ANNUAL REPORT 2019

Swedish Centre for Nuclear Technology
Svenskt Kärntekniskt Centrum

March 2020

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Swedish Centre for Nuclear Technology

Financiers

Strålsäkerhetsmyndigheten
Oskarshamns Kraftgrupp AB
Forsmarks Kraftgrupp AB
Westinghouse Electric Sweden AB
Ringhals AB

Beneficiaries

Chalmers University of Technology
KTH – Royal Institute of Technology
Uppsala University

Foreword

For the nuclear energy industry and research organisations, the year 2019 introduced developments of both positive and negative flavour. The support for nuclear power gained traction with the general public, political parties and non-governmental organisations alike, no doubt due to the increasing urgency of tackling climate change. The debate on the future of nuclear power has therefore moved from the circles of technology savvy rationalists to the pages of national periodicals through the mouths of entrepreneurs, climate activists and local politicians. Despite the increased visibility and support, however, Sweden has permanently shut down one of the units at the Ringhals power plant at the end of 2019 and will do the same with a second unit by the end of 2020. Decommissioning of two units at Oskarshamn is already underway.

Despite having to close down older units, the year 2019 brought about positive change for nuclear technology research, which saw a considerable boost in decisions to finance national initiatives. SKC enters into a new contract period for a 4-year-period, contributing with 52 MSEK to the development of bright minds. Swedish Foundation for Strategic Research has earmarked 40-60 MSEK over a period of 5 years exclusively for R&D of Gen-IV technology, small modular reactors and accelerator driven systems. Likewise, Research Council has decided to fund advanced nuclear technology research with nearly 30 MSEK between 2019 and 2022. Not to mention that Swedish Radiation Safety Authority continues to fund research with roughly 80 MSEK annually.

The above shows interest in both maintaining Swedish nuclear power production capacity and advanced technologies. In particular, the interest for the development and potential deployment of SMRs is gaining ground. This interest is primarily driven by the realisation that global environmental crisis cannot be solved exclusively with hoping for windy and sunny weather flexible power consumption.

Of course, recent developments also highlight that the pitfall of nuclear power is not necessarily its perceived lack of safety or waste management hurdles. Instead, the cost of construction and troubling trend of project overruns has become the *de facto* showstopper. And so, new-build projects such as Olkiluoto 3 in Finland and Flamanville 3 in France demonstrate that we need to either become exemplary in leadership, project management and supply chain management as well reorganise licensing processes. Or that we start building simpler, smaller and cheaper power plants in the future. Or both.

It is the ambition of SKC to facilitate the development of the skills, mindsets, networks, experience, hardware and software that we need to run existing units efficiently and safely. But it is just as relevant to create a foundation for the possibility of replacing or adding to the existing production capacity.

Stockholm, March 31st 2020

Merja Pukari

Director, SKC

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Swedish Centre for Nuclear Technology

Partners

The Swedish Centre for Nuclear Technology – (Svenskt Kärntekniskt Centrum, SKC) 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 (KTH/SCI). The SKC collaboration has followed a three-year contract which was expired at the end of 2019. A new, four-year contract has been agreed upon for the period of 2020-2023.

Partners in the SKC collaboration during 2017-2019, in their capacity as financiers, represent the Swedish nuclear power industry:

- Forsmarks Kraftgrupp AB
- OKG AB
- Ringhals AB
- Westinghouse Electric Sweden AB

Partners in the collaboration in their capacity as beneficiaries represent the academia:

- Chalmers University of Technology
- KTH Royal Institute of Technology
- Uppsala University

Goals

SKC supports education and research in disciplines applicable to nuclear technology. The education programme is also supported by financial contributions to senior positions at the universities.

The overall goals of SKC during 2019 have been to:

- Increase interest among students to enter nuclear technology education
- Enable the SKC financing partners to recruit qualified personnel with a nuclear technology education
- Offer attractive education in the nuclear technology area
- Maintain strong and internationally acknowledged research groups within areas that are vital for and unique to the nuclear technology area
- Create organizations and skills at the universities such that research can be performed on account of the financers of the SKC also outside the boundaries of the SKC agreement

SKC's research funding is used within three research areas:

- Nuclear Power Plant Technology and Safety
- Reactor Physics and Nuclear Power Plant Thermal Hydraulics
- Materials and Chemistry

Some areas of interest to the SKC partners within the research programmes are:

- Core Physics and Plant Dynamics
- Nuclear chemistry
- Detectors and measurement
- Material physics and engineering
- Fuel Technology
- Reactor Diagnostics
- Thermal-Hydraulics

SKC was established to provide long-term support to securing knowledge and competence development at an academic level for the Swedish nuclear industry. SKC strives to contribute to a continued safe, effective and thus reliable electricity production.

Organisation and Funding

SKC runs according to multi-year contract periods. The three-year contract that governed SKC in 2019 came into effect on January 1st, 2017 and terminated December 31st, 2019. The total volume for the three years was 25,4 MSEK. A new four-year contract in the volume of 52 MSEK has been signed between 8 partners for the period of 2020-2023.

SKC's financing partners in the contract period (2017-2019) were:

- Forsmarks Kraftgrupp AB
- Oskarshamns Kraftgrupp AB
- Ringhals AB
- Westinghouse Electric Sweden AB

The contract for the period states that the financers contribute with 8,46 MSEK annually to senior positions at the universities and to research activities. Support has been provided as base funding, specific funding of e-learning projects and specific support to several research projects.

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.

- During 2019, the Advisory Council consisted of:
- Gustaf Löwenhielm, Chairman
- Mattias Olsson, Forsmarks Kraftgrupp AB
- Georg Lagerström, Oskarshamns Kraftgrupp AB
- Björn Forssgren, Ringhals AB
- Ingemar Jansson, Westinghouse Electric Sweden AB

The director of SKC acts as a secretary of the meetings.

During 2019, the SKC Board consisted of:

- Karl Bergman, Chairman, Vattenfall AB
- Peter Wedin, Forsmarks Kraftgrupp AB

- Jan Karjalainen, Oskarshamns Kraftgrupp AB
- Henric Lidberg, Ringhals AB
- Anders Andrén, Westinghouse Electric Sweden AB
- Leif Kari, replaced by Anna Delin April 1st, 2010, KTH Royal Institute of Technology
- Olof Karis, replaced by Jan-Erik Rubensson October 15th, 2019, Uppsala University
- Leif Åhman, Chalmers University of Technology
- Anneli Hällgren, Strålsäkerhetsmyndigheten – observer
- Lotta Henrysson, Vattenfall AB - observer

SSM was represented in the Board according to the SKC contract that allows an observer status for the regulator. The Head of Human Resources from Vattenfall's Business Area Generation has been invited to the meetings as an observer.

Six board meetings were held in 2019. The Director of SKC attends the Board meetings, reports the progress as well as presents proposals to the board.

The Director also has an observer position in the SSM Research Board.

Financial Statement 2019

The following financial statements concerns the payments received by SKC from the four financiers and the expenditures made to the three universities as project and base support. The administration of SKC is an additional expenditure item. Financial statement for 2019 concludes the contract period for 2017-2019; remaining funds will be transferred to the next period of 2020-2023.

Payments to SKC from financiers	
Forsmarks Kraftgrupp AB	2 380 000
Oskarshamns Kraftgrupp AB (1)	595 000
Ringhals AB	3 173 333
Westinghouse Electric Sweden AB	2 116 667
Total payments	**8 265 000**

Expenditures by SKC	
Chalmers	-2 695 000
KTH	-3 100 000
Uppsala University	-1 928 000
SKC administration	-542 000
Total expenditures	**-8 265 000**

(1) A payment of 198 000 SEK for Q4 2019 has been paid in 2020

Symposium 2019

SKC holds an annual symposium in order to provide a forum for presenting projects as well as various research and education activities that are funded by SKC. The 2019 symposium was held on October 15-16 at the Albanova University Centre, hosted by KTH.

Reports on the progress in research projects and education development were provided during both days, with the second day used for in-depth presentations of several research projects. Posters on research projects were set up to encourage information exchange on a more personal level. Both presentations and posters are crucial in disseminating knowledge amongst students and staff on the kind of research that is being conducted by research groups at the respective universities.

Additionally, speakers from outside the academia were invited to the symposium to share their in-depth reflections on select topics. During the first of the two days, Uffe Bergman, a Principle Engineer from Westinghouse, provided an overview of the Swedish nuclear fuel development. A plenary session was held on the second day, on the topic of perspectives of nuclear technology research environment and the way forward. A panel consisting of Joakim Amorim (Programme manager, Stiftelsen för Strategisk Forskning) Per Seltborg (Head of research, Strålsäkerhetsmyndigheten), Daniel Westlén (Svenskt Kärntekniskt Centrum, Director), Pär Olsson (Professor, KTH) and Christian Ekberg (Professor, Chalmers) was moderated by Anders Andrén (Consulting Engineer, Westinghouse)

Symposium dinner at Nymble was complemented with entertainment by an improvisational group.

Sigvard Eklund Prize

Every year, SKC rewards the best PhD thesis, Master thesis, and Bachelor thesis within the field of nuclear technology in Sweden. The prize is awarded in the memory of Sigvard Eklund, most well known for being the Secretary General of the IAEA 1961-1981.

Sigvard Eklund Prize winners Mattia Bergagio (left) and Daniel Fransén (middle) with Henric Lidberg (right) representing SKC Board.

The Sigvard Eklund Prize for the best Ph.D. thesis of the year was awarded to Mattia Bergagio from KTH for his *Experimental and analytical study of thermal mixing at reactor conditions*.

Daniel Fransén, also from KTH, was recognised as the author of the best Bachelor's thesis, *A time alternating classical–quantum method for simulating radiation damage in crystalline materials*

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

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

**Chalmers
University of Technology**

Introduction

The following Chalmers divisions/departments were actively engaged in research related to nuclear technology education and research in 2019:

- Div. of Energy and Materials, Nuclear Chemistry, Dept. of Chemistry and Chemical Engineering.
- Div. of Subatomic and Plasma Physics, Dept. of Physics.
- Div. of Materials Microstructure, Dept. of Physics.
- Div. of Advanced Non-destructive Testing, Dept. of Materials and Manufacturing Technology.

Chalmers has a strong track record of nuclear research activities and actively participates in international research projects. Several EU-funded projects are in progress with Chalmers involvement (both as coordinator and participant). Chalmers has strongly contributed to attracting international funding for supporting the Swedish nuclear competence base and the nuclear research infrastructure. Chalmers has also had close collaboration with the Swedish nuclear industry, primarily with Ringhals, in the application of reactor diagnostics.

Much of the strategic nuclear research is coordinated in the national centre SAINT (Swedish Academic Initiative in Nuclear Technology Research). The centre currently has participation by Uppsala University, Chalmers, the University of Gothenburg, Stockholm University and Lund University. The centre focuses on:

- Generating synergies and maintaining high educational quality of national education within radiation sciences.
- Work for a national strategy within radiation science research.
- Assist, coordinate and encourage researchers in their science outreach.
- Act as an independent source of information for industry, the public and other actors.
- Increase the impact of the academic actors by speaking with a common voice.

The facilities and tools available at the supported divisions are as follows:

- An interactive teaching room allowing mixing on-site and off-site students and using student-centred pedagogical approaches.
- Fully equipped laboratories for α, β, γ experiments and activity measurements, e.g. HPGe-, LSC- and PIPS-detectors.
- A hot cell laboratory for γ activity.
- A special laboratory for research on advanced nuclear fuels (collaboration with KTH), including both a SEM and XRD facility.
- Several irradiation sources including a 10 kGy/h 60Co and 137Cs facilities ranging from 50 Gy/h and down to 1 Gy/h.
- An Atom Probe Tomography Instrument.*
- Three Transmission Electron Microscopes.*
- Three Scanning Electron Microscopes.*
- Two Focused Ion Beam Workstations.*
- A pulsed beam for variable energy slow positrons

*Managed by Chalmers Materials Analysis Laboratory (CMAL), a Chalmers infrastructure hosted by the Dept. of Physics

Some highlights for 2019 are listed below:

- Chalmers was actively involved in the development of the SAINT educational package on "Radiation science for the curious minds", with Dr. Klara Insulander Björk from Chalmers being the project leader of this collaboration between Chalmers, Uppsala University and the University of Gothenburg. The entire educational package, financed by SKC, can be found at: https://saint.nu/nyfiken/ .
- Prof. Christophe Demazière wrote a book on "Modelling of nuclear reactor multi-physics – From local balance equations to macroscopic models in neutronics and thermal-hydraulics". The book also contains more than 70 short videos and online quizzes. The videos were developed with partial support from SKC. More info about the book at: http://www.elsevier.com/books/isbn/9780128150696 .
- A one-week workshop "Deterministic modelling of nuclear systems" was developed and organized, as part of the Horizon 2020 ESFR-SMART project, by Prof. Christophe Demazière. The workshop made use of a hybrid learning environment (on-site + off-site students) and a flipped classroom set-up (textbook + webcasts + on-line quizzes delivered in advance + active learning assignments in the classroom using MATLAB Grader). The workshop had 22 on-site and 39 off-site registered participants.
- The CORTEX project, led by the Department of Physics at Chalmers, is progressing as planned. The first results of machine-learning based anomaly classifications are extremely encouraging, with an error in classification of only 0.11% and the possibility to recover the actual location of the anomaly with a mean absolute error of 4 cm.
- New funding was obtained from the Swedish Research Council (one coordinated by C. Ekberg, one by T. Retegan-Vollmer and one by C. Demazière and P. Vinai) and from the Swedish Radiation Safety Authority (one coordinated by C. Demazière and one coordinated by S. Holgersson).
- Dr. Kristina Lindgren participated at the IGRDM in Japan, leading to participation in an EU application (ENTENTE) on reactor pressure vessel steels that was granted early 2020.
- The SSF funded SAFETY project and accident tolerant fuel, led by Mattias Thuvander, progressed according to plan. The project is a cooperation between Chalmers (Physics and Chemistry), KTH and UU.
- A popular science book on the discovery of fission and the role of women scientists in it, written originally in English by Imre Pázsit and Nhu-Tarnawska Hoa Kim-Ngan, was published in Swedish and Japanese in 2018. A book seminar, marking the Japanese publication, was held in Tokyo in May 2019 at the Swedish Embassy, organised by the Japan Institute for Scandinavian Studies.

Utilisation of Funding

Research Projects

At the Division of Subatomic and Plasma Physics, Department of Physics, two projects were funded by SKC:

- "Development of interactive teaching materials in nuclear reactor modelling", for which the funding was primarily used for covering 5% of Prof. Christophe Demazière's salary (95 kkr in salary and overheads). The total costs for 2019 amounted to 196 kkr (with a SKC financing of 178 kkr).
- "Validation experiments for coupled reactor physics simulations", for which the funding was primarily used for covering 15% of Prof. Christophe Demazière's and 15% of Assoc. Prof. Paolo Vinai's salaries (370 kkr in salaries and overheads). The total costs for 2019 amounted to 519 kkr (with a SKC financing of 504 kkr).

At the Division of Materials Microstructure, Department of Physics, one project was funded by SKC: "Ageing of reactor pressure vessel steel welds", for which the funding of 400 kkr was used to cover 35% of Dr Kristina Lindgren's salary, cost for participation at the IGRDM meeting in Japan, and instrument fees at CMAL.

Base Funding

At the Division of Subatomic and Plasma Physics, Department of Physics, the base funding was used for covering 14% of Prof. Christophe Demazière's, 11% of Assoc. Prof. Anders Nordlund's and 13% of Assoc. Prof. Paolo Vinai's salaries (in total 569 kkr for salaries and overheads).

At the Division of Energy and Materials, Department of Chemistry and Chemical Engineering, Nuclear Chemistry group, the base funding was used for partly covering Prof. Christian Ekberg and senior researcher Stellan Holgersson for a total of 300 kkr.

At the division of Materials Microstructure, the base funding was used to partly cover wages of Dr Kristina Lindgren, now post-doc at the division after finishing her SKC-funded PhD project within MåBIL, for other projects than the main project listed above. The funding was further used for costs related to participation of Assoc. Prof. Mattias Thuvander's at the conference M&M in the US, where APT work on SCC of irradiated stainless steel was presented.

Education

Bachelor Level Education

The Division of Subatomic and Plasma Physics at the Department of Physics is involved in several Bachelor courses dealing with energy, for which introductory lectures on nuclear energy are provided.

Master Level Education

Some of the stand-alone courses listed hereafter (e.g. the workshop on "Deterministic modelling of nuclear systems" or the book "Modelling of nuclear reactor multi-physics – From local balance equations to macroscopic models in neutronics and thermal-hydraulics") are also offered as MSc courses at an advanced level.

A master project, Precipitation in Ni-base Alloys for Spacer Grid Application, by Mas Ipin (student at the master programme in Nuclear Science and Technology at Chalmers) was supervised by Mattias Thuvander. The project will be finalized during 2020. A master project, The Corrosion of Novel FeCrAl and AFA Steels in Liquid Lead for the Generation-IV LFRs, by Pratik Lokhande (student at the master programme Materials for Nuclear Energy at Grenoble Institute of Technology) was supervised by Mattias Thuvander.

A master project, Modelling the effect of stationary fluctuations in nuclear reactors using probabilistic methods, by Andreas Tatidis (student at the master programme in Nuclear Science and Technology at Chalmers) was supervised by Prof. Christophe Demazière and Assoc. Prof. Paolo Vinai.

The courses given by nuclear chemistry during 2019 were high in attendance, seen in the last years prospect, with the basic nuclear chemistry having 12 students and the radiopharmaceutical course having 10 students. Since we have no master program, these were all Swedish students.

Doctoral Level Education

Some of the stand-alone courses listed hereafter (e.g. the workshop on "Deterministic modelling of nuclear systems" or the book "Modelling of nuclear reactor multi-physics – From local balance equations to macroscopic models in neutronics and thermal-hydraulics") are also offered as PhD courses.

The same goes for the detailed course on the chemistry of actinides, lanthanides and super heavy elements. This course is now offered once every second year to both PhD students and potentially to other students.

Stand-alone coursework

Chalmers was actively involved in the development of the SAINT educational package on "Radiation science for the curious minds", with Dr. Klara Insulander Björk from Chalmers being the project leader of this collaboration.

A one-week workshop "Deterministic modelling of nuclear systems" was developed and organized, as part of the Horizon 2020 ESFR-SMART project, by Prof. Christophe Demazière. The workshop made use of a hybrid learning environment (on-site + off-site students) and a flipped classroom set-up (textbook + webcasts + on-line quizzes delivered in advance + active learning assignments in the classroom using MATLAB Grader). The workshop had 22 on-site and 39 off-site registered participants. The workshop was developed with 50% EU funding and 50% internal funding. The pedagogical principles tested in this workshop will be used in a new Horizon 2020 project recently granted (GRE@T-PIONEeR – Graduate education alliance for teaching the physics and safety of nuclear reactors). The project will be coordinated by the Department of Physics and will start in late 2020 for a duration of three years.

Prof. Christophe Demazière wrote a book on "Modelling of nuclear reactor multi-physics – From local balance equations to macroscopic models in neutronics and thermal-hydraulics". The book also contains more than 70 short videos and online quizzes. The videos were developed with partial support from SKC. More info about the book at:
http://www.elsevier.com/books/isbn/9780128150696 .

In the frame of an ERASMUS Staff Mobility Agreement between Chalmers and the Budapest University of Technology and Economics (BME), Prof. Imre Pázsit gave a course "Noise Techniques in Nuclear Systems" to the master students of the Institute of Nuclear Techniques (NTI) of BME. In the frame of the same agreement, Prof. Máté Szieberth of BME NTI visited Chalmers and gave a course on Monte Carlo techniques to the PhD students and postdocs of the Division of Subatomic and Plasma Physics.

Infrastructure

SKC funding has not been utilised for procuring or maintaining infrastructure of relevance in 2019

Research Projects

Development of interactive teaching materials in nuclear reactor modelling

Objective

An interactive book for Elsevier on nuclear reactor modelling was developed with the title "Modelling of nuclear reactor multi-physics – From local balance equations to macroscopic models in neutronics and thermal-hydraulics". The interactive features of the book include embedded short videos presenting each of the concepts throughout the entire book, as well as on-line quizzes. The SKC funding was aimed at supporting part of the development of the videos (which remain the property of Chalmers and are thus available to the SKC partners on request).

Participants

Prof. Christophe Demazière, Chalmers University of Technology

Progress

The preparation of the book was completed. The book and all the interactive features were delivered to Elsevier in June 2019. The book was released on November 18th, 2019 and is available for order from Elsevier at:

http://www.elsevier.com/books/isbn/9780128150696

71 videos/webcasts explaining the key concepts were produced, as well as 77 interactive quizzes allowing the readers to test their understanding.

Outlook

The project is completed.

Relevant Publications

C. Demazière, Modelling of nuclear reactor multi-physics - From local balance equations to macroscopic models in neutronics and thermal-hydraulics. ISBN-978-0-12-815069-6 (and ISBN-978-0-12-815070-2 for the eBook), Academic Press/Elsevier (2020).

Validation experiments for coupled reactor physics simulations

Objective

Chalmers collaborated with CEA Cadarache, France and provided technical support to a Post-Doctoral student employed by and at CEA for utilizing the CORE SIM tool (developed by Chalmers), for modelling the ZEPHYR facility, for simulating artificially-induced perturbations in ZEPHYR and for interpreting the simulations.

Participants

Prof. Christophe Demazière, Chalmers University of Technology
Assoc. Prof. Paolo Vinai, Chalmers University of Technology
Vasudha Verma, CEA Cadarache
Guillaume Ricciardi, CEA Cadarache
Robert Jacqmin, CEA Cadarache

Progress

Simulations were performed with the CORE SIM tool on a system representative of ZEPHYR, with nodal macroscopic nuclear cross-sections generated with Serpent. First neutron noise calculations were performed for a so-called absorber of variable strength. Thereafter, the modelling of fuel assembly vibrations was given attention. In a system representative of ZEPHYR, i.e. a small research reactor, different modelling strategies for modelling vibrations were examined. All of them relied on the use of the so-called ε/d model at different levels of refinement: (a) the model was applied at the pin level, (b) the model was applied at the nodal level by introducing the perturbation at the boundary between the homogenized regions, and (c) the model was applied at the nodal level by smearing the perturbations onto the homogenized regions neighbouring the vibrating assembly. The incentive of the study was to determine the best modelling approach for modelling fuel assembly vibrations with nodal core simulators. With (a) representing the reference solution, it was demonstrated that the nodal approach (b) outperforms the nodal approach (c). More specifically, it was found that the spatial distribution of the neutron noise in the close vicinity of the vibrating fuel assembly can only be properly modelled using (b). Since the modelling approach (c) is being used in some commercial core simulators, this study demonstrates that such a modelling approach cannot reproduce the neutron noise close to the vibrating fuel assembly. The results of core simulator using this approach should thus be considered with care. Nevertheless, a few mean free paths away from the perturbation, the approach (b) and (c) lead to identical results.

Outlook

The project is completed.

Relevant Publications

V. Verma, C. Demazière, P. Vinai, G. Ricciardi, and R. Jacqmin, Assessment of the neutron noise induced by stationary fuel assembly vibrations in a Light

Water Reactor. Proc. Int. Conf. Mathematics & Computational Methods Applied to Nuclear Science & Engineering (M&C 2019), Portland, OR, USA, August 25-29, 2019 (2019).

Development of UN synthesis and doped UN systems for ATF applications in light water reactor systems

Objective

Chalmers is working on developing nitride based nuclear fuels with applicability within light water reactor systems. Accident tolerance and enhanced core performance with respect to steam oxidation resistance are key topics within nuclear fuel development today. Uranium nitride is a potential high-performance fuel during normal reactor operation but is inherently incompatible with water/steam. Nitride based fuels therefore require water proofing in order to be an actual consideration for LWR systems. The project objectives are as follows, improve UN purity during fabrication using carbothermic reduction and screen for viable water proofing dopants with regards to UN fuel.

Participants

Luis Gonzalez, Chalmers University of Technology

Marcus Hedberg, Chalmers University of Technology

Christian Ekberg, Chalmers University of Technology

Teodora Retegan, Chalmers University of Technology

Progress

Synthesis of uranium nitride by internal gelation coupled with carbothermic reduction has been used for materials fabrication. Work on reducing the residual of carbon and oxygen in the UN materials post carbothermic reduction has been performed and materials are now regularly produced containing impurity levels of about 1000 ppm each of carbon and oxygen. This purity level is considered acceptable. A system has been set up to online monitor UN synthesis and measure level of completeness of the nitride synthesis step. Previous work has been performed on using sugar species as reducing agents during carbothermic reduction. This work has been continued and finalized. Using monosaccharides as carbon source instead of carbon powder can be performed by retaining acceptable nitride purities in the final UN materials. Impurity levels reached with the method were about 2600 ppm oxygen and 600 ppm carbon. This production route was abolished, not due to final material impurity, but due to difficulties in the internal gelation part of the process. Purity wise the process appear optimizable to a level meeting material purity demands. Challenges in the gelation process however made the change from carbon powder to monosaccharides unnecessarily complicated with respect to the advantages gained by adding a soluble carbon source to the system. Regarding screening for ATF dopants thorium has been investigated as a potential dopant. UN and (U,Th)N microspheres have been produced and sintered into dense pellets using SPS. This is to our knowledge the first time SPS has been applied to directly sinter UN based microspheres and work on sintering parameters have been performed in order to find sintering parameters suitable for preparation of dense UN pellets. The produced UN and (U,Th)N pellets have been subjected to interaction studies with water at 100, 200 and 300 °C. Early results indicate complete pellet disintegration during fuel/coolant interaction implying that Th addition does not stabilize UN by formation of a protective ThO2 film on the UN pellet surface. Continuing forward synthesis of UN from UO2 reactions with methane/N2 **mixtures will be studied as well as inclusion of Cr as protection agent in UN fuels.**

Outlook

The project is ongoing.

Relevant Publications

L. Gonzalez, M. Hedberg, L. Huan, P. Olsson, T. Retegan, Application of SPS in the fabrication of UN and (U,Th)N pellets from microspheres, manuscript, submitted to Journal of Nuclear Materials

Ageing of Reactor Pressure Vessel Steel Welds

Objective

The reactor pressure vessel (RPV) is a life-limiting component of a nuclear reactor. Neutron irradiation during operation decreases the ductility of the RPV steel. The most important mechanism for making the steel brittle is the formation of nanometre-sized particles, consisting of Ni, Mn, Si and Cu. In particular, welds are affected as they often contain higher concentrations of the listed elements. In the Ringhals unit 3 and 4 reactors, the Ni- and Mn-contents are higher than in most other reactors, making studies of these important. The aim of this project is to study ageing of RPV steel welds, both the effect of neutron irradiation and purely thermal effects, to better understand the mechanisms of ageing and to provide a basis for predicting the lifetime of RPVs. Since the microstructural changes during irradiation are on a very small scale, atom probe tomography (APT) is the most suitable technique for this type of study.

Participants

Kristina Lindgren, Chalmers University of Technology
Mattias Thuvander, Chalmers University of Technology

Progress

Earlier, surveillance material and weld metal irradiated in a materials test reactor has been compared in order to study the effects of neutron flux. This is further studied by post irradiation annealing (PIA), to study how the clusters dissolve, and by coupling this to the recovery of mechanical properties of the material. This is done in collaboration with PhD-student Magnus Boåsen and Prof. Pål Efsing at KTH. Furthermore, material from the decommissioned Barsebäck unit 2 RPV welds was analysed using APT. The Barsebäck plant is a BWR and thus the neutron fluence and temperature are lower than for the PWR that is usually studied, but the very low fluence and flux are of interest as a comparison in order to further understand the mechanisms. The effects of thermal ageing were studied on the welds of a Ringhals pressurizer that was changed in 2011. Different welds were compared using APT, and a contribution to a manuscript written by Magnus Boåsen was made. The above-mentioned research was presented in several contexts; at the SKC annular symposium, and at two conferences, Euromat 2019 in Stockholm and IGRDM in Gifu, Japan.

Outlook

The project is ongoing.

Relevant Publications

A manuscript on PIA of the RPV is being written together with KTH (Boåsen/Efsing).

Publications with Full or Partial SKC Funding

Doctoral Theses

A. Vesterlund, "Method Development for Signatures in Nuclear Materials for Nuclear Forensic Purposes", 29th November 2019.

Licentiate Theses

No published licentiate theses were funded by SKC 2019

Peer Review Journals

Y. Dong, A. Etienne, A. Frolov, S. Fedotova, K. Fukuya, C. Hatzoglou, E. Kuleshova, K. Lindgren, A. London, A. Lopez, S. Lozano-Perez, Y. Miyahara, Y. Nagai. K. Nishida, B. Radiguet, D.K. Schreiber, N. Soneda, M. Thuvander, T. Toyama, J. Wang, F. Sefta, P. Chou, E.A. Marquis, Atom Probe Tomography Interlaboratory Study on Clustering Analysis in Experimental Data Using the Maximum Separation Distance Approach, Microsc. Microanal. 25 (2019) 356.

Conferences

V. Verma, C. Demazière, P. Vinai, G. Ricciardi, and R. Jacqmin, Assessment of the neutron noise induced by stationary fuel assembly vibrations in a Light Water Reactor. Proc. Int. Conf. Mathematics & Computational Methods Applied to Nuclear Science & Engineering (M&C 2019), Portland, OR, USA, August 25-29, 2019 (2019).

Other Publications

C. Demazière, Modelling of nuclear reactor multi-physics - From local balance equations to macroscopic models in neutronics and thermal-hydraulics. ISBN-978-0-12-815069-6 (and ISBN-978-0-12-815070-2 for the eBook), Academic Press/Elsevier (2020).

Relevant Publications without SKC Funding

V. Dykin and C. Demazière, Predictive BWR core stability using feedback reactivity coefficients projected on neutronic eigenmodes. Annals of Nuclear Energy, 124, 1-8 (2019).

N. Olmo-Juan, C. Demazière, T. Barrachina, R. Miró, and G. Verdú, PARCS vs CORE SIM neutron noise simulations. Progress in Nuclear Energy, 115, 169-180 (2019).

C. Demazière, V. H. Sanchez-Espinoza, and B. Chanaron, Advanced numerical simulation and modelling for reactor safety – Contributions from the CORTEX, HPMC, McSAFE and NURESAFE projects. Proc. 9th European Commission Conferences on EURATOM Research and Training in Safety of Reactor Systems and Radioactive Waste Management (FISA 2019 - Euradwaste' 19), Pitesti, Romania, June 4-7, 2019 (2019) (invited).

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M. Viebach, C. Lange, S. Kliem, C. Demazière, U. Rohde, D. Hennig and A. Hurtado, A comparison between time domain and frequency domain calculations of stationary neutron fluctuations. Proc. Int. Conf. Mathematics & Computational Methods Applied to Nuclear Science & Engineering (M&C 2019), Portland, OR, USA, August 25-29, 2019 (2019).

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A. Mylonakis, P. Vinai, and C. Demazière, Neutron noise modelling for nuclear reactor diagnostics. Proc. 27th Annual Symposium of the Hellenic Nuclear Physics Society (HNPS2018), Athens, Greece, June 8-9, 2018 (2019).

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K. Insulander Björk, A. Herman, M. Hedberg, C. Ekberg, "Scoping Studies of Dopants for Stabilization of Uranium Nitride Fuels", Nucl. Sci. Eng., Vol. 193, No. 11, pp. 1255-1264, 2019

E. Aneheim, S. Palm, H. Jensen, C. Ekberg, P. Albertsson, S. Lindegren, "Towards elucidating the radiochemistry of astatine- Behaviours in choloform", Scientific reports, Vol. 9, No. 1, pp. 1-9, 2019

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L. Nagy, I. Pázsit, L. Pál, G. Klujber and M. Szieberth, Measurements and simulations to investigate the feasibility of neutron multiplicity counting in the current mode of fission chambers. Proc. ANIMMA 2019, June 17-21, 2019 Portoroz, Slovenia

L. Nagy, I. Pázsit and L. Pál, Multiplicity counting for thermal neutrons from fission detector currents with multi-point time distributions. Paper a197, Proc. INMM 60th Annual Meeting, JW Marriott Desert Springs, Palm Desert, California, USA, 14 - 18 July 2019

I. Pázsit, L. Pál and A. Enqvist, Extension of the Böhnel model of multiplicity counting to include space- and angular dependence. Paper a167, Proc.

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I. Pázsit, Theory of neutron fluctuations with applications in nuclear safeguards and noise diagnostics in research and power reactors. Proc. VINANST-13, The Vietnam Conference on Nuclear Science and Technology. 7-9 August 2019. Vinpearl Resort & Spa Ha Long, Reu Island, Bai Chay, Ha Long City, Vietnam.

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KTH
Royal Institute of Technology

Introduction

The following divisions/departments at KTH have been mainly engaged in nuclear technology education and research in 2019:

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

The first two of them (Nuclear Engineering and Solid Mechanics) received a direct financial support from SKC during 2019. Both the theoretical and experimental research is pursued at KTH.

The Centre for Nuclear Engineering at KTH (CEKERT) is the platform to coordinate nuclear technology research and education, and it included 9 faculty members during 2019. As one of its coordinated activities, CEKERT 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 2019 the number of enrolled students was 22.

KTH has strong international collaborations in nuclear technology with many organisations from different countries through Euratom-funded projects, OECD/NEA and IAEA research programs. In Sweden, the most active collaborations are with Chalmers, Uppsala, Linköping, Luleå and within KTH, as well as with nuclear authority (SSM) and industrial partners such as Westinghouse, SKB, Sandvik, Uniper, LeadCold, Jernkontoret, Outokumpu, Safetech, Vattenfall, Studsvik and Swedish nuclear power plants.

Division of Nuclear Engineering has two main laboratories and rely otherwise mostly on high-performance computations with support from large national and international facilities (PRACE, SNIC, CINECA, etc). The division has yearly allocations of about 70 million core-hours used for modelling and simulation. The experimental facilities are:

- HWAT loop: High-pressure water test loop for PWR, BWR and SCWR thermal-hydraulic investigations with pressure range up to 25 MPa, total flow 1 kg/s and total power 1 MW.
- LOFAT: Low-pressure fuel-assembly test facility for detailed laser-doppler measurements of turbulent flow structure in nuclear fuel assemblies with spacer grids.
- Advanced nuclear fuel laboratory: built from scratch and continuously developed since 2009. Furnaces for synthesis and for sintering, glove boxes, gas analysis, element analyser, particle size analyser. Capacity for manufacture of low-activity actinide compound powders and pellets. Characterization using optical and electron microscopy, TGA, XRD, etc in collaboration with Materials science and with Surface and corrosion science.

Division of Nuclear Power Safety has two laboratories. The infrastructure and research facilities are generally composed of the SWECOR platform with severe accident research facilities, the TALL loop for thermal-hydraulic investigation of heavy liquid metal (HLM) coolant, and facilities for basic research on multi-phase flow as well as a machining workshop. The examples of specific facilities are:

- CONMT infrastructure: A reinforced concrete containment (4×4×4 m) designed to accommodate high-temperature high-pressure energetic experiments in severe accident study.
- INDUC infrastructure: High- and middle-frequency induction furnaces employed for melt generations of various simulants of corium in melt-coolant interaction and coolability experiments (e.g., DEFOR and PULiMS).
- MISTEE facility: A X-ray radiation-shielding room (3×6×3 m) and high-speed (up to 100 000 fps) visualization system with simultaneous X-ray radiography and photography used to investigate opaque multi-phase flows (e.g. liquid metals), and energetic micro-interactions in steam explosion.
- TALL facility: A seven-meter tall heavy liquid metal (HLM) loop to study the thermal-hydraulics in HLM- cooled systems (e.g. accelerator-driven system for transmutation and lead-cooled fast reactors).
- SIMECO-2 facility: A scaled down lower head of reactor vessel in the dimensions of internal diameter × height × width = 1000mm × 500mm × 120mm to study turbulent heat transfer of stratified melt pools.
- MRSPOD facility: A vertical tube furnace with a 1300 mm x 120 mm cylindrical quartz tube and 3 heating zones to investigate melt penetration, solidification and remelting, and relocation in a multi-component and multiphase porous debris bed.
- SPAYCOR facility: An electrically heated downward-facing specimen of 120mm x 80mm area cooled by the spraying of a 3x2 array nozzle assembly.
- MICBO facility: A well-instrumented platform designed to study thermal-hydraulics of boiling phenomenon at micro scales.

Some highlights relevant to activities and areas funded by SKC for 2019 are listed below:

- Dr Mattia Bergagio, supervised by Henryk Anglart, was awarded the Sigvard Eklund Prize for his PhD thesis on "Experimental and analytical study of thermal mixing at reactor conditions".
- Daniel Fransén, supervised by Pär Olsson, was awarded the Sigvard Eklund Prize for his BSc thesis on "A time alternating classical–quantum method for simulating radiation damage in crystalline materials".

Utilisation of Funding

During 2019 KTH received the SKC funding of 3100 kkr for PhD student projects (1600 kkr), a text-book on fast neutron Generation-IV reactors (250 kkr), Master's programme in Nuclear Energy Engineering (250 kkr), and three faculty positions in Division of Nuclear Engineering (1000 kkr). As describe below, the base funding was used in several ways to support research, education and cooperation with the surrounding society.

Research Projects

One PhD student project at Division of Nuclear Engineering was funded by SKC with 800 kkr for the student's salary in 2019:

- Studies of irradiation assisted stress corrosion cracking.

Two PhD student projects at Department of Solid Mechanics were funded by SKC with 800 kkr for partial students' salaries in 2019:

- Mechanical modelling of intergranular stress corrosion cracking in sensitized stainless steel 316, PhD student Michal Sedlak supervised by Prof. Bo Alfredsson and Adjunct Prof. Pål Efsing.
- Brittle fracture in aged low alloy steels, mechanical properties and modelling from a local plasticity perspective, PhD student Magnus Boåsen supervised Adjunct Prof. Pål Efsing.

SKC funding of 250 kkr was allocated to Prof. J. Wallenius's salary who is writing a text-book on fast neutron Generation-IV reactors with S. Bortot at the division of Nuclear Engineering. The text-book is intended to be published in an electronic format, allowing for interactive reading and integration of computational exercises. A total of 18 chapters are planned out of which five have been written. The schedule for completing the text-book has been delayed, in part due to the parental leave of one of the co-authors. It is expected that nine chapters will be finished by end of spring semester 2020.

Another SKC funding of 250 kkr was allocated to the Master's programme in Nuclear Energy Engineering at KTH, for Programme's expenses, including partial salary of Programme Director's (Assoc. Prof. Jan Dufek).

Base Funding

The Division of Nuclear Engineering at Department of Physics received the base funding of 1000 kkr for covering partial salaries of the faculty positions of Prof. Pär Olsson, Prof. Henryk Anglart and Assoc. Prof. Jan Dufek. The base funding was distributed to the staff as follows:

- Prof. Pär Olsson 357 000 SEK
- Prof. Henryk Anglart 357 000 SEK
- Prof. Jan Dufek 286 000 SEK

Education

Bachelor Level Education

Bachelor level education was not directly supported by SKC funding at KTH, but the nuclear technology related groups at KTH are involved a few Bachelor courses dealing with energy, for which introductory lectures on nuclear energy are provided.

Master Level Education

Master level education was fulfilled by the Master's Programme in Nuclear Energy Engineering at KTH, which offers the courses to following student:

- students admitted through KTH own admission (internal and external, termed as "TNEEM" in the following text),
- students in EMINE (European Master in Innovative Nuclear Energy Engineering), a part of KIC InnoEnergy educational program in which students get a KTH dual diploma with either ENSTA - University Paris-Saclay, Paris or Grenoble Institute of Technology, Grenoble-INP,
- dual diploma students in Nuclear Energy Engineering in cooperation with Tsinghua University, Beijing,
- students of the dual diploma programme between KTH and Korean Advanced Institute for Science and Technology (KAIST),
- double degree students in the frame of KTH's Double Degree agreements within the Master of Science in Engineering programmes and within the ERASMUS program.

All dual diploma and double degree students are termed as "DD" in the following text.

Admission of new students in 2019

In 2019, 22 new students were admitted to our master programmes (TNEEM + DD + EMINE). Figure K-1 shows the trend of the number of students enrolled over the years 2014 – 2019. The growing trend lasted till 2017, while a drop in the number of enrolled students occurred in 2018 and the total number of students dropped further by 3 in 2019.

The reason of the overall small admission of students is the decrease in the number of students from the Dual Diploma Programme between KTH and Tsinghua University (TU) (10 students in 2016 and 2017, and only 5 students in 2018, and 4 students in 2019). This drop is due to a KTH self-imposed limit for admission of TU students (due to an imbalance of the flow of students between KTH and TU).

The number of students admitted through KTH own admission has been poor in 2019 (2 external and 0 internal students).

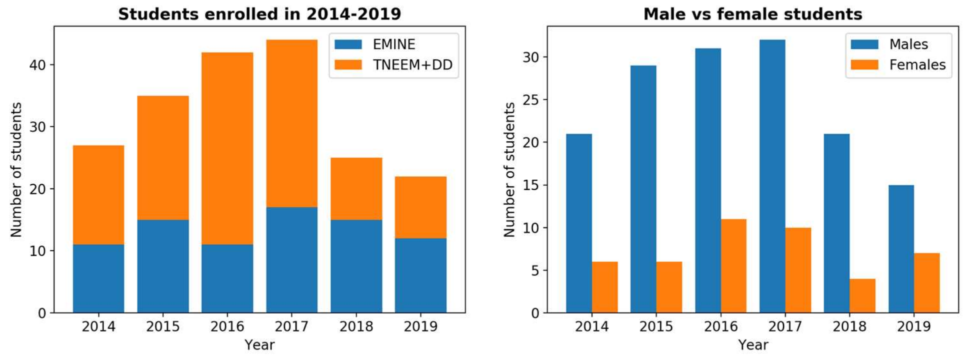

Figure K-1: Number of students enrolled in 2014-2019.

As for EMINE students, 12 students were admitted in 2019, which is a drop of three students with respect to 2018. This is caused mainly by the smaller number of fee-waivers and scholarships offered to EMINE students by InnoEnergy. Costs of all InnoEnergy programmes are being reduced by EIT, and some smaller programmes, such as EMINE, may be cut from the EIT support in the future. Nevertheless, EMINE still represents our biggest source of students, and EIT decided to enrol new EMINE students for 2020.

Gender-wise, majority of students are males. In 2019, 7 female and 15 male students were admitted. Percent-wise, the fraction of females has increased to 32% in 2019 from 16% in 2018. This number has a large statistical fluctuation due to the overall small number of students.

Majority of our students study dual-diploma or double-degree programmes, and attend only the first year at KTH. Negotiations are ongoing about the possibility for EMINE students to select KTH for their second-year study. This is motivated by the fact that France has significantly increased restrictions on accepting students from certain countries, which is causing problems to 2nd-year EMINE students who, so far, can select only France for their 2nd year study.

Courses currently offered at Y1

Table K-1 gives compulsory courses and Table K-2 gives elective courses that are offered by the division of Nuclear Engineering, Power Safety and Nuclear Physics at Year 1 of the Master's programme.

Courses currently offered at Y2

Table K-3 gives compulsory courses and Table K-4 gives elective courses that are offered by the division of Nuclear Engineering, Power Safety and Nuclear Physics at Year 2 of the Master's programme.

Master theses defended in 2019

Table K-5 summarises the master theses supervised at KTH and successfully defended in 2019. Apart of these theses, 10 DD Tsinghua students and 17 EMINE students wrote their theses and defended under supervision of our partner universities in 2019.

Table K-1: Compulsory courses in Year 1 of the Master's programme

Code	Teacher	Course Name	ECTS
SH2603	T. Bäck	Radiation, Protection, Dosimetry and Detectors	6
SH2600	J. Dufek	Nuclear Reactor Physics, Major Course	9
SH2706	H. Anglart	Sustainable Energy Transformation Technologies	9
SH2702	H. Anglart	Nuclear Reactor Technology	8
SH2612	W. Ma	Nuclear Power Safety	6

Table K-2: Elective courses in Year 1 of the Master's programme

Code	Teacher	Course Name	ECTS
SH2605	P. Olsson	Radiation Damage in Materials	6
SH2704	J. Dufek	Monte Carlo Methods and Sim. in Nucl. Technol.	6
SH2701	H. Anglart	Thermal-Hydraulics in Nucl. Ene. Engineering	6
SH2610	Inv. speakers	Leadership for Safe Nuclear Power Industry[1]	6
SH2613	J. Wallenius	Generation IV Reactors	6
SH2611	J. Wallenius	Small Reactors	6
SH2614	J. Wallenius	The Nuclear Fuel Cycle	6
SH2302	B. Cederwall	Nuclear Physics	8
SH2703	J. Dufek	Nuclear Reactor Dynamics and Stability	6
SH2705	S. Ghias	Compact Reactor Simulator	6
SH2774	V. Arzhanov	Numerical Methods in Nuclear Engineering	6
SH262V	Inv. speakers	Elements of Back-end of Nucl. Fuel Cycle[2]	7.5
SH2772	M. Jolkkonen	Chemistry and Physics of Nuclear Fuels[3]	8

Table K-3: Compulsory courses in Year 2 of the Master's programme

Code	**Teacher**	**Course Name**	**ECTS**
AK2030	J. Berg	Theory and Methodology of Science	4.5
SH2007	P. Olsson, T. Bäck	Research Methodology in Physics	6
SH204X	T. Bäck	Degree Project in Physics, Second Cycle	30

[1] SH2610 was not given in 2019 due to KTH regulations concerning the age limit of invited teachers. The course is undergoing a restructuring now in order to make it possible to give it in autumn 2020.

[2] SH262V was given in summer 2019; however, it has been decided that SH262V will not be given in summer 2020 as its funding could not cover its increased budget. Moreover, the possible COVID-19 pandemic could prevent the international students from attending the course.

[3] SH2772 was not given in 2019 due to having no students' registrations.

Table K-4: Elective courses in Year 2 of the Mater's programme

Code	Teacher	Course Name	ECTS
SH2701	H. Anglart	Thermal-Hydraulics in Nucl. Ene. Engineering	6
SH2774	V. Arzhanov	Numerical Methods in Nuclear Engineering	6
SH2614	J. Wallenius	The Nuclear Fuel Cycle	6
EF2200	M. Ivchenko	Plasma Physics	6
SH2610	Inv. speakers	Leadership for Safe Nuclear Power Industry	6
SH2615	V. Arzhanov	Neutron Transport Theory	6
SH2772	M. Jolkkonen	Chemistry and Physics of Nuclear Fuels	8
ED2235	H. Bergsåker	Atomic Physics for Fusion	6
MJ2411	A. Martin	Renewable Energy Technology	6

Table K-5: Master theses supervised and defended at KTH in 2019

Name of the student	Examiner	Title of the thesis
C. Petersson	J. Wallenius	Erosion-Corrosion experiments on Steels in liquid lead and Development of Slow Strain Rate testing rig
B. Leenders	J. Dufek	Assesment of the isotopic inventory build-up in ISOL targets operated with 100-MeV protons and the migration of the volatile species in the ISOL system
G. Acharya	J. Wallenius	Investigating the Application of Self-Actuated Passive Shutdown System in a Small Lead-Cooled Reactor
F. Dehlin	J. Wallenius	Implementation of an Autonomous Reactivity Control (ARC) system in a small lead-cooled fast reactor
S. Ohlsson	J. Wallenius	IGSCC in weld with high content ferrite
J. Pedersen	H. Anglart	Analysis of the Super-history powering method in Monte Carlo neutron transport simulations
C. Wang	W. Ma	A Preliminary Design Study for a Small Passive Lead-bismuth Cooled Fast Reactor
L. Emil	J. Wallenius	A new model for Pellet Cladding Interaction risk assessment

Alumni

From our statistics, we can see that about 60% of all our alumni get jobs in nuclear-power related industry in Sweden or abroad. Moreover, almost 30% of our international students find jobs in Sweden and they thus represent a very significant source of employees for the Swedish industry. In fact, the number of our international students getting jobs in Sweden exceeds that of Swedish students by a large margin.

TNEEM booklet

The first TNEEM booklet was compiled for students starting in autumn of 2019. It can be downloaded from here. The 2019 TNEEM booklet contains students' feedbacks from the autumn semester 2018 and the spring semester 2019. Apart of the fields mentioned in the previous sections, the booklet contains a field "Changes to be introduced in the coming term" where teachers have a space to describe the possible changes they intend to implement in the course (as a response to the collected students' feedback).

Suggestions for improvement of the TNEEM booklet:

- We may include a new field in the coming 2020 TNEEM booklet that would include teacher's comments on students' feedback. This could clarify some possible misunderstandings that some students may have when giving their feedback.
- We may include a section with instructions to students who intend to carry out a master degree project at our divisions. The instructions would relate to the available topic options supervised at our divisions and a list of industrial partners or institutions that offer relevant degree projects.

Doctoral Level Education

A number of courses are given at the doctoral level and some 25 PhD students are enrolled in the fields of Nuclear Engineering and Nuclear Power Safety

Infrastructure

Nuclear Engineering has not had any infrastructure funding from SKC in 2019.

Research Projects

Mechanical modelling of intergranular stress corrosion cracking in sensitized stainless steel 316

Objective

The project objective is to develop a micro-mechanical model for crack growth due to intergranular stress corrosion (IG-SCC). The model will combine fracture mechanics with diffusion, oxidation, degradation and damage of the material.

Participants

The work is performed at KTH Solid Mechanics. Project leaders are Professor Bo Alfredsson and Adjunct Professor Pål Efsing. Michal Sedlak is active in the project as PhD student.

Progress

During 2019 one manuscript was finalized, submitted and published in Engineering Fracture Mechanics. The work couples fracture mechanics, diffusion and oxidation in accord with the slip-oxidation model. The research for two further manuscripts were performed where the oxide layer build-up was adaptively modelled. These two works comprise the remaining work for the PhD thesis of Michal Sedlak.

Outlook

The project will be finished by end of April 2020 with the dissertation of Michal Sedlak. The dissertation is planned for April 21, 2020. Dr Thierry Couvant from EDF will be the faculty opponent.

Relevant Publications

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, 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.

Brittle fracture in aged low alloy steels, mechanical properties and modelling from a local plasticity perspective

Objective

The objective of the project is to develop a micro-mechanical model representing the behaviour of aged low alloy steel representative of those used in pressure bearing components in LWRs. The study includes constraint effects and micro mechanical modelling from a grain to grain interaction perspective.

Participants

The work is performed at KTH Solid Mechanics by Magnus Boåsen as the active Ph. D. student. Project leaders are Adjunct Prof. Pål Efsing supported by Prof. Jonas Faleskog and researcher Carl Dahlberg.

Progress

In 2019, two manuscripts have been accepted and published in the open literature. In addition to this Bosåen discussed his Licentiate thesis with Christian Niordson as the discussion leader in 2019.

Outlook

The project will be finished by mid-September 2020 with the dissertation of Magnus Boåsen. The dissertation is preliminary planned for September 18, 2020, with Professor Jaques Besson from Ecole de Mines in Paris acting as the faculty opponent.

Relevant Publications

M. Boåsen, P. Efsing and U Ehrnsten, On flux effects in a low alloy steel from a Swedish reactor pressure vessel, J. Nucl Mater., 2017, vol 484, pp. 110-119.

M. Boåsen M. Stec, P. Efsing and J. Faleskog, A generalized probabilistic model for cleavage fracture with a length scale – influence of stress state and application to surface cracked experiments, Eng Fract Mech, 2019, vol 214, pp. 590-606.

C. Dahlberg, M. Boåsen, Evolution of a length scale in strain gradient plasticity, I J of Plasticity, 2019, vol 112, pp-22+-241.

K. Lindgren, M. Boåsne, K. Stiller, P. Efsing, M. Thuvander, Cluster formation in in-service thermally aged pressurizer welds, J. Nucl Mater., 2018, vol 504, pp.23-28.

K. Lindgren, M. Boåsne, K. Stiller, P. Efsing, M. Thuvander, Evolution of precipitation on reactor pressure vessel steel welds under neautron irradiation, J. Nucl Mater., 2017, vol 488, pp.222-230.

Studies of irradiation assisted stress corrosion cracking

Objective

The objective of the project is to investigate radiation and H2O2-induced corrosion of stainless steel in Radiation Physics and Chemistry.

Participants

The work is performed at KTH Nuclear Engineering by Elin Toijeras the active PhD student. Project leader is Prof. Pär Olsson who has collaboration on this project with Prof. Mats Jonsson from KTH Nuclear Chemistry.

Progress

During 2019, Elin Toijer published a manuscript on radiation and H2O2-induced corrosion of stainless steel in Radiation Physics and Chemistry. Experiments aiming at elucidating the detailed mechanism of the reaction between the aqueous radiolysis product H2O2 and metal oxide surfaces (using ZrO2 as a model) have been finalized during 2019 and Elin Toijer will submit the manuscript in spring 2020.

Elin Toijer has submitted a manuscript on solute – point defect interactions in fcc Ni in collaboration with colleagues from France (EDF, CEA and Univ Lille) to Journal of Nuclear Materials. She has completed study of the effect of solute diffusion to grain boundaries and effect on yield strength in fcc Ni. She has completed most of the work for another study on defect dynamics in paramagnetic fcc Ni. Elin has finished all courses for her PhD and has completed the last of her teaching activities. Elin participated in the Euromat-2019 conference in Stockholm and presented her work there.

Outlook

The plan for Elin Toijeras is to defend her thesis at a public dissertation in early fall 2020.

Relevant Publications

E. Toijer, M. Jonsson, H2O2 and γ-radiation induced corrosion of 304L stainless steel in aqueous systems, Rad. Phys. Chem. 159 (2019) 159.

Publications with Full or Partial SKC Funding

Licentiate Theses

Ignas Mickus, Response Matrix Reloaded: for Monte Carlo Simulations in Reactor Physics. Main supervisor Jan Dufek has some support from SKC, 2019.

Magnus Boåsen, Modelling framework for ageing of low allow steel, KTH, 2019

Peer Review Journals

W. Fan, H. Li, H. Anglart, Numerical investigation of spatial and temporal structure of annular flow with disturbance waves, Int. J. of Multiphase Flow 110 (2019) 256.

H. Anglart, Progress in understanding and modelling of annular two-phase flows with heat transfer, Nucl. Eng. Design 345 (2019) 166.

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Uppsala University

Introduction

Within the department of Physics and Astronomy, the division of Applied Nuclear Physics together with the division of materials theory comprises research and education within a broad range of applications. Among these applications, safe nuclear power operation constitutes an important part of our efforts and comprises the three duties of a Swedish university; education, research and cooperation with the society at large. Obviously, this part of our activities is of direct relevance for SKC and in this annual report we present an overview of the most important events of the year 2019.

We may conclude that our finding presented in the annual report for 2018 regarding the renewed political interest for nuclear power has been valid also during 2019. As in 2018, we have experienced an increased interest from the political sphere and the society at large for taking part of our view on matters like the Swedish future electricity supply in view of climate change and securing our welfare society.

Highlights of 2019, relevant to activities and areas funded by SKC

The Swedish Foundation for Strategic Research, SSF, issued a call in August regarding, among other fields, "future nuclear power". A research consortium consisted of UU, (main applicant) Chalmers and the universities in Gothenburg and Stockholm and Prof. Mats Jonsson at KTH, wrote an application regarding the Gen IV system. The proposed project comprises recycling technology, fuel manufacturing, reactor monitoring, safeguards, uncertainty propagation, radiation protection and material research. Among other partners, the application is supported by Vattenfall, Westinghouse and Studsvik Nuclear. It is fair to say that the effort with this application occupied a substantial fraction of the total workload during autumn 2019.

Two successful applications to VR were approved. The first one was written in collaboration with SCK·CEN in Belgium. The application project regards research on novel safeguards approaches applied to the MYRRHA facility.

The second successful application was a starting grant for Ali Al-Adili. The research project concerns fission research related to Gen-IV reactor systems and it will be conducted in collaboration with the Joint Research Centre of the European Commission in Geel, Belgium. We will develop and use a novel detector setup, VERDI (VElocity foR Direct particle Identification), to measure fission yields. In particular, the measurement technique allows for extraction of information about prompt neutron emission. The aim is to achieve a better understanding of the fission process and improved description of the isotope vector throughout the fuel cycle.

We initiated a formal collaboration with the Idaho National Laboratory for research on new methodologies on fuel development. Together with INL and Idaho State University, we wrote an application to Office of Nuclear Energy within the Consolidated Innovative Nuclear Research programme for development of our tomography technique. The application successfully passed the first scrutiny stage.

During 2019, we also became a member of the international n_TOF collaboration at CERN. The collaboration operates a neutron time-of-flight facility with energies ranging from thermal to several hundred of MeV. We will be especially involved in fission experiments, which will lead to improved nuclear data for current reactor systems but also for the various future nuclear energy concepts. The membership fee for UU is currently covered by SSM.

The proposed European Joint Programme on Radioactive Waste Management (EURAD, https://www.ejp-eurad.eu) was accepted by the European Commission and started in June 2019. UU (Peter Jansson) leads a work package "Spent Fuel Characterization and Evolution until Disposal" in the programme, funded by SKB AB, performed in a collaboration between many European partner organisations.

In the nuclear data evaluation work a complete code-system was released under an MIT open source licence. The code system allows for regression of the nuclear model parameters, handles experimental inconsistencies and treats model defects.

As in 2018, we were engaged in the reference group issued by SSM regarding the governmental request to investigate the competence supply within, among others, nuclear technology.

The neutron facility NESSA is becoming closer to commissioning since the procurement of the neutron generator during 2019. A large part of 2019 was dedicated to dimensioning the radiation shield around the generator and the subsequent ordering of building material for finalising the experimental area. NESSA is scheduled to be in operation early 2021 and it is our ambition that it shall function as a valuable tool for material research, detector development, irradiation experiments and nuclear education in Sweden.

Another infrastructure that has been on hold for several years but now is refurbished for operation is the BETTAN facility. BETTAN is a high-end experimental platform for testing of tomographic algorithms and measuring strategies. It has previously been the backbone for our development work of tomography as a means for fuel development and validation of production codes. Our new collaboration with Idaho National Laboratory has again put the light on the necessity to develop efficient methods for accurate post irradiation examinations and the tomography is in this context a feasible technique as has been demonstrated at the Halden site where our methodology was used.

Utilisation of Funding

During 2019 no project funding was received from SKC. As describe below, the base funding was used in several ways to support research, education and cooperation with the surrounding society.

Research Projects

On-going projects with previous full or partial project SKC funding are presented in the project section below as well as on-going project that benefits from the base funding.

Base Funding

In addition to the regular activities, an important but varied business is conducted in our division, which often has the nature of ad hoc and which also assumes that some form of base financing is available. The lack of such basic funding from the state power has been noticeable for a long time, and SKC's basic contributions have thus been decisive factors for the development of our activities.

Cooperation with the surrounding society

In order to effectively meet the need for nuclear-relevant information to the general public, the media and the political sphere, employees have been assigned to the SKC base funding to varying degrees over the years. This activity takes place within what is called collaboration with the surrounding society.

Because of the important role of nuclear power in society and the political dimension in which it operates, and that it is often questioned on incorrect grounds, we have chosen to make this task more extensive than is commonly found at the country's higher education institutions. This choice has been made possible by allowing us to supplement the state power's modest funding of this task with parts of SKC's contribution. A brief account on the efforts is presented in Appendices.

For our part, this task is not just about balancing the image of nuclear power through our public lectures, school class visits, seminars for the country's high school teachers and other things that often associated with this activity. We also create and maintain contacts to a great extent with the political sphere and other policy makers, where we provide information on the state of research and other aspects of nuclear power use. Appearance in radio and television is also part of this business. Furthermore, a substantial effort of this the work is to follow commentary fields in the mass media and social media and making corrections and remarks. Work on writing debate articles in the subject is also done.

Typically, about 15 % of the SKC base funding was allocated within this activity and was distributed among several employees.

Education

For a long period of time, we have been operating in an environment with a declining student base and thus declining state funding for our teachers. Since it is easy to close courses with few participants, while it is much more difficult to reintroduce discontinued courses, we have decided to seek to retain and offer a wide range of nuclear courses from basic to master and doctoral levels. This choice is primarily conditioned by the fact that we want to be well prepared with both courses and teachers whenever the need arises, but also to be able today to offer interested students education in the field, which would not have been possible without SKC's contribution.

Together with other external grants, the SKC funding has enabled course development and the start of courses within the MSc in Energy Systems (ES), Technical Physics (F) and Systems in Technology and Society (STS). The grant has also made it possible to develop and market a special nuclear package on the ES program. Typically, 10 % of full-service salary was allocated to these activities.

Research

Most of our research activities are funded through external project support from the Swedish Research Council, SKC, SSM, EU and SSF. However, experience has shown the importance of adequate base funding that can be used as "seed money" to test new research and education ideas and to be able to carry out feasibility studies which, if successful, may form the basis for applications of larger projects. Thus, such funds have the nature of venture capital, which is of great value in our quest to remain at the forefront of our research and education. Below follow a few examples of activities that have benefit from the SKC funding. About 60 % of the base funding was allocated to this category.

- The feasibility of a high-resolution tomography system for fuel development of ATF has been investigated. This is now a project funded by SSF that includes a doctoral student and his supervisor.
- Parts of the SKC grant have been used within the TMC project, where the connection between nuclear data uncertainties and uncertainties in reactor parameters (both safety parameters and aging parameters) is investigated. This project has later been able to find support from, e.g., the EU.
- Together with Scott Holcombe at IFE, Halden, a feasibility study has been carried out on the use of fission gases in the nuclear fuel plenum for failure identification, i.e. identification of leaking rod in fuel bundles using tomographic technology. Plans are also currently underway for the feasibility study of the use of caesium nuclides for the same purpose. The technology can potentially be used to speed up the identification and replacement of damaged fuel rods.

Infrastructure

About 15 % of the funding has been allocated to the development of the NESSA facility (see below).

Education

The division of Applied Nuclear Physics (TK) has a tradition of providing high-quality education and teaching in a variety of educational programmes and electable courses. Additionally, there is a long-term involvement in contract education as outlined below. The objective is to provide students and course participants with knowledge about and understanding of nuclear energy systems to the benefit of Swedish society in general and the nuclear industry in particular.

Staff from the Division of applied nuclear physics uphold positions as managers of three education programmes. These are:

- The Master Programme in Energy Systems Engineering (Civilingenjörsprogrammet I energisystem, ES)
- The Bachelor Programme in Physics (Kandidatprogrammet i fysik),
- The Bachelor Programme in Nuclear Engineering (Högskoleingenjörsprogrammet i kärnkraftteknik, KKI).

Henrik Sjöstrand, Matthias Weiszflog and Michael Österlund, respectively, are coordinators for the programmes. Cecilia Gustavsson continues to serve as one of two directors of undergraduate studies within the Department of Physics and astronomy.

In addition to courses within the programmes mentioned above, division staff provides nuclear energy relevant courses, i.e., nuclear technology, energy physics and technical thermodynamics, within the framework of other Uppsala University engineering programmes. The division is also managing the UU competence centre NANSS (Nordic Academy for Nuclear Safety and Security), which presently functions as a hub and portal for organizing contract education within the field of nuclear technology.

We are very happy to report that the Uppsala Union of Engineering and Science Students awarded their Distinguished Teaching Award for 2019 to one of our teaching staff, Ali-Al Adili who is involved in our Master and Bachelor programmes.

Bachelor Level Education

Bachelor Programme in Nuclear Technology (Högskoleingenjörsprogrammet I kärnkraftteknik)

Following discussions with stakeholders concerning the future need for new/replacement staff within, e.g., operations and maintenance Högskoleingenjörsprogrammet i kärnkraftsteknik (KKI) was restarted in the autumn of 2019 after a two-year hiatus. The programme had a very successful start in 2010, but in 2017 the KKI programme was put on hold because uncertainties within society about the future of nuclear power in Sweden caused student interest to decrease to a level where it became impossible to operate the program.

For the autumn semester 2019 there were 29 applicants to the program, 12 of those were first-hand applicants, most of which fulfilled the qualification requirements. At the start of the autumn semester 5 students choose to commence their studies. The reasons for the low ratio between the number of students actually starting the programme and the total number of applicants and students admitted to the programme, is not totally clear. One may speculate that the very high availability of job opportunities that exist for 'högskoleingenjörer' in all branches of engineering, allowed applicants that already had an engineering degree to obtain positions during the spring and summer preceding the start of the autumn semester. The plan is to continue to provide the program, but to develop and expand the possibilities for distance learning in order to increase the possibility for students outside Uppsala to participate.

The biggest hurdle to overcome is the need to convey the message, and to convince prospective students, that there are good prospects for a future career within the Swedish nuclear energy sector. This must be clearly communicated not only by the university, but also the nuclear industry itself, through marketing and otherwise in order to make the programme sustainable.

End-of-autumn-semester evaluations of the programme by the students are very positive. Activities within the programme, in addition to lectures and other teaching, that stands out and that are very appreciated by the students are a reactor lab exercise at the Joseph Stephan Institute in Slovenia, simulator exercises at KSU Oskarshamn, and "NPP plant knowledge" exercises at Barsebäck. Also, in addition to the teaching provided by the UU teachers that are involved in the program, several highly expert guest lecturers from the NPP:s and authority has contributed with teaching, something that is very appreciated by the students and sort of 'icing on the cake' since the industry perspective is a very important part

Master Level Education

Master Programme in Energy Systems Engineering (Civilingenjörsprogrammet i energisystem, ES)

The Nuclear Power Track: The Master of Energy Systems (ES) Engineering programme offers a nuclear engineering track where students are given the opportunity to develop their skills and abilities in a relevant context. The package focuses on physics, modelling, and simulation. The ES programme also contains an introduction to nuclear technology for all students of the program.

The track prepares the students to perform their master thesis in nuclear engineering. Such master theses are conducted annually. Since Fukushima, the number of applicants for the track has declined. Given the number of students, the support from SKC is crucial for offering this wide track to our students. The programme Manager for the Energy Systems programme is Henrik Sjöstrand.

Courses included in the nuclear engineering track:

- Modern Physics 5 credits, level = basic.
  Provides basic nuclear physics

- Nuclear Power Technology and Systems, 10 ECTS credits, level = advanced.
  A course that gives the students a good overview of the nuclear energy system and the methods used from the reactor to the final repository.

- Future nuclear energy systems - analyses and simulations 5 credits, level = advanced.
  Focus on Gen IV and reactor modelling and simulation using Monte Carlo codes.

- Applied reactor physics 5 credits, level = advanced.
  The course is given together with Vattenfall Fuel. This course specialises in industry-relevant issues such as enrichment optimization from an economic perspective.

- Empirical Modelling 10 credits, level = advanced.
  In this course, the students get acquainted with reactor stability margins, etc., using actual measurement data.

- Safety analyses in the energy sector 5 credits, level = advanced.
  In this course the students learn how to perform Probabilistic and Deterministic Safety Analysis.

More information is available on:
https://www.teknat.uu.se/utbildning/student/program-och-kurser/energisystem/kurser/kurspaket/

Master's Programme in Engineering Physics (Civilingenjörsprogrammet i teknisk fysik, F)

The Master's Programme in Engineering Physics includes two courses with relevance for nuclear technology. The first one, Energy Physics I (5 credits, level = basic), is a general course on different energy sources, especially those of importance for the Nordic energy supply. The second one, Energy Physics II with Nuclear Energy (10 credits, level = advanced), is focused on reactor physics, criticality, reactor safety and reactor dynamics, but includes chapters on nuclear fusion and electricity distribution. These courses are also offered within the Master's Programme in Physics. Unfortunately, they suffer from the same shortage of students as the corresponding courses within the Master Programme in Energy Systems Engineering.

Project and thesis work

About 25 students were taking project course or doing their thesis work with supervisors from the division of applied nuclear physics, the majority of them with relevance for nuclear engineering. Among these were 4 master theses within the Master Programme in Energy Systems Engineering (30 credits, level = advanced), 5 master theses within the Master Programme in Engineering Physics (30 credits, level = advanced) and 1 master thesis within the Master's Programme in Physics (30 credits, level = advanced).

Doctoral Level Education

In 2019, five PhD students, employed in the Division, were involved in thesis projects in nuclear technology relevant for SKC. Another 12 PhD students in the Division were involved in projects in accelerator-based ion physics and fusion research. The students and their preliminary thesis titles are:

- Bernardo Bechierini, "Investigating fission fragments with the (2E, 2n) VERDI spectrometer".
- Zhihao Gao, "Fission yields for next generation nuclear power".
- Lorenzo Senis, "Gamma Emission Tomography for Post-Irradiation Examination of Accident Tolerant Nuclear Fuel".
- Vaibhav Mishra, "Nuclear safeguards directed to the application of multivariate analysis techniques to existing and future nuclear fuel cycles".
- Vikram Rathore, "Nuclear fuel diagnostics for Gen-IV".

Stand-alone coursework

Contract education

Uppsala University continues to provide contract education within an agreement with industry partners. NANNS (www.nanss.uu.se) functions as the portal for advertising upcoming courses that are reoccurring. Additionally, we develop new courses or variants of existing ones for customers on a demand basis.

The objective of the contract education activities, which commenced in 2003, is to provide good opportunities for the continued education and competence building of existing and newly recruited personnel within the nuclear industry. The agreements provide the power plants access to various courses provided by Uppsala University on a demand basis while ensuring Uppsala University the possibility of maintaining teaching staff for the contract education courses. Our teachers, active within contract education, also participate in research within the Division of applied nuclear physics.

During 2019 UU has provided 7 weeks of courses in reactor physics and radiation protection both in Uppsala, and on-site at the nuclear power plants. This is lower than expected, the reason being that on occasions courses had to be cancelled due to too few applicants or withdrawals. This concerned the courses Tillämpad reaktorfysik 5 hp, Kärnkraftsteknologi (H1), 12 hp and Aktivitetsmätning with Ge-detektorer, 1w, that are normally provided on an annual basis.

During 2019 simulator instructors from all KSU-simulators have participated in a 'teach-the-teachers' reactor-physics course with the objective of providing the instructors with an improved understanding of underlying physical processes and to provide them with explanation models that can be used during simulator training of existing and future reactor operators. The revised courses on radiation protection Fördjupad strålskyddsutbildning (FS1), 6 hp and the refresher course Fördjupad strålskyddsutbildning (FS2), 1w has proved popular with a relatively high number of participants.

During 2020 we will intensify our contacts with, e.g., the HR-departments of the NPP:s in order to better communicate the availability of courses and to identify future needs and new concepts for education and training of NPP staff. The collaboration with KSU AB concerning teaching materials and simulator training continues in the same way as before.

SKC Distance Learning (Strålningsvetenskap för nyfikna)

In a collaborative effort, staff from Chalmers and UU are collaborating in the development of e-learning course materials within a diverse range of radiation science subjects. The objective is to inspire interest in radiation science subjects and to provide, e.g., upper secondary school pupils and teachers with knowledge, information and study materials that may be used within science courses and student's projects. We have also noticed an interest from society in general. Recorded videos, exercises, etcetera are made freely available in the SAINT web site, https://saint.nu/nyfiken/. The collaboration has also served to strengthen the bonds and contacts between Chalmers and UU and additionally, provided good opportunities for staff knowledge development concerning techniques and practices for e-learning.

Infrastructure

NESSA

Project leader: Dr. Alexander Prokofiev

We have continued the development of the NESSA facility (NEutron Source in UppSAla), placed at the FREIA hall at Ångström laboratory. This 14 MeV neutron source will be cutting-edge and among the most intense in Europe.

The infrastructure is intended for use in research, education, and irradiations for industry. The research will comprise detector development, nuclear data measurements, as well as development of neutron-tomography techniques. NESSA will be used in education at both graduate and post-graduate levels, the latter in particular in the framework of summer schools for early-stage researchers from European and other countries within the EU project ARIEL (Availability and Use of Nuclear Data Research Infrastructures for Education and Learning).

A contract for the delivery of the generator has been singed in May 2019. After a factory acceptance test in the U.S. (planned for August 2020), and a site acceptance test in Uppsala (planned for November 2020), the operations are expected to start in spring 2021.

During 2019 extensive simulations of radiation transport at NESSA have been performed to optimize the design of the facility and to ensure compliance with rules from the regulator. Construction of the facility has progressed and by the end of 2019 the installation of the heavy shielding was almost completed. In parallel, we are working on the Safety Analysis Report of NESSA for SSM.

The ARIEL project, with 22 European partner universities and research centres, has officially started in September 2019. Work on another EU proposal, RADNEXT (RADiation facility Network for the EXploration of effects for indusTry and research) involving NESSA was also started in 2019.

BETTAN

The tomographic test platform BETTAN consists of robotics that move simulated fuel pins from a storage onto a magnetic turntable. The pins contain radioactive material (in total about 0.5 Ci) and emulate typical geometry and absorption conditions for actual fuel ins. The computer control can be programmed to place the pins on the turntable in various fuel geometries. The control also manages the measuring device consisting of four BGO detectors that moves across the fuel setup.

BETTAN has been the heart of several tomography projects during the course of time but has not been operative since many years because of lack of project funding. The interest of developing new, more efficient PIE methods has sparked a renew interest for the tomography methodology and BETTAN is now in a state of refurbishment. Specifically, the control codes will be reviewed as will the position indicators in order to fulfil stricter radiation regulations.

In the short-term perspective, the BETTAN facility is planned to be part of our new collaboration with INL.

Research Projects

Nuclear Fuel Diagnostics

Research leader: Dr. Peter Andersson

This project was initiated in 2015 with funding from SKC. It regards the studies of the behaviour of nuclear fuel and material upon irradiation, and the development of instrumentation for post-irradiation examination of nuclear fuels and materials. In particular, the focus is on development of non-destructive gamma-ray spectrometry and tomography.

During the SKC MÅBiL, quantitative tomographic reconstruction techniques were developed in collaboration with the Halden Reactor. Subsequently, this was applied e.g. for the studies of LOCA transient test rods in order to study the relocated fuel distribution and the packing fraction of fuel in the balloon formation, following the in-core transient simulation performed in the Halden reactor.

After MÅBiL was terminated, the nuclear fuel project has flourished as other financing sources have been found. In particular, it continues in the form of two spin-off project, 1) SSF SAFETY (work package 4) with the aim to support the development of accident tolerant fuels for Light Water Reactors, and 2) VR Fuel Diagnostics, with the aim to support nuclear fuel development for Gen IV reactors.

The ongoing activities concern the development of a new GET instrument, aimed at achieving higher spatial resolution, in the order of 100 μm. This will be achieved by optimizing the GET system components for the purpose of enhancing the count rate, which in turn allows for achieving more sampled measurement positions in the same interrogation time.

After the closure in 2018 of the Halden reactor, we have started a collaboration with INL, where non-destructive PIE techniques and in particular GET development is the focus. A joint application was sent to CINR with the aim of creating a GET system at INL for test fuels irradiated in TREAT as well as in other Idaho test reactors.

Objective

The overarching objective is to increase the non-destructive rate data generation rate in test irradiation of nuclear fuels, in order to allow for a faster innovation cycle in nuclear fuel development.

Participants

UU participants: Peter Andersson (PI), Vikram Rathore (PhD student), Lorenzo Senis (PhD student), Ane Håkansson (Professor), Peter Jansson (Researcher), Erik Andersson Sunden (Researcher)

Halden participants: Scott Holcombe (Fuel and Materials), Terje Tverberg (Fuels and Materials)

Idaho participants: Jason Schulthess (INL), Nicholas Boulton (INL), Daniel LaBrier (ISU)

Progress

Development of segmented High-Purity Germanium Detector for GET.

Establishing a collaboration with INL to allow for continued activity after Halden closure.

Outlook

Trial and demonstration of segmented detector concept for GET of nuclear fuel.

Development of fast predictive methods for feasibility of quantitative determination of nuclide, for use in optimization of GET device and for qualification of GET technique for operational usage (to beforehand know whether if a specific nuclide can be assessed or not).

Relevant Publications

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.

P. Andersson, S. Holcombe, T. Tverberg, Inspection of LOCA Test Rod IFA-650.16 Using Gamma Emission Tomography, EHPG, Sandefjord , 19-24 May 2019.

Measurements of fission cross-sections at the n_TOF facility

Research leader: Dr. Diego Tarrío

Participants

Diego Tarrío (PI, researcher), Stephan Pomp (Professor)

Objective and progress

The n_TOF (Neutron Time-Of-Flight) facility, located at CERN (Switzerland) is an experimental neutron facility that became operational in 2001. It offers a very high instantaneous neutron flux covering a wide neutron energy range, that spans from thermal up to GeV neutrons.

This facility was built with the intention of addressing different needs of new and accurate nuclear data to drive the future nuclear technologies, devoted to, for example, increase the burn-up efficiency of the nuclear fuels, and to reduce the amount of radiotoxic nuclear waste. The unprecedented energy range covered by this facility makes it capable of providing with nuclear data for a variety of nuclear energy technologies, ranging from thermal reactors to Accelerator-Driven Systems (ADS).

The n_TOF facility includes two experimental areas placed at, approximately, 20 and 200 meters from the neutron production target, providing with different neutron beam intensities that make possible to study short-lived nuclei, and with time-of-flight resolutions good enough to study individual fission and capture resonances. A new irradiation station, very close to the neutron production target, is being built, and it will make accessible a neutron flux 100 times more intense. This new facility will make possible to study the radiation effects in different materials and electronic components.

The scientific work at n_TOF is performed by a collaboration consisting of about 150 researchers from 40 institutes. The Uppsala group has just joined the collaboration in 2019, what will significantly improve our capabilities of doing front-line research in nuclear reaction studies, using a world leading facility.

The Uppsala group plans to use the n_TOF facility to perform experimental studies of fission reactions, taking advantage of a dedicated experimental setup based on position-sensitive Parallel Plate Avalanche Counters (PPACs). This setup has been used in the past to provide with fission cross-sections and angular distributions of different actinides and subactinides. Dr. Diego Tarrío has a wide experience in the use of this setup as well as in the data analysis and interpretation, acquired during his Ph.D. (defended in 2012) and complemented in the following years at Uppsala by frequent scientific interchanges with the n_TOF collaboration. A recent result of such a continued interchange is the recent publication: Colonna et al., "The fission experimental programme at the CERN n_TOF facility: status and perspectives" Eur. Phys. J. A 56, 48 (2020).

The annual membership fees for Uppsala University to the n_TOF collaboration are currently covered by SSM (Strålsäkerhetsmyndigheten).

Outlook

We foresee that this recently started project will open for new possibilities to expand the research topics of our group, and that it will contribute to the competence building in the field of nuclear physics and nuclear technology research. Furthermore, it will strength the position of Sweden as a main actor in outstanding measurements of nuclear data required for the development of future nuclear technologies.

Our main research interest is in fission studies and the programme has been outlined in a recent publication.

Relevant Publications

Colonna et al., "The fission experimental programme at the CERN n_TOF facility: status and perspectives" Eur. Phys. J. A 56, 48 (2020).

Measurements of neutron-induced reactions at GANIL-NFS

Research leader: Prof. Stephan Pomp

Objective

UU is part of the NFS collaboration that will use the Neutrons For Science (NFS) facility at GANIL, Caen, France, to provide high-accurate nuclear data for different reactions induced by neutrons. Two kinds of neutron beams will be available at NFS; quasi-monoenergetic beams, and so-called white neutron beams with a continuous energy spectrum. The available neutron energy range stretches from below 1 MeV up to 40 MeV with a high time-averaged flux.

We are primarily interested in light-ion production and fission studies. The aim is to improve nuclear modelling and hence the evaluated nuclear data libraries used in applications.

Participants

Stephan Pomp (PI, Professor), Alexander V. Prokofiev (researcher), Diego Tarrío (researcher), Erik Andersson Sundén (researcher), Leo Lehtilä (Master student).

Progress

The NFS facility has received authorization to start operations and on Dec 5, 1019, a first neutron beam was delivered. After finally, with many years of delay, reaching this major milestone, commissioning work has started.

During 2019, we continued developing experimental equipment for NFS. The Medley chamber has been thoroughly renovated and was shipped from Ångström to GANIL in December. The chamber is now being installed in the experimental hall.

Our research projects at NFS are integrated in, and partly funded by, several EU projects; SANDA (Supplying Accurate Nuclear Data for energy and non-energy Applications), ARIEL (Accelerator and Research reactor Infrastructures for Education and Learning), Eurofusion, and in the future RADNEXT (RADiation facility Network for the EXploration of effects for indusTry and research). SANDA and ARIEL started in 2019.

A master student, Leo Lehtilä, has been working within this project and during 2019 completed his thesis "Implementation and characterization of Silicon detectors for studies on neutron-induced nuclear reactions".

Outlook

UU will use the Medley chamber beam characterisation during the commissioning phase of the different NFS neutron beams. We also plan to use Medley for light-ion production and fission studies. During 2019, we have started developing ultra-thin silicon detectors in the framework of a contract with Micron Semiconductor Ltd. Manufacturing. First detectors will be delivered and tested during 2020.

First experimental runs on light-ion productions measurements are expected to take place during 2021. Fission experiments are planned as a second step.

Relevant Publications

L. Lehtilä, "Implementation and characterization of Silicon detectors for studies on neutron-induced nuclear reactions", Master thesis, Uppsala Universitet 2019.

Fission yields for next generation nuclear power

Objective

The project was initiated in 2011 as a collaboration between Uppsala University (UU) and the University of Jyväskylä (JYU), Finland. The purpose of the project is to provide high quality data on Independent Fission Yields (IFY), defined as the relative amounts of specific nuclides produced in fission. With Generation IV nuclear power the change in 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 burn-up. This will affect the reactor criticality, through beta delayed neutrons and reactor poisons, as well as the decay heat and the burn-up monitoring. Accurate knowledge of the fuel inventory is also important for safe handling, reprocessing and final storage of the waste.

An intermediate goal of the project is to develop a proton-to-neutron converter for the Ion-Guide Isotope-Separation-Online (IGISOL) setup at the JYU physics laboratory (JYFL). Such a target would facilitate measurements of neutron induced IFY. In parallel other reaction mechanisms, such as proton induced fission, are studied. These data provide valuable information on fission dynamics that can guide the development of more refined fission models.

Participants

Andreas Solders (PI, Ass. Prof., UU), Zhihao Gao (PhD student, UU), Mattias Lantz (Researcher, UU), Stephan Pomp (Professor, UU), Ali Al-Adili (Researcher, UU), Michael Österlund (Ass. Prof., UU), Heikki Penttilä (Researcher, JYU), The IGISOL group (JYU)

Progress

So far, a proton to neutron converter has been developed and commissioned and several campaigns with proton induced fission of 238U have been conducted, resulting in two doctoral thesis, seven original articles and 18 conference contributions. Since September 2018 PhD-student, Zhihao Gao, is working in the project and his first focus has been to experimentally validate simulations of the neutron production target and the ion-guide for neutron induced fission, with the aim of improving the yields of fission products in neutron induced experiments. This work has resulted in a conference contribution at the ND2019 conference in Beijing and a publication of the results are being prepared.

In August 2019 a one week beam time resulted in the measurement of 19 isomeric yield ratios (IYR) from 238U(p,f). To analyse these data Zhihao Gao is developing a new analysis routine, based on machine learning algorithms.

Outlook

A request for beam time for 2020 has been submitted to the JYFL program advisory committee. The aim of this campaign is to measure IYR in alpha-induced fission of 232Th to compare with previous results on 238U(p,f). Furthermore, model calculations suggest that the dominating fissioning system in this reaction will be 234U, a nucleus of interest for the uranium-thorium cycle. To test these ideas, and to study how the reaction mechanism might influence the path to fission, discussions with the research group at TRIGATRAP in Mainz are held to make complementary measurements of these yields in thermal neutron induced fission of 233U.

Relevant Publications

V. Rakopoulos, et al., "Isomeric fission yield ratios for odd-mass Cd and In isotopes using the phase-imaging ion-cyclotron-resonance technique", Physical Review C 99:1 (2019).

A. Mattera, et al., Production of Sn and Sb isotopes in high-energy neutron-induced fission of natU, The European Physical Journal A 54:3 (2018).

Correlated data for enhanced fission modelling

Objective

The project was initiated in 2013 as a collaboration between Uppsala University (UU) and the Joint Research Centre in Geel Belgium. The purpose of the project is to provide high quality data on fission neutron and fragment yields. Correlation measurement are particularly needed to enhance the understanding and modelling of nuclear fission.

An intermediate goal of the project is to develop the VERDI (2E-2v) fission fragment spectrometer to provide high precision yields. To do so we are planning dedicated characterisation experiments at the ILL reactor facility in France.

Another goal is to measure the average neutron emission at high excitation energies and as a function of fragment mass using liquid scintillators.

Participants

Ali Al-Adili (PI, researcher, UU), Diego Tarrío (researcher, UU), Stephan Pomp (Professor, UU), Andreas Solders (Assoc. professor, UU), The JRC collaboration

Progress

So far, we have developed VERDI with an installation of a second MCP (for a time of flight measurement). This was in the framework of the Ph.D. thesis of Kaj Jansson. We have also made a nubar measurement on the thermal fission of U-235 and on Cf-252(sf).

We have recently received a starting grant from VR to recruit a PhD student to the project. We have also received European support for scientific travels to Belgium.

Outlook

In the near future we will perform a new measurement, on the fast neutron induced fission on U-235, using the same setup as the one from the first experiment.

Relevant Publications

Jansson, K., Al-Adili, A., Andersson Sundén, E., Göök, A., Stephan, O. et al. (2018). The impact of neutron emission on correlated fission data from the 2E-2v method. European Physical Journal A, 54.

ICEWATER

Objective

The aim of the ICEWATER (Irradiation Corrosion Experiment in Water) project is to design and build equipment for accelerated testing of irradiation assisted stress corrosion cracking (IASCC) in metals, primarily in austenitic stainless steels. The tests are performed under approximate light-water reactor conditions, i.e. simultaneous irradiation and tensile loading in high temperature high pressure water with oxidizing agents. Using protons instead of neutrons will allow for faster, safer and cheaper experiments while introducing various engineering challenges due to high energy and short stopping range of the particles.

Participants

Research leader: Mattias Klintenberg, Division of Materials Theory, Department of Physics and Astronomy, Uppsala University

Ph.D. student: Erki Metsanurk, Division of Materials Theory, Department of Physics and Astronomy, Uppsala University

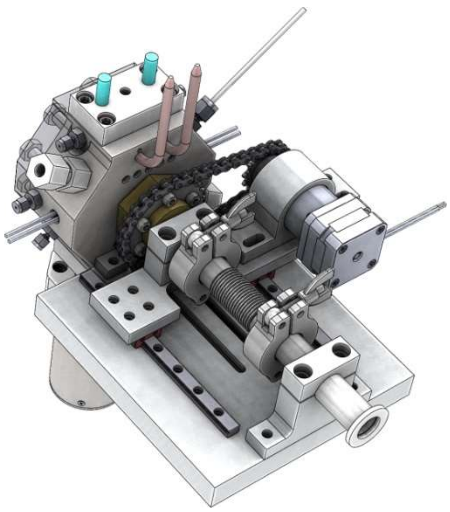
Progress

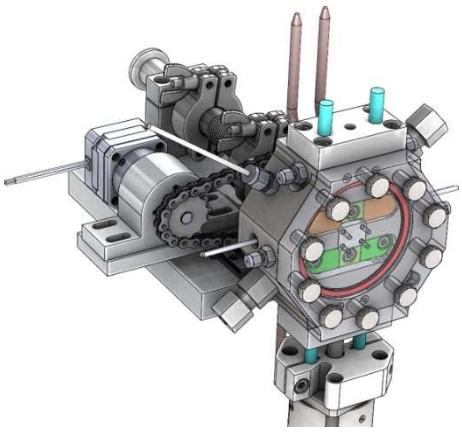
In 2019 the design was finalized, sourcing the standard components and machining of the custom components was started. The design has a preliminary solution to most of the challenges identified and tested during previous years while being both simple and extendable. The main features are following:

- The possibility of performing visual inspection during initial low temperature experiments by replacing the steel cover with a transparent plastic one. That helps with identifying possible boiling, ensuring that the mechanism moves as designed under pressure, confirming the correct water level etc.
- Remotely controlling the distance between the sample and the stainless-steel window through which protons enter the cell. This is crucial since if the gap is too small the amount of water next to the

sample could become non-existent due to possible local boiling. On the other hand, if the gap is too large, no protons will reach the sample. The expected distance should be between 100 and 200 micrometres.

- Pressurization of the cell does not put any initial load on the thin sample. Since it is very hard to measure the stress and strain in the sample from inside the cell, the mechanism is designed in a way that allows for detecting the starting of the loading. Initially both clamps that hold the sample can move, i.e. movement of the pull rods does not put any stress on the sample. After waiting for the system to equilibrate in terms of the pressure and temperature, the pull rods are pulled until the top clamp hits the body of the device which is detected through impedance measurement between the body and the clamp. That puts the system in a good known starting point for the tensile testing.
- The temperature in the sample can be estimated by performing an impedance measurement. Water inlet and outlet are placed right next to the sample in order to maximize the cooling to counteract the possible local overheating.
- The minimum guaranteed bulk temperature is 260 °C, limited by PTFE components whereas the temperature next to the sample is probably considerably higher, depending on the proton current, and needs to be estimated through experiments.





Outlook

The device will be built in 2020.

Nuclear data evaluation and uncertainty quantification

This project was started with funding from SKC through the MÅBil project. In this project, we connect macroscopic fuel and aging parameters to the fundamental nuclear physics processes by using the world-leading nuclear model code TALYS.

We are improving the TENDL and JEFF library with a focus on isotopes with high relevance to address material issues coupled both to fuel and aging performance, such as flux at the reactor vessel, gas production, and input parameters to DPA calculations. The goal is to quantify these parameters including their uncertainties. One of the most important parts of this work is to calibrate the model input parameters and their uncertainties by using differential and integral experimental data. During the project, we have found that by using Gaussian Processes (GP) many of the issues coupled with nuclear data calibration, can be addressed.

Objective

The overarching goal is to improve reactor relevant nuclear data libraries. The focus for 2019 was to provide an evaluation code system that allowed for regression of the nuclear model parameters, handle experimental inconsistencies and treat model defects for Fe56, including integration with the Talys based (T6) code system.

Participants

UU participants: Henrik Sjöstrand (PI), Georg Schnabel (postdoc - 2019063), Joachim Hansson (postdoc 20190824-), Erik Andersson Sundén (Researcher).

Progress

Scientific details are already provided in the 2018 years SKC report (see Appendices) and in [1],[2], and [3]. In this year's work, a code system, referred to as a pipeline, was made available at GitHub in [4] and [5] under an MIT license. At [4], a short description of the pipeline is given: "This repository contains a pipeline that has been created for the evaluation of neutron-induced reactions of the isotope Fe56 using the nuclear models code TALYS. It features several innovations in evaluation methodology, such as the automatic correction of experimental uncertainties using marginal likelihood optimization, Gaussian process priors on energy-dependent model parameters, and the application of the Levenberg-Marquardt algorithm to optimize more than hundred TALYS model parameters exploiting parallelization on a computer cluster. "

In an effort to disseminate the results the state of the art of the pipe-line is reported at [6] maintained by G. Schnabel: "During evaluation work many choices have to be made concerning the selection of experimental data, their uncertainties, model parameters, and statistical algorithms to adjust model parameters based on the information from experiments. It is very difficult to convey all information in a technical report or paper that would be required to reproduce an evaluation and reproducibility is important in nuclear data evaluation. Therefore, all choices made in an evaluation should ideally be implemented as a sequence of scripts, also referred to as a pipeline. In this way, other people can comparatively easily reproduce the evaluation by rerunning the pipeline, scrutinize and test the impact of assumptions or do an improved evaluation using an available evaluation pipeline as a starting point. A prototype of an evaluation pipeline is provided here, which contains several innovations in evaluation methodology, such as the automatic correction of experimental uncertainties using marginal likelihood optimization (MLO), Gaussian process priors on energy-dependent model parameters, and the optimization of model parameters using a customized Levenberg-Marquardt algorithm, which considers prior knowledge. The pipeline can be used in combination with a cluster to perform a full-scale evaluation. In its current form, it implements the evaluation of neutron-induced cross sections of Fe56 and has been successfully employed to adjust more than hundred parameters of the nuclear models code TALYS after sensitivity analysis of about thousand model parameters."

It was chosen to use the Docker technology to distribute the work as motivated in [6]: "Automation, reproducibility, and transparency are important topics in the ongoing discussions about how to improve the process of nuclear data evaluation. Over the last few years, the Docker technology is rapidly gaining momentum in the IT industry and it can also help nuclear data evaluation to get more transparent, automated, and reproducible. The Docker application helps to manage and operate with so-called Docker images and Docker containers. Loosely speaking, a Docker container can be regarded as a light-weight virtual machine which can run applications isolated from the rest of the computer system. Docker images are templates to create Docker containers. The advantage of using Docker images is that an application can be bundled with all its dependencies. The installation of such a bundle becomes very easy thanks to the Docker application. The setup of complex evaluation pipelines that depend on a lot of components, such as databases, libraries, interpreters for specific languages, nuclear physics codes, etc. becomes trivial. This circumstance facilitates sharing of data and code between researchers. Collaborating is facilitated and consequently the whole research and evaluation process accelerated."

Some results from the code package are illustrated in Figure 1 and Figure 2. As can be seen, the evaluation reproduces the experimental data reasonably well. However, some posterior uncertainties are underestimated.

To conclude on the progress of 2019 year's work. Model defect treatment, elaborated on the example of n+Fe-56 neutron cross-section data, has been interfaced with the T6 framework to enable a full cross-section data evaluation, including uncertainties and model defects, and considering the treatment of inconsistent data as well. The work is distributed as an R pipeline [4] and associated docker files [5]. The integration with T6 is done by providing a TASMAN patch [7]. The documentation of the work is primarily provided within the provided code-systems and in the attached references.

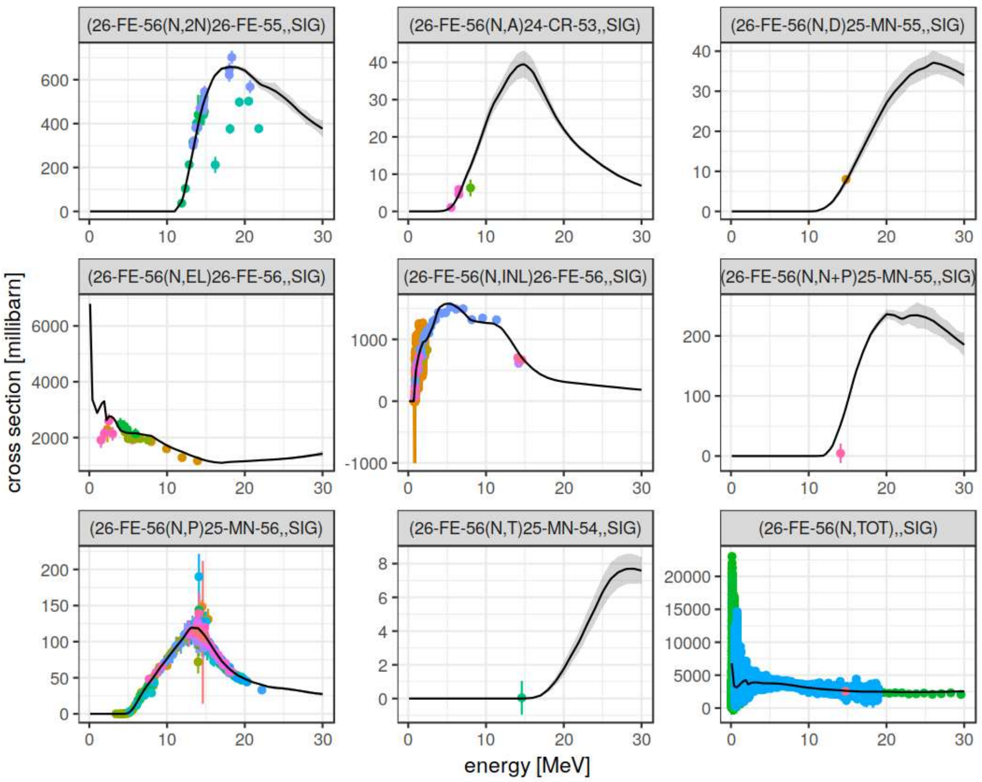


Figure 1. Posterior (black-line) of angle-integrated cross-section and experimental data (coloured dots). Posterior uncertainties are also provided (grey-bands)

Outlook

From Figure 1and Figure 2, some of the posterior uncertainties are underestimated. For 2020 it is the goal to also incorporate the findings in [8], in the pipeline and also account for model defects in the observable domain using GP. Although adding GPs to the model in the observable domain shows promise, the main challenge that needs to be overcome before being able to deploy such a solution at scale is to reduce computational complexity. Possible avenues forward are sparse or variational approximations. In addition to the reduction of computational complexity, further research needs to be performed in regard to construction of GP kernels with appropriate qualities for describing cross section data. Unrelated to the GPs is the approximation of the full posterior co-variance matrix. Currently, the diagonal of the hessian is approximated using finite differences at the posterior mode. Other options will be investigated in 2020.

During 2020, the lessons learned from this project will also be integrated into the newly approved SKC-project: "Calibration of fuel performance codes – treating model inadequacies, nuisance parameters, and unrecognized systematic uncertainties"

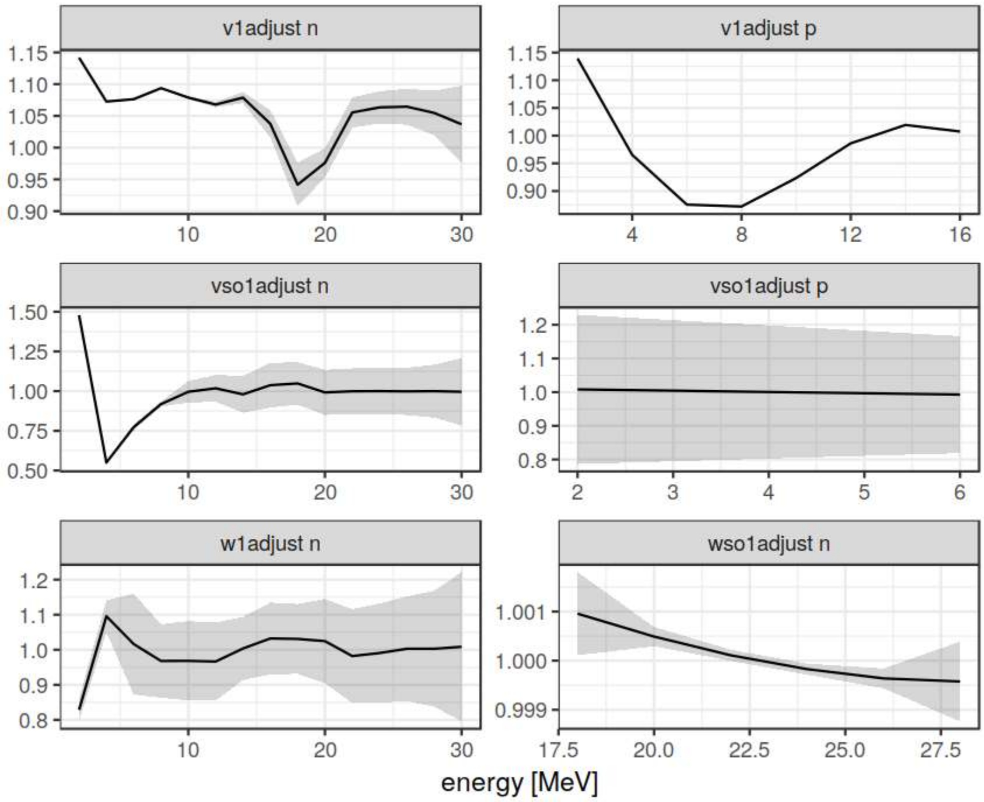


Figure 2. Illustration of the posterior parameters, including their uncertainties for a subset of the parameters. The central value (black-line) and its variation with energy and uncertainty bands (grey-bands) are shown.

Relevant Publications

[1] H. Sjöstrand and G. Schnabel, 'Monte Carlo integral adjustment of nuclear data libraries: experimental covariances and inconsistent data', EPJ Web of Conferences, vol. 211, no. 7007, 2019.

[2]G. Schnabel, H. Sjöstrand, D. Rochman, and A. J. Koning, 'Interfacing TALYS with a Bayesian treatment of model defects and inconsistent data', presented at the International Conference on Nuclear Data for Science and Technology, 2019, Beijing, China, May 19-24, 2019, 2019.

[3] P. Helgesson and H. Sjöstrand, "Treating model defects by fitting smoothly varying model parameters: Energy dependence in nuclear data evaluation," Annals of Nuclear Energy, vol. 120, pp. 35–47, Oct. 2018, doi: 10.1016/j.anucene.2018.05.026.

[4] https://github.com/gschnabel/eval-fe56

[5] https://github.com/gschnabel/eval-fe56-docker and

[6] http://www.nucleardata.com/

[7] https://github.com/gschnabel/tasmanPatch

[8] G. Schnabel and H. Sjöstrand, 'A first sketch: Construction of model defect priors inspired by dynamic time warping', EPJ Web of Conferences, vol. 211, 2019.

Publications with Full or Partial SKC Funding

Doctoral Theses

No doctoral theses funded by SKC 2019.

Licentiate Theses

No licentiate theses funded by SKC during 2019.

Peer Review Journals

A. Al-Adili, V. Rakopoulos, and A. Solders, 'Extraction of angular momenta from isomeric yield ratios', The European Physical Journal A 55:4, 2019

R. Capote et al., "Unrecognized Sources of Uncertainties (USU) in Experimental Nuclear Data," Nuclear Data Sheets, vol. 163, pp. 191–227, Jan. 2020, doi: 10.1016/j.nds.2019.12.004.

Z. Gao et al., 'Fission studies at IGISOL/JYFLTRAP: Simulations of the ion guide for neutron-induced fission and comparison with experimental data', Nuclear Data Sheets, (submitted)

D. Kumar, S. B. Alam, H. Sjöstrand, and C. De Saint Jean, 'Influence of nuclear data parameters on integral experiment assimilation using Cook's distance', EPJ Web of Conferences, vol. 211, 2019

V. Rakopoulos et al., 'Isomeric fission yield ratios for odd-mass Cd and In isotopes using the phase-imaging ion-cyclotron-resonance technique', Physical Review C 99:1 (2019)

G. Schnabel and H. Sjöstrand, 'A first sketch: Construction of model defect priors inspired by dynamic time warping', EPJ Web of Conferences, vol. 211, 2019.

H. Sjöstrand and G. Schnabel, 'Monte Carlo integral adjustment of nuclear data libraries: experimental covariances and inconsistent data', EPJ Web of Conferences, vol. 211, no. 7007, 2019.

J.-C. Sublet et al., 'Neutron-induced damage simulations: Beyond defect production cross-section, displacement per atom and iron-based metrics', The European Physical Journal Plus, vol. 134, no. 7. Springer Berlin/Heidelberg, 2019.

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.

H. Atak, A. Anastasiadis, P. Jansson, Zs. Elter, E. Andersson Sunden, S. Holcombe, P. Andersson, The degradation of gamma-ray mass attenuation of UO2 and MOX fuels with nuclear burnup. Manuscript under review in the Progress of Nuclear Energy journal.

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Colonna et al., "The fission experimental programme at the CERN n_TOF facility: status and perspectives" Eur. Phys. J. A 56, 48 (2020).

Conferences

Z. Gao, 'Measurements of isomeric yield ratios in proton-induced fission at the IGISOL facility - 2019', presented at the Swedish Nuclear Physicist's Meeting XXXIX, Lund, Sweden, October 23 - 25, 2019.

M. Lantz, ' Fission studies at IGISOL/JYFLTRAP: Isomeric yield ratio measurements from 25 MeV natU(p,f), in the quest for angular momentum studies', presented at the International Conference on Nuclear Data for Science and Technology, 2019, Beijing, China, May 19-24, 2019, 2019.

S. Pomp, et al., 'Isomeric yield ratio measurements at IGISOL/JYFLTRAP for assessing angular momenta of fission fragments' presented at the NUSTAR Annual meeting 2019, Feb 25 - Mars 1, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany, 2019

G. Schnabel, H. Sjöstrand, D. Rochman, and A. J. Koning, 'Interfacing TALYS with a Bayesian treatment of model defects and inconsistent data', presented at the International Conference on Nuclear Data for Science and Technology, 2019, Beijing, China, May 19-24, 2019, 2019.

G. Schnabel , "Learning from Google : About A Computational EXFOR Database for Efficient Data Retrieval and Analysis"; Conference: International Conference on Nuclear Data for Science and Technology, May 19-24, 2019, Beijing, China; Permalink: http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-396399; (2019)

G. Schnabel ; "Mixture GLS with examples"; Conference: IAEA Technical Meeting on Uncertainty Quantification in Nuclear Data Evaluation; Permalink: http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-396526; (2019)

H. Sjöstrand and G. Schnabel, 'The identification and treatment of unrecognized uncertainties and the impact on evaluated uncertainties – SG44', presented at the Working Party on International Nuclear Data Evaluation Co-operation (WPEC): Investigation of Covariance Data in General Purpose Nuclear Data Libraries WPEC subgroup 44 (SG44) NEA Headquarters, Boulogne-Billancourt, France, 25 June 2019, 2019.

H. Sjöstrand, G. Schnabel, and D. Rochman, 'Integral adjustment of nuclear data libraries : finding unrecognized systematic uncertainties and

correlations', in Conference program & Abstract book : 2019 International Conference on Nuclear Data for Science and Technology, May 19-24, 2019, Beijing, China, 2019, pp. 212–212.

H. Sjöstrand, G. Schnabel, D. Rochman, and D. Siefman, 'Treating inconsistent data in integral adjustment using Marginal Likelihood Optimization', presented at the Working Party on International Nuclear Data Evaluation Co-operation (WPEC): Efficient and Effective Use of Integral Experiments for Nuclear Data Validation WPEC subgroup 46 (SG46) NEA Headquarters, Boulogne-Billancourt, France, 25-26 June 2019, 2019.

A. Solders et al., 'Fission studies at IGISOL/JYFLTRAP: Measurements of neutron-induced fission yields', presented at the International Conference on Nuclear Data for Science and Technology, 2019, Beijing, China, May 19-24, 2019.

A. Solders et al., 'DEIFIN: a TALYS-based tool for the comparison of fission model codes', presented at the International Conference on Nuclear Data for Science and Technology, 2019, Beijing, China, May 19 - 24, 2019.

A. Solders et al, 'Fission yield studies using mass measurement techniques' presented at the NUSTAR Annual meeting 2020, Mars 2 - 6, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany, 2020

2019 P. Andersson, Gamma Emission Tomography for Nuclear Fuel Diagnostics. Presented at the CARAT meeting in Oxford, UK.

2019 P. Andersson, Gamma Emission Tomography for Nuclear Fuel Diagnostics. Presented at the CARAT meeting in Oxford, UK.

P. Andersson et al., Inspection of LOCA Test Rod IFA-650.16 Using Gamma Emission Tomography. Presented at the EHPG Sandefjord, Norway.

P. Andersson et al., Segmented HPGe Detector for Gamma Emission Tomography of Nuclear Fuel and Comparison with Existing Detectors. Presented at the European Material Research Society, Spring Meeting, Nice, May 27-31.

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Alexis C.Trahan, et al., Results of the Swedish spent fuel measurement field trials with the Differential Die-Away Self-Interrogation Instrument, Nuclear Instruments and Methods A, Volume 955, 1 March 2020

Jansson P., Bengtsson M., Bäckström U., Svensson K., Lycksell M., Sjöland A.; "Data from calorimetric decay heat measurements of five used PWR 17x17 nuclear fuel assemblies"; Data in Brief; Vol: 28; DOI: 10.1016/j.dib.2019.104917; (2020)

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G. Schnabel and H. Sjöstrand, 'VR contribution to PPPT nuclear data development: Evaluation of neutron cross section data in the fast energy range: ENR-PRD.MAT.IREMEV.7.1-T003', 2019.

Cross-University Collaboration

E-learning project

Introduction

In 2016, the SKC board decided to dedicate funding to lift the competence of SKC-funded staff within the area of e-learning. A workshop was held in 2017 and Chalmers and Uppsala University decided to carry out a collaborative project. The content of the project was decided jointly by the involved researchers and it was decided to produce e-learning based course material in Swedish at a scientific level appropriate for high school or early university level. The material can thus be used by high school teachers in their regular teaching, addressing a wide range of pupils who have not yet decided on possible university education. The material covers essential parts of the learning goals of the high school course "Physics 1a" and the format has been iterated with active high school teachers. The material is freely available on the web at www.saint.nu/nyfiken and may also be used in professional education and for e.g. a summer school. A summer school is planned for the summer of 2020. The project as a whole thus intends to serve a triple purpose to:

- Lift the competence level within e-learning among SKC-funded staff.
- Lift the general knowledge on radiation science in society.
- Inspire students to pursue studies within nuclear and radiation science.

Content of the e-learning material

The material covers nine subject areas and each area is presented by a researcher within the respective field. The subjects range from fundamental nuclear physics to natural radiation, radiopharmaceuticals and reactor physics. Each researcher has produced one or more video lectures, a quiz for each video lecture for repetition of the information in the video, and an assignment for deepening and reflecting on the subject matter.

Progress in 2019

Finalization of the course material

Quiz questions and assignments were finalized by the involved teachers. The quiz questions are made available both in web quiz format and as pdf forms. Solutions are also provided. Final corrections of the video material were made and subtitles in both Swedish and English were added. KSU was consulted for production of web quizzes and subtitles.

Four laboratory demonstration videos were produced, showing experimental determination of half-life, deduction of the inverse square law, radiation shielding capabilities of different materials and practical radiopharmaceutical work. Measurement data is available in spreadsheet format on the webpage, along with task formulation and solutions to these. Språng kommunikation, a communications bureau which was previously consulted for production of the video lectures, also produced the laboratory videos and made the final corrections of the lecture videos.

Marketing of the course material

The course material was marketed through several channels. For professional education, KSU was consulted, and the entire material has been made available to them for incorporation in their offered range of e-based education.

A social media campaign was developed by Språng kommunikation, directly targeted at high school teachers. The campaign was run on Facebook October 9 – November 23, reached 208 641 persons within the targeted interest groups and gave rise to 149 053 interactions in that time span. The number of views of the videos on YouTube increased by approximately 2 000 in that period. Note that the current number of views displayed on YouTube is not representative since some videos have been updated, starting the view counter from zero for that video.

Information on the material was also communicated to several media. A major article was published in the Q1 2020 issue of "Fysikaktuellt", the organ of the Swedish Physical society, which is distributed to all high schools in Sweden. A press release on the material was sent out by Chalmers, resulting in a news clip and interview with Klara Insulander Björk in both Swedish Radio P4 Göteborg and P3 News.

The material is made available through the channels for school communication of Uppsala University, Chalmers and Gothenburg University and was presented both orally and through a poster at the "Teacher's day" during the conference "Physics days 2019".

Utilisation of funding

The funds have been used as follows, numbers in SEK

Completion of course material by individual researchers at Chalmers	250 000
Completion of course material by individual researchers at UU	200 000
Coordination	100 000
Additional video production (laboratory videos and marketing material)	99 000
Marketing, including Facebook campaign and article in "Fysikaktuellt"	119 000
Production of web-quiz material and captioning (by KSU)	96 000
Translation of subtitles to English	71 000
Other costs, including transfer of funds to 2020 for a summer school	65 000
Total	1 000 000

Appendices

Appendix A. Cooperation with the surrounding society

TK outreach activities March 2019-March 2020

Members of the applied nuclear physics division have been involved in various kinds of outreach activities; some examples are given below.

Popular science activities

- Science festival SciFest2019 on 7-9 March 2019, where the workshop "En strålande upplevelse" was attended by elementary and high school classes for two days, and for the general public the third day.
- Workshops named "Radioaktiva bordet", "Hur bestämmer man ålder på en mumie – accelerator och kol-14 datering" and "Musikens fysik" were held during Kulturnatten at Museum Gustavianum on 14 September, where the entire physics department arranged activities together with the museum. There were also five popular science talks about different aspects of nuclear physics, nuclear power and ionizing radiation given by members of the division.
- The workshop "Radioaktiva bordet" was held at the Standup for Nuclear event at Mynttorget in Stockholm on 20 October. The event was arranged by the Swedish Nuclear Society.
- A workshop named "Spännande, skrämmande, livsfarligt och livsviktig" about nuclear power and ionizing radiation was held for 60 female third year high school pupils during the event Uptown Tech arranged by Uppsala university on 23-24 November.
- Talks about nuclear power have been held at Senioruniversitetet in Stockholm, at Round Table in Stockholm, at the Rotary club in Sala, for staff at Akademiska Hus, at a Pi-samtal in Stockholm and for the general public at Ringhals nuclear power plant.

School interactions

- There have been talks at high schools in Uppsala about nuclear physics, nuclear power, ionizing radiation and nuclear myths. School classes from Uppsala, Stockholm and Vilhelmina has made study visits combined with talks on these subjects.
- During 2019 there have been three high school projects performed where the pupils measured the content of cesium-137 and natural radioactivity in environmental samples that they had gathered.
- The school interaction part of the citizen science project Strålande Jord was completed when the participating schools received preliminary results from the measurements of cesium-137 in the mushroom samples they had collected.

Interactions with politicians

- Talks about the role of nuclear power and its role in the power grid and for climate mitigation have been given for different political parties in Uppsala and Stockholm.
- A talk has been given at a seminar in Riksdagen.

- A talk about nuclear myths was given to the politicians from the towns near the Swedish nuclear power plants.
- A talk on nuclear power was given at an energy seminar with members of parliament participating.
- Information has been given to politicians from several political parties on issues related to nuclear power.

Media and public interactions

- Members of the division have been interviewed in Swedish radio on topics related to nuclear power and the Fukushima nuclear accident.
- There have been several interviews in newspapers and Swedish Radio related to the reopening of the bachelor programme in nuclear technology.
- In February P1 Vetenskapsradion had several programmes where a member of the division was interviewed about nuclear power.

Debate articles and comments

- A number of debate articles with incorrect statements about nuclear power have been responded to in a number of newspapers, including Dagens Nyheter and Svenska Dagbladet.
- Incorrect statements by reporters at newspapers, Swedish Radio, and Swedish Television has been commented on by contacting the reporters.
- A number of replies on debate articles have been issued.

Other activities

Several entries on Wikipedia related to nuclear physics and nuclear power have been created or edited.

Appendix B. Total Monte Carlo for fuel and materials 2018 - MÅBiL

The presentation below was intended for the annual Report 2018 but was accidently omitted then.

Ph.D. student: Petter Helgesson

Main supervisor: Ass. Prof. Henrik Sjöstrand

Overview

The project was finalized during 2018 with the completion a successful defence of a Ph.D. thesis by Petter Helgesson.

In this project, we connect macroscopic fuel and aging parameters to the fundamental nuclear physics processes by using the world leading nuclear model code TALYS and the Total Monte Carlo method (TMC) [1]. With a Talys based code package, nuclear data libraries can be produced for all isotopes, reaction channels, and secondary particle productions for the entire nuclide map. This so-called TENDL library is in that respect superior to classical libraries such as ENDF/B-VII and JEFF3.0. Furthermore, the TENDL library has the advantage that it can produce complete covariance information, which is essential to calculate proper damage metrics.

In the project, we are using and improving the TENDL and JEFF library to address material issues coupled both to fuel and aging performance, such as flux at the reactor vessel, gas production, and input parameters to DPA calculations. The goal is to quantify these parameters including their uncertainties. The project is also part of the IAEA Coordinated Research Project: Primary Radiation Damage Cross-Sections [2]. One of the most important parts of this work is to calibrate the model input parameters and their uncertainties by using differential and integral experimental data. During the project, we have found that by using Gaussian Processes (GP, see below) many of the issues coupled with nuclear data calibration, can be addressed.

Gaussian Processes.

When model defects are present, the model for the underlying nuclear physics does not exactly reproduce reality, no matter what parameters are chosen for the model, i.e., when fitting a defect model to data, the results can become very misleading by introducing a bias which supersedes the estimated uncertainty. One way to treat model defects in a systematic way is to model the defect using a Gaussian Process (GP). A GP is a collection of random variables, any finite number of which has a multivariate normal distribution. We express the experimental data; their uncertainties; the model; and a model defect modelled by a GP as,

where Y is the random vector from which experimental data is drawn from, is the model, x, is the vector of the independent variable, βis the parameter vector, is the measurement uncertainty, is the model defect:

where, in turn, $\varepsilon\_m (x) \sim GP(0,k(x,x'))$, prior to observing the data for some choice of the covariance function $k(x,x')$. By model the model defect using a GP and fit the model parameters and the GP to the experimental data simultaneously, it is possible to both reproduce experimental data, and obtain a good description of the underlying physics. It is possible to work with the GP both in the parameter and observable domain.

Reached milestones for the project

One of the main goals was to publish methods that better takes into account the experimental differential data to calibrate the nuclear data and its uncertainties and to apply these methods to reactor-relevant structural materials. Articles in Nuclear Data Sheet [3] (2014), Progress of Nuclear Energy [4] (2017), and Nuclear Inst. and Methods in Physics Research A [5] (2016) have addressed these issues as well as [9] and [10] (2017). During 2018, GPs for the parameter domain were developed [11] and applied to an example evaluation for Fe56.

In reference [4] (2017) uncertainties in the effectiveness of using so-called "shielding assemblies" aiming to extend the life of pressurized water reactors was reported. The uncertainty was determined to be 2%, but there are some indications that the uncertainty might be bigger and consequently, we have put forward a method for a new Fe56 evaluation. See above.

To improve the He production prediction (important for He-embrittlement) and to provide nuclear data uncertainty estimates, a new 59Ni evaluation has been produced. The work is included in JEFF3.3 and published [6].

One of the goals was to publish methods to better take into account the use of integral data. This has been done [7] and improved during 2018 [12].

The impact of Nuclear Data on different fuel configurations was thoroughly studied in Ref [6], including also fission yield uncertainties.

In respect to fission gas uncertainties, some preliminary work has been performed [9], and the new work in [10] addresses fission yield determination in particular.

Activities during 2018

With respect to the challenges with calibrating damage metrics to large experimental databases, most of the challenges were outlined in Ref [4], where the consequences concerning model defects, too rigid co-variance matrix and inconsistent experimental data is described. During 2018 methods for GP for the model domain and for multi-channel physics (i.e., the reactions in iron) has continued to be developed. This was done by un-constraining the parameters in the energy domain (See Figure 3). I.e., the parameters are allowed to become energy dependent around a parameter β.

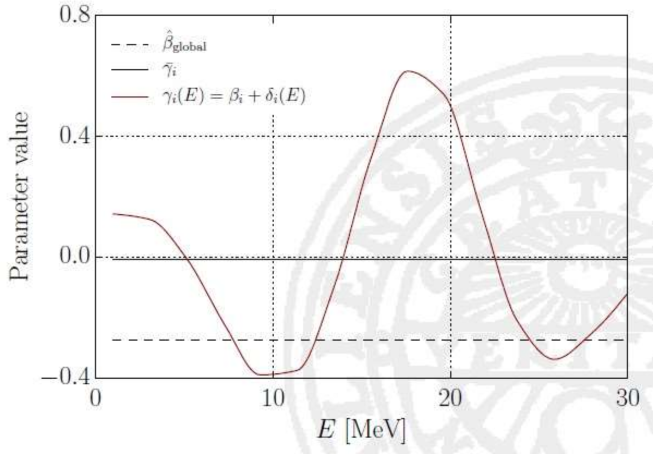

Figure 3. Illustration of the use of GP in the parameter domain. Normally the parameters are energy independent, but here we allow the parameters to vary with Energy using a GP.

Figure 4 illustrates the deviation between a fit to an assumed truth from a synthetic data study using a TALYS like model. As can be seen, the use of GP (red) substantially improves the result.

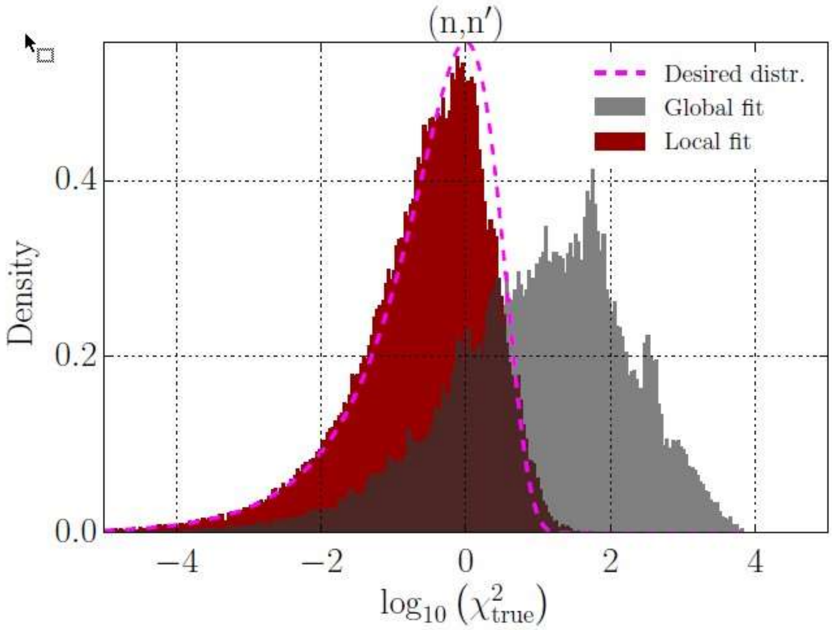

Figure 4. Results on a synthetic data study (140 000 points). Allowing the parameters to be energy dependent using GP (red) or using classic fits (grey). The example here is the inelastic cross-section of Fe56, important for damage calculations.

The results have been reported both in [11] and in the Ph.D. thesis of P.Helgesson. The method was continuously developed over the year to also handle inconsistent data, and an example evaluation was derived at the end of the year and presented to the international community.

In addition, during the year the methods to calibrate nuclear data using integral experiments were also improved [12]

Finally, during 2018 code documentation and hand-over were performed. In such a way, Petter Helgesson has created a foundation for continued projects in the realm of nuclear data for material damage calculations, and a researcher (Georg Schnabel) was also hired during 2018 to continue the project. This led to, e.g., that a new co-variance structure for the GP were presented [13]. The exact forms and funding for the continued work need to be worked-out during 2019.

Publications and conference contributions 2018

PhD-Thesis

during Helgesson P.; "Approaching well-founded comprehensive nuclear data uncertainties : Fitting imperfect models to imperfect data"; Publisher: Acta Universitatis Upsaliensis; ISBN: 978-91-513-0334-5; Permalink: http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-348553; (2018)

Published articles in journals

Helgesson P., Sjöstrand H.; "Treating model defects by fitting smoothly varying model parameters : Energy dependence in nuclear data evaluation"; Journal: Annals of Nuclear Energy; Vol: 120; DOI: 10.1016/j.anucene.2018.05.026; Permalink: http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-348552; (2018)

Conference contributions

Sjöstrand H., Helgesson P.; "Justified co-variance data by treating model defects; fitting optimized energy-dependent model parameters in Fe-56 nuclear data evaluation"; Conference: 30th WPEC Meetings SG44 meeting Paris May 2018; Permalink: http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-356845; (2018)

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