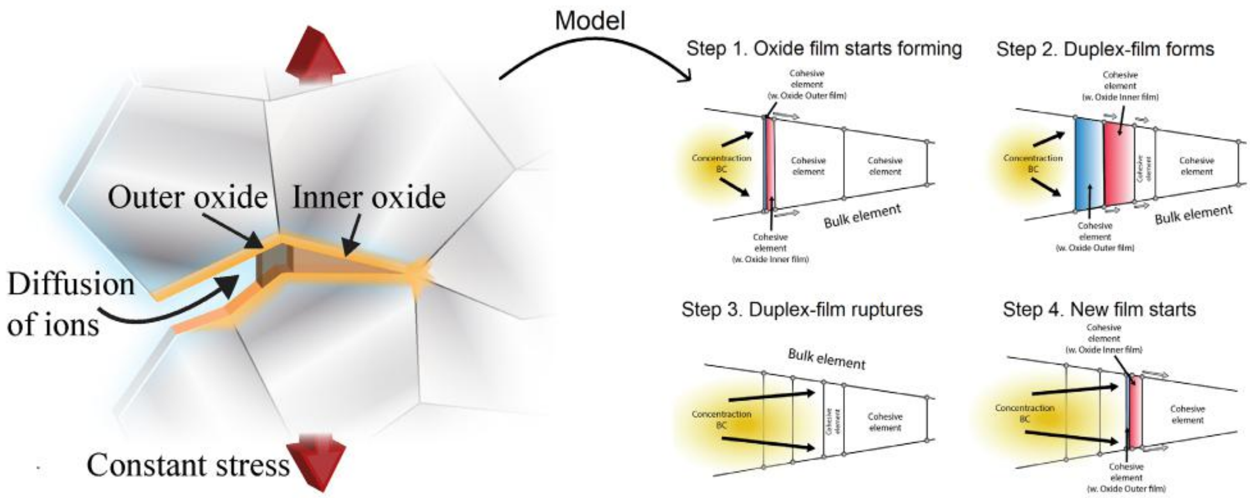
Although the damage phenomenon is well established, and measures are taken to minimize the risk by using materials with good resistance to stress corrosion cracking and carefully controlling the ion content in the cooling water, knowledge on the damage mechanism was incomplete. Therefore, the project was initiated to further the understanding on the environment degradation process with interaction between ions, crack tip loading, degradation of material toughness and damage. Improved understanding for the physical mechanisms involved would result in improved methods to safeguard against intergranular stress corrosion cracking during the remaining service life of our existing nuclear power plants.

Progress

The project started in August 2012 and continued to April 2020, when it ended with the dissertation of Michal Sedlak Mosesson. The thesis title is Modelling of intergranular stress corrosion cracking mechanism. Faculty opponent was Dr Thierry Couvant from Électricité de France (EDF).

Methodology

The model introduced in Michal Sedlak's PhD was developed in a modular framework. The first module updated is the electrochemical model. This module is undergoing changes, the total energy in the model is considered with Gibbs free energy using the chemical potential. The influence from

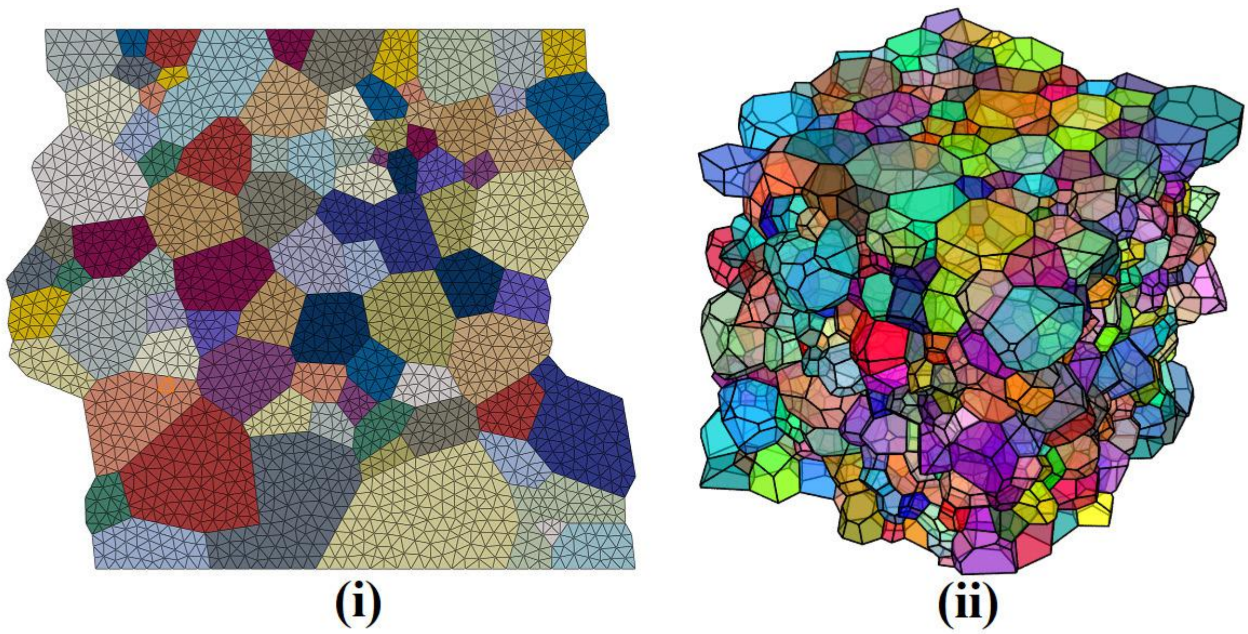


The representation of the adaptive framework of the FE-model on the schematic duplex-oxide growth

hydrogen embrittlement will also be implemented with Hydrogen enhanced plasticity (HELP) and for decohesion HEDE. The effect on the chromium mobility is also considered.

The oxidation module is transformed to an Integration point formulation instead of node formulation, still including the duplex-oxide, see the figure above.

The fracture mechanics module is enhanced with a crack path module, introducing cohesive elements in the grains with remeshing capabilities. The process will introduce the possibility of branching and both inter- and transgranular stress corrosion cracking. For both 2D and 3D, see the figure below.



A FE-representation of grains in a representative volume element, (i) 2D and (ii) 3D with symmetric boundary condition. For both inter- and transgranular cracks.

Communication

Two articles from the PhD project have been reworked. One is published and one is under review. All articles are sent to high ranked international journals in their respective fields and published open-access. Presented at Kärnteknikdagarna 2020. An abstract was submitted to the conference 20TH Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors (Aug 15-19).

Publications

M. Sedlak Mosesson, B. Alfredsson and P. Efsing, A duplex oxide cohesive zone model to simulate intergranular stress corrosion cracking, International Journal of Mechanical Sciences, vol. 917, art. no 106260, 2021.

M. Sedlak, B. Alfredsson and P. Efsing, A coupled diffusion and cohesive zone model for intergranular stress corrosion cracking in 316l stainless steel exposed to cold work in primary water conditions, Engineering Fracture Mechanics, vol. 217, art. no 106543, 2019.

M. Sedlak, B. Alfredsson and P. Efsing, A cohesive element with degradation controlled shape of the traction separation curve for simulating stress corrosion and irradiation cracking, Engineering Fracture Mechanics, vol. 193, pp. 172-196, 2018.

M. Sedlak Mosesson, B. Alfredsson and P. Efsing, A coupled diffusion and cohesive zone model with adaptive oxide thickness to simulate intergranular stress corrosion cracking, submitted for publication, 2020.

M. Sedlak, B. Alfredsson and P. Efsing, Modelling of IGSCC mechanism through coupling of a potential-based cohesive model and Fick's second law, In: ICF14, Proceedings of the 14th International Conference of Fracture, Rhodes, Greece, June 18-23, 2017.

M. Sedlak, B. Alfredsson and P. Efsing, Modelling of IG-SCC mechanism at LWR conditions through coupling of a potential-based cohesive model and Fick's second law, In: ENVDEG 17, 17th International Conference on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, Ottawa, Canada, August 9-13, 2015.

2016-1
*Ageing of Low Alloy Steels used for major components in Nuclear Power Plants**

Main supervisor
Pål Efsing

Discipline
Solid Mechanics

Keywords
Low alloy steel, thermal ageing, irradiation effects, cleavage fracture, brittle fracture, weakest link, long term operation, intergranular fracture, transgranular fracture, crystal plasticity

Formal project start
2016-04-01

Time of completion
2020-09-18

Research done by doctoral student
Magnus Boåsen

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

Motivation

The ability to assess the structural integrity of components in a nuclear power plant and to couple this to the ageing effects influencing the mechanical properties of the material is of utmost importance as long term operation nears the operating Swedish power plants.

Ageing of low alloy steels affects the structural integrity of operating components as it causes embrittlement and a hardening of the material. The hardening is caused by the evolution of the microstructure during operation. In nuclear applications, the most common causes of ageing of low alloy steels are irradiation and thermal ageing. Examples of components of high interest are the reactor pressure vessel, which is exposed to neutron irradiation, and the PWR pressurizer, exposed to the highest temperature in the primary system of a Pressurized Water Reactor Nuclear Power Plant, PWR-NPP.

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 project focused on the development 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 specifically to study the effects of thermal ageing on the mechanical properties of a low alloy steel.

The study is based on microstructural and mechanical property observations derived from both actual surveillance programs from the Swedish Nuclear fleet and from R&D work performed at Ringhals NPP. From this a basic understanding of active processes and their respective influence on the ageing

* *SSM was the primary financier of this project. SKC and Ringhals AB were secondary financiers.*

can be derived. By including a number of parametrical studies and experiments a firm basis for modelling of thermal ageing could be derived based on the observation of multicomponent degradation mechanism basis. The model description can then be transferred to the realm of irradiation effects by recognizing the similarities of the active mechanisms and resulting microstructures.

Progress

The project started in the spring of 2016 and continued until the fall of 2020 with the dissertation of the Ph.D: student Magnus Boåsen with a thesis entitled "Modeling of structural integrity of aged low alloy steels using non-local mechanics". The faculty opponent was Professor Jacques Besson of the Centre de Matériaux at Mines ParisTech, Paris, France.

Methodology

The project started with a series of fracture mechanical tests at KTH coupled with microstructural studies performed at Chalmers on aged welds from a retired component provided to the project by Ringhals AB. By tests on the aged material and reference materials provided in parallel the influence on the mechanical properties could be visualized and separated at the same time as vital information of be cause and effect was derived. Form the collected data, a physical model of the resulting fracture probability was derived based on the weakest link theory of the observed mechanisms and resulting hardening effect form the ageing.

Communications

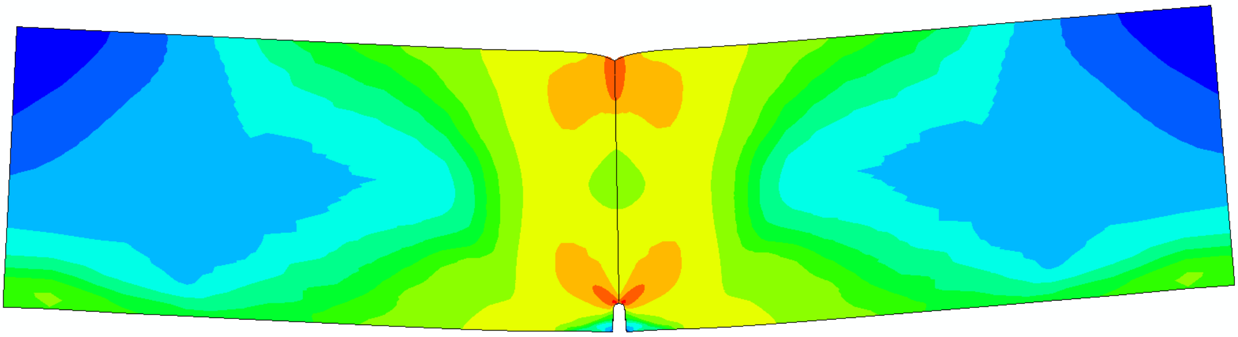
The project results have continuously been made public through publications in international journals with review procedures, and international scientific conferences with review procedures, at workshops with the nuclear utilities, and at the annual SKC Symposium. Four publication was included in the thesis, whereof three are published in the open literature, and the fourth is under finalization. The work was presented at The Fontevraud-9 conference, Contribution of Materials Investigations and Operating Experience to Light Water NPPs' Safety, Performance and Reliability in Avignon, 2017. A number of further publications and presentations have been part of the project, of which a sample is included below.

During the entire period of the project, a reference group consisting of representatives from the SSM, representatives from KTH and Chalmers, and the nuclear utilities has been active with meeting on a general basis of 1–2 meetings/year.

Publications

CFO. Dahlberg and M. Boåsen , Evolution of the length scale in strain gradient plasticity, International Journal of Plasticity, vol. 112, 2019, p.220-241.

M. Boåsen, M. Stec, P. Efsing, J. Faleskog, A generalized probabilistic model for cleavage fracture with a length scale - Influence of stress state and application to surface cracked experiments, Engineering Fracture Mechanics, vol. 214, 2019, p.590-608



3-point SEN(B) (Single Edge Notch Bend) sample modeled in FEM deformed at loading.

Intergranular fracture surface from a thermally aged sample of Low Alloy steel from a retired component

M Boåsen, CFO Dahlberg, P Efsing, J Faleskog, A weakest link model for multiple mechanism brittle fracture — Model development and application Journal of the Mechanics and Physics of Solids, vol 147, article id: 104224, 2021

M. Boåsen, K. Lindgren, M. Öberg, M. Thuvander, J. Faleskog, P. Efsing, Analysis of thermal embrittlement of a low alloy steel weldment using fracture toughness and microstructural investigations, TRITA-SCI-RAP 2020:004. Solid Mechanics, KTH Royal Institute of Technology, Stockholm, Sweden. To be published.

M. Boåsen, P. Efsing, U. Ehrnstén, On flux effects in a low alloy steel from a Swedish reactor pressure vessel, Journal of Nuclear Materials, vol. 484, 2017, p.110-119

K. Lindgren, M. Boåsen, K. Stiller, P. Efsing, M. Thuvander, Evolution of precipitation in reactor pressure steel welds under neutron irradiation, Journal of Nuclear Materials, vol. 488, 2017, p.222-230

K. Lindgren, M. Boåsen, K. Stiller, P. Efsing, M. Thuvander, Cluster formation in in-service thermally aged pressurizer welds, Journal of Nuclear Materials, vol. 504, 2018, p.23-28

M. Boåsen, K. Lindgren, J. Rouden, M. Öberg, J. Faleskog, M. Thuvander, P. Efsing, Thermal ageing of low alloy steel weldments from a Swedish nuclear power plant – a study of mechanical properties, Fontevraud 9, conference proceedings and presentation, 2018, Avignon, France

K. Lindgren, M. Boåsen, K. Stiller, P. Efsing, M. Thuvander, Thermal ageing of low alloy steel weldments from a Swedish nuclear power plant – the evolution of the microstructure, Fontevraud 9, conference proceedings, 2018, Avignon, France

M. Boåsen, Modeling of structural integrity of aged low alloy steels using non-local mechanics, Ph.D. thesis, 2020.

M. Boåsen, Modeling framework for ageing of low alloy steel, Lic thesis 2019.

Research done by doctoral student
Kristoffer Tofveson Pedersen

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

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

Main supervisor
Christophe Demazière

Discipline
Reactor Physics

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

Formal project start
2020-09-01

Expected time of completion
2025-08-31

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, it is proposed to develop a Reduced-Order Model (ROM) to study the stability properties of nuclear reactors during load follow conditions. In a ROM, the balance equations describing the time- and space-dependence of the neutron flux are projected onto a few properly chosen basis functions of space only. The main advantage of a ROM is to replace the complexity of the modelling of a nuclear reactor 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. The incentive in the establishment of the homogeneous model was to be able to derive the governing equations analytically as far as possible, so that the influence of the parameters onto the stability of the core can be better identified and understood.

The ROM approach to be initially followed is a "physics"-based ROM approach, in which the spatial basis functions on which the spatial dependence of the neutron flux is projected are the eigenmodes of the neutron diffusion operator. The radial, azimuthal and axial dependence of such functions were determined analytically, and successfully compared to the eigenfunctions numerically estimated from an in-house core simulator.

The projection of the governing equations onto those analytical eigenfunctions is on-going, from which the stability of the core with respect to Xenon oscillations will be assessed.

Methodology

Once the analytical model above is finalized and the stability of the core with respect to the input data and parameters understood, the same analysis will be repeated while keeping the heterogeneous nature of the core. For that purpose, all the calculations, basis functions inclusive, will be carried out numerically.

At some later phase of the project, the results of the ROM will be compared to high-fidelity simulations. The results of those simulations will also be used to construct other types of ROM, using e.g. a Proper Orthogonal Decomposition. Other projection-based ROM, such as the Proper Generalized Decomposition, are planned to be investigated. Those ROM will be compared to the "physics"-based ROM.

Communication

The project was presented at the SKC annual symposium on October 20th-21st, 2020. A short popular science video explaining the project objectives and methods was also prepared for the Energy Dialogue conference organized by KTH on November 19th, 2020.

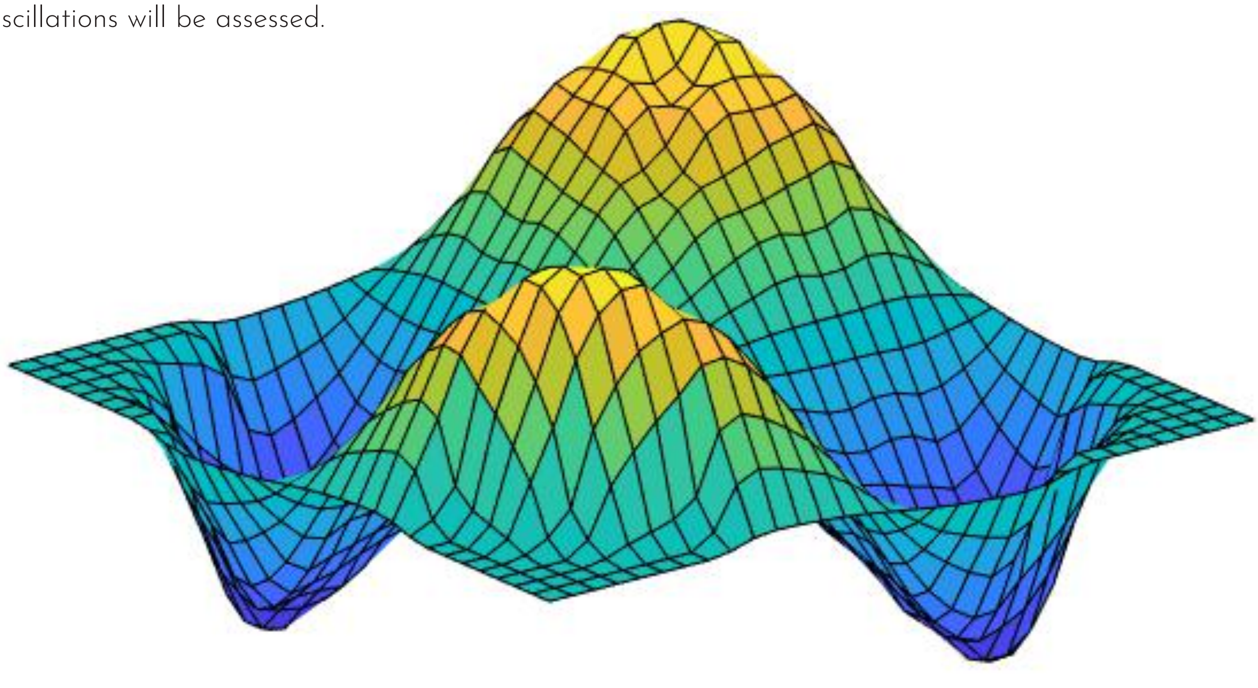


Illustration of the radial dependence of one of the eigenmodes in a non-homogeneous reactor core

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

Main supervisor
Jonas Faleskog

Formal project start
2020-08-17

Discipline
Jonas Faleskog

Expected time of completion
2025-06-25

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

Motivation

Ductile 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. It 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, has since the start in late August 2020, studied key references on the topic, damage continuum mechanics material models, and initiated the development of a non-local model suited for finite element analysis. The latter is a necessity for numerical analysis based on damage mechanical models. Here, the influence of two length scales associated with two different failure mechanisms are investigated.

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

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

Research done by doctoral student
Mustafa Subasic

Main supervisor
Bo Alfredsson

Formal project start
2020-08-17

Expected time of completion
2025-08-31

Discipline
Solid mechanics

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

Motivation

Corrosion fatigue is a material degradation phenomenon that may develop as a consequence of long time usage with cyclic thermal or mechanical loads at the presence of an aggressive environment. If unattended it may eventually lead to leakages and possibly failures. One such application is the pipe systems in nuclear power plants where the water introduces an increased environmental risk for fatigue initiation. The existing Swedish nuclear power plants approaches the originally assessed 40 years of service life. All of the remaining 6 nuclear power plants in Sweden 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 failure mode, which can be used by the plant operators during the LTO of the existing Swedish nuclear power plants. The objective is an improved risk and life prediction method for corrosion fatigue in the pipe systems.
The project focuses on the conditions at the Swedish pressurized and boiling water reactors. The project results will be directly distributed to the engineers working at the Swedish nuclear power plants where they will lead to improved design tools and validation methods against corrosion fatigue at mixing points and systems with stagnant and/or turbulent flow. It will assist in establishing inspection intervals 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 control and focus the proactive safety work at the production units.

Progress

The project started in August 2020. During the autumn, work started on designing the experimental set-up including the hollow pipe specimens. At the end of 2020, a preliminary design was ready, and a preliminary numerical model was developed which included the coupled mechanical and corrosion phenomena. Corrosion fatigue was simulated for the preliminary design. Based on the simulations and results in the literature it was decided that the design should meet the requirements for testing the damage mode at Swedish nuclear power plant conditions.

An experiment plan has been defined. Test material has been selected and acquired from the Oskarshamn nuclear power plant. The material is a 304 stainless steel plate that was recovered from the archives after construction of the Barsebäck nuclear power plant. A literature survey on corrosion fatigue experiments and modelling techniques is completed.

Methodology

The developed experiment including measurement and surveillance system 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 is designed and manufactured, Studsvik where the experiments 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 favourable 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 2020.

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

The plan is to publish the research work in international scientific journals with review procedure and present at international and national conferences as well as at the annual SKC symposium.

2019-7
SEMRA: Steam explosion modelling and risk analysis for light water reactors

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 are an inherent risk in light-water reactors (LWRs), posed by the very use of water as a coolant during accidents. There is a need to better understand these risks in currently operating and future NPPs, but state-of-the-art on steam explosions remains fragmented, with large spread in the prediction of explosion loads across modelling approaches and code users.

The SEMRA project develops what is intended to be the most comprehensive modelling approach for the analysis of ex-vessel steam explosions in LWRs, and couples it with a risk analysis methodology to support decision making in modifying severe accident management (SAM) strategies. The deterministic model we develop will be applicable for any type of LWR, and any scenarios of melt release. It will be accompanied by an artificial neural network (ANN)-based surrogate model to enable fast calculations for risk assessment and uncertainty analysis.

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

Progress

The project is to be started in January 2021, the initial focused will be on the review of SE state-of-the-art.

An abstract on modelling of SE in conditions of multiple jet releases was submitted to the 19th International Topical Meeting on Nuclear Reactor Thermal Hydraulics. The conference will be held in Belgium, in March 2022.

Textbook

SKC is supporting professor Janne Wallenius and researcher Sara Bortot in their effort to write a new textbook on fast neutron Generation IV reactors. The text-book has been under production since early 2018 and is expected to be published late 2021.

Motivation

The authors have been deeply involved in the development of lead-cooled and sodium-cooled reactors, as well as in fuel development for minor actinide transmutation. They felt that at this point in time, it would be prudent to translate the huge body of knowledge created within the global Generation-IV research effort into a pedagogical treatise that would allow students and professionals in the nuclear engineering field to learn how to design reactors meeting the objectives set out by GIF.

FAST NEUTRON GENERATION IV REACTORS

Janne Wallenius
Sara Bortot

2021

About the book

In this textbook, the science and engineering of fast neutron reactors intended for recycle of plutonium and minor actinides is presented to an audience of masters students, and nuclear engineers professionally active in other areas of the field. "Generation-IV" (Gen-IV) reactors were defined by the Generation-IV international forum (GIF) as reactors that would by design meet a set of desired objectives related to sustainability, safety, economy and non-proliferation. A significant body of research has been dedicated to the development of Gen-IV reactors between the shift of the millennium and today. This has resulted in a much improved understanding of the physics and chemistry of minor actinide transmutation, as well as solutions to issues related to the use of liquid metals and helium gas as coolant.

The first chapter of the book is dedicated to the operational experience from reactors using the set of coolants identified by GIF as suitable for meeting Gen-IV objectives. It is likely the most comprehensive list of such reactors found in current literature.

The second chapter provides a well defined and partially novel understanding of the physics of breeding. This includes a reactivity based definition of the fundamental breeding ratio parameter, and its dependence on the choice of fuel, coolant, power density and core geometry. Several non-intuitive aspects of breeding are explained by use of this definition, such as the possibility to design a breeder with a fuel featuring an η-value less than 2.0. Moreover, the breeding ratio of a metallic fuel is actually worse than for all ceramic fuels, if the U:Pu ratio is identical, in apparent contradiction to statements in most other textbooks on the topic.

Chapters three and four are dedicated to fast reactor kinetics and safety parameters for classical (U,Pu) fuels, as well as for fuels containing minor actinides. In particular, the detrimental effect of americium on Doppler feedback, the delayed neutron fraction and the coolant temperature coefficient is discussed in depth, in order to explain how the margin to fuel and clad failure during transients decreases when this element is introduced into the driver fuel of a fast neutron Gen-IV reactor.

The fifth chapter describes how a fully closed fuel cycle can be design based on the use of a combination of light water reactors and fast neutron Generation-IV reactors, and the utility of this approach for reducing the radiotoxic inventory directed to geological repositories, as well as for reducing the associated heat load. A cost benefit analysis is conducted, indicating that a 100-fold reduction in required isolation time of residual high level waste, combined with a reduction in volume of the associated repository can be achieved. The corresponding cost penalty for production of nuclear electricity in the entire fleet is estimated to be at least 20%.

The following chapter summaries extensive efforts in determining suitable manufacturing routes and physical properties of minor actinide bearing fuels, as well as their their behavior under irradiation.

Chapter seven describes physical and chemical and thermal hydraulic properties of liquid metal coolants, in particular with respect to passive safety.

Chapter eight discusses radiation damage, liquid metal embrittlement and corrosion issues, including the development of novel, highly corrosion tolerant alumina forming steels conducted at KTH.

At this point, the majority of the chapters outlined above have been written. However, some chapters on the design of Generation-IV fast neutron reactors remain to be written. The authors will also continue working on a more detailed discussion on the economics and licensing of fast neutron Gen-IV reactors.

Research done by
doctoral student
Gustav Robertson

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

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

Main supervisor
Henrik Sjöstrand

Discipline
Thermomechanics, statistics.

Keywords
Thermomechanics, fuel performance modelling, machine learning, calibration, inverse uncertainty quantification

Formal project start
2020-09-01

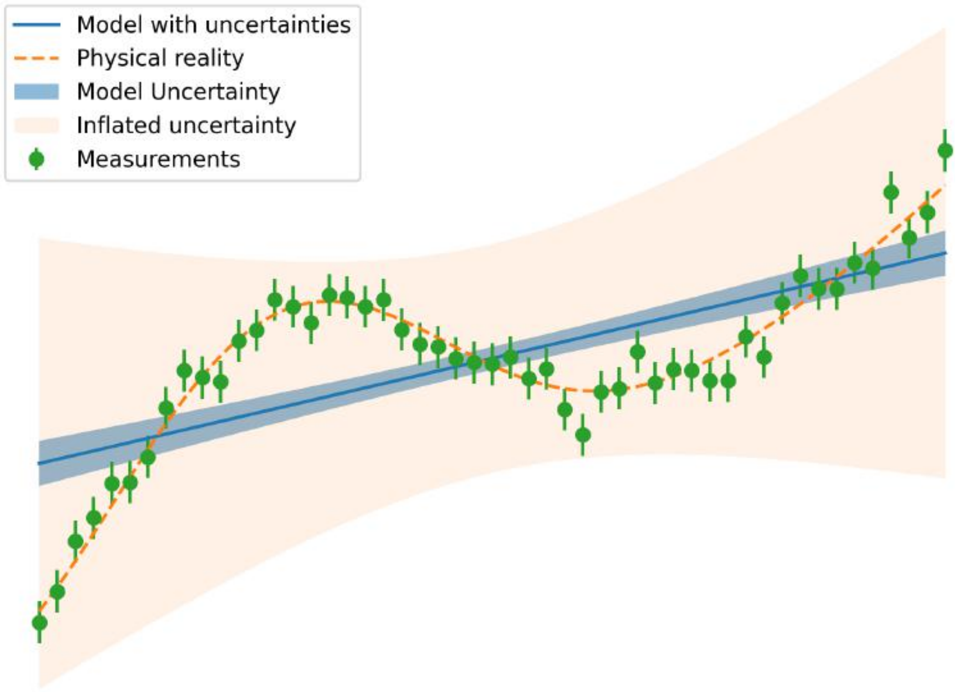
Expected time of completion
2024-09-01

Motivation

The proposed project addresses challenges in the 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 phenomenological models; integral, biased and sparse calibration-data; various types of input uncertainties; computationally costly executions; and model inadequacies. This makes uncertainty quantification (UQ) particularly challenging.

Specifically, the UQ within fuel performance simulations is a crucial component in establishing safety limits for plant operation. This manifests as conservative estimates of operation limits or as an evaluation showing that for a given plant operation the fuel cladding barrier will not be breached. 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 that are 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. From another perspective, an overly



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

cautious and conservative treatment causes less efficient operation and fuel utilization with both cost and increased waste disposal impacts.

To summarize, the project aims to ensure safety via reliable quantification of margins at the same time as it enables efficient use of fuel and as such brings benefit to 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).

One of the most demanding challenges in model calibration is caused by so-called model inadequacies. A model inadequacy is when independent of the choice of model parameters the model cannot recreate the physical reality. This often has severe consequences if not accounted for properly. A simple example is shown in the figure above, 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 implication if the model was to predict a nuclear engineering safety parameter. During 2020, the primary work has been to address such model inadequacies to obtain well-founded uncertainty bands (see the yellow bands of the inflated uncertainty in the figure above).

Fuel performance codes are used to determine, among other quantities, cladding oxidation and hydrogen pickup. These phenomena, if not limited, can have a direct negative impact on fuel safety. For example, hydrogen uptake has an adverse effect on the mechanical properties of the zirconium alloy, and cladding oxidation consumes the cladding and the oxide is a much poorer heat conductor. It is since long known that the models to determine these quantities are inadequate. In a pre-study, performed as a diploma work [1], two different methods were used to address these model inadequacies. Westinghouse data and the fuel performance code TRANSURANUS were used. Both methods performed well for the oxidation quantity, however, the hydrogen pick-up calibration was not successful since it derived uncertainties that could not explain the spread of the data.

On 2020-09-01 the Ph.D. student Gustav Robertson was employed for the project. In order to study the problem in more depth, a simple model of the oxidation and hydrogen pickup was constructed. In addition, a synthetic database, mimicking the behavior of the real Westinghouse data was constructed. The method from the pre-study, the so-called margin method [2], which was deemed most suitable to integrate with the standard protocol of the industry, was chosen to be developed further.
With the new implementation, it was found that the margin method could produce a successful joint calibration of both the oxidation and the hydrogen model where the uncertainties could explain the model error. The first draft of a paper has been written and an abstract with the results and the method has been submitted to TopFuel2021.

To conclude, model inadequacies are a severe problem when calibrating fuel performance codes. During 2020 a successful method to address the problem has been developed and implemented. The results are planned to be presented at TopFuel2021.

Communication

In 2020 the work has been presented in a master thesis [1] and in a series of external seminars [2-4], and an internal "4-month seminar" [5], which is probably the best public account of the 2020 work progress.

Beginning 2021 an internal 6-month seminar is planned at Westinghouse, to report the progress of the project.

A literature review has been performed and an extensive "literature database" has been constructed, which is publicly accessible.

In addition, an abstract has been submitted to TopFuel-2021 and a paper is planned to be presented in 2021.

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. For the near future, practical arrangements regarding data availability are being sorted. Therefore the next steps are either to augment the testbed with more multivariate and strongly interconnected problems with more feedback loops etc. or to prove the already developed statistical methodology on real cladding oxidation and hydrogen data coming from PIE and poolside measurements.

References

[1] Joakim Nyman, "Joint Calibration of a Cladding Oxidation and a Hydrogen Pick-up Model for Westinghouse Electric Sweden AB"

[2] G.Robertson, "The golden combination of MCMC and Gaussian processes for calibration", SAINT Conference 2021

[3] G.Robertson, "CaNel– Calibration of Nuclear fuel performance codes : Treating model inadequacies, nuisance parameters and unrecognized systematic uncertainties", SKC Symposium 2020

[4] G.Robertson, "CaNel–Calibration of Nuclear fuel performance codes : Machine learning for nuclear safety", KTH Energy Dialog ue 2020

[5] G. Robertson; "CaNel – Calibration of Nuclear fuel performance codes : Treating model inadequacies, nuisance parameters and unrecognized systematic uncertainties", Internal 4-month seminar, 2020

2020-2
Development of a fully coupled electrochemical and micro mechanical SCC model

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

Research done by post-doctoral researcher
Michal Sedlak Mosesson

Main supervisor
Pål Efsing

Formal project start
2020-11-01

Discipline
Solid mechanics

Expected time of completion
2022-11-01

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

Motivation

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

SKC has supported the work at the group of Solid Mechanics performed by 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.

Progress

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. Collaboration with Prof. Itai Panas from Chalmers is ongoing to create a model for alloy 690. 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".

Methodology

The model introduced in Michal Sedlak's PhD was developed in a modular framework. The first module updated is the electrochemical model. This 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.

The oxidation module is transformed to an Integration point formulation instead of node formulation, still including the duplex-oxide.

The fracture mechanics module is enhanced with a crack path module, introducing cohesive elements in the grains with remeshing capabilities. The process will introduce the possibility of branching and both inter- and transgranular stress corrosion cracking. For both 2D and 3D.

Communication

Two articles from the PhD project have been reworked. One is published and one is under review. All articles are sent to high ranked international journals in their respective fields and published open-access. An abstract was submitted to the conference 20TH Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors (Aug 15-19).

Publications

M. Sedlak Mosesson, B. Alfredsson and P. Efsing, A duplex oxide cohesive zone model to simulate intergranular stress corrosion cracking, International Journal of Mechanical Sciences, vol. 917, art. no 106260, 2021.

2020-12

Influence of alloying and neutron flux on irradiation effects in fuel rods

Research done by post-doctoral researcher
David Mayweg

Research host
Chalmers, Department of Physics, Microstructure Physics

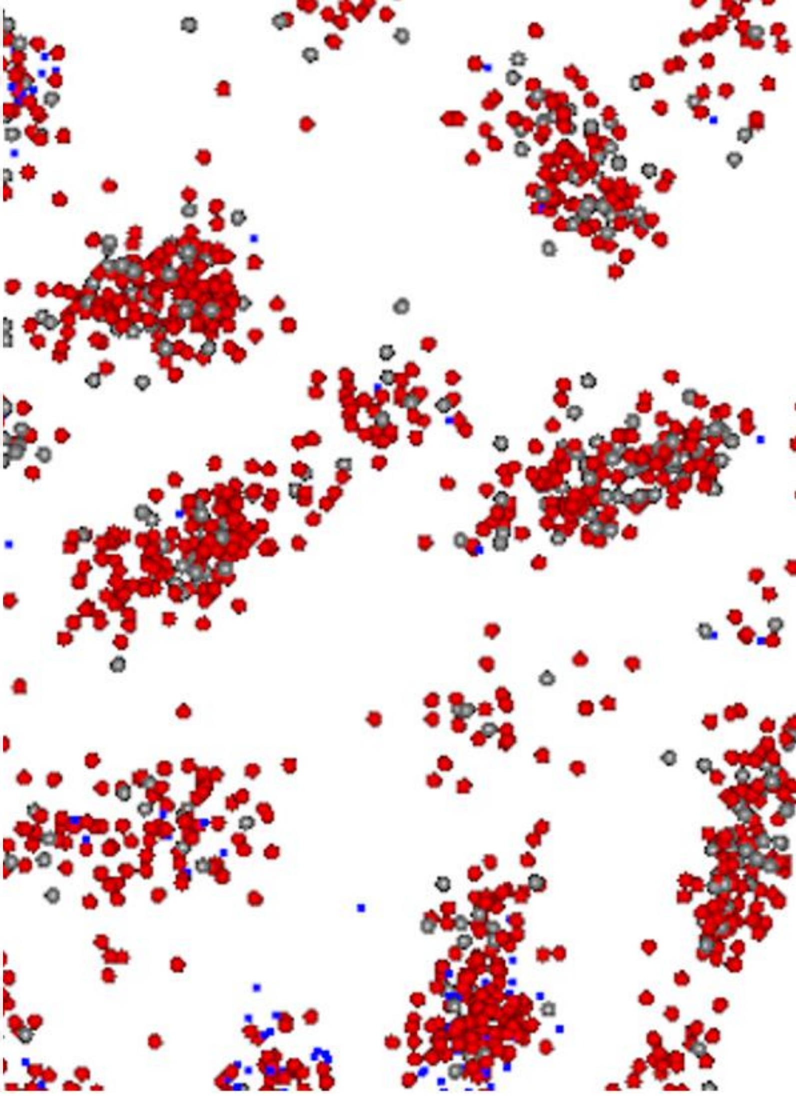
Main supervisor
Mattias Thuvander

Discipline
Nuclear Materials (Fuel)

Keywords
Zircaloy, irradiation effects, corrosion

Formal project start
2021-04-01

Expected time of completion
2023-03-31



The image shows atoms of Fe, Cr and Ni in neutron irradiated Zircaloy-2. These alloying elements form clusters at dislocations loops, which is believed to affect phenomena like growth and creep.

Motivation

Fuel cladding tubes are degraded by corrosion, hydrogen up-take and irradiation. The project will focus on detailed characterization of fuel rods made of two zirconium alloys that have been in operation at Oskarshamn for six years. The two alloys have different composition regarding the important alloying elements Fe and Cr. The samples have already been supplied to Chalmers, as part of an ongoing PhD-project. The post-doc will study irradiation damage of the metal, including dissolution and amorphization of second phase particles (SPPs) and irradiation-induced dislocation loops. The main techniques that will be used are transmission electron microscopy (TEM) and atom probe tomography (APT). An important rationale is to get the most information out of these unique samples as possible, given the time-consuming and costly handling of active material. The PhD-student working on the same material is concentrating on the effect of irradiation on the oxide formation and the hydrogen up-take. The post-doc project will be a valuable compliment focusing on understanding the effect of the Fe and Cr alloy content and the effect of neutron flux on the properties of the metal relating to phenomena like irradiation growth and creep.

Progress

The project will start in spring 2021, no progress during 2020.

Methodology

Samples irradiated at Oskarshamn of Zircaloy-2 and Alloy 2 will be investigated using Atom Probe Tomography (APT) and Transmission Electron Microscopy (TEM).

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

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

Research done by doctoral student
TBD

Formal project start
2021-03-31

Expected time of completion
2025-03-31

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 (H2O2), the hydroxyl radical (HO•) and to some extent also the hydroperoxyl radical (HOO•). Molecular oxygen (O2) 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 set-ups where the impact of water radiolysis is simulated by adding H2O2 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 will start in spring 2021, no progress during 2020.

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
TBD

Formal project start
2021-04-30

Expected time of completion
2025-04-30

Main supervisor
Jan Dufek

Discipline
Reactor Physics

Keywords
Reactor physics, artificial intelligence, artificial neural networks

Motivation

In this project, we propose the application of Artificial Neural Networks (ANNs) to the modelling of the nuclear nodal data to build new models with dependence on a very large number of instantaneous and past operational conditions, which will allow for more flexible and accurate reactor simulations than possible with existing data models. This can translate into a better optimisation of fuel loads and an improved reactor economy.

Nodal diffusion codes, that are used in industry for reactor simulations, require spatially homogenised and energy collapsed nodal data, such as group cross sections, diffusion coefficients, discontinuity factors, etc.. These data depend on instantaneous and past nodal conditions (history effects) that are given by state variables such as the fuel depletion, the fuel temperature, the moderator density, and other. The nodal data at a certain state can be computed by lattice codes.

The nodal diffusion codes require fast access to the pre-computed nodal data at various instantaneous and past operational conditions, and it is, therefore, necessary to build nodal data models with dependences on these state variables. These dependences are usually tabulated or approximated by multivariate functions, but these models have certain limits. As 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 become too large. The polynomial approximation based models have shown their potential in considering many state variables; however, such models have their principal difficulties as well, such as the selection of suitable polynomial terms.

The major objective of the project is to develop an optimal ANN-based model for nuclear nodal data that will outperform the existing models in terms of accuracy and flexibility (the number of state variables) while ensuring fast delivery of results. The ANN optimisation work will focus on several areas, including the selection of the activation functions, the number of layers and nodes and, most importantly, the optimisation of the form in which the inputs (called features in ANN terminology) are provided to the ANN. The last area, called the "feature engineering", has a great potential to utilise the experience that has been accumulated over many years with developing the traditional data models.

Progress

The open PhD position for the project became advertised online on LinkedIn, ResarchGate, KTH home page, AF Platsbanken, and AcademicPositions in November 2020 and was closed a month later. Out of the five top applicants that were interviewed, the best applicant was offered the position. Unfortunately, the candidate declined the position after accepting it initally. KTH rules forbid it to offer the position to other candiates and so the recruitment must start anew in 2021.

Methodology

Artificial Neural Network (ANN) is a computing system with a structure inspired by biological neural networks. ANN represents a collection of interconnected units (neurons) that are simple processors which operate in parallel. Neurons are structured in layers, and each neuron from a layer is connected with each other neuron of the next layer. The signals that propagate via the network are amplified by weights associated with neuron connections. The signals that are read by the first layer represent the inputs to the ANN, while the neurons of the last layer provide the outputs (results). The ANN characteristics are given by the number of neuron layers, by the way in which each neuron processes the signals from all its connection links (using the so-called activation function), and by setting the connection weights. The process of setting the connection weights is known as ANN learning. During its learning, the ANN is served with input-output pairs. With sufficient learning, ANNs are, in principle, able to approximate any multidimensional function to any required precision.

ANNs have certain key advantages that make them very attractive for certain problems:

- ANNs can learn and model non-linear and complex relationships between inputs, and they can generalise after learning from the input-output pairs and their relationships.

- Most importantly, ANNs do not impose any restrictions on the input variables. For instance, they have no restriction on the distribution of the input phase-space points - which, in the case of nodal data models, is a great advantage over polynomial-based models that need a very uniform sampling of the points in the phase space.

ANNs have already been applied to some problems in nuclear engineering. ANNs have been tested for monitoring of NPP operation and for prediction of safety core parameters. More recently, ANN was used for prediction of reactor core configuration behaviour and meeting the safety requirements. Researchers also use the computer vision ability of ANNs to enhance nuclear safety: a trained ANN has been used to identify cracks in the reactor by analysing video frames.

Communication

Publications are foreseen in the third and fourth year of the project. As the project did not start yet, we have no publications yet.

Swedish Centre for Nuclear Technology