



# SKC

Swedish Centre for Nuclear Technology

# Annual

# Report 2016

March 2017  
SKC 17-01

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## Summary and highlights of 2016

2016 has resulted in a clearer situation of the Swedish energy market, and the year was mainly influenced by the energy agreement in Sweden in June. The energy commission work held several hearings in 2015 and concluded with a broad national agreement how the energy production will be handled until 2040, including the need for nuclear power as a key ingredient in the transition to a fossil-free energy system.

Several activities were performed within SKC during 2016. The Finnish PhD student network on nuclear technology (YTERA) visited KTH in Spring with about 30 participants. SKC was well represented at CHARM, UTNARM and ARMADA and the interest from students seems to remain and we can always guide the students to the best courses, and future employers through our parties. A first SKC Student Day was performed at Chalmers in collaboration with SNEC (Sustainable Nuclear Energy Centre at Chalmers) where about 20 students participated, and several posters and shorter TED-like presentations were given. Prizes to best poster/talk was given at the evening dinner.

The annual SKC symposium was held this year outside Gothenburg, at Hindåsgården, 11-12 October. This event had an increased focus on the students, and the plenary session also included 5 short presentations from their research. We had also an invited speaker from VTT in Finland, Eija-Karita Puska, who presented the activities there, but also the national research programme, SAFIR among other things. The Sigvard Eklund prize was also given an increased attention through the possibility of the winners to present their work at the plenary session. Day 2 contained two in-depth sessions in parallel, and was concluded with a final panel discussion on the need to coordinate the nuclear technology competence needs in Sweden.

Due to the decision in 2015 to close reactors, OKG has decided to reduce the contribution to SKC proportionally. This has resulted in a reduced budget, and hence fewer new projects. The most important now is to make sure SKC delivers excellent results regarding high quality research and education, devoted students, and results that can be implemented in nuclear industry. This has always been the strength of SKC, and we should be proud of the performance. We will make sure the ongoing projects can continue before starting new activities within the centre.

In 2016, Per Brunzell chose to leave the post as chairman of the Advisory Board. Nils-Olov Jonsson was elected by the SKC board and held a first Advisory board meeting at the symposium at Hindåsgården.



In the SKC board, Andreas Roos changed responsibilities at OKG and left his position to Pontus Tinnert, Head of the technology office of OKG.

As the first plans of SKC were written down in 1992, at that time called the KTC (Kärntekniskt centrum), we would like to celebrate SKC with a 25-year anniversary in 2017.

## Goals and focus

SKC:s vision är att tillsammans med svensk kärnkraftsindustri och akademiskt kärntekniskt kunnande av absolut världsklass, skapa tillväxt och fortsatt utveckling mot optimal ekonomisk miljömässig och säker drift.

The SKC cooperation is aimed at contributing to a **safe, effective and thus reliable nuclear energy production**, which is an important part of the Swedish need for climate friendly electricity. Ensuring safety is the major prerequisite to achieve the goal of life time extension. This is taken care of through work at several departments, shown in Appendix 1-3 from, Chalmers, KTH and Uppsala University respectively.

Regarding education, several levels are required to pursue the future need in the nuclear industry. Master programmes at the universities are popular, and the quality of the courses is very high, see examples in Appendix 1 from Chalmers, and Appendix 2 from KTH. The courses are developing more and more into platforms using e-learning at various stages, which makes courses more accessible as well as easier to manage. This is one focus area of SKC for the coming year.

The Bachelor programme of Uppsala University (see Appendix 3) has been appreciated by the nuclear industry, however there is a lack of students. The programme will be mothballed until new frameworks with industry is in place. Another approach to education is the contract education for ongoing knowledge improvement of professionals in the field. This could also benefit from the e-learning activities within SKC.

As a response to the industry's needs and demands of research, a large part of the SKC project funding has been allocated to material studies in the **MÅBiL** project, which is research within material, ageing and fuel, consisting of the following areas:

- ✓ Study of materials with respect to Accident Tolerant Fuels (ATF).
- ✓ Study of materials with respect to ageing.
- ✓ Study of nuclear physical processes during normal and/or transient conditions which affect the aforementioned points.

A more detailed account of MÅBiL and its activities is presented in Appendix 4.

During 2016, SKC participated in the student fairs of KTH (Armada), Uppsala University (Utnarm), and Chalmers (Charm).

The Sigvard Eklund Prize to the best Ph.D. thesis of the year was awarded to Luca Messina at KTH for his work on modelling radiation embrittlement in reactor pressure vessel steels. Alica Marie Raftery, KTH, received the prize for the best masters' thesis for her work on Uranium-nitride fuel. Fredrik Höök and Adam Bruce, UU, received the prize for best bachelor thesis for work on designing a test equipment for irradiation-assisted stress corrosion cracking.



The prizes were awarded to the winners at the dinner ceremony of SKC's yearly symposium, this year held at Hindåsgården, October 11-12.

## And finally ...

A new contract is in place. This runs from 2017 to 2019 and ensures that the ongoing activities can be continued and finalised. However, with a reduced budget there is a limited possibility to commence new projects.

Another major challenge is how to keep a strong national nuclear competence to allow for continuous operation of the Swedish nuclear industry. This will be of main focus in the near future. One attempt in this direction is to focus on improving and finding new ways of educating students and professionals in nuclear technology related topics. A project on e-learning activities has been initiated with the goal of developing courses and a common platform in nuclear technology.

SKC is intended to continue serving as a bridge between universities and industry even in a time of structural changes and financial challenges. With the new agreement we now create an opportunity for SKC's financiers to ensure continuous cooperation on the long-term, and to find the most beneficial way forward for Swedish nuclear industry.



*Hans Henriksson, SKC Director, 2017-03-29*



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## SKC-Partners, Tasks and Goals

Swedish Centre for Nuclear Technology SKC (**S**venskt **K**ärntekniskt **C**entrum [www.swedishnuclear.se](http://www.swedishnuclear.se)) was originally founded in 1992 under the name of KTC, Kärntekniskt Centrum, at KTH. The centre is a collaboration administrated at the School of engineering sciences at KTH (KTH/SCI). The SKC collaboration follows a three-year contract on which ended Dec 31, 2016. The next period, 2017-2019, has been agreed with the same parties as the previous contract. The partners in the SKC collaboration are the nuclear industry (financing parties)

- Forsmarks Kraftgrupp AB ([www.vattenfall.se/om-oss/var-verksamhet/var-elproduktion/forsmark](http://www.vattenfall.se/om-oss/var-verksamhet/var-elproduktion/forsmark))
- OKG AB (<http://www.okg.se>)
- Ringhals AB ([www.vattenfall.se/om-oss/var-verksamhet/var-elproduktion/ringhals](http://www.vattenfall.se/om-oss/var-verksamhet/var-elproduktion/ringhals))
- Westinghouse Electric Sweden AB (<http://www.westinghousenuclear.com>)

and academy

- Chalmers University of Technology ([www.chalmers.se](http://www.chalmers.se))
- KTH Royal Institute of Technology ([www.kth.se](http://www.kth.se))
- Uppsala University ([www.uu.se](http://www.uu.se))

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

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

- 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
- 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 climate-friendly reliable electricity production.

The overall goals of SKC during 2016:

- ✓ 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.



## Organization and funding

SKC runs according to three-year contract periods of which the present contract ended December 31. The total volume for the three years was 32.3 MSEK.

SKC's financing partners in the present contract period (2014-2016) are:

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

The contract states that the financiers should contribute 10.766 MSEK annually to senior positions at the universities and to research activities. About half the support has been provided as a guaranteed base funding, and the rest has been possible to re-distribute between the universities.

An Advisory Council has been formed in which discussions on strategy and funding has taken place. The members are selected such that their professional backgrounds cover the areas of nuclear technology that is considered relevant to the financiers during the present contract period. The council provides advice to the SKC board and the director but takes no decisions.

During 2016, the Advisory Council consisted of:

- Per Brunzell, Chairman, (until October 2016)
- Nils-Olov Jonsson, Chairman (from October 2016)
- Mattias Olsson, Forsmarks Kraftgrupp AB
- Georg Lagerström, Oskarshamns Kraftgrupp AB
- Björn Forssgren, Ringhals AB
- Ingemar Jansson, Westinghouse Electric Sweden AB

The Swedish Radiation Safety Authority, Strålsäkerhetsmyndigeten (SSM), was represented in the Advisory Council during 2016 by Nils Sandberg as observer. Hans Henriksson act during their meetings as secretary.

During 2016, the SKC Board consisted of:

- Karl Bergman, Chairman, Vattenfall AB
- Jan Greisz, Forsmarks Kraftgrupp AB
- Pontus Tinnert, Oskarshamns Kraftgrupp AB (Pontus replaced Andreas Roos in October 2016)
- Henric Lidberg, Ringhals AB
- Eva Simic, Strålsäkerhetsmyndigheten – observer status
- Anders Andrén, Westinghouse Electric Sweden AB
- Leif Kari, KTH Royal Institute of Technology
- Åsa Kassman Rudolphi, Uppsala University
- Mats Viberg, Chalmers University of Technology (Leif Åberg proposed as new member in December)

SSM was represented in the Board according to the SKC contract that allows an observer status for the regulator. Four meetings were held in 2016. The Director of SKC attends the Board meetings reports the progress as well as presents proposals to the board. The Director has also an observer position in the SSM Research Board, and Hans attended three meetings in 2016.



## SKC Financial statements 2016

## Revenues, SEK

Payment Forsmarks Kraftgrupp AB	2 380 000
Payment Oskarshamns Kraftgrupp AB	2 380 000
Payment Ringhals AB	3 173 332
Payment Westinghouse Electric Sweden AB	2 833 332
<b>Sum Payment</b>	<b>10 766 664</b>
Payment French laboratory support	3 468 713
<i>Balance on account for French Laboratory support, 2015</i>	<i>3 826 660</i>
<b>Sum Payment</b>	<b>3 468 713</b>
<b>Sum incoming payments</b>	<b>14 285 176</b>

## Spending, SEK

Payout Chalmers	3 187 000
Payout KTH	3 200 000
Payout UU	3 430 000
Payout SKC central administration	949 664
<b>Sum Payout</b>	<b>10 766 664</b>
Payout French laboratory support (covering activities in 2015 and 2016)	3 325 183,89
<b>Sum Payout</b>	<b>3 325 184</b>
<b>Remaining funds French Laboratory support</b>	<b>3 970 189</b>



The contributions from the financing partners during 2016 of SKC to the budget split as follows:

Forsmark	22.1%
OKG	22.1%
Ringhals	29.5%
Westinghouse	26.3%

It should be noted that the future partition (2017-2019) between the parties will be the following:

Forsmark	28,1%
OKG	9,4%
Ringhals	37,5%
Westinghouse	25,0%

## Comments

- For 2016 an administrative cost of 250 000 SEK was transferred from the French support to SKC's central administration.
- The account for central administration has been spent by the end of the contract 2016, and distributed to projects within SKC.
- The remaining funds for the French Laboratory Support is planned to be used during the period 2017-2018, according to a proposal of agreement between KTH and CEA, with SKC as administrator.





## Winners of the Sigvard Eklund Prize

SKC organises each year a prize ceremony to the memory of Sigvard Eklund, former IAEA Secretary General.

The Director of SKC handed over the Sigvard Eklund Prize in three categories, best Bachelor, best Master and best Doctoral thesis, during the SKC symposium at Hindåsgården October 11, 2016.



The Sigvard Eklund Prize Winners: Ph.D. Luca Messina, KTH, Master Alicia Marie Raftery, KTH, Bachelors Fredrik Höök, UU and Adam Bruce, UU together with Hans Henriksson, Director of SKC.

The prize for best Bachelor thesis, 25 000 SEK, has been equally divided between Adam Duvheim Bruce and Fredrik Höök, Uppsala University, for their thesis:

***"Design av provutrustning för analys av bestrålningsinducerad spänningskorrosion"***.

The prize for best Master thesis, 35 000 SEK, has been awarded Alicia Maria Raftery, KTH, for her thesis:

***"Fabrication and Characterization of UN-USix Nuclear Fuel"***.

The prize for best Doctoral thesis 2015, 50 000 SEK, was given to Luca Messina, KTH. The thesis is entitled:

***"Multiscale modeling of atomic transport phenomena in ferritic steels"***.



## Appendix 1 - Chalmers University of Technology



# CHALMERS

*Sustainable Nuclear Energy Centre*

The Sustainable Nuclear Energy Centre (SNEC) coordinates the research and education related to nuclear technology at Chalmers. SNEC aims to provide arenas where researchers, MSc students, PhD students and industry meet to discuss and exchange ideas, information, and knowledge. The following Chalmers divisions/departments are participating actively in SNEC:

- 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.

The main occasions for networking and information exchange are the events arranged by SNEC during 2016. These were:

- The “SNEC-day”, which was organised on February 4. The event was visited by over a hundred participants and the subject discussed was the consequences of the decommissioning of four nuclear reactors in Sweden.
- A workshop on sustainability aspects of nuclear energy was held on May 2. Researchers from the divisions involved with SNEC discussed the topic together with other researchers from different disciplines such as philosophy, economics and energy systems.
- A half-day gathering where MSc/PhD-students had the opportunity to show their results to representatives from industry and to each other, was arranged on June 16. The event was visited by 35 people. The event was jointly organised with SKC and students from Uppsala and KTH were also invited. Six students from KTH showed up.
- The annual SKC symposium was jointly organised by SNEC and SKC. The event took place at Hindåsgården close to Gothenburg on October 11-12. The topic was how to maintain the Swedish nuclear competence base.
- An activity for master students was held on November 1. Master thesis project proposals from the industry were presented to the students.
- Four newsletters have been distributed to students, researchers and industry, presenting researchers and their work, as well as important events relating to nuclear technology research at Chalmers.

SNEC’s coordinator and director made a road trip to external stakeholders in 2015, concluding that there was a definite interest for a national nuclear competence center, which could act as a point of contact for nuclear related questions. In addition, the evaluation of SKC carried out in 2015-2016 showed that the industry requests more coordination within the academy on a national level. Finally, discussions with our academic colleagues revealed a common wish for increased networking, a platform for common grant applications, coordinated use of research infrastructure and a possibility to speak with a common voice in discussions, e.g. on how to maintain the Swedish nuclear competence base. Based on this, SNEC has been working on establishing such an academic collaboration, discussing its form and tasks with academic partners and stakeholders, and an application for establishment of a national academic center has been sent to Chalmers’ president. Currently, the collaboration involves only Chalmers and Uppsala University.



## Use of the SKC funding

### Costs of SNEC

The SKC funding has partly been used to directly support the running costs of SNEC. These costs have been used as shown below.

<b>Kostnadsslag</b>	<b>Utfall (1601-1612)</b>	<b>Kommentar</b>
Personell costs	35 801.97	Salary C. Ekberg
Equipment	0.00	
Bought services	352 084.38	Klara Insulander Björk
Travel and conferences	16 430.86	
OH	13 067.72	
Other	0.00	
<b>Totalt</b>	<b>417 384.93</b>	

The SKC base funding is also supporting three divisions at Chalmers:

- Div. of Energy and Materials, Nuclear Chemistry, Dept. of Chemistry and Chemical Engineering:  
210 000 kr
- Div. of Subatomic and Plasma Physics, Dept. of Physics. 1 130 000 kr
- Div. of Materials Microstructure, Dept. of Physics. 160 000 kr

In addition, the MÅBiL project supports PhD students Aneta Sajdova at Nuclear Chemistry (660 000 kr) and Kristina Lindgren at Materials Microstructure (610 000 kr). Adding this to the base funding, the total SKC support has been used as follows:

### Division of Subatomic and Plasma Physics

<b>Cost category</b>		<b>Comments</b>
Personell costs	599 603.09	Salaries for I Pázsit, C Demazière, P Vinai, K Jareteg, and A Nordlund
Equipment	0.00	
Bought services	140 703.62	
Travel and conferences	135 536.65	
OH	314 791.64	
Other	80 865.57	
<b>Totalt</b>	<b>1 271 500.57</b>	



### Division of Materials Microstructure

<b>Cost category</b>		<b>Comments</b>
Personell costs	479 002.02	Salary K. Lindgren
Equipment	0.00	
Bought services	29 720.00	
Travel and conferences	51 349.22	
OH	237 105.97	
Other	7 109.20	
<b>Totalt</b>	<b>804 286.41</b>	

### Division of Nuclear Chemistry

<b>Cost category</b>		<b>Comments</b>
Personell costs	71 116,00	Salary C. Ekberg
PhD student	416 846,30	Salary A. Sajdova, 80%
Equipment	31 131,00	Chemicals, gas and lab materials
Travel and conferences	15 044,88	C. Ekberg, T. Retegan, A. Sajdova
OH	359 940,10	
<b>Totalt</b>	<b>872 962,28</b>	

## Activities and common resources

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

- A pulsed beam for variable energy slow positrons.
- Access to all major system codes for neutronic and thermal-hydraulic calculations.
- Fully equipped laboratories for  $\alpha$ ,  $\beta$ ,  $\gamma$  experiments and activity measurements, e.g. HPGe-, LSC- and PIPS-detectors.
- A hot cell laboratory for  $\gamma$  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  $^{60}\text{Co}$  and  $^{137}\text{Cs}$  facilities ranging from 50 Gy/h and down to 1 Gy/h.
- An Atom Probe Tomography Instrument.\*
- Three Transmission Electron Microscopes.\*
- Two Scanning Electron Microscopes.\*
- Two Focused Ion Beam Workstations.\*

\*Managed by the infrastructure unit at the Dept. of Physics



**The following PhD projects were supported, either fully or partially, by SKC during 2016:**

- Development of an integrated neutronic/thermal-hydraulic model using a CFD solver (PhD student: Klas Jareteg; supervisor: Professor Christophe Demazière).
- Accident tolerant nitride based fuel (PhD student: Aneta Sajdova; supervisor: Professor Christian Ekberg).
- Ageing of Reactor Pressure Vessel Steel Welds (PhD student: Kristina Lindgren; supervisor: Associate Professor Mattias Thuvander)

**Some noteworthy accomplishments during 2016:**

- Imre Pázsit at Subatomic and Plasma Physics was awarded the Order of the Rising Sun by the Japanese government, and also the Leo Szilard medal by the Hungarian Nuclear Society.
- Christian Ekberg at Nuclear Chemistry was elected member of the Royal Society of Arts and Sciences (KVVS).
- Christophe Demazière at Subatomic and Plasma Physics was promoted to full professor.
- Dina Chernikova at Subatomic and Plasma Physics and Teodora Retegan at Nuclear Chemistry both earned the academic title “Docent”.
- The 10-MEUR EU project ASGARD, which was coordinated by the Nuclear Chemistry group and involved 16 organizations from all over Europe, was very successfully completed.
- Christophe Demazière at Subatomic and Plasma Physics was granted funding from NKS for a project with VTT and IFE Halden on hybrid neutron transport methods, Chalmers is coordinating the project.
- A 952-page book titled “The Hydrolysis of Metal Ions” was published by Christian Ekberg and Paul Brown (ISBN: 978-3-527-33010-2).
- A book chapter on a coming book on Molten Salt Reactors titled “Molten Salt Reactors and Thorium Energy - A volume in the Woodhead publishing series in energy” (Thomas Dolan (Ed), Elsevier, 2017), was completed and submitted by Imre Pázsit and Victor Dykin at Div. of Subatomic and Plasma Physics with the title “Chapter 5: Kinetics, dynamics and neutron noise in stationary MSRs”. Imre Pázsit also contributed to the chapter “Worldwide activities”, describing the on-going MSR-related Swedish activities in Chalmers, KTH and Uppsala.
- Div. of Subatomic and Plasma Physics hosts Dr. Yasunori Kitamura, Kyoto University Research Reactor Institute, who arrived in early December 2016 and will stay until the end of May 2017.
- The Nuclear Chemistry group hosted Dr. Dan Costin from CEA Cadarache, working with interactions between MOX fuel and sodium coolant for a sodium cooled fast reactor.

## Education

### Master education

The Div. of Subatomic and Plasma Physics, Dept. of Physics, Div. of Materials Microstructure, Dept. of Physics, and the Div. of Energy and Materials, Nuclear Chemistry, Dept. of Chemistry and Chemical Engineering, together with the Div. of Advanced Non-destructive Testing, Dept. of Materials and Manufacturing Technology, and the Div. of Physical Resource Theory, Dept. of Energy and Environment, organize a two-year international master program in Nuclear Science and Technology. This master program is based on a contract between E.ON and Chalmers, and is also financially supported by SKC.

The program is engineering oriented and aims at students with backgrounds in physics, chemistry, mechanical or electrical engineering. The master programme is the only nuclear education in Sweden combining physics and chemistry in one educational program. The philosophy of this programme is to have a “top-down” approach in teaching the physics of nuclear reactors, i.e. starting with an overview of how nuclear reactors work, followed by a detailed description of the main governing physical phenomena and corresponding equations, and finally elective and specialized courses.



### A few highlights for 2016:

- The master program was presented to students both at CHARM and later at information sessions preparing the students for selecting master programs.
- As in previous years, a guest lecturer from WANO (World Association of Nuclear Operators) was invited for two days to talk about safety culture in October.
- As part of a French-Swedish agreement regarding exchange of nuclear services as part of the European Spallation Source, the students for the master program have been to a research reactor in Saclay, France in spring 2016. The exercise was in form of a two-and-a-half day laboratory exercise on a small open pool reactor. The participating students were: Simon Persson, Johan Almlad, Jessica Lybark, Huaiqian Yi, Sriram Venkatesan, Michael Johansson, and Niklas Hansson.
- The course “Physics of nuclear reactors” was offered, for the second time in a row, as a flipped course, making use of pre-recorded videos and on-line quizzes combined with in-class activities. Data about students’ pre-class activities were continuously analysed in order to adjust the in-class activities depending on the students’ needs, following a Just-in-Time Teaching – JiTT – approach.
- The course “Modelling of nuclear reactors” was offered, for the fourth time in a row, as a flipped course, following the same pedagogical principles as the course “Physics of nuclear reactors”. In addition, the course was offered on-line, combining on-site and off-site students. The remote attendees were from other universities in Sweden and other European countries. The course is also offered through Chalmers Professional Education as a professional education course.
- A unique interactive teaching room was developed and built at the Department of Physics in Chalmers. In addition to moveable furniture making it easier to design in-class learning activities, the room is fully equipped with audio, video, and IT systems that allow blending on-site and off-site students. The room will thus be primarily used for distance education and some test projects have been successfully carried out. The Division of Subatomic and Plasma Physics was heavily involved in the design, testing and commissioning of the room, based on the experience acquired with the on-line course “Modelling of nuclear reactors”.
- The course “Noise techniques in nuclear systems” was offered the first time as an on-line course, available also for off-site students. The format of the lecture was, however, a traditional one, not a flipped course. The lectures were given in the interactive teaching room mentioned above, and were also recorded, hence they are also available off-line. The remote attendees were from the Technical University of Budapest , who became interested to take further courses in our master program.
- Preparations were made at the Division of Subatomic and Plasma Physics to start up a double-degree PhD project jointly with the Technical University of Budapest (BME), mostly with Hungarian financing. A Hungarian student was selected and enrolled in Budapest on 2016-09-01; the double degree agreement between Chalmers and BME is nearing completion, after which the student will be formally enrolled from the same date at Chalmers. He stayed at Chalmers between 13 June – 12 December and completed all obligatory GTS (General and Transferable Skills courses).





## SKC-relevant courses

The following SKC-relevant courses were given, with the number of students in parenthesis. If the courses have been followed also by students not enrolled directly at Chalmers, this is listed as “# Chalmers students + # other students”.

The courses listed with Swedish names are given by the Gothenburg University (GU) and are eligible for the students of the MSc program. These courses are given in Swedish. The number of students listed includes both Chalmers and GU students.

- Nuclear materials TIF265, 7.5 ECTS (8)  
*”The course gives an introduction to materials science in general, but with a focus on radiation effects and material degradation in the reactor environment.”*
- In-service inspection technologies MTT065, 7.5 ECTS ()  
*”The course aims at improving the knowledge about non-destructive testing technologies and their application within Swedish nuclear plants. The course will give an insight into what can be described as Risk Based Quality Assessment.”*
- Introduction to nuclear reactors TIF215, 7.5 ECTS (14)  
*”The course aims to give a broad orientation of the field of Nuclear engineering and in particular nuclear reactors and to provide an understanding of fundamental concepts in nuclear engineering.”*
- Physics of nuclear reactors TIF210, 7.5 ECTS (7)  
*”The course covers the multi-disciplinary aspects of the physics of nuclear reactors. As a consequence, the physics of both neutron transport, flow dynamics, and heat transfer is presented.”*
- Modelling of nuclear reactors TIF205 (5 + 2)  
*”The course covers the modelling aspects of nuclear reactors, i.e. what system of equations needs to be solved. The main techniques are presented in the course in a generic manner, and for practical reactor calculations.”*
- Applied nuclear engineering TIF195, 7.5 ECTS (7)  
*”The course aims to give an introduction to the use of calculational methods and computer codes for solving nuclear problems, and an understanding for advantages and disadvantages of different calculational methods”*
- Noise techniques in nuclear systems TIF245, 7.5 ECTS (3 + 3)  
*”The course discusses the neutron fluctuations that arise in a multiplying medium: their origin, mathematical treatment and their use in reactor diagnostics and surveillance.”*
- Nuclear reactor safety TIF250, 7.5 ECTS (7)  
*”The course introduces the safety aspects of the current commercial NPPs. Safety requirements of nuclear reactors are described, safety evaluation of NPPs is illustrated and methodologies and tools employed in safety analysis are discussed.”*
- Nuclear chemistry I KBT192, 7.5 ECTS (6)  
*”The course aims to inform about the origins and effects of ionizing radiation, radiation protection and use of radioactive compounds and teach practical radiochemical laboratory work”*
- Nuclear chemistry II KBT168, 7.5 ECTS (4)  
*”The course aims to inform about the applications of nuclear chemistry in industry, research and medicine, to teach the principles of work with elements in trace amounts and to teach practical radiochemical laboratory work with  $\alpha$ -emitters”*
- Radioecology and radioanalytical chemistry KBT216, 7.5 ECTS (4)



*"The course aims to inform on naturally occurring and man-made sources of ionizing radiation in our environment, how radionuclides are transported in the ecological system and to teach practical radioanalytical chemistry with focus on environmental samples"*

- Chemistry of Lanthanides, Actinides and Super-Heavy Elements KBT171 (2)  
*"The course aims to inform on the chemistry, production and use of the lanthanide, actinide and transactinide elements and to teach actinide and transactinide detection methods and practical work with actinides"*
- Radiofarmaceutical chemistry KBT221, 7.5 ECTS (2)  
*"The course aims to inform on the use, production and properties of radioactive nuclides for diagnosis and therapy in nuclear medicine. Also, synthesis of radio-labelled compounds, production and test of radiopharmaceuticals and practical labeling work is taught"*
- Future sustainable energy systems FFR170, 7.5 ECTS (111)  
*"The course should give the student knowledge of the general development of the energy system (past development and outlook for the future), its environmental and resource impacts, as well as tools to analyze these developments."*
- Computational fluid dynamics MTF072, 7.5 ECTS (1)  
*"The aim of the course is that the students obtain a thorough understanding of the finite volume method for CFD. A large part of the course will be devoted to the turbulence modeling."*
- Fusion energy RRY115, 7.5 ECTS (7)  
*"This course introduces basic principles and technological issues relevant to fusion energy generation and its practical use as a limitless large-scale electric power source in the future. It stresses the basic physical and technological concepts which are used in the development of future fusion power systems."*
- Grundläggande strålningsfysik RFA400, 7.5 ECTS (30)  
*"Under kursens gång får du lära dig vad strålning är, hur den uppkommer, hur vi kan mäta strålning och hur den kan skada levande vävnad. Du får också lära dig något om olika tillämpningar och om hur man handskas med strålning och strålkällor på ett strålsäkert sätt."*
- Nationell strålskyddsberedskap RFA410, 7.5 ECTS (9)  
*"I den här kursen får du lära dig hur den svenska beredskapen mot strålningsolyckor är organiserad och hur olika myndigheter och organisationer samverkar. Du får också tillfälle att utföra strålningsmätningar och använda datorbaserade verktyg för att göra uppskattningar av stråldoser."*
- Strålskydd vid katastrofmedicinska insatser RFA420, 7.5 ECTS (14)  
*"I kursen behandlas olika aktörers uppgifter från skadeplats till akutmottagning och eventuell specialistvård. Du får också lära dig hur man utför mätningar för att avgöra om en person är kontaminerad med radioaktiva ämnen, samt hur personsanering går till."*
- Detektorer och mätmetoder inom strålskydd och beredskap RFA430, 15 ECTS (?)  
*"I denna kurs om detektorer och mätmetoder för joniserande strålning får du lära dig och hur olika detektortyper fungerar i olika sammanhang, och om hur du väljer rätt detektor för uppgiften."*
- Strålskydd och miljöeffekter i kärnbränslecykelns olika skeden RFA440, 7.5 ECTS (?)  
*"I den här kursen får du kunskaper om de olika stegen i kärnbränslecykeln, från uranbrytning till slutförvaring eller upparbetning, och vilka strålskyddsaspekter som finns i de olika stegen."*





**The following course was also offered, but was not chosen by any students:**

- Solvent Extraction KBT196, 7.5 ECTS  
*“The course aims to inform about two phase liquid-liquid equilibria, the solution chemistry of metal ions, the use of solvent extraction processes in industry and research, equipment for solvent extraction and to teach practical solvent extraction work”*

## PhD education

A specific Doctoral School in Nuclear Engineering is available at Chalmers. The Doctoral School was designed in such a way that students with various backgrounds could be accepted to the Doctoral School. This corresponds to the fact that nuclear engineering is by essence a cross-disciplinary area, and consequently might attract students with various backgrounds (physics, chemistry, mechanical engineering, electrical engineering). Such a mix of students within one single Doctoral School creates a very rich and stimulating environment for the students during their PhD studies. Correspondingly, the list of compulsory courses is kept at a strict minimum so that the students can best choose the courses depending on their background and their research project.

Another strength of the school is the fact that the elective courses that are offered in the Master of Nuclear Science and Technology and corresponding to an advanced level can also be taken as PhD courses. The resulting mix between MSc students and PhD students favours discussions between the students, each having his/her own paradigm. This also creates a natural bridge between the MSc and PhD educations, which will ultimately result in more students interested in pursuing an academic career.

The PhD students enrolled in the school have also the possibility to attend courses at other universities both in Sweden and abroad.

## Completed theses

**In SKC-related subjects, the following master theses were successfully presented during 2016:**

- Otto Gärdin, Development of a Clad Stress Predictor for PCI Surveillance using Neural Networks (performed at Westinghouse, Västerås)
- Mu Lin, Octanol as a Diluent in a Grouped ActiNide EXtraction Process (performed at Nuclear Chemistry)
- Markéta Florianová, Treatment of alpha active scintillation cocktail waste (Master student from Prague University performing her thesis work at Nuclear Chemistry)

**Some master thesis projects were started but not yet finished by the end of 2016:**

- Federico López-Cerón Nieto, RELAP5 to TRACE model conversion for a Pressurized Water Reactor (performed at Universitat Politecnica de Valencia, Spain)
- Sebastian Carbol, Development of hybrid neutron transport methods for core calculations (performed at Subatomic and Plasma Physics)
- Elaine Tang, Understanding the cost structure of building new nuclear power plants in Europe (performed at Sweco, Göteborg)



- Niklas Hansson, Study of radium and barium complex formation with EDTA in alkaline sodium chloride media using the specific ion interaction theory (performed at Nuclear Chemistry)

**In SKC-related subjects, the following Licentiate theses were successfully presented during 2016:**

- Silvia Tuzi, Oxidation of Nickel Alloy X-750 in Boiling Water Reactor Environment (Materials Microstructure)
- Kristina Lindgren, Radiation Induced Precipitation in Reactor Pressure Vessel Steel Welds (Materials Microstructure)
- Artem Matyskin, On the solubility of radium sulfate and carbonate (Nuclear Chemistry)
- Anna Vesterlund, Gamma Spectrometric Measurements of Nuclear Material for Nuclear Forensic Purposes (Nuclear Chemistry)
- Ola Embréus, Kinetic modelling of runaway in plasmas (Subatomic and Plasma Physics)

**In SKC-related subjects, the following PhD theses were successfully presented during 2016:**

- Mikael Andersson, Control Rod Homogenization in Heterogeneous Sodium-Cooled Fast Reactors (Subatomic and Plasma Physics)
- Zsolt Elter, Neutron monitoring based on the higher order statistics of fission chamber signals (Subatomic and Plasma Physics)
- Ivan Kajan, Transport and Containment Chemistry of Ruthenium under Severe Accident Conditions in a Nuclear Power Plant (Nuclear Chemistry)
- Marcus Hedberg, Production and Characterization of ZrN and PuN Materials for Nuclear Fuel Applications (Nuclear Chemistry)
- Mariliis Lehtveer, Modeling the role of nuclear power and variable renewables in climate change mitigation (Physical Resource Theory)

## Planned activities for 2017

- The MSc program will continue during 2017, comprising essentially the same courses as in 2016.
- A national nuclear competence center (SAINT) will be established together with Uppsala University, and the main activities planned for 2017 are:
  - A mapping of the Swedish academic environments with nuclear competences
  - Involvement of other research environments in the center
  - Collaborative efforts within education, in particular in order to increase student recruitment and adapting education content to current needs
  - Arranging at least two workshops or conferences, topics and dates to be decided
- An e-learning project also involving Uppsala University will be coordinated by Chalmers. The purpose is to develop course material that will serve as an introduction to nuclear technology, which should be offered at an academic level suitable to attract students to the courses and education programs on nuclear technology.
- Four of the applications for EU funding that were prepared in 2016, have been granted funding, and activities will start in these projects in 2017:
  - The Division of Subatomic and Plasma Physics will coordinate a major European project during the period 2017-2021 called CORTEX (CORE monitoring Techniques and EXperimental validation and demonstration). The applied funding amounts to 5.092 MEuros and the consortium led by Chalmers includes in total 20 partners (with 3 non-European partners: 2 from Japan and 1 from USA). The project also includes an Advisory End-User Group, made of utilities and a TSO, to keep the research focused on the industrial needs. The funding granted for



Chalmers will be used for coordination (C. Demazière), one PhD student, one Post-Doc and for the leading of some of work packages and the supervision of the students (C. Demazière and P. Vinai). The CORTEX project aims at developing core monitoring techniques that can be used to detect and characterize operational problems, before they have any inadvertent effect on plant safety and availability.

- The division of Subatomic and Plasma Physics will participate in the project ESFR-SMART (European Sodium Fast Reactor Safety Measures Assessment and Research Tools). The project, led by PSI, aims at further enhancing the safety of Generation-IV SFRs and in particular of the commercial-size European Sodium Fast Reactor (ESFR). Chalmers is mostly involved in developing new pedagogical approaches based on flipped classrooms and distance education set-ups in the work package on dissemination, education and training, based on the expertise developed by C. Demazière in Chalmers.
- The division of Nuclear Chemistry will participate in the project MEET-CINCH (Modular European Education and Training Concept In Nuclear and RadioChemistry), with the objectives: a) To extend further the number of VET courses developed in previous EU projects and make them better available to the respective end-users. b) To attract new talents to the nuclear field and c) To use the modern Flipped Classroom concept to complement the available tools for teaching and training in the nuclear and radiochemistry field. The funding granted for Chalmers (237266,25 EUR) will be used by Teodora Retegan to participate in all fields of the project.
- The division of Nuclear Chemistry will participate in the project GENIORS (GEN-IV Integrated Oxide fuels Recycling Strategies) This is a follow up of previous EU projects focused on the separation for transmutation in Gen IV nuclear systems. The separation of useful material from used nuclear fuel is the crucial point to reach the high set goals given by the Gen IV nuclear systems. The project is led by CEA in France and Chalmers is the only Swedish participant. The funding received by Chalmers will fund a PhD student performing work within separation and transmutation.

## Publications

Publications from 2016, which were published within SKC-financed projects (including MÅBiL), are listed below. Three publications were prepared by K. Jareteg in 2016, which were submitted early 2017 (see specific project report below). A. Sajdova presented her work by oral and poster presentations at two conferences.

K. Lindgren, licentiate thesis: Radiation Induced Precipitation in Reactor Pressure Vessel Steel Welds, 2016.

On the analysis of clustering in an irradiated low alloy reactor pressure vessel steel weld, K. Lindgren, P. Efsing, K. Stiller and M. Thuvander, *Microscopy and Microanalysis*. Accepted in January 2017.

Evolution of precipitation in reactor pressure vessel steel welds under neutron irradiation, K. Lindgren, M. Boåsen, P. Efsing, K. Stiller and M. Thuvander, *Journal of Nuclear Materials*. Submitted in December 2016.

## Specific project reporting

A report for the SKC financed PhD project at Chalmers “Development of an integrated neutronic/thermal-hydraulic model using a CFD solver” (PhD student Klas Jareteg) is found below.

Projects which were part of the MÅBiL collaboration are reported separately.



## Development of an integrated neutronic/thermal-hydraulic model using a CFD solver

PhD student: Klas Jareteg, Department of Physics, Chalmers University of Technology  
Supervisor: Professor Christophe Demazière

### Project background

The PhD project aims at investigating an integrated approach to the modelling of nuclear reactors in a fine-mesh environment based on open-source Computational Fluid Dynamics (CFD) solvers. For that purpose, neutron transport algorithms and methods are developed and implemented. The neutron transport, fluid dynamics, and heat transfer are resolved within the same tool, using compatible discretization techniques (both in space and time) and compatible meshes. This kind of new computational approach allows better capturing physical phenomena that have been found to play a significant role in the performance of modern fuel assemblies (e.g., in advanced BWR rod bundles, effect of radial void fraction distribution on neutronic calculations).

### Completed milestones

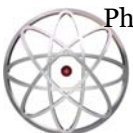
- 2016 Investigations of two-fluid characteristics and phase instabilities
- 2015 Development of a transient coupled scheme for the fine-mesh calculations  
Development of a population balance methodology for bubbly flows
- 2014 Consolidation of a neutron transport solver within the coupled framework
- 2013 Improvements of the coupled scheme including mesh coupling and parallelization  
Increase of size of simulated systems from pins to part assemblies
- 2012 Development of a fine-mesh coupled neutronics/thermal-hydraulics scheme

### Research activities 2016

To simulate the two-phase flow regimes in a BWR in a fully-dimensional and time-resolved manner requires computational methods relying on averaging approaches. One such methodology is the two-fluid model where both phases are averaged over the computational grid. It is well known that such an approach has unfavorable numerical characteristics in terms of lack of hyperbolicity for the system of equations describing the conservation of mass and momentum. To increase understanding of the fundamental behavior of such issues and investigate the stability properties of the solver, simulations were performed on a two-fluid approach for a 3D system. The investigations focused on the role of the different interfacial momentum transfers (see example in the figure below). It was shown that although physically appearing average fields are retrieved, the underlying instabilities put doubt on the value of such simulations (Jareteg et al (2017), Submitted to Chemical Engineering Science).

In addition, the population balance methodologies, previously studied within the project, were consolidated, including comparisons between a proposed DQMOM approach and an existing MUSIG methodology. Such solvers are of interest both for the sub-cooled boiling regime but also for bubbly flows of low to moderate void fractions. Both methods aim to recover the bubble size distribution in the channel, relying on a population balance approach. The two methods were compared for flow under sub-cooled conditions with a low fraction of a bubbly vapor phase and it was shown that the newly proposed method has advantages in terms of more efficient usage of the CPU-time as well as being superior in terms of recovering a large range of bubble sizes (Jareteg et al (2017), Submitted to Journal of Computational Physics).

Furthermore, the implementation of the transient multi-physics solver was verified based on a novel algorithm which relies on extraction of the point-kinetic component of the neutron flux from a sinusoidal perturbation. The multi-physics solver showed an excellent agreement with the theoretical expressions and was used as an example for a publication of the novel verification method (Demazière et al (2017), Submitted to Journal of Computational Physics).



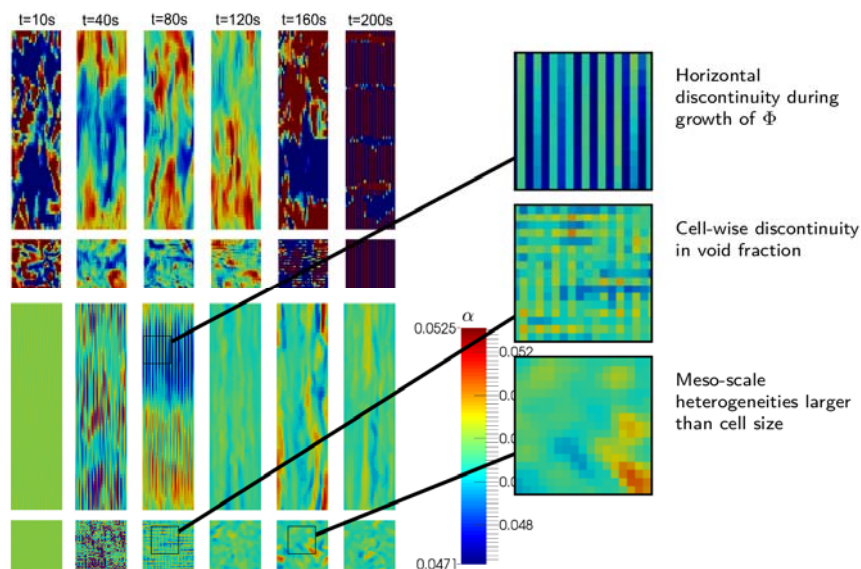


Figure 1. Comparison between two-fluid model stability properties without (top) and with (bottom) a virtual mass force (Jareteg, et al (2017), Submitted to Chemical Engineering Science)

## Publications

- 2017 **K. Jareteg**, S. Sasic, P. Vinai, C. Demaziere (2017). "A numerical framework for bubble transport in a subcooled fluid flow". *Submitted to Journal of Computational Physics*
- K. Jareteg**, H. Ström, S. Sasic, C. Demazière (2017). "On the dynamics of instabilities in two-fluid models for bubbly flows". *Submitted to Chemical Engineering Science*
- C. Demaziere, V. Dykin, **K. Jareteg** (2017). "Development of a point-kinetic verification scheme for nuclear reactor applications". *Submitted to Journal of Computational Physics*
- 2015 **K. Jareteg**, P. Vinai, S. Sasic, C. Demazière (2015). "Coupled fine-mesh neutronics and thermal-hydraulics - modeling and implementation for PWR fuel assemblies". *Annals of Nuclear Energy, Special Issue: "Multi-Physics Modeling of LWR Static and Transient Behavior"*
- A. Jareteg, **K. Jareteg**, S. Sasic (2015). "Formulation of stresses in dry granular flows". *CMFF2015, Budapest, Hungary*
- K. Jareteg**, R. Andersson, C. Demazière (2015). "Development and test of a transient fine-mesh LWR multiphysics solver in a CFD framework". *M&C 2015, Nashville, Tennessee*
- H. Ström, S. Sasic, **K. Jareteg**, C. Demazière (2015). "Behaviour and Stability of the Two-Fluid Model for Fine-Scale Simulations of Bubbly Flow in Nuclear Reactors". *International Journal of Chemical Reactor Engineering* 13.4, pp. 449–459
- K. Jareteg**, H. Ström, S. Sasic, C. Demazière (2015). "Numerical investigation of instabilities in the two-fluid model for CFD simulations of LWRs". *M&C 2015, Nashville, Tennessee*
- E. Pettersen, C. Demazière, **K. Jareteg**, E. Schönfeldt T, B. Lauritzen (2015). "Development of a Monte-Carlo based method for calculating the effect of stationary fluctuations". *M&C 2015, Nashville, Tennessee*
- K. Jareteg**, S. Sasic, P. Vinai, C. Demazière (2015). "Development of a Coupled Two-Fluid/DQMOM Methodology for Heated Bubbly Flows". *CMFF2015, Budapest, Hungary*
- 2014 C. Demazière, **K. Jareteg** (2014). "Developing a course in nuclear reactor modelling and going from campus-based to web-based teaching". *PHYSOR 2014, September 28 - October 3, Japan*
- K. Jareteg**, P. Vinai, S. Sasic, C. Demazière (2014). "Influence of an SN solver in a fine-mesh neutronics/thermal-hydraulics framework". *PHYSOR 2014, September 28 - October 3, Japan*
- K. Jareteg**, P. Vinai, C. Demazière (2014). "Fine-mesh deterministic modeling of PWR fuel assemblies: Proof-of-principle of coupled neutronic/thermalhydraulic calculations". *Annals of Nuclear Energy* 68.0, pp. 247–256



H. Ström, S. Sasic, **K. Jareteg**, C. Demazière (2014). "On the validity of the Two-fluid model for simulations of bubbly flow in nuclear reactors". *13th International Conference on Multiphase Flow in Industrial Plants (MFIP)*

**2013** **K. Jareteg**, P. Vinai, C. Demazière (2013). "Investigation of the possibility to use a fine-mesh solver for resolving coupled neutronics and thermal-hydraulics". *M&C 2013, Sun Valley, Idaho*



## Appendix 2 - KTH Royal Institute of Technology



### Overview of activities in 2016

KTH is the largest technical university in Sweden providing a broad spectrum of research and education in the nuclear engineering field. Both the theoretical and experimental research is performed employing a high-bay experimental infrastructure for investigations of, e.g., thermal margins in nuclear reactors, nuclear and construction material properties, new nuclear fuels and severe accidents scenarios and phenomena in nuclear power plants. Nuclear engineering research performed at KTH has a very high international reputation, resulting from numerous publications and citations.

The Centre for Nuclear Energy Engineering at KTH (CEKERT) has currently 14 faculty members. Research and education within the field of nuclear energy engineering is carried out in several divisions within the School of Engineering Sciences and the School of Chemical Science and Engineering.

### Staff directly involved in SKC activities

#### Reactor Physics group:

- 1 Assoc. Prof. - Pär Olsson (head of research group)
- 1 Professor - Waclaw Gudowski

#### Reactor Technology group:

- 1 Professor - Henryk Anglart (head of research group)
- 1 Assoc. Prof. - Jan Dufek
- 1 Ph.D. student - Mattia Bergagio – 50% SKC

#### Solid Mechanics group:

- 2 Professors – Bo Alfredsson and Jonas Faleskog (member of SSM:s research council)
- 1 Adj Professor – Pål Efsing
- 2 Researchers – Carl Dahlberg and Martin Öberg
- 3 Ph D Students – Michel Sedlak (70% SKC) and Rickard Shen (VAB/E.On/Fortum) are full time students, and Martin Bjurman (RAB/OKG/FKA) is Industrial Ph. D. student on 70%





## Highlights and major research outcome

Mattia Bergagio presented his licentiate thesis on December 16, 2016. The thesis title is “*Experimental analysis of thermal mixing at reactor conditions*”.

## Major archival publications

J. Dufek and G. Holst. Correlation of errors in the Monte Carlo fission source and the fission matrix fundamental-mode eigenvector. *Annals of Nuclear Energy* 94:415-421, 2016.

J. Dufek and K. Tuttelberg. Monte Carlo criticality calculations accelerated by a growing neutron population. *Annals of Nuclear Energy* 94:16-21, 2016.

M. Bergagio, R. Thiele and H. Anglart. Analysis of temperature fluctuations caused by mixing of non-isothermal water streams at elevated pressure. *Int. J. Heat and Mass Transfer* 104:979-992, 2017.

R. Pegonen, S. Bourdon, C. Gonnier and H. Anglart. Hydraulic modelling of the Jules Horowitz Reactor: Mass flow split between 36 fuel elements. *Nuclear Engineering and Design* 308:9-19, 2016.

R. Pegonen, S. Bourdon, C. Gonnier and H. Anglart. An improved thermal-hydraulic modelling of the Jules Horowitz Reactor using the CATHARE2 system code. *Nuclear Engineering and Design* 311:156-166, 2017.

A.R. Marklund, F. Michel and H. Anglart. Demonstration of an improved passive acoustic fault detection method on recordings from the Phénix steam generator operating at full power. *Annals of Nuclear Energy*. 101:1-14, 2017.

R. Pegonen, S. Bourdon, C. Gonnier and H. Anglart. Hot fuel element thermal-hydraulics in the Jules Horowitz Reactor. *Nuclear Engineering and Design* 300:149-160, 2016.

H. Li and H. Anglart. Modelling of annular two-phase flow using a unified CFD approach. *Nuclear Engineering and Design* 303:17-24, 2016.

H. Li and H. Anglart. CFD prediction of droplet deposition in steam-water annular flow with flow obstacle effects. *Nuclear Engineering and Design* <http://dx.doi.org/10.1016/j.nucengdes.2016.11.021>. Available online 22 December, 2016.

## Major conference presentations

H. Anglart, M. Bergagio and R. Thiele. Experimental and numerical investigation of wall temperature fluctuations due to thermal mixing in an annulus. Proc. 1st Pacific Rim Thermal Engineering Conference, PRTEC, Hawaii's Big Island, USA, March 13-17, 2016.

H. Kromer, T. Laneryd, H. Anglart, L. Al-Maeeni and R. Bel Fdhila. Experimental investigation of flow nucleate boiling heat transfer in a vertical minichannel. Proc. 1st Pacific Rim Thermal Engineering Conference, PRTEC, Hawaii's Big Island, USA, March 13-17, 2016.

H. Anglart, H. Kromer, L. Al-Maeeni, T. Laneryd, R. Bel Fdhila and A. Fonellosa Carro. Measurement of ebullition cycle characteristics in subcooled nucleate boiling of water flowing in a narrow vertical gap. Int. Conf. on Multiphase Flows ICMF, Firenze, Italy, May 22-27, 2016.

H. Anglart. Recent advances in heat transfer research and modelling. 6<sup>th</sup> Int. Conf. Workshop REMOO-2016, Budva, Montenegro, May 18-20, 2016.





## Fixed funding

The fixed funding has been used to support teaching in the nuclear engineering field. The main goal has been to continue providing high quality teaching within the Master Programme and in particular, in the core areas of nuclear engineering such as:

- Reactor physics,
- Reactor technology,
- Thermal-hydraulics.

The fixed funding was distributed to support teacher positions as follows:

Professor position in Reactor Physics	555 kkr
Professor position in Reactor Technology	555 kkr
Associate professor position in Reactor Technology	390 kkr

The fixed funding has been used according to the planned budget for year 2016.

## Education

### Report on educational activities in Nuclear Energy Engineering (TNEEM)

- **Programme Director – Waclaw Gudowski**

The Master Program in Nuclear Energy Engineering (TNEEM) is developing well and reaches new achievements.

TNEEM is today a part of few dual diploma agreements in nuclear energy engineering:

1. In European Master in Innovative Nuclear Energy Engineering – EMINE, a part of KIC InnoEnergy educational program, in which students are getting Dual Diploma with either of ENSTA - University Paris-Saclay, Paris or Grenoble Institute of Technology, Grenoble-INP. We produce about 15-20 DD Masters each year.
2. Dual Diploma in Nuclear Energy Engineering with Tsinghua University, Beijing
3. Dual Diploma in Nuclear Energy Engineering with Korea Advanced Institute of Science and Technology, KAIST
4. Few international students each year are enrolled to TNEEM in the frame of KTH's dual diploma agreement in civil engineering.

TNEEM is getting more and more applicants and more enrolled students each year. Fig. 1 shows the statistics over applicants and enrolled students. It is really encouraging dynamics.



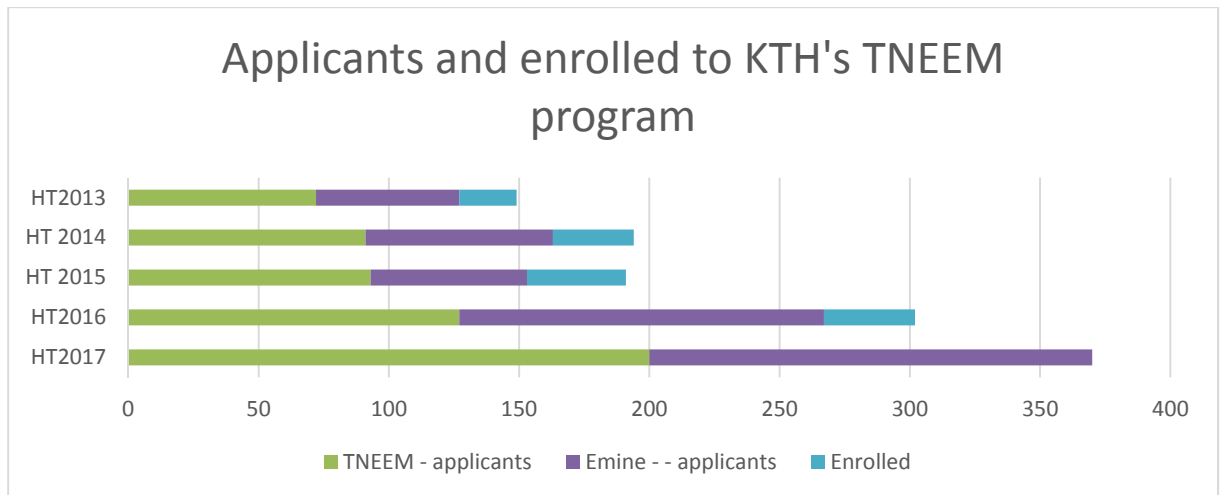


Figure 1. Development of TNEEM program in terms of applicants and enrolled students

It is worth to mention that in 2011 TNEEM program had 25 applicants and 4 students were formally enrolled. In 2017 we have hundreds of applicants and ~40 students enrolled. An impressive achievement!

In 2016 and in coming years particular efforts have been and will be put on E-learning platform development which is now called at KTH – Technology Empowered Engineering Education – TEEE or **TE<sup>3</sup>**. The ambition is that by years 2017-2018 the entire master program will be offered in the frame of E-learning technology.

A very important part of the TNEEM program are Reactor Physics Laboratory Exercises at CEA/INSTN-Saclay. This cooperative program is funded by SKC and is very highly appreciated both by the students and involved parties KTH and CEA/INSTN

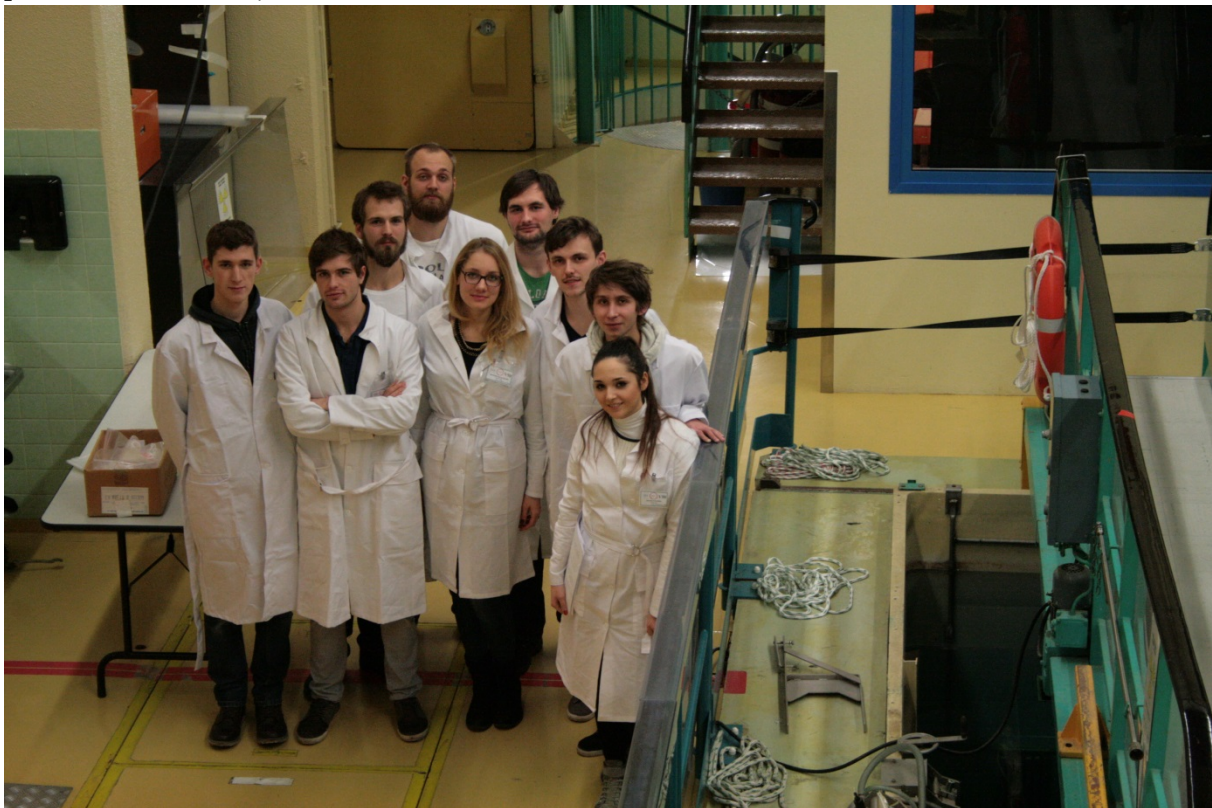


Figure 2 TNEEM students as ISIS reactor in Saclay.



## Technology Empowered Engineering Education –TE<sup>3</sup>development strategy for TNEEM

During 2016 a TE<sup>3</sup> strategy has been further developed by/at KTH using three web-based platforms integrated now into a common KTH's platform – **CANVAS**.

This TE<sup>3</sup> strategy is based – as described in the Annual Report 2016 on 3 pillars:

**Pillar I: Promotion of the program and navigation through the entire TNEEM program.**

**Pillar II: platform for the registered TNEEM Program students**

**Pillar III: Distance education - education on demand for *non-academic stakeholders***

*Development of TE<sup>3</sup> tools for the course: Nuclear Reactor Physics, SH2600.*

In the Fall Semester of 2016 a TE<sup>3</sup> approach has been further developed and implemented in the Nuclear Reactor Physics Course SH2600 at KTH using Maple T/A intelligent system.

43 students registered for Nuclear Reactor Physics did 9 “Home Assignments” summing up to 65 problems been solved and GRADED by the computer software. On January 16, 2017 38 students made the fully electronic examination based on developed “Exerciser” Maple T/A platform.

Students got 8 questions with some “sub-questions” to be solved during 5 hours. Each question has been individualized; there were different problem parameters or conditions for each and every student. The risk of cheating and copying the results has been drastically minimized. Once the students submitted the final answers they got immediately the final exam results. A very important pedagogical and educational progress has been achieved – a “zero time” delay between the exam and information about the results.

The results of the exam are presented at Fig. 2

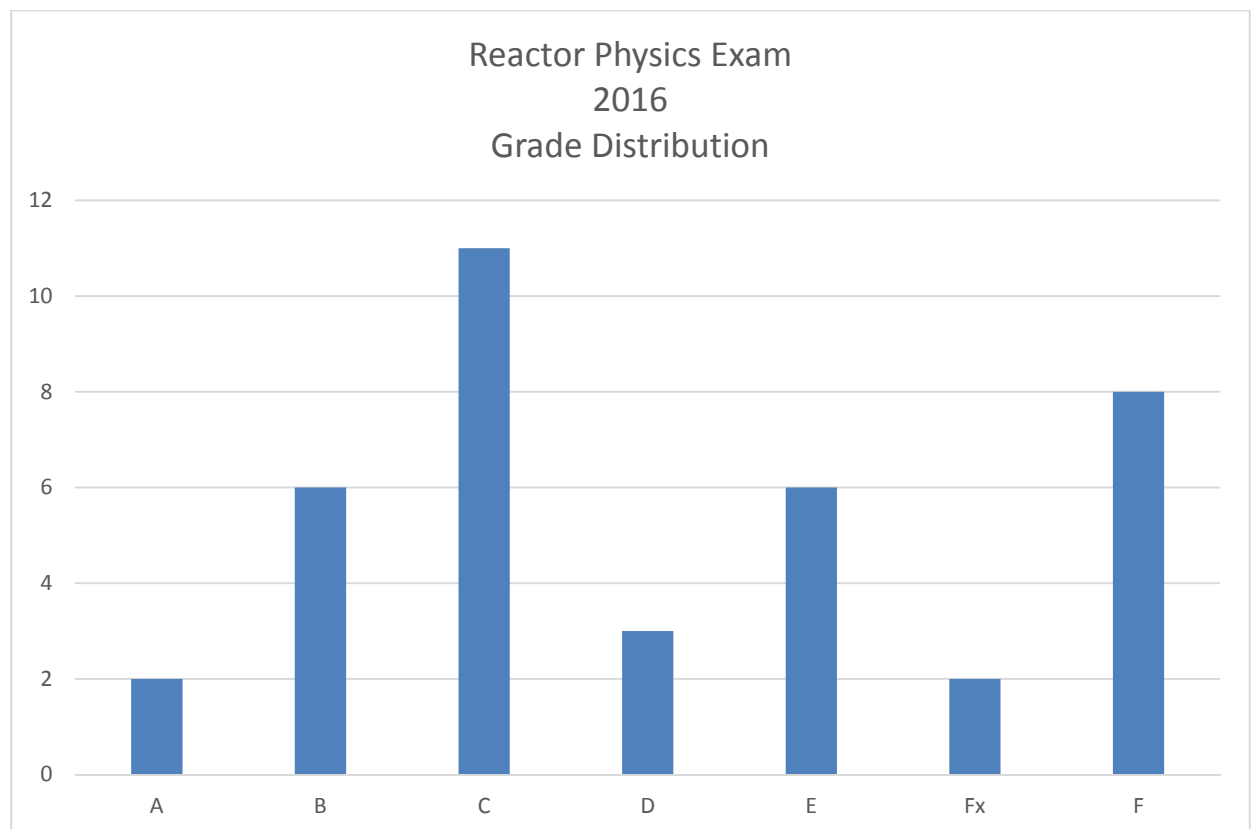


Figure 3. Results of the exam in Nuclear Reactor Physics - HT2016.



The results are not significantly different from previous, conventional exams, even if difficulty of this exam was a bit higher due to many efforts put to home assignments.

There is a clear strong incentive for the teachers to develop a **TE<sup>3</sup>** platform for home assignments and examinations, in spite of a significant and pretty high “initial threshold”:

*“Having 40 students on the course, 9 home assignments with 8 problems each, gives about 2600 problems to assess and grade. Assuming 5 minutes required for each problem well over 200 hours of assessment work – **5 weeks of teachers work done instantly by the computer!***

*A serious examination grading requires at least 1 hour per student which for this particular course would take about one week of work! Again – this work is done instantly and intelligently by the computer!”*

Number of students complaining about final exam grading was very standard and not different than for conventional exams, this year it was below 10 %.

### Development of the Summer Course: Elements of the Back-end of the Nuclear Fuel Cycle: Geological Storage of Nuclear Spent Fuel (Code SH262V, 7.5 ECTS)

This Summer Course is an exceptional example of a successful cooperation of KTH with other stakeholders, like nuclear industry, local communities and other universities. The most important development features are:

- This course has been designed and organized by the Royal Institute of Technology (**KTH**), the Center for University Studies Research and Development (**Nova - Oskarshamn**) and by the Swedish Nuclear Fuel and Waste Management Company (**SKB**) and supported by the Linnaeus University and the University of Illinois at Urbana-Champaign.



Figure 4. Cooperating parties in the Summer Course SH262V-2016.



- b) The course consists of a combination of classroom lectures and field excursions and work. The unique feature of the course is that the students visit Clab (an interim geological repository for spent fuel), the Laxemar Site (study area for bedrock and surface geology), the Äspö Hard Rock Laboratory (research laboratory for geological spent fuel disposal), and the Canister Laboratory (development center for spent fuel encapsulation technology).
- c) The course is heavily sponsored and funded by the local Oskarshamn community and SKB
- d) A comprehensive multimedia report has been produced including video recorded lectures and students presentations. Click the link  
[https://www.dropbox.com/s/smgflg74d9g70qq/Summer\\_Course\\_SH262V-Report-2016.pdf?dl=0](https://www.dropbox.com/s/smgflg74d9g70qq/Summer_Course_SH262V-Report-2016.pdf?dl=0)
- e) All the lectures of the Summer Course are now available on the TE<sup>3</sup> platform:

- **Session 1 Lecture 01 Welcome 13/06/2017**  
<https://mediasite.neutron.kth.se/Mediasite/Play/9fb2765ac18a4b5b9b537795a832af091d>
- **Session 1 Lecture 02 Gudowski 13/06/2017**  
<https://mediasite.neutron.kth.se/Mediasite/Play/b52879c98aef453286cada718da7abbf1d>
- **Session 1 Lecture 03 Kozlowski 13/06/2017**  
<https://mediasite.neutron.kth.se/Mediasite/Play/d1549c6d915f4ff79bc6a03ebd5c400c1d>
- **Session 1 Lecture 04 Wikberg et.al. 13/06/2017**  
<https://mediasite.neutron.kth.se/Mediasite/Play/377463a752a141eeaa6e927ea0a4ae401d>
- **Session 1 Lecture 05 Discussion 16/06/2017**  
<https://mediasite.neutron.kth.se/Mediasite/Play/9b5f5df55560414e9bde1747356c11ea1d>  
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- **Session 2 Lecture 01 Roy 14/06/2017**  
<https://mediasite.neutron.kth.se/Mediasite/Play/4377dcc0650649c996e6c597b5d35a461d>  
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- **Session 3 Lecture 01 Claesson 15/06/2017**  
<https://mediasite.neutron.kth.se/Mediasite/Play/562f929878fd4fbfab0011a4c67ae9aa1d>
- **Session 3 Lecture 02 Lemdahl 15/06/2017**  
<https://mediasite.neutron.kth.se/Mediasite/Play/faf6aec772894165b6052d3f906892811d>
- **Session 3 Lecture 03 Dopson 15/06/2017**  
<https://mediasite.neutron.kth.se/Mediasite/Play/1a3bcffbc28e4f1da863204348869dc31d>
- **Session 4 Lecture 01 Roy 16/06/2017**  
<https://mediasite.neutron.kth.se/Mediasite/Play/a476ode39f624641802a045c16b376961d>
- **Session 4 Lecture 02 Åström 16/06/2017**  
<https://mediasite.neutron.kth.se/Mediasite/Play/cd2f6e81a77e4ee69b25409a43adb7c11d>
- **Session 4 Lecture 03 Rees 16/06/2017**  
<https://mediasite.neutron.kth.se/Mediasite/Play/9039929309144676ab075921462987151d>
- **Session 4 Lecture 04 Sun-Yuliang 16/06/2017**  
<https://mediasite.neutron.kth.se/Mediasite/Play/93bafa7e5fd3483b943baf875c0040201d>
- **Session 5 Lecture 01 Morosini 17/06/2017**  
<https://mediasite.neutron.kth.se/Mediasite/Play/279ac1feb3884fca9fe1aeda1923edd1d>
- **Session 5 Lecture 02 Stenberg 17/06/2017**  
<https://mediasite.neutron.kth.se/Mediasite/Play/ae7e60c1f5014b67abcd0b2dd644ec991d>
- **Session 5 Lecture 03 Alakangas Mathurin 17/06/2017**  
<https://mediasite.neutron.kth.se/Mediasite/Play/148b4ecb88f74f60a342a5e29c87093b1d>
- **Session 5 Lecture 04 Vidstrand 17/06/2017**  
<https://mediasite.neutron.kth.se/Mediasite/Play/77cceb53ae1b40e989da217bd12f75a21d>
- **Session 5 Lecture 05 Gu Long 17/06/2017**  
<https://mediasite.neutron.kth.se/Mediasite/Play/225a280e6a0a4c1bb5e66df5061dc5681d>
- **Session 6 Final Presentation - Group 1 - 23/06/2017**  
<https://mediasite.neutron.kth.se/Mediasite/Play/e192b6c33b8b46dca3224918bb975e1f1d>
- **Session 6 Final Presentation - Group 2 - 23/06/2017**  
<https://mediasite.neutron.kth.se/Mediasite/Play/ec30e76058e74f2aac6489fdc5ef003d1d>
- **Session 6 Final Presentation - Group 3 - 23/06/2017**  
<https://mediasite.neutron.kth.se/Mediasite/Play/d20f0204630d4e81a1a02245915778ec1d>
- **Session 6 Final Presentation - Group 4 - 23/06/2017**  
<https://mediasite.neutron.kth.se/Mediasite/Play/cbb9f0480f8042b0be1a3ea563494ecb1d>
- **Session 6 Final Presentation - Group 5 - 23/06/2017**  
<https://mediasite.neutron.kth.se/Mediasite/Play/f2d8f54fc23241f193eb5808147012661d>
- **Session 6 Final Presentation - Group 6 - 23/06/2017**  
<https://mediasite.neutron.kth.se/Mediasite/Play/288638f3c9bb40e18ac96497f94d0dc91d>





- **Session 6 Final Presentation - Group 7 - 23/06/2017**  
<https://mediasite.neutron.kth.se/Mediasite/Play/5c1fc606281f4ef892e5a0dbf1df2a011d>
  - **Session 6 Final Presentation - Group 8 - 23/06/2017**  
<https://mediasite.neutron.kth.se/Mediasite/Play/8da49283338b4be09c50139da295a40b1d>
  - **Session 6 Final Presentation - Group 9 - 23/06/2017**  
<https://mediasite.neutron.kth.se/Mediasite/Play/7f194c9c793f405da5273228cf7c9fc11d>
- f) In 2016 a dedicated text book has been made available for the students.



Figure 5. Students of the Summer Course SH262V-2016.

The course gained a very good international reputation having many international students, see Fig. 4 for details.

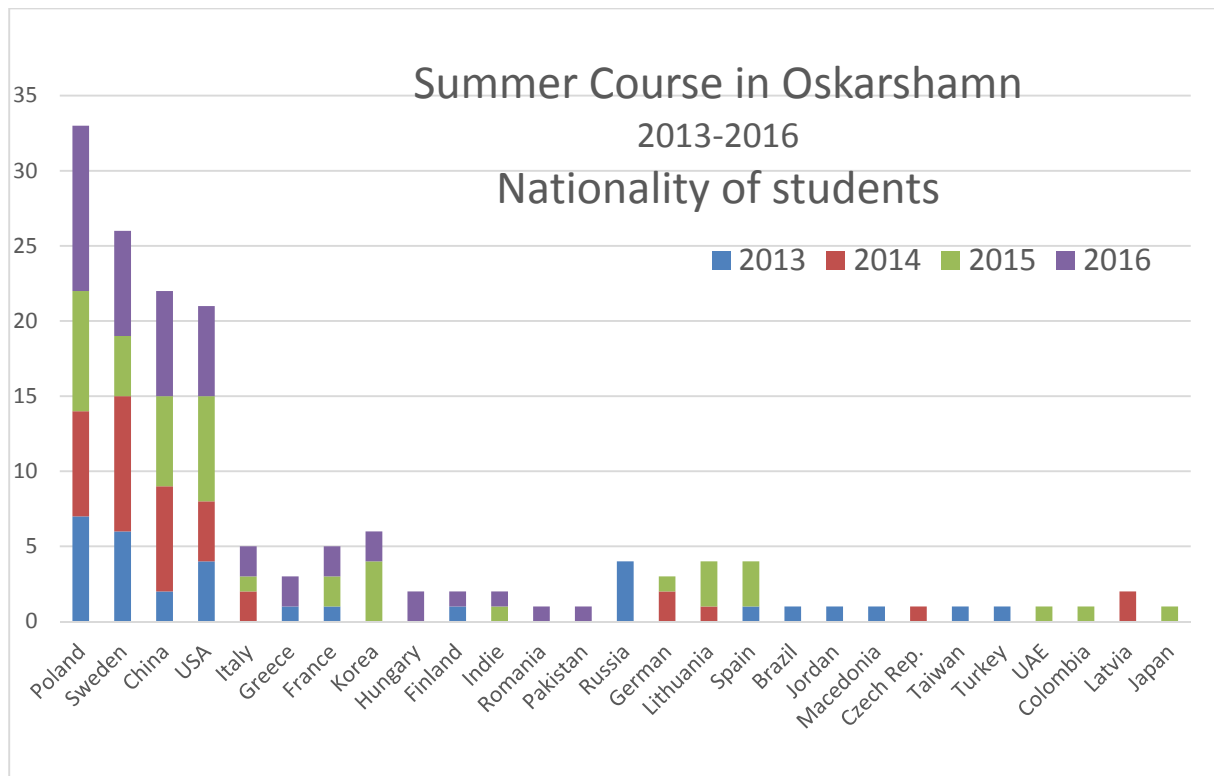


Figure 6. Nationality of the students of the Summer Course SH262V in the years 2013-2016.



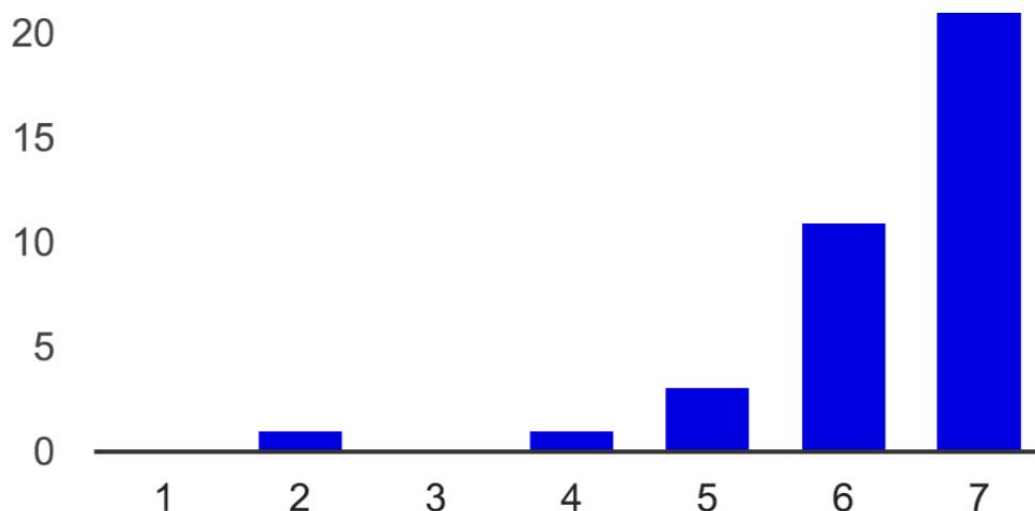


Figure 7. Students' evaluation of the course SH262V-2016.

### Development of the course : Leadership for Safety in the Nuclear Energy Industry (Code SH2610, 6 ECTS)

This course is a very good example of KTH's cooperation with industrial/external partners.

Lectures, coordinated by prof. Waclaw Gudowski are given by:

1. Lars Högberg, former Director General of the Swedish Nuclear Power Inspectorate (SKI-SSM)
2. Kerstin Dahlgren, senior safety expert at **Vattenfall**
3. Lars Axelsson, **Swedish Radiation Safety Authority (SSM)**, senior expert in nuclear and airline safety.
4. Anders Jörle, vice president **Public Affairs of Swedish Space Corporation**, former director of information at SKI and media spokesperson at the Swedish Ministry of Foreign Affairs.
5. Lars Gunnar Larsson, senior expert in nuclear power, former Deputy Director General of SKI, former nuclear power expert in the European Bank for Reconstruction and Development.
6. Per Lindell, former CEO E.ON Nuclear Sweden, former chairman of **E.ON Nuclear Safety Council**.
7. Judith Melin, former Director General of the Swedish Nuclear Power Inspectorate (**SKI**) and of the Swedish Coastal Guard; member of E.ON Nuclear Safety Council
8. Tord Sterner, formerly ASEA-ATOM
9. Leif Öst, former CEO, **Barsebäck Kraft AB**

This course was put fully at the **TE<sup>3</sup>** platform and can be easily viewed at the following link:

<https://mediasite.neutron.kth.se/Mediasite/Catalog/catalogs/sh2610-leadership>

In 2016 a course book: Leadership for safety in Nuclear Energy has been published. Financial support from SKC is respectfully acknowledged: *KTH and The Swedish Centre for Nuclear Technology (SKC) are acknowledged for the financial support to this work.*



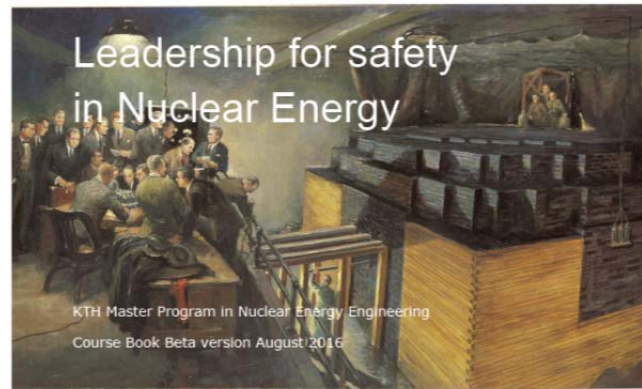


Figure 8. The cover of the text book: Leadership for safety in Nuclear Energy.

## Summary

A very successful year 2016 for TNEEM program development at KTH:

- Fantastic dynamics of applicants and enrolled students to nuclear engineering program at KTH
- Technology Empowered Engineering Education project development: many courses on TE<sup>3</sup> platform
- Two course books published with a strong support of SKC and industrial partners
- TNEEM student Alicia Marie Raftery got Sigvard Eklund's prize 2016 for the best Master Thesis



Figure 8. The Sigvard Eklund Prize Winners: Ph.D. Luca Messina, KTH, Master Alicia Marie Raftery, KTH, Bachelors Fredrik Höök, UU and Adam Bruce, UU together with Hans Henriksson, Director of SKC.





## Theses and Examination

The following theses have been completed during 2016:

### Department of Physics

<b>Master theses</b>			
<b>Trita</b>	<b>Title</b>	<b>Namn</b>	<b>Examinator</b>
2016;80	Analysis of the Fission Matrix Basedz Monte Carlo Method for Criticality Simulations	G. Holst	H. Anglart
2016;67	Comparison of MELCOR and MAAP calculations of core relocation phenomena in Nordic BWR's	A. Tuvelid	H. Anglart
2016;40	Multi-mode modeling applied to the Main Feedwater System and Auxiliary Feedwater System switch in a Pressurized Water Reactor"	L. Mesa-Moles	W. Gudowski
2016;61	CFD Pre-test Analysis of SIMECO-2 Experiment	Y. Li	W. Ma
2016;52	CFD modeling of annular flow for prediction of the liquid film behavior	M. Camacho	J. Dufek
2016;43	Oxidation of alumina forming alloys for low temperature applications	P. Dömstedt	W. Gudowski
2016;33	Water Hammer Phenomenon Analysis using the Method of Characteristics and Direct Measurements using a "stripped" Electromagnetic Flow Meter	J. Carlsson	J. Dufek
2016;32	BWR In-Core Instrumentation Sensitivity to Material and Geometrical Distortions	M. N Fernberg	H. Anglart
2016;38	Advanced Modeling of Pellet-Cladding Interaction	A. Gojan	H. Anglart
2016;34	Ultrasonic Testing of INCONEL Alloy 600	T. Engström	H. Anglart
saknas	Power tilt analysis in a Pressurized Water Reactor	M. Maligot	W. Gudowski
2016;64	Degradation mechanisms of UN and UN-10U3Si2 pellets of varying microstructure by comparative steam oxidation experiments	S. Uygur	J. Wallenius
<b>Bachelor theses</b>	4		
<b>Lic. exam</b>	4, No nuclear Technology		
<b>Dr. exams</b>	4 (1 subject: Nuclear Technology, Luca Messina)		



**Department of Solid Mechanics**

<b>Master theses</b>			
	Evaluation of fatigue initiation in specimens for virtual design of case-hardened gear wheels	P. V Levente	B. Alfredsson
	Replikprovning som metod för prognos av kryplivslängd	S. Hansson	B. Alfredsson
	3D FE Simulations of Resistance Spot Welding	D. Löveborn	P-L. Larsson
	Towards the measurement of two independent viscoelastic functions using spherical indentation	H. Mohammed	P-L. Larsson
	Correlation study between FEA and physical testing for a hypoid gear set	C. Gregefors	B. Alfredsson
	Analysis of concussions in professional ice hockey	J. Svensson	T. C. Gasser
	Micromechanical study of PFZ in aluminum alloys	H. Shariati	J. Faleskog
	Bestämning av mekaniska egenskaper hos ett material för skumpanel - experiment och modellkalibrering	L. Löqvist	B. Alfredsson
	Automated surveillance of spectrum loading and impact on fatigue life	V. Eriksson	M. Olsson
	Fatigue analysis of engine brackets subjected to road induced loads	T. Ek	S. Östlund
	The Effect of Geometry on the Mechanical Properties of Paper Fiber Bonds	A. Brandberg	A. Kulachenko
	Experimental and numerical investigation of the tribological properties of a test joint	K. Sten	P-L. Larsson
	Vibration Design of Cockpit	J. Lindestaf	M. Olsson
	Non-linear behaviour of nanofibrillar cellulose foams	F. Karlberg	A. Kulachenko
	Effects of warm pre-stressing on cleavage fracture	A. Eriksson	J. Faleskog
<b>Bachelor theses</b>	16		
<b>Lic. exam</b>	2		
<b>Dr. exams</b>	6		

**Total number of theses and examination****Reported number of theses from Nuclear Engineering and Solid mechanics**

Number of Master theses: 27

Number of Bachelor theses: 20

Licentiate exams: 6

Ph.D. exams: 10



## Research Project funding and outcome during 2016

### Experimental analysis of thermal mixing at reactor conditions

- Ph.D. student: Mattia Bergagio
- Supervisor: Prof. Henryk Anglart

### Funds spending

The project has been supported by SKC with 450 kkr during 2016. The funds were used for partial covering of the salary cost of the PhD student.

### Activities within the project under 2016

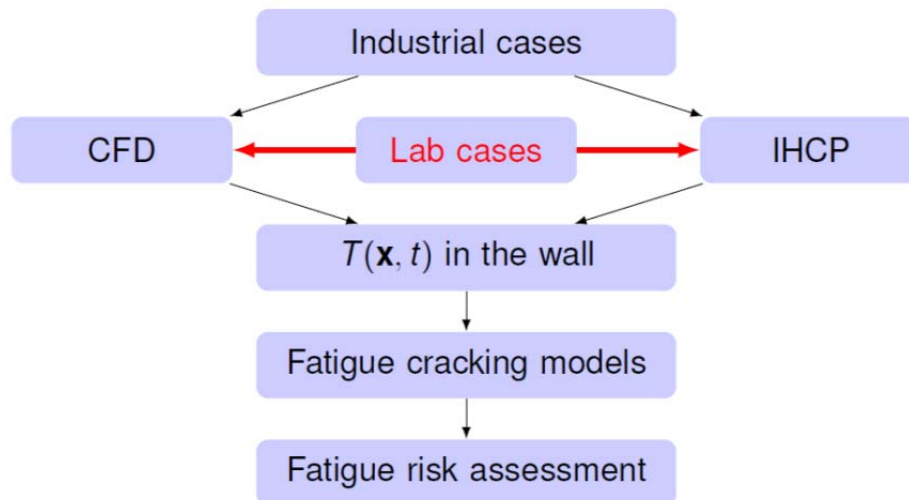
The main outcome of the project during 2016 was the final description and analysis of experimental data on thermal mixing of cold and hot streams at reactor conditions, which can lead to thermal fatigue. High-cycle thermal fatigue arising from turbulent mixing of non-isothermal flows is a key issue associated with the life management and extension of nuclear power plants. The induced thermal loads and damage are not fully understood yet. With the aim of acquiring extensive data sets for the validation of codes modelling thermal mixing at reactor conditions, thermocouples recorded temperature time series at the inner surface of a vertical annular volume where turbulent mixing occurred. There, a stream at either 333 K or 423 K flowed upwards and mixed with two streams at 549 K. Pressure was set at  $72 \times 10^5$  Pa. The annular volume was formed between two coaxial stainless-steel tubes. Since the thermocouples could only cover limited areas of the mixing region, the inner tube to which they were soldered was lifted, lowered, and rotated around its axis, to extend the measurement region both axially and azimuthally.

Trends, which stemmed from the variation of the experimental boundary conditions over time, were subtracted from the inner-surface temperature time series collected. An estimator assessing intensity and inhomogeneity of the mixing process in the annulus was also computed. In addition, a frequency analysis of the detrended inner-surface temperature time series was performed. In the cases examined, frequencies between 0.03 Hz and 0.10 Hz were detected in the subregion where mixing inhomogeneity peaked. The uncertainty affecting such measurements was then estimated. Furthermore, a preliminary assessment of the radial heat flux at the inner surface was conducted.

The uncertainty associated with the aforesaid temperature measurements is found to reach 1.58K and 3.87K at 1000 Hz and 100 Hz sampling frequencies, respectively. It must be emphasized that the largest contribution to uncertainty at 100 Hz was inferred from tabulated data provided by the manufacturer, whereas the same uncertainty source at 1000 Hz was estimated from end-to-end calibration data. It is reasonable to suppose that uncertainty at 100 Hz could be decreased by proper end-to-end calibration data. Nevertheless, the acceptability of accuracy, at least at 1000 Hz, and the simplicity of the annular geometry allow to validate numerical models for the prediction of thermal mixing and fatigue by using the experimental data acquired. Given the scarcity of measurement points in the radial direction at a certain point of interest, the radial component of the heat flux at the inner radius of the annular volume was approximated with the help of a Crank-Nicolson discretization of the one-dimensional heat conduction equation for the respective thermocouple. A corrective term, called azimuthal correction, was then introduced to account for the misalignment of the thermocouple with the radial direction. This method was partially verified by comparing it with an analytical solution and a combined analytical/computational one. Generally speaking, the azimuthal correction is small; hence, a rigorous verification of the rectified heat flux is not required. However, solving an inverse heat conduction problem (IHCP) for the three-dimensional thermocouple discs will help to demonstrate the reliability of our approach.

Based on the present data and performed analyses, a new approach for estimation of thermal fatigue risks was envisioned. Since this risk is directly related to amplitudes and frequencies of temperature oscillations in the solid material, the focus of the research was on new reliable methods to predict these parameters for real industrial conditions. A schematic of the proposed fatigue risk assessment (FRA) approach is shown below.





### *Planned activities*

A three-dimensional inverse heat conduction problem (IHCP) solution algorithm will be developed and validated against experimental data. In industrial applications, either CFD or IHCP will be used to provide temporal temperature field  $T(\mathbf{x}, t)$ . This solution will be used as input to fatigue cracking models to provide fatigue risk assessment (FRA).

### *Publications and presentations*

1. M. Bergagio, R. Thiele and H. Anglart. Analysis of temperature fluctuations caused by mixing of non-isothermal water streams at elevated pressure. *Int. J. Heat and Mass Transfer* 104:979-992, 2017.
2. M. Bergagio. Experimental analysis of thermal mixing at reactor conditions. Licentiate Thesis, Stockholm, Sweden, 2016.



## Department of Solid Mechanics at KTH

Solid Mechanics is a classic discipline within engineering sciences, ranging from basic to applied science. The subject can be regarded as a link between material science and applied mechanics with emphasis on the latter. Solid Mechanics deals with the mechanical properties of materials and structures. Research at the department is focused on computational mechanics, fracture mechanics, composite mechanics, contact mechanics, material mechanics, paper mechanics and fatigue. A primary goal of the research is to develop methods for reliable design of structures, materials, systems and processes.

The education in solid mechanics consists of basic courses in strength of materials and solid mechanics, elasticity and FEM, and advanced courses in more specialized areas such as, for example, material mechanics, fracture and fatigue, testing techniques, biomechanics, paper mechanics and dynamic problems in solid mechanics. There is a close interaction between research and teaching on all levels. New developments in solid mechanics are reflected in a continuous updating of the content of the courses.

Presently the department has 7 full professors, 2 associate professors and one adjunct professor. Furthermore, there are 1 researcher, 2 post-doctors and approximately 20 PhD students in the PhD-programme in Solid Mechanics. The department has a well-equipped laboratory and a work shop with two engineers and two technicians.

### Fixed funding

The department receives no fixed funding from SKC. All activities are funded from research projects, commission or educations.

### Personnel active in operations in the SKC area

Adjunct professor Pål Efsing (Adjunct from Vattenfall AB)

Professor Bo Alfredsson

Professor Jonas Faleskog (member in SSM's research council)

Dr Carl Dahlberg

Mr Martin Öberg Head of Laboratory

Mickal Sedlak (70% SKC) PhD student in Mechanical modelling of intergranular stress corrosion in stainless steel

Magnus Boåsen (25% SKC) PhD student in Radiation effects on material mechanical properties of low alloyed reactor pressure vessel steel

Rickard Shen (80% VAB/E.On/Fortum) PhD student in Influence of micro-structure and residual strains on stress corrosion in nickel-base alloys

Martin Bjurman (100% Studsvik) Industrial PhD student in Thermal ageing of cast and welded austenitic structures with ferrite.

### Examinations in Solid Mechanics at KTH 2016

6 PhD degrees

2 licentiate degrees (both continues to PhD degree)

15 diploma works at master level

16 diploma works at bachelor level

All educated are relevant for the nuclear industry through the general orientation of the subject and the abilities the students have attained with focus on methods, tools, materials behaviour and mechanics.



## Project in solid mechanics in SKC during 2016

### Project 1:

### **Mechanical modelling of intergranular stress corrosion in sensibilised stainless steel 316**

PhD student: Michal Sedlak

Supervisor: Pål Efsing, Bo Alfredsson

### Funds spending

Michal Sedlak 80% and Bo Alfredsson 10% of respective time in the project. Total cost of salary was 883 200 SEK. Budget funding was 600 SEK from SKC and 283 SEK from KTH in-kind. No deviation from budget.

### Couplings to other projects during 2016

Experimental verification of coupled model for IG-SCC in sensitized stainless steel 316L with funding from the materials group. Budget was 100 thousand for experiments in 2016. The work is in progress.

### Activities within the project under 2016

The FEM model of the IG-SCC was completed in 2015. In 2016, the model has been adapted to the material data for ductile and brittle fracture. Numerical reference results have been developed for the cohesive element. The fracture mechanics simulation techniques have been described in the first manuscript which is submitted for publication in an international scientific journal.

Work on paper two has started. This paper will deal with the coupled processes of diffusion, corrosion, degradation of fracture mechanical properties and fracture.

Work for experimental verification of the model continues with accelerated IG-SCC testing. Attempts were made for 316L, 304L, 304, 304 sensitized with saturated ionic solutions and also increased temperature. So far, no measurable SCC occurred. The work continues.

The coupled and modular numerical model for IG-SCC was finalized.

### Presentations and Publications

The model for IG-SCC was presented at the SKC convent in Hindås October 11 – 12, 2016 and at NSCM29, the 29th Nordic Seminar on Computational Mechanics, October 26 – 28, 2016 in Gothenburg.

Article 1 with title: *A cohesive element with degradation controlled shape of the traction separation curve for the IGSCC and IASCC simulation* was sent for international scientific publication.

### Planned activities for 2017

- Completion of accelerated experiments of IG-SCC.
- Completion of Manuscript 2 on the characteristics of the connected model for IG-SCC.
- Manuscript 3 on the experiments and numerical modeling of them.
- Manuscript 4 of the IG-SCC with grain structure and crystal plasticity. PhD degree for Michal Sedlak.



## Project 2:

### **Radiation effects on material mechanical properties of low alloyed reactor pressure vessel steel**

PhD student: Magnus Boåsen

Supervisor: Pål Efsing, Bo Alfredsson

#### Funds spending

Cost of salaries: Magnus Boåsen 25% of total payroll costs, 210 000 SEK, in 2016. Budget funding was 200 000 SEK from SKC. No deviation from the budget. Supervision by Efsing was funded by agreement between KTH and Ringhals AB.

#### Couplings to other projects during 2016

Coordination for micro-structural analysis of RPV materials and thermal aged material at Chalmers with Kristina Lindgren and Mattias Thuvander.

Coordination and implementation of projects WIDE within NKS in cooperation with VTT / Finland and Lindgren / Thuvander at Chalmers. The work in progress.

The project is partly funded by SSM

#### Activities during 2016

Magnus has participated in the development of specifications for material extraction from the reactor pressure vessel at Barsebäck 2. The report has been distributed via NKS.

Magnus has put together and had published an article on the evaluation of non-stable matrix defects in relevant materials which was to put the project disposal by Ringhals.

#### Milestones achieved during the period

Analysis of the material requirement for the implementation of fracture mechanics assessment of reactor pressure vessel at Barsebäck 2.

#### Presentations and Publications

“On flux effects in a low alloy steel from a Swedish reactor pressure vessel”, Boåsen, Efsing, Ehrnsten, J. of Nuclear Materials, Vol 484, February 2017, Pages 110–119.

#### Planned activities for 2017

Completion of the publication on changes in microstructure and hardness in the heat treated and radiated material from the UMD study above, in cooperation with Chalmers.

Initial trials with fracture mechanics testing of RPV steel focusing on materials from Barsebäck 2 is planned as a joint project with VTT Finland. At KTH will activities on the impact of constraint around the crack tip will be investigated through controlled testing of specimens with different defect depths. Initially, the thermally aged material used to ensure the methodology before testing begins on irradiated materials.

Materials mechanics modeling of the behavior of materials and the ability to link microstructure, flux impact and mechanical properties.



## Appendix 3 - Uppsala University



### SKC relevant research and education within the Division of Applied Nuclear Physics

Division for Applied Nuclear Physics: <http://www.physics.uu.se/en>

#### Foreword

The Division of applied nuclear physics (TK) comprises research and education within a broad range of applications. Among these applications, the safe operation of nuclear power constitutes an important part of our efforts to fulfil the three duties of a Swedish university; education, research and cooperation with the society at large. Obviously this part of our activities is also of direct relevance for SKC and in this annual report we will present an overview of the most important features of the year 2016.

As has been the common state during the last few years, the unclear future status of the Swedish nuclear power utilisation has governed a good part of our strategies. Together with the fact that state funding is scarce, the strained finances of the nuclear industry have forced us to revise some research plans and to not renew short-term employments. In particular the fact that our bachelors programme in nuclear technology has been put on hold due to lack of student interest has generated some serious concerns regarding our financing situation. As a result, we have, regrettably, experienced that three of our highly valued colleagues have been forced to move on to other commitments. Our research within Generation IV has also been subject to considerations and only a few, more or less funded, projects are currently conducted. For the future this spells bad news since the ability to maintain educational capacity is heavily dependent on our success to attract young scientists to the nuclear field and in order to succeed here, research in novel nuclear technology is a determining factor.

The role of nuclear power for the Swedish society and to mitigate climate change has been the focus area in our outreach during 2016. This outreach has been manifested by several debate articles, discussions with the political sphere, posts in social media, addressing students at various universities in Sweden and through the work done in Analysgruppen. Letters to the minister of research, the research council and work in several referral groups, e.g. regarding strategies of the Swedish Energy Agency are also part of our extensive work within the "third task".

In spite of some rather gloomy happenings during 2016 we may conclude that the major part of our activities is still intact and, in fact, are forecasted to develop in the future. We also see signs for a change in the attitude to nuclear power in the society at large. In particular there are indications of new insights within the political sphere that nuclear education is important for our welfare society and we foresee a commitment from the state to support such education in the future. This directs us to the conclusion that our activities are of high relevance and will become even more so.





## Education

Teaching and education continue to be areas of considerable importance for the Division of applied nuclear physics. The division's personnel are responsible for managing three education programmes. These are:

- the Bachelor Programme in Nuclear Engineering, (*Högskoleingenjörprogrammet i kärnkraftteknik, KKI*), which is in its 7<sup>th</sup> year since the start in autumn 2010.
- the Master Programme in Energy Systems Engineering, (*Civilingenjörprogrammet i energisystem, ES*), which one of the large master of science in engineering programmes at Uppsala University.
- Also since 2016, the division's personnel is responsible for one of the faculty's bachelor programmes, namely the Bachelor Programme in Physics, (*Kandidatprogram i fysik*).

Michael Österlund, Henrik Sjöstrand and Matthias Weiszflog, respectively, have been appointed as coordinators for the three educational programmes. In addition to courses within these programmes, division staff also provides courses in nuclear technology, energy physics and technical thermodynamics within the framework of other UU engineering programmes.

Additionally, the division of applied nuclear physics has continued its contract education activities during 2016. The objective of the contract education activities, which commenced in 2003, is to ensure the continued education and competence building of existing and newly recruited personnel within the nuclear industry, whereas the objective of the Bachelors' programme is to supply the industry with graduating engineering students with a solid knowledge of nuclear technology, well suited to take on positions within the nuclear power plants primarily within operations and maintenance. Michael Österlund remains director of studies for nuclear contract education.

In 2015 the agreements between Uppsala University and the nuclear industry concerning contract education and support for the Bachelors' programme in Nuclear Engineering expired and provisional agreements were made regarding the study year 2015/2016. At the end of 2016 a new long-term agreement concerning contract education was signed with FKA/RAB and presently a similar agreement is negotiated with OKG. The collaboration with KSU AB concerning teaching materials, simulator training for course participants and Bachelor students continues in the same way as before.

The agreements provides the power plants access to various courses provided by Uppsala U. on a demand basis while ensuring Uppsala University the possibility of maintaining teaching staff for the contract education courses. All TK teachers active within contract education also participate in research within the Division of applied nuclear physics.

What contract education courses should be offered and when is determined in collaboration with the power plants by means of an advisory board with members from the Division of applied nuclear physics and the power plants. In collaboration with the FORS-group organized by the NPPs, the course in Advanced Radiation Protection (FS-1) has been thoroughly revised the first revised courses were successfully given during 2016.

Since late 2015, NANSS (Nordic Academy for Nuclear Safety and Security) has functioned as the contact point between industry and Uppsala University with the responsibility of handling all administrative aspects of the contract education. In order to provide information about available courses and to handle admissions a web portal has been developed, [www.nanss.uu.se](http://www.nanss.uu.se).



### Education within the Engineering Master Programmes

Within the Engineering Master Programmes, the following courses with relevance for nuclear power are given by the division's personnel:

- Energy Physics I  
Master Programme in Engineering Physics, year 4, 5 credits  
45 students (autumn 2016)
- Energy Physics II with Nuclear Energy  
Master Programme in Engineering Physics, year 4, 10 credits  
6 students (spring 2016)
- Nuclear Power – Technology and Systems  
Master Programme in Energy Systems Engineering, year 4, 10 credits  
8 students (autumn 2016)
- Future Nuclear Energy Systems – Analysis and Simulations  
Master Programme in Energy Systems Engineering, year 4, 5 credits  
7 students (spring 2016)
- Safety Analyses in the Energy Sector  
Master Programme in Energy Systems Engineering, year 5, 5 credits  
7 students (autumn 2016)
- Energy System Physics  
Master Programme in Sociotechnical Systems Engineering, year 3, 10 credits  
28 students (autumn 2016)
- Applied Reactor Physics  
Also given as contract education course, 5 credits  
11 students (spring 2016)

In 2016, in total about 80 students followed at least one course in which nuclear technology was presented and examined. About 15 students immersed themselves in the field of nuclear energy by taking at least two (and up to four) courses.

### Bachelor of Science in engineering with a specialisation in nuclear engineering (KKI)

The Bachelor's programme in nuclear engineering is a one-year educational programme aimed at students with at least 2 years of prior studies in primarily mechanical or electrical engineering at a Swedish university or technical college. The programme, which is the only one of its kind, is supported by the Swedish NPPs with the objective of securing a supply of engineers with a good, non-site specific knowledge of nuclear technology at the Bachelor's level. Graduates from the programme are awarded the degree of *Högskoleingenjörsexamen i kärnkraftteknik*. The main objectives of the programme are to 1) increase the volume of employable people available to the nuclear industry and 2) decrease the industry's total training cost by reducing the need for on-the-job education and training.

The programme, which comprises 60 hp, contains the following courses:

- Introduction to nuclear engineering (5 hp)
- Reactor physics (5 hp)
- Nuclear thermal hydraulics and steam turbine technology (5 hp)
- Light water reactor technology (5 hp)
- Chemistry, materials and fuels for reactor applications (5 hp)
- Nuclear power safety (5 hp)
- Power Engineering (5 hp)
- Nuclear power operation (5 hp)
- Future nuclear energy systems (5 hp)
- Degree project in nuclear power technology (15 hp)



In many of the courses experts from industry and authority are involved as guest teachers, collaborating with the UU teachers.

An important aspect of the learning process is for the student to gain knowledge about the nuclear process and the different actors within the nuclear industry. With that in mind a number of study visits are included in the programme. During 2015 students have made study visits to FKA, OKG and RAB, the SKB facilities in Oskarshamn, the Westinghouse nuclear fuel fabrication plant in Västerås, Siemens Turbo machinery in Finspång (steam turbines) and ABB in Ludvika (generators and transformers).

During the first semester the students participate in a one-week reactor training session at the ISIS training reactor in Saclay, France as part of the course in reactor physics. Following the Reactor physics and Thermo-hydraulics courses, the course Light water reactor technology includes a one week session at the Barsebäck NPP in order for the students to gain a practical understanding of the principles of LWRs, workmanship, radiation protection and various operational procedures at NPPs. The course also includes a training session in KSU's simulators in Studsvik.

### Recruitment

Considerable effort has been put into recruitment activities for the study year 2016/2017 on a scale significantly larger than that of other engineering programmes within UU. Following interviews with programme students it was decided to focus the recruitment activities on arranging lunch seminars at several engineering colleges and universities around Sweden and on participation in student careers fairs, e.g., UTNARM, CHARM and LARM, with only limited advertising in media such as educational supplements distributed with regular newspapers, which historically has proved to have a very limited effect on recruitment.

As shown in Table 1 below, since its inception in 2010 when the “nuclear renaissance” was at its peak, the programme has experienced a decrease in student enrolment associated with the aftermath of the Fukushima accident, the strong political focus on renewable energy sources and especially during 2016, the decisions about closure of Swedish reactors and the possibility of staff layoffs. These factors combined with the fact that “högskoleingenjörer” of all subjects are in high demand within Swedish industry in general, having had a disastrous effect on student recruitment. Out of 38 applicants in total, only two students are following the programme during 2016/2017. The consequences of this outcome is discussed in the section “*The future of the Bachelors' programme*”

Study year	Applicants	1 <sup>st</sup> -hand applicants	Applicants admitted to the programme	Students registered at start of first semester	Students active at end of semester 2
2010/2011	80	47	34	21	19
2011/2012	57	26	36	12	11
2012/2013	60	29	36	14	12
2013/2014	46	22	21	10	8
2014/2015	45	19	14	9	9
2015/2016	64	16	15	7	7
2016/2017	38	7	4	2	2

Table 1. Recruitment statistics for the period 2010-2015 (source: Universitets- och högskolerådets antagningsstatistik).

### Students' review of the programme

The students report a high degree of satisfaction with the quality of education. In the final programme evaluation, the class of 2015/2016, when questioned about their experience of the overall quality of the programme, gave the mark  $5.0 \pm 0$  on a scale from 1 (unacceptable) to 5 (excellent). On the question on whether the students would recommend other students to enrol in the programme or not, the response was also  $5.0 \pm 0.0$  on a scale from 1 (not recommended) to 5 (highly recommended). This is an all-time high and reflects on the high standards set by the highly motivated teachers involved in the programme and is also evidence that the programme curriculum has been fine-tuned over the years to provide student with the best possible education.



### Students' achievements

At the time of writing (February 2016) 51 students have successfully completed their Bachelors' theses. A summary of the theses produced during 2016 is found at the end of this chapter. We are happy to report that two of the 2015/2016 students, Fredrik Höök and Adam Bruce, were awarded the 2016 Sigvard Eklund prize for the best diploma work on the Bachelors' level.

### Employment

Students graduating from the Bachelors' programme continue to be in demand by industry and almost without exception the students' first employment has been within the nuclear power plants and we are happy to note that the interest among those students to pursue a career within NPP operation is still very high, despite the signals from both industry and politicians about premature closure of four nuclear reactors.

### The future of the Bachelors' programme

As a result of uncertain prospects for careers within Swedish nuclear industry student interest in nuclear engineering on a Bachelors' level has declined to a point where it cannot be motivated to continue the programme under the present circumstances. Following discussions between with our industry sponsors it has been decided by the faculty board the Faculty of Science and Technology to put the programme on hold for the study year 2017/2018 with a possibility of re-starting the programme the following year, should circumstances change for the better. During 2017 we will collaborate with the NPPs in order to address the problem of dwindling student interest and what measures should be taken by industry and academy in concert in order prevent a possibly serious shortage of qualified engineers with nuclear engineering knowledge.

### Contract education for the industry

We are happy to report that during 2016 the Division of applied nuclear physics provided industry with 18,5 weeks of contract education courses (Table 2) within the agreements on higher education, an increase by more than 20% from the previous year.

Course	Credits / duration
Reaktorteknologi (H1)	12 hp
Tillämpad reaktorfysik	5 hp
Fördjupad strålskyddsutbildning (FS1)	6 hp
Aktivitetmätning m. Ge-detektorer	1 w
Värme- och strömningslära (operatörsutbildning FKA, RAB, OKG)	1-2 w
Reaktorfysik (operatörsutbildning, FKA)	1 w

Table 2: Contract education courses provided on one or more occasions during 2016.



## Development of teaching/education in the nuclear field

UU will continue its efforts to strengthen the collaboration with the NPPs in order to increase the quality and scope of contract educations offered. During 2016 the possibility of providing courses within the Bachelors' programme was investigated and discussed with our industry partners and during 2017 the outcome of ongoing competence development assessments within industry will provide guidance as to which courses should be adapted to a format suitable for contract education requirements.

- UU is one of about 25 organizations behind an EU project called ANNETTE, which was granted during 2015. The project covers the development of an "Advanced Master" training programme for professionals in the nuclear business. The project is coordinated by ENEN (the European Nuclear Education Network), and will run during 2016-2019.
- With support from SKC, in a collaborative effort UU will participate in the development of on-line nuclear energy education aimed at engineering students on the undergraduate level. Initially the objective of this effort is primarily to interest engineering students enrolled in different engineering programmes at Swedish universities in nuclear education and the possibility for a future career within the nuclear sector.

## Student's theses during 2016

### **Ph.D. theses**

1. Klimek I.; "Modelling and Measurements of MAST Neutron Emission"; Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 1364.
2. Skiba M.; "Making TOFu: Fusion Plasma Neutron Emission Spectrometry with a Fully Digital Data Acquisition System"; Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 1435.

### **Licentiate theses**

1. Branger E.; "Studies of Cherenkov light production in irradiated nuclear fuel assemblies"; Publisher: Uppsala universitet; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-307952>; (2016).
2. Rakopoulos V.; "Measurements of Isomeric Yield Ratios of Proton-Induced Fission of natU and natTh at the IGISOL-JYFLTRAP facility"; Publisher: Uppsala University; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-293852>; (2016).

### **Masters theses completed**

1. Kim Landelius: Qualification of Westinghouse BWR lattice physics methods against critical experiments.
2. Arne Sahlberg: Ensemble for Deterministic Sampling with positive weights: Uncertainty quantification with deterministically chosen samples.
3. Sebastian Leo Eile Svanström: Load following with a passive reactor core using the SPARC design.
4. Mattias Åkerman: Improved peaking factors with radial enrichment distribution for PWR fuel assembly.

### **Bachelors theses completed (KKI)**

Diploma theses on the Bachelors' level are with few exceptions performed within industry, table 3. Due to a lack of suitable projects during 2016 two students choose to perform diploma works within research groups at Uppsala University.



Filip Aldahan, Joakim Svensson Grape	Beräkning av kostnader för lågaktiv kärnavfallshantering	Marie Westberg	OKG
Adam Bruce, Fredrik Höök	Design av provutrustning: för analys av bestrålningsinducerad spänningskorrosion	Erki Metsanurk	UU
Olof Eriksson, Victor Eriksson	Metod för framställning av layouter till Forsmarks Kraftgrupp AB:s övervakningssystem	Maria Fernroth	FKA
Thaer Hamad, Angelica Westlin	Gapanalys mellan ISO 14001:2015 och OKGs verksamhetssystem	Marie Junéll	OKG
Carl Hemmingsson	Modellering av PRISM-reaktor	Staffan Qvist	UU
Sara Pedersen	Instruktionsuppdatering av ASI 1970 på Forsmark 1	Berndt Norrman	FKA

### Research Projects

The following PhD students perform research of high relevance for reactor operation and nuclear fuel performance, with direct support from SKC in terms of PhD salary and/or supervisor salary:

### Nuclear data uncertainty propagation with Total Monte Carlo for fuel – method development and applications

Ph.D. student: **Petter Helgesson**

Main supervisor: Univ. lekt. Henrik Sjöstrand

Assistant supervisors: Prof. Arjan Koning (IAEA, Vienna), Dr. Dimitri Rochman (PSI, Switzerland), Prof. Klaes-Håkan Bejmer, Prof. Stephan Pomp

Petter Helgesson started his Ph.D. studies in August 2013 in collaboration with Nuclear Research and Consultancy Group (NRG) in Petten, the Netherlands. A detailed description of the aims of this project is found in the previous annual report.

Petter works within the MÅBiL project, and his results hitherto are also reported in the MÅBiL Annual Report.

During 2016, there has been a continued emphasis on aging parameters, and in this work, Petter Helgesson connects macroscopic fuel and aging parameters to the fundamental nuclear physics processes by using the nuclear model code TALYS and the Total Monte Carlo Method (TMC) method.

During 2016 Petter has continued investigated  $^{59}\text{Ni}$ , since the two-step thermal neutron reaction sequence  $^{58}\text{Ni}(n,\gamma)^{59}\text{Ni}(n,\alpha)^{56}\text{Fe}$ , ( $Q_{\text{value}} = 5,1 \text{ MeV}$ ) results in non-linear He production rates and is an important contribution to the He production in steel in thermal spectrum. The reaction sequence is also a significant contribution to the damage energy. He is also investigating the hydrogen producing reaction sequence:  $^{58}\text{Ni}(n,\gamma)^{59}\text{Ni}(n,p)^{59}\text{Co}$ , ( $Q_{\text{value}} = 1.9 \text{ MeV}$ ). Currently, existing evaluated data has no uncertainty information, neither for  $^{59}\text{Ni}(n,\alpha)^{56}\text{Fe}$  nor  $^{59}\text{Ni}(n,p)^{58}\text{Co}$  reactions, in the thermal region.

To improve the He production prediction and to provide nuclear data uncertainty estimates, new  $^{59}\text{Ni}$  cross section data has been produced. As opposed to existing evaluated data (for nuclides in general) the helium and hydrogen production cross sections have been produced using relevant resonance parameters using Multi Level Breit Wigner approximation.

The lack of well-documented measurements on the cross sections in the resonance region makes the actual values of the resonance parameters very uncertain. The cross-sections are generated from average unresolved resonance parameters and sampled with a high uncertainty, after which they are adjusted to the experimentally known thermal cross sections and their uncertainties. The cross-sections have been produced in ENDF-6 format, including so-called random files, for usage by the nuclear community.

To check the performance of the random files, they have been tested on an MCNP-6 model. The results were compared to He and H production rates in a reference case. It was found that the inclusion of  $^{59}\text{Ni}$  increased the helium production rate by a factor of  $5.2 \pm 0.3$ . The uncertainty is due to the uncertainty in nuclear data. It was





also found that there were some discrepancies between the results obtained with these new files and the result which was obtained using ENDF/B- VII.1. The results have also been validated against experimental transmission data.

The results have been accepted for JEFF.3.3 T2 (Joint Evaluated Fission and Fusion File test version 2). The results were presented at ND2016, and a full article has been written and reviewed by SKC and was submitted beginning 2017.

The work has during 2016 been presented at the IAEA Nuclear Reaction Data and Uncertainties for Radiation Damage Technical Meeting, at ND2016, JEFF Co-ordination Group Meeting.

During 2016, Petter has also continued to work on statistical stringent ways to include experimental information in TMC. For this, collaboration with Los Alamos has been started. In this work, different techniques to evaluate nuclear data have been evaluated. This will allow us to choose the best approach when assessing nuclear data for a wide range of quantities. The work has had some emphasis on the prompt fission neutron spectrum, which plays an important role in e.g. pressure vessel dosimetry. The work has been accepted for presentation at the International Symposium on Reactor Dosimetry 2017.

## Fuel diagnostics

Principal researcher: **Dr. Peter Andersson**

Participating researchers: Staffan Jacobsson Svård and Ane Håkansson, Division of Applied Nuclear Physics, Department of Physics and Astronomy, Uppsala University and Scott Holcombe OECD Halden Reactor Project, Norway

## Background

The OECD Halden Reactor (OECD-HRP) is a world-leading laboratory for research on nuclear fuel and reactor materials. The unique HBWR reactor enables studies of nuclear fuel behavior during normal operation as well as transient and accident scenarios, such as LOCA. The closed loops used in the reactor even allow fuel ruptures during the tests. Uppsala University has established collaboration with OECD-HRP, which covers the following topics:

- Take part in developing analysis techniques
- Perform analyses of collected data from irradiation experiments
- Participate in the evaluation of Accident-Tolerant Fuels

## Project description and status

The MÅBIL sub-programme Fuel diagnostics started in February 2015 with the assignment of Peter Andersson on a postdoc position which is 50% funded by SKC. During 2016, the focus has been on non-destructive measurements of irradiated nuclear fuel using gamma tomography.

New methods have been developed for the quantitative, high resolved reconstruction of gamma-emitting nuclides in cross-sectional images of fuel assemblies using the gamma tomography technique. These methods have been incorporated in an analysis code, UPPREC. The code uses an iterative process, where the important attenuation distribution of the gamma rays in the fuel is first neglected to perform a naïve reconstruction. Subsequently, this is used for localization of rod positions with the template matching technique [1], to allow for the attenuation correction in the response function used by the reconstruction code. Using the improved description of the



gamma transport, a new reconstruction less affected by systematic errors can be performed, where in turn structural components of the assembly may be localized and accounted for, finally achieving a quantitative image of the reconstructed nuclide concentration in the assembly, where all important attenuating structures are correctly accounted for. The methods used have been presented in a draft submitted to *Annals of Nuclear Energy* in the end of 2016 [2].

We participated in the ongoing HRP LOCA test series, by performing and analysing the measurements of the relocated fuel distribution using gamma tomography. The inspection which was proposed and planned by us was executed in the beginning of 2016. Preliminary qualitative reconstructions were performed and the analysis tools have also been modified in order to account for the nonhomogeneous attenuation distribution of relocated fuel fragments, to allow for quantitative reconstructions. The subsequent quantitative analysis is still ongoing. The preliminary qualitative results have been presented at EHPG Sandefjord [3] and TopFuel Boise [4]. The technique has been integrated in the LOCA series for the future tests.

The fission gas release fraction has been studied in a HRP fuel assembly using the tomographic reconstruction of  $^{85}\text{Kr}$  in the fuel plenum and the  $^{137}\text{Cs}$  in the fuel stack. The concentration of  $^{85}\text{Kr}$  in the fuel was calculated based on the  $^{137}\text{Cs}$  concentration corrected for differences in e.g. fission yield and half-life to estimate the fraction of produced fission gas that had been released. The results were in good agreement with benchmark data collected using the conventionally used technique of single-rod gamma scanning. Tomography has the potential to speed up the measurements, as compared to single rod scanning, and in addition it requires less manual handling of the fuel. The results were presented in NIM A [5].

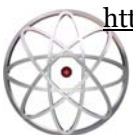
### Fulfilling of projects goals

The goals stated for the fuel diagnostics project in the MÅBiL application for 2014-2016 was to support the research and development of techniques for evaluation of fuel performance in connection to irradiation testing. Special focus was put on developing experimental techniques for future assessments of Accident-Tolerant Fuels (ATF), stated explicitly in terms of; (1) Fission gas release from fuel during transients, and; (2) Fuel behaviour during accident conditions, such as LOCA.

The results so far show that the goals have largely been reached within the project. Firstly, new methodology for measurements of fission gas release have been tested, analysed and presented in a scientific journal. Secondly, tomographic measurements have been performed of test rods subjected to LOCA in the HBWR, and preliminary results indicate that ballooning and failure of cladding as well as cracking and relocation of pellet material can be assessed with this technique. The technique has been included in the plans for the future LOCA tests, and further refinement of the method to get quantitative data packing fraction estimates is underway. In the end, the experimental techniques developed within MÅBiL are expected to be highly useful in the analyses also of irradiation tests of new fuel types such as enhanced accident tolerant fuels, once these are irradiated and available for this type of assessment.

### References

- [1] Davour A., Jacobsson Svård S., Andersson P., Grape S., Holcombe S., Jansson P., Troeng M.; "Applying image analysis techniques to tomographic images of irradiated nuclear fuel assemblies"; *Journal: Annals of Nuclear Energy*; Vol: 96; DOI: [10.1016/j.anucene.2016.05.024](https://doi.org/10.1016/j.anucene.2016.05.024); 2016
- [2] Andersson P., Holcombe S.; "A computerized method (UPPREC) for quantitative analysis of irradiated nuclear fuel assemblies with gamma emission tomography at the Halden reactor"; Submitted to *Annals of Nuclear Energy*, 2016.
- [3] Andersson P., Holcombe S., Tverberg T.; "Inspection of LOCA Test Rod IFA-650.15 Using Gamma Emission Tomography"; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-283654>; 2016
- [4] Andersson P., Holcombe S., Tverberg T.; "Inspection of a LOCA Test Rod at the Halden Reactor Project using Gamma Emission Tomography"; Conference: Top Fuel; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-303810>; 2016



[5] Holcombe S., Andersson P., Jacobsson S., Halistadius L.; "Determination of the Rod-wise Fission Gas Release Fraction in a Complete Fuel Assembly Using Non-destructive Gamma Emission Tomography"; Journal: Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment; Vol: 837; DOI: [10.1016/j.nima.2016.08.061](https://doi.org/10.1016/j.nima.2016.08.061)

## Research projects

A number of research projects have been carried out within the division during 2016 that are funded from other sources than SKC. A short account of some major research projects are described below:

### Neutron-induced nuclear reactions at intermediate energies

#### Ph.D. student: Kaj Jansson

Main supervisor: Univ. lekt. Dr. Cecilia Gustavsson

Assistant supervisors: Prof. Stephan Pomp, Dr. Alexander Prokofiev, Dr. Ali Al-Adili

Kaj started during spring 2012 on the NFS project to be carried out at GANIL, France. Objective of the work is to measure standard cross sections in the MeV range. Kaj has mainly been working on detector simulations for the upgrade of the Medley setup with PPAC detectors, design and programming of a data acquisition system. The development work for NFS formed the background for Kaj's licentiate thesis, presented in 2015.

Due to delays in the construction of NFS in France, moving the setup to GANIL has been postponed and Kaj has meanwhile been working on projects at JRC-GEEL in Belgium. This work has included analysing experimental data on the neutron standard  ${}^6\text{Li}(n,\alpha)$  measured at JRC-GEEL with a Frisch-grid ionization chamber. During 2016 he has also worked on developing and improving the VERDI spectrometer (2E-2v instrument) at JRC-GEEL. Using this setup, the average neutron multiplicity as a function of fragment mass can be obtained and preliminary data from a  ${}^{252}\text{Cf}(sf)$  source has been measured and presented.

Kaj's dissertation is foreseen during 2017.

### Studies of Cherenkov light emission and detection for nuclear safeguards purposes

Ph.D. student: Erik Branger

Main supervisor: Dr. Sophie Grape

Assistant supervisors: Ass. Prof. Staffan Jacobsson Svård, Dr. Peter Jansson

Erik Branger is a Ph.D. student working with the nuclear safeguards instrument device called the Digital Cherenkov Viewing Device (DCVD). The purpose of the instrument is to verify spent nuclear fuel with respect to both gross defect and partial defect evaluation. Within the project, Erik's focus is on improving the abilities and performance of the instrument via improvements in prediction ability, measurement procedure and evaluation methodology.

During the last year Erik has been working on characterizing the Cherenkov light emissions from spent nuclear fuel, and to quantify what effect fuel parameters such as fuel pellet diameter and cladding thickness have on the subsequent Cherenkov light production. Based on these results, comparisons were made for different prediction models taking detailed fuel geometry into account, and comparing the results to prediction models using a simplified geometry. The results of these studies form the basis of two papers submitted to Journal of Instrumentation.



A new prediction method was developed based on this data, to predict the Cherenkov light intensity of fuel assemblies taking more details into account than the old models. The new method assesses the fuel inventory of fission products, based on the operator declared irradiation history, and uses simulations of the Cherenkov light production in the correct fuel geometry to obtain predictions. The method requires significant one-time computations to be performed, but once done the predictions are made fast enough that the method can be used in the field with only limited access to computer resources. The new prediction method has been implemented by the DCVD manufacturer, and is currently under review by the IAEA, and will eventually replace the old methods.

In December 2016, Erik presented his licentiate thesis, which was based on the simulation studies of Cherenkov light production, investigation of the systematic differences existing between different prediction models, and the proposed new prediction method.

## Measurements of independent fission yields from a fast neutron spectrum

Ph.D. student: **Andrea Mattera**

Main supervisor: Prof. Stephan Pomp

Assistant supervisors : Dr. Mattias Lantz, Dr. Andreas Solders

Andrea started working on the ALFONS project in spring, 2011. ALFONS, co-financed by SSM and SKB, aims at measuring independent fission yields in thermal and fast neutron spectra at the IGISOL facility in Jyväskylä, Finland. Key elements of the forthcoming thesis are description of the design and the characterization of the Be(p,n)-neutron source for IGISOL, results from the various tests, as well as intercomparison of theoretical fission model codes.

During 2016 several tests have been performed at the new IGISOL-4 beamline. These tests received support through the transnational access programme of the EU project CHANDA (solving CHallenges in Nuclear DATA). Unfortunately, the technical problems with the new cyclotron already mentioned in the last annual report continued and we still had to rely on the existing, less intense proton beam. Nevertheless, we could, during 2016, successfully demonstrate that the new neutron source and the IGISOL-4 beamline are functional and extract fission fragments to the gamma measurement station. During the December beamtime, also supported by CHANDA, we could, e.g., identify several tin isotopes and in the ongoing analysis we should be able to extract their relative fission yields.

In addition to the experimental work, Andrea has developed a code system for systematic comparison of fission model codes. First results have been presented at a conference and are meanwhile accepted for publication. Andrea is scheduled to defend his thesis in June 2017.

## Studies of independent fission yields from fast neutrons

Ph.D. student: **Vasileios Rakopoulos**

Main Supervisor: Dr. Mattias Lantz

Assistant Supervisors: Prof. Stephan Pomp, Dr. Andreas Solders

Vasileios joined the division in spring 2012 to work on the ALFONS project together with Andrea Mattera. He has been involved in the tests of the ion guide and neutron field characterizations in Jyväskylä in 2015. Vasileios works in parallel with Andrea Mattera. His main focus is on isomeric yield ratios (IYR), comparison of experimental data with theoretical calculations using the TALYS and GEF codes. The IYR is production rate of an isomeric state relative to the ground state in fission. This information can be used to extract spin states of the fission fragments before neutron emission to gain information of the fission process. It is also relevant for delayed neutron emission since the half-life of the isomer differs from that of the ground state.



On the 7th of April 2016 Vasileios defend his licentiate thesis entitled "Measurements of Isomeric Yield Ratios of Proton-Induced Fission of natU and natTh". The data analysed was taken in several experiments between 2010 and 2014, using proton induced fission on uranium and thorium. In one of the experiments there were also data taken through gamma spectroscopy as a compliment to the Penning trap data. In 2016 a first attempt to measure fission yields from neutron induced fission was made and data was acquired using gamma spectroscopy. Presently, Vasileios is analysing this new data and, at the same time, working on the comparison with theoretical predictions and the interpretation of the results.

## Application of the Total Monte Carlo method to LWR's fuel assembly depletion calculations using deterministic lattice codes

Principal investigator: **Dr. Augusto Hernandez Solis**

During the year 2016, the Total Monte Carlo (TMC) research group emphasized in the development of a tool for performing uncertainty analysis applied to LWR fuel assembly depletion calculations. This work was part of an international collaboration<sup>1</sup> that took place among some nuclear institutions around Europe, in order to benchmark the effect that two important issues would have in the criticality assessment of a fuel assembly: 1) the fact that different uncertainties exists within the many nuclear data libraries (NDL), 2) and the fact that different methodologies for uncertainty propagation (both statistical and deterministically) are employed by different institutions. Thus, the aim was not only to perform an uncertainty analysis of criticality and spent fuel state-variables as a function of burnup and cooling time, but also to assess the impact that different NDL co-variances and UQ methodologies would have in the computation of the uncertainty limits of interest.

The contribution given by the TMC group to this joint effort was based on the perturbation of the multi-group macroscopic cross-sections that are given by the NJOY code and are a function of the background cross-sections (i.e. degree of dilution) and the temperature, respectively. In other words, a methodology to propagate (in this particular study) cross-sections uncertainties through lattice codes was required to be developed in accordance to the library format that a certain code utilizes. Due to the fact that the ENDF multi-group format given by GROUPR is easy to read, understand and manipulate, a new computational scheme was developed to statistically perturb the GROUPR ASCII file in order to create posterior perturbed WIMS libraries. Thus, as many different WIMS libraries are created, as many times the lattice code will be run in order to create a deterministic output into a stochastic one. This is exemplified in figure 1.

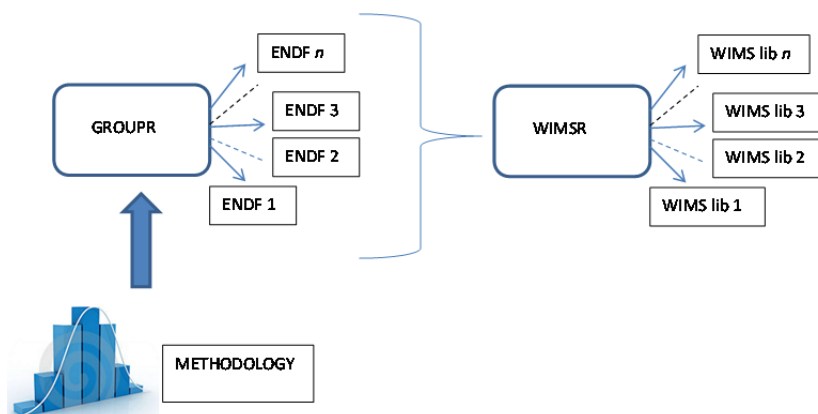


Figure 1. TMC scheme applied to multi-group libraries used by deterministic lattice codes.



By employing the DRAGON deterministic transport code as the main tool for depletion calculations, the aforementioned TMC method gave the following results for 300 calculations of  $K$  infinite as a function of burnup. Different simulations are given due to running different TENDL-2015 randomized libraries, which have been based on nuclear data co-variances. The aim is to show the uncertainty limits that can be obtained in a depletion criticality calculation.

Also, during 2016 the TMC method was applied to neutron transport codes, such as OpenMOC to investigate the importance of angular distribution uncertainties. In this work, a computational module made for the purpose of reading self-shielded cross-sections, which have been pre-computed by the deterministic DRAGON code, has been developed.

The work has been presented at international conferences and in international journals during 2016.

<sup>1</sup><http://dx.doi.org/10.1016/j.nds.2017.01.001>

## Unattended Gamma Emission Tomography for Partial-Defect Verification (GET)

Participating researchers: Ass. Prof. Staffan Jacobsson Svärd, Dr. Peter Jansson, Dr. Sophie Grape, Dr. Peter Andersson, Dr. Anna Davour

The International Atomic Energy Agency (IAEA) initiated two support programme projects in 2012, UGET and PGET, which were executed during 2013-2015. The projects comprised researchers from Sweden (UU) and the U.S. (PNNL and LLNL) as well as participants from Finland, EC, IAEA and SSM. The capabilities for Gamma Emission Tomography for unattended verification of nuclear fuel assemblies were evaluated, and a final was published as PNNL report 25995. Funding was granted by SSM via the Swedish Support Programme to the IAEA. In the project, the feasibility of verification of individual pins and in addition the verification of the declared burnup history has been studied for a variety of fuel assembly types and for different cooling times. The quality of the assessment has been determined in terms of ROC curves, showing the detection probability as a function of false-positive rate.

Now the UGET project has been finalised, and the project was merged with PGET. The resulting project is starting up.

## Characterization of Spent Fuel in connection to Encapsulation and Final Reposition

Responsible researcher: **Dr. Peter Jansson**

With funding from the Swedish Nuclear Fuel and Waste Management Company, methods for characterization of spent nuclear fuel using gamma ray- and neutron measurement techniques are developed. SPIRE (“Spent fuel characterization Program for the Implementation of geological REpositories”), a research collaboration between several European and international organisations, has been initiated by Uppsala University and SKB in order to release possible synergy effects to efficiently solve remaining issues of used nuclear fuel characterisation. These issues may have an impact on the performance (e.g. safety and economic impact) of engineered barriers in geological and other types of storage of used nuclear fuel. SPIRE is coordinated by Dr. Peter Jansson.





## Multivariate analysis for use in nuclear safeguards

Participating senior researchers: Ass. Prof. Sophie Grape, Dr. Carl Hellesen, Dr. Zsolt Elter

This SSM-funded project has started and a postdoc, Dr. Zsolt Elter, has been hired. In this project, the use of gamma spectroscopy on nuclear fuels is studied in order to verify fuel parameters of interest to safeguards inspections. Currently, the transfer function between isotopic concentrations in the fuel to the detector signal is studied by Monte Carlo simulation using a detector model based on the CLAB gamma scanning station. In addition there are possibilities to use machine learning algorithms in order to best gain from the signals in the determination of fuel parameters, such as burnup, cooling time, initial enrichment and fissile content. Different sets of nuclear measurement techniques will be explored in addition to gamma spectroscopy, with the aim to enhance the analysis capabilities within nuclear safeguards. The methods evaluated or developed within this project are foreseen to be useful in particular, but not exclusively, in encapsulation plants.

## Research projects

*The following research projects confine work within Gen IV technology. Although outside the research framework of SKC, these projects are relevant from a general knowledge and competence building perspective:*

### Instrumentation and safeguards evaluations of a Generation IV reprocessing facility

PhD student: **Matilda Åberg Lindell**

Main supervisor: Dr. Sophie Grape

Assistant supervisors: Prof. Ane Håkansson, Dr. Peter Andersson

Matilda is working with nuclear safeguards issues related to the future Generation IV nuclear fuel cycle. Her focus was during the first years to investigate methodologies for detecting diversion of sensitive material. Currently Multivariate methods are being evaluated for use on spectroscopic data on used nuclear fuel. Their performance is tested for verification of parameters such as initial enrichment, cooling time, burnup and fuel type (MOX/UOX). Training and validation data are generated using serpent, and experimental validation is planned in the future of the project.

Matilda has been on sick leave until Q3 2016 but from that on she is now preparing two articles based on her recent findings. She is planned for dissertation late 2017.

### Core Diagnostics in the ASTRID Sodium Fast Reactor (CODIAS)

Ph.D. student: **Vasudha Verma**

Main supervisor: Dr. Carl Hellesen

Assistant supervisors: Ass.Prof. Staffan Jacobsson Svärd, Prof. Ane Håkansson, Dr. Peter Jansson, Ass. Prof. Michael Österlund

Vasudha is working on developing an advanced neutron monitoring system for Generation IV sodium cooled fast reactors (SFR). The first part of her Ph.D. project has been focused on investigating how a reactivity event such as the inadvertent withdrawal of a control rod may be detected by power monitoring systems. Vasudha has shown that using a combination of in-vessel ex-core fission chambers in the radial neutron shield, and in-vessel in-core self-powered detectors, such events may be detected in the early stages, allowing for appropriate actions to be taken in time. Although self-powered detectors are used extensively in light water reactors, this is the first study of their use in SFRs.

Vasudha will defend her thesis in the beginning of the summer 2017.



## Numerical studies of fast reactors, including sensitivity studies of ASTRID-type cores

Participating senior researchers: Ass. Prof. Staffan Jacobsson Svärd, Dr. Carl Hellesen

This VR-funded project has been defined and an announcement was issued with the aim of hiring a postdoc early 2017 to work in collaboration with French CEA for a period of 2 years.

## Research on Gen IV systems

Responsible researchers: **Dr. Carl Hellesen**

The project is focused on the transient safety of Sodium cooled Fast Reactors (SFR) in severe accidents. A part of the project studies the behaviour of different types of SFR cores under such accident scenarios. The goal is to optimize the core design.

The second part of the project is focused on further improving the safety of SFR cores using a novel safety system called ARC. It has been demonstrated that fast reactor using MOX fuel, which is sensitive to reactivity excursions, can survive even the most severe types of reactivity excursion if equipped with the ARC system.

## Publications and conferences

### Work published/accepted in scientific journals

The following scientific papers were published during 2016:

1. Al-Adili A., Hamsch F., Stephan P., Stephan O., Vidali M.; "Fragment mass-, kinetic energy- and angular distributions for  $^{234}\text{U}(n, f)$  at incident neutron energies from  $E_n = 0.2$  to  $5.0$  MeV"; Journal: Physical review C; Vol: 93; No: 3; DOI: 10.1103/PhysRevC.93.034603; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-185332>; (2016)
2. Alhassan E., Sjöstrand H., Helgesson P., Österlund M., Pomp S., Arjan J., Rochman D.; "Selecting benchmarks for reactor simulations : an application to a Lead Fast Reactor"; Journal: Annals of Nuclear Energy; Vol: 96; DOI: 10.1016/j.anucene.2016.05.033; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-264414>; (2016)
3. Alhassan E., Sjöstrand H., Helgesson P., Österlund M., Pomp S., Koning A., Rochman D.; "On the use of integral experiments for uncertainty reduction of reactor macroscopic parameters within the TMC methodology"; Journal: Progress in nuclear energy (New series); Vol: 88; DOI: 10.1016/j.pnucene.2015.11.015; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-264410>; (2016)
4. Davour A., Jacobsson Svärd S., Andersson P., Grape S., Holcombe S., Jansson P., Troeng M.; "Applying image analysis techniques to tomographic images of irradiated nuclear fuel assemblies"; Journal: Annals of Nuclear Energy; Vol: 96; DOI: 10.1016/j.anucene.2016.05.024; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-295146>; (2016)
5. Favalli A., Vo D., Grogan B., Jansson P., Liljenfeldt H., Mozin V., Schwalbach P., Sjöland A., Tobin S., Trellue H., Vaccaro S.; "Determining initial enrichment, burnup, and cooling time of pressurized-water-reactor spent fuel assemblies by analyzing passive gamma spectra measured at the Clab interim-fuel storage facility in Sweden"; Journal: Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment;



Vol: 820; DOI: 10.1016/j.nima.2016.02.072; Permalink:  
<http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-280888>; (2016)

6. Gorelov D., Penttilä H., Al-Adili A., Eronen T., Hakala J., Jokinen A., Kankainen A., Kolhinen V., Koponen J., Lantz M., Mattera A., Moore I., Pohjalainen I., Pomp S., Rakoupoulos V., Reinikainen J., Rinta-Antila S., Simutkin V., Solders A., Voss A., Äystö J.; "Developments for neutron-induced fission at IGISOL-4"; Journal: Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms; DOI: 10.1016/j.nimb.2016.02.049; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-291551>; (2016)
7. Helgesson P., Sjöstrand H., J. Koning A., Rydén J., Rochman D., Alhassan E., Pomp S.; "Sampling of systematic errors to estimate likelihood weights in nuclear data uncertainty propagation"; Journal: Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment; Vol: 807; Publisher: Elsevier; DOI: 10.1016/j.nima.2015.10.024; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-265321>; (2016)
8. Helgesson P., Sjöstrand H., J. Koning A., Rydén J., Rochman D., Alhassan E., Pomp S.; "Combining Total Monte Carlo and Unified Monte Carlo: Bayesian nuclear data uncertainty quantification from auto-generated experimental covariances"; Journal: Progress in nuclear energy (New series); Vol: 96; Publisher: Elsevier; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-313644>; (2017)
9. Rochmann D, Hernandez Solis A.; "Nuclear Data Uncertainties for Typical LWR Fuel Assemblies and a Simple Reactor Core"; Journal: Nuclear Data Sheets; Vol: 1; No: 76; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-314195>; (2017)
10. Holcombe S., Andersson P., Jacobsson S., Halištadius L.; "Determination of the Rod-wise Fission Gas Release Fraction in a Complete Fuel Assembly Using Non-destructive Gamma Emission Tomography"; Journal: Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment; Vol: 837; DOI: 10.1016/j.nima.2016.08.061; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-302519>; (2016)
11. Jansson K., Al-Adili A., Bevilacqua R., Gustavsson C., Hamsch F., Pomp S., Vidali M.; "Measurement of the  ${}^6\text{Li}(n,\alpha)$  neutron standard cross-section at the GELINA facility"; Journal: The European Physical Journal Conferences; Vol: 122; Conference: CNR\*15; DOI: 10.1051/epjconf/201612208006; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-313909>; (2016)
12. Jansson P., Tobin S., Liljenfeldt H., Fugate M., Favalli A., Sjöland A.; "Axial and azimuthal gamma scanning of nuclear fuel - implications for spent fuel characterization"; Journal: Journal of Nuclear Materials Management; Vol: 45; No: 1; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-299483>; (2016)
13. Martinik T., Henzl V., Grape S., Jansson P., Swinhoe M., Goodsell A., Tobin S.; "Design of a Prototype Differential Die-Away Instrument proposed for Swedish Spent Nuclear Fuel Characterization"; Journal: Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment; Vol: 821; DOI: 10.1016/j.nima.2016.02.052; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-268336>; (2016)



14. Qvist S., Hellesen C., Gradecka M., Dubberley A., Fanning T., Greenspan E.; "Tailoring the response of Autonomous Reactivity Control (ARC) systems"; Journal: *Annals of Nuclear Energy*; Vol: 99; DOI: 10.1016/j.anucene.2016.09.036; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-310730>; (2017)
15. Qvist S., Hellesen C., Thiele R., Dubberley A., Gradecka M., Greenspan E.; "Autonomous Reactivity Control (ARC) - Principles, geometry and design process"; Journal: *Nuclear Engineering and Design*; Vol: 307; DOI: 10.1016/j.nucengdes.2016.07.018; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-305316>; (2016)
16. Vaccaro S., Tobin S., Favalli A., Grogan B., Jansson P., Liljenfeldt H., Mozin V., Hu J., Schwalbach P., Sjöland A., Trellue H., Vo D.; "PWR and BWR spent fuel assembly gamma spectra measurements"; Journal: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*; Vol: 833; DOI: 10.1016/j.nima.2016.07.032; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-301364>; (2016)
17. Verma V., Filiatre P., Hellesen C., Jacobsson Svärd S., Jammes C.; "Neutron flux monitoring with in-vessel fission chambers to detect an inadvertent control rod withdrawal in a sodium-cooled fast reactor"; Journal: *Annals of Nuclear Energy*; Vol: 94; DOI: 10.1016/j.anucene.2016.04.019; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-297046>; (2016)
18. Vo D., Favalli A., Grogan B., Jansson P., Liljenfeldt H., Mozin V., Schwalbach P., Sjöland A., Tobin S., Trellue H., Vaccaro S.; "Passive gamma analysis of the boiling-water-reactor assemblies"; Journal: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*; Vol: 830; DOI: 10.1016/j.nima.2016.06.013; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-296168>; (2016)

### Papers submitted during 2016

1. Andersson P., Holcombe S.; "A computerized method (UPPREC) for quantitative analysis of irradiated nuclear fuel assemblies with gamma emission tomography at the Halden reactor"; Journal: *Annals of Nuclear Energy*; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-313485>; (2016)
2. Helgesson P, Sjöstrand H., Uncertainty driven nuclear data evaluation including thermal (n, $\alpha$ ): applied to  $^{59}\text{Ni}$ , (prepared and reviewed by SKC during 2016, submitted to NDS 2017)

### Conference contributions

1. Al-Adili A., Tarrío D., Hamsch F., Gook A., Jansson K., Solders A., Rakopoulos V., Gustavsson C., Lantz M., Mattera A., Oberstedt S., Prokofiev A., Vidali M., Österlund M., Pomp S.; "Analysis of prompt fission neutrons in U-235(nth,f) and fission fragment distributions for the thermal neutron induced fission of U-234"; Conference: 5th International Workshop on Compound-Nuclear Reactions and Related Topics (CNR), OCT 19-23, 2015, Tokyo, JAPAN; DOI: 10.1051/epjconf/201612201007; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-314830>; (2016)
2. Andersson P., Holcombe S., Tverberg T.; "Inspection of a LOCA Test Rod at the Halden Reactor Project using Gamma Emission Tomography"; Conference: Top Fuel; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-303810>; (2016)
3. Diakaki M., Tarrío D., et al.; "Towards the high-accuracy determination of the  $^{238}\text{U}$  fission cross section at the threshold region at CERN - "n\_TOF"; Vol: 111; Conference: WONDER-2015 – 4th International



Workshop On Nuclear Data Evaluation for Reactor applications; DOI: 10.1051/epjconf/201611102002; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-285245>; (2016)

4. Helgesson P. et al., Novel nuclear data evaluation combining sampling of experimental uncertainty components and TALYS parameters - Applied to helium production due to  $^{59}\text{Ni}$  in stainless steel, Oral and poster presentation at ND2016, International Conference on Nuclear Data for Science and Technology, 11-16/9 Bruges Belgium.
5. Hernandez Solis A., Sjöstrand H., Alhassan E., Helgesson P.; "Development Of Drag-MOC : A tool for the study of uncertainty analysis through the deterministic OpenMOC transport code"; Conference: Reactor physics meeting PHYSOR 2016; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-274321>; (2016)
6. Holcombe S., Andersson P.; "Gamma Emission Tomography Measurements of Fuel Assemblies at the Halden Reactor"; Conference: Top Fuel; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-303812>; (2016)
7. Jansson K., Fréreau M., Al-Adili A., Göök A., Gustavsson C., Hamsch F., Oberstedt S., Pomp S.; "The new double energy-velocity spectrometer VERDI"; Conference: International Conference on Nuclear Data for Science and Technology; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-313910>; (2016)
8. Jansson P.; "The proposed SPIRE project : Challenge, Scope and Impact"; Conference: Exchange forum number 7 of the IGD-TP; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-307167>; (2016)
9. Lantz M., Al-Adili A., Gorelov D., Jokinen A., Kolhinen V., Mattera A., Moore I., Penttila H., Pomp S., Prokofiev A., Rakopoulos V., Rinta-Antila S., Simutkin V., Solders A.; "Fission yield measurements at IGISOL"; Conference: 5th International Workshop on Compound-Nuclear Reactions and Related Topics (CNR), OCT 19-23, 2015, Tokyo, JAPAN; DOI: 10.1051/epjconf/201612201008; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-314832>; (2016)
10. Leal-Cidoncha E., Tarrío D., et al; "Fission Fragment Angular Distribution measurements of  $^{235}\text{U}$  and  $^{238}\text{U}$  at CERN n\_TOF facility"; Vol: 111; Conference: WONDER-2015 – 4th International Workshop On Nuclear Data Evaluation for Reactor applications; DOI: 10.1051/epjconf/20161110002; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-285241>; (2016)
11. Mattera A., Al-Adili A., Lantz M., Pomp S., Solders A., Rakopoulos V.; "Comparing Nuclear Fission Codes : GEF as standalone code vs GEF+TALYS"; Publisher: International Atomic Energy Agency; Conference: IAEA Technical Meeting on Fission Product Yields Data; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-313825>; (2016)
12. Mattera A., Pomp S., Al-Adili A., Lantz M., Solders A., Rakopoulos V.; "A methodology for the intercomparison of nuclear fission codes using TALYS"; Conference: International Conference on Nuclear Data for Science and Technology; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-313827>; (2016)
13. Paradela C., Tarrío D., et al.; "High accuracy  $^{235}\text{U}(n,f)$  data in the resonance energy region"; Vol: 111; Conference: WONDER-2015 – 4th International Workshop On Nuclear Data Evaluation for Reactor applications; DOI: 10.1051/epjconf/201611102003; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-285247>; (2016)



### Other reports and books

1. Andersson P., Holcombe S., Tverberg T.; "Inspection of LOCA Test Rod IFA-650.15 Using Gamma Emission Tomography"; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-283654>; (2016)
2. Grape S., Jacobsson Svärd S., Jansson P., Hellesen C., Branger E.; "Forskning inom teknisk kärnämneskontroll vid Uppsala universitet under 2014–2015"; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-305263>; (2016)
3. Holcombe S., Andersson P., Jacobsson Svärd S., Hallstadius L.; "Non-destructive Determination of the Rod-wise Fission Gas Release Fraction Using Gamma Emission Tomography on Complete Fuel Assemblies"; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-288934>; (2016)
4. Smith E., Jacobsson Svärd S., Mozin V., Jansson P., Miller E., Honkamaa T., Deshmukh N., White T., Wittman R., Trelue H., Grape S., Davour A., Vaccaro S.; "A Viability Study of Gamma Emission Tomography for Spent Fuel Verification: JNT 1955 Phase I Technical Report"; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-306584>; (2016)
5. Dimitriou P., Hamsch F., Pomp S.; "Fission Product Yields Data Current status and perspectives : Summary report of an IAEA Technical meeting"; Publisher: IAEA; Conference: Fission Yields Technical Meeting, Vienna, 23-26 May, 2016; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-306150>; (2016)
6. Griffin P., Sjöstrand H., Simakov S.; "Nuclear Reaction Data and Uncertainties for Radiation Damage : Summary Report of the Technical Meeting, IAEA Headquarters, Vienna, Austria 13 – 16 June 2016 (INDC(NDS)-0719)"; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-301968>; (2016)
7. Helgesson P., Sjöstrand H.; "Justified and complete gas-production cross sections with uncertainties for Ni-59 and consequences for stainless steel in LWR spectra"; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-313642>; (2016)
8. Helgesson P., Sjöstrand H., Rochman D., Koning A.; "Ni-59 cross section evaluation : covariance focus"; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-313641>; (2016)
9. Helgesson P.; "Evaluation of the Ni-59 cross sections including thermal (n,α), (n,p) and complete uncertainty information"; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-313638>; (2016)

### Networking and collaborations

- Sweden: KTH, Chalmers, Stockholm University, Gothenburg University and SIPRI
- Belgium: Joint Research Centre IRMM in Geel, CSK-CEN in Mol
- The Netherlands: NRG Petten
- Finland: Univ. of Jyväskylä
- France: GANIL, IPNO and CEA
- Japan: Kyushu University, initiating collaboration with Tokyo Technical Institute
- Switzerland: CERN, PSI
- Thailand: Chiang Mai University
- Kenya: University of Nairobi
- USA: LANL, UCB, LBNL, LLNL, PNNL, ANL, ORNL
- Norway: OECD Halden Reactor Project and IFE, Technical University in Trondheim
- IAEA
- The World Nuclear University
- EU: CHANDA (35 partners)
- RADSAGA network project with about 25 participating organizations from academy and industry





- Nordic Academy for Nuclear Safety and Security, NANSS
- ENEN (European Nuclear Education Network): Via the ANNETTE project on the development of training for professionals in the nuclear business for an “Advanced Master” degree, UU has strengthened the collaboration with about 25 European organizations active in this project.
- ESARDA (European Safeguards Research and Development Association): UU is very active in this Europe-wide research association; Sophie Grape is chairing the ESARDA working group of Training and Knowledge Management, with Karin Persson as an additional group member, while Peter Jansson is co-chairing the ESARDA working group on Non-Destructive Assay, with Staffan Jacobsson Svård as an additional group member.
- SKB, LANL: Research regarding nuclear fuel characterisation related to the back-end of the nuclear fuel cycle has been performed in close collaboration between Uppsala University, SKB AB and Los Alamos National Laboratory.
- MÅBiL project with participants from UU, KTH and Chalmers
- Initiating the Swedish Academic Initiative in Nuclear Technology, SAINT, together with Chalmers.

## Outreach

### General

- Dr. Sophie Grape is a member of Kärnavfallsrådet.
- Dr. Mattias Lantz is chairman of Analysgruppen
- All nuclear power plants are represented in the steering committee of the bachelors programme in nuclear technology.

### Mass media

- January 19, debate article SvD Näringsliv
- April 28, interview Reaktion nr 2
- June 30, interview Sveriges Radio
- July 18, debate article SvD
- Numerous posts in social media for rectifying misunderstandings regarding nuclear power

### Popular science

- March 3-5, SciFest 2016



### Others

- January 20, seminar at Energiforsk
- February 3, lunch seminar Svensk Energi
- Lunchföredrag om kärnkraftutbildning:  
February 17, KTH Campus Telge  
March 7, Uppsala teknolog- och naturvetarkår  
March 8, Chalmers Lindholmen  
March 9, Högskolan i Borås  
March 10, Jönköpings tekniska högskola
- November 1, letter to minister of research, Helene Hellmark Knutsson, regarding nuclear competence building in Sweden.

## Additional information and commitments during 2016

- NESSA - A neutron facility at Uppsala University. Applied Nuclear Physics plan to purchase a high-intensity neutron generator has evolved and we have identified a supplier for a  $10^{11}$  neutrons per second source. The neutron generator will be situated in the FREIA hall of the Ångström laboratory and is tentatively called NESSA, NEutron Source in UppSala. NESSA is planned to be used both as a part of research and education as well as an irradiation facility. NESSA can be used for both detector development and material studies. When commissioned, NESSA will form an unique research facility in Europe and we foresee it to be a valuable tool for research and development relevant also for the nuclear power sector.
- During 2016 we have intensified our dialogue with Tokyo Technical Institute aiming at creating various research and educational collaborations.

## Plans and visions

One of our missions, relevant for SKC, is to work for achieving safe, secure and sustainable nuclear energy systems. On the global level this seems imperative in order to solve the monumental issues mankind faces. To obtain this we believe that new Generation III and III+ power reactors together with adequate waste disposal systems is the first step in this direction. Such a development is mainly an undertaking for the industrial part of the world. However, in this context the role of the universities as providers of competence to the industry must thoroughly be addressed.

For the long-term perspective, Generation IV systems are likely to be considered and in order to address the needs of competence and capacity building, the role of the universities is imperative. As we see it, Gen IV is one efficient way to attract young scientists to the nuclear field, addressing not only future technology but also current technology. As these researchers also function as teachers enable us to augment our capacity to educate nuclear engineers for the current as well as future needs.

In addition, considering the need to electrifying developing countries and in the light of climate change, it is reasonable that the industrial and academic foundation of the industrialised countries is utilised for the safe and secure implementation of nuclear energy on the global scale. In this scenario applied nuclear physics in Uppsala shall play a role.

Below is a brief account on important parts of the strategy to fulfil our mission regarding nuclear technology.

### Visions



To contribute to the environmental-friendly energy supply in the world by:

- enhancing safety and security in current nuclear power plants,
- contributing to the development of new nuclear power technologies that are sustainable in a long-term perspective,
- educating future employees, experts and researchers within the nuclear field.



## Appendix 4 - MÅBiL Annual Report 2016



### Finances

The SKC financing through MÅBiL has been used to fund the following projects in 2016:

UPPSALA  
UNIVERSITET



Project name	Student/ PostDoc	Supervisor	Uni	Budget (kkkr)	Usage
Total Monte Carlo - Fuel and Materials	Petter Helgesson (PhD stud.)	Henrik Sjöstrand	UU	330	40% of P. Helgesson's salary
Theoretical and Experimental Studies of Uranium Nitrides	Aneta Sajdova (PhD stud.)	Christian Ekberg Teodora Retegan	CTH	660	80% of A. Sajdova's salary, plus some lab/chemical costs, travel and supervision.
Ageing of Reactor Pressure Vessel Steel Welds	Kristina Lindgren (PhD stud.)	Mattias Thuvander	CTH	610	80% of K. Lindgren's salary (lab costs covered by Chalmers)
Amorphous metals for the nuclear industry	Maciej Kaplan (PhD stud.)	Björgvin Hjörvarsson	UU	660	100% salary for L. Thorsson (first ½ year) and M. Kaplan (late sept – end of 2016)
ICEWATER	Erki Metsanurk (PhD stud.)	Mattias Klintenberg Pål Efsing	UU	610	100% of E. Metsanurk's salary
Nuclear Fuel Diagnostics	Peter Andersson (PostDoc)	Staffan Jacobsson Svärd Scott Holcombe	UU	330	50% of total project expenses, which have been lower than budget due to parental leave.
Irradiation assisted stress corrosion cracking	Elin Toijer (PhD stud.)	Pär Olsson Mats Jonsson Pål Efsing	KTH	375	E. Toijer's salary plus some travel, SKC funding covers approx. 80% of total costs.

## Background on the sub-projects

### Total Monte Carlo – fuel and materials

The TMC (Total Monte Carlo) sub-project has one part dedicated to fuel and one to materials. The approach is the same – the nuclear model code TALYS is used to generate nuclear data libraries which are then used to simulate nuclear reactions in nuclear fuels and other materials respectively.

The novelty of using TALYS and the TMC method for nuclear fuel simulations is that all relevant nuclear parameters of the fuel can be calculated with experimentally conditioned uncertainties. The work focuses on calculating parameters that have been identified as relevant for the industrial partners, such as fission gas production and simulation of transients. This also ties well in with the work on nuclear fuel diagnostics where these parameters are being studied experimentally.

The reactor internals are exposed to high fluxes of neutrons and gamma irradiation during long timespans, which affects and weakens the material. This limits, for example, the life span of the reactor pressure vessel. New materials or limitations of the neutron flux contributes to increase life spans. In order to quantify this, good knowledge is needed of the radiation field in the reactor pressure vessel and the closest vicinity. TALYS and TMC will be used also for simulations of this.



### Theoretical and experimental studies of uranium nitrides

Uranium nitride is among several fuel types that can replace a currently used  $\text{UO}_2$  in LWRs. It is also suggested for use in future “Generation four nuclear reactors”. The main advantages of UN compared to  $\text{UO}_2$  are higher thermal conductivity, higher fissile atom density and comparably high melting point. On the downside, uranium nitride is incompatible with water – it hydrolyses, dissolves and undergoes a mechanical erosion in hot circulating water. The hydrolysis process of pure UN that leads to  $\text{UO}_2$  and  $\text{NH}_3$  formation and the mechanism is not yet well understood. Thus, various parameters of this reaction are being studied, e.g. the starting temperature and pressure, the exact structure of reaction products and also the effect of a fuel composition: density, porosity, additives etc. on the reaction mechanism and reaction kinetics.

### Ageing of reactor pressure steel welds

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 nanometer-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 R3 and R4 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 study.

### Amorphous metals for the nuclear industry

Amorphous metals are continuing to be interesting as an approach of enhancing the accident tolerance of nuclear fuel rods. The main challenge of amorphous metals is their thermal stability, which is mainly defined by the glass transition temperature ( $T_g$ ) and crystallisation temperature ( $T_x$ ). The behaviour of the thermal stability is still an open question, however, there are several criteria one can follow. Alloys which contain elements with a high melting point generally exhibit a higher thermal stability than alloys which consist of elements with lower melting points. Furthermore, alloys consisting of minimum three elements, a negative enthalpy of mixing ( $\Delta H_{\text{mix}}$ ) and a significant size mismatch between the elements are said to increase glass forming ability and thermal stability. What is also interesting is that additions of metalloid elements (such as Si), often times significantly enhances glass forming and thermal stability of amorphous alloys. This is probably due to large size mismatch and localisation of electrons, the latter of which may cause embrittlement of the alloy. However, it is possible that other, thus far unknown, reasons also have an influence on this matter.

### ICEWATER

The aim of ICEWATER project is to construct test device to study irradiation assisted stress corrosion cracking (IASCC) in different types of austenitic stainless steels. Whereas crack initiation and propagation tests using preirradiated materials are fairly common, very few studies have been performed to assess the synergistic effect of irradiation and chemical environment. In addition, IASCC tests performed on neutron-irradiated materials is expensive, time-consuming and requires special handling and machinery due to the high residual activity. Because it has been shown that the damage by protons is similar in nature to that of the neutrons, but can be performed in much quicker, cheaper and more safe ways, it could possibly pave way for more systematic studies behind the underlying mechanisms of IASCC.

### Nuclear fuel diagnostics

The OECD Halden Reactor (OECD-HRP) is a world-leading laboratory for research on nuclear fuel and reactor materials. The unique HBWR reactor enables studies of nuclear fuel behavior during normal operation as well as transient and accident scenarios, such as LOCA. The closed loops used in the reactor even allow fuel ruptures during the tests. Uppsala University has established a collaboration with OECD-HRP, which covers the following topics: 1) Take part in developing analysis techniques, 2) Perform analyses of collected data from irradiation



experiments and 3) Participate in the evaluation of Accident-Tolerant Fuels. A recent collaboration project resulted in the construction and demonstration of a tomographic measurement device, designed specifically for use at OECD-HRP, which has now been brought into use and started to produce data on test fuel from the HBWR.

### Irradiation assisted stress corrosion cracking

Irradiation-assisted stress corrosion cracking (IASCC) is one of the potentially life limiting phenomena of components in light water reactors today as suggested in time limiting ageing mechanism analyses, TLAA, at various power plants. The decrease of critical stress for onset of crack initiation, and the time dependent degradation of the mechanical strength of the metallic components can severely limit the lifetime of reactor vessel internal components. The combined effect of persistent radiation, aggressive water chemistry and applied primary and secondary strains are the underlying factors for the cracking. The underlying mechanisms for IASCC are not satisfactorily understood and make predictions on the cracking behavior, considering all environmental factors, very challenging.

## Progress in 2016

### Total Monte Carlo – fuel and materials

During 2016, there has been a continued emphasis on aging parameters, and in this work, Petter Helgesson connects macroscopic fuel and aging parameters to the fundamental nuclear physics processes by using the nuclear model code TALYS and the Total Monte Carlo Method (TMC) method.

During 2016 Petter has continued investigated  $^{59}\text{Ni}$ , since the two-step thermal neutron reaction sequence  $^{58}\text{Ni}(n,\gamma)^{59}\text{Ni}(n,\alpha)^{56}\text{Fe}$ , ( $Q_{\text{value}} = 5,1 \text{ MeV}$ ) results in non-linear He production rates and is an important contribution to the He production in steel in thermal spectrum. To improve the He production prediction and to provide nuclear data uncertainty estimates, new  $^{59}\text{Ni}$  cross section data has been produced. The cross-sections have been produced in ENDF-6 format, including so-called random files, for usage by the nuclear community.

To check the performance of the random files, they have been tested on an MCNP-6 model. The results were compared to He and H production rates in a reference case. It was found that the inclusion of  $^{59}\text{Ni}$  increased the helium production rate by a factor of  $5.2 \pm 0.3$ .

During 2016, Petter has also continued to work on statistically stringent ways to include experimental information in TMC. For this, a collaboration with Los Alamos has been started. In this work, different techniques to evaluate nuclear data have been evaluated. The work has had some emphasis on the prompt fission neutron spectrum, which plays an important role in e.g. pressure vessel dosimetry.





### Theoretical and experimental studies of uranium nitrides

In 2016, mainly an internal sol gel method with use of a water soluble source of carbon-glucose was investigated and resulted in a manufacture of series of UN doped materials (U-Cr, U-Al, U-Ni and U-Th). An analog set of materials was also produced with use of carbon nano-powder. Preliminary experiments were performed with those materials by testing them in boiling water at normal pressure.

A pure uranium nitride pellet was used as a reference sample. This pellet collapsed after 2 hours of boiling. A bubble formation from the pellet surface was observed signaling either degassing of pores or gaseous ammonia formation. U-Cr pellet was boiled for 5 hours without collapsing, U-Al and U-Ni pellets dissolved after a few minutes in boiling water. This indicates a clear improvement in corrosion resistance of U-Cr material.

Besides, a production of a pure and/or doped UN material by ammonolysis was done. The product contained only a residual amount of carbon which was well below the allowed limit.

### Ageing of reactor pressure steel welds

In 2016, the results from the irradiated RPV material have been further analysed. It was found that the cluster number density and size increase with fluence, as expected. There was no sign of so called "late blooming precipitates" i.e. sudden changes of cluster characteristics leading to sudden embrittlement after long times of irradiation. The influence of flux was discussed in the comparison of the materials irradiated in Halden and the surveillance material. It was found that the high flux Halden materials have smaller clusters with a higher number density. However, the increase in hardness follows the same trend for surveillance and Halden materials, i.e. the smaller size of the clusters is compensated by the larger number density. A collaboration with KTH (Magnus Boåsen) was initiated, on post irradiation annealing (PIA) of the RPV steels, aiming at combining our microstructural studies with investigations of the recovery of the mechanical properties.

In addition to the irradiated samples, analyses have also been made on welds from a pressurizer, to try to understand the reason for their embrittlement. In this case the ageing is purely thermal, but it is clear that nano-sized precipitates form even at these relatively low temperatures (345°C), also without irradiation, after long enough time. The precipitates are mainly found along dislocations, which also contain segregated Mo, see Figure 2. Samples from the pressurizer have also been sent to Manchester University for TEM studies. In 2016, APT analysis of the thermally aged RPV head (320°C for 20 years) have been performed to compare with the pressurizer. No Cu-rich clusters were found, explaining the non-existent change in hardness for this particular part of the RPV.

### Amorphous metals for the nuclear industry

The Mo-Si-Zr system was evaluated with respect to thermal stability in early 2016 by MSc. Student Maciej Kaplan. The thesis can be found on DiVA portal under the name "Thermal Stability of Amorphous MoSiZr Thin Films". In short, the Mo-Si-Zr-alloy remained amorphous at temperatures up to 1073 K, which is high in comparison to many other alloys. Evaluation was done by iterating heat treatments in vacuum and ex-situ GIXRD and XRR. Oxidation was also observed, despite heat treatments in vacuum, however, its behaviour was not investigated further.

After employing Maciej Kaplan, the work started with searching for a new material system to investigate. A scan of the periodic table was made with respect to atomic size and mixing enthalpy of elements, from binary through ternary to quaternary. The aim of this was to identify a material system which would be purely metallic with a significant size mismatch and  $\Delta H_{mix}$  as close to zero as possible. The reasoning behind this "neutral"  $\Delta H_{mix}$  is a minimisation of the thermodynamic drive force for crystallisation, hence increasing Tg/Tx. Consequently, the Zr-Nb-Cr-Mo system was chosen for investigation, which is also chosen to have a small neutron cross section. It is expected to have a higher thermal stability than other conventional amorphous Zr-alloys, such as Zr-Co-Al-Ag or Zr-Cu-Fe-Al. Subsequently, roughly 60 thin film (~80-100 nm) samples of the Zr-Nb-Cr-Mo-alloy were manufactured by combinatorial sputtering. The as-grown samples are currently being characterised by GIXRD (for structural analysis) and XRR (for thickness analysis). No crystallinity has been found in any of the thin samples which have been analysed thus far.



Samples for evaluation of mechanical properties have been grown, however, problems with crystallinity and adhesion to substrate were observed.

### ICEWATER

Three experiments were performed at Tandem Laboratory at Uppsala University in order to assess the buildup of activity in the window material which will act as a barrier between the beamline vacuum and high-temperature high-pressure (HTHP) environment in the test cell.

A sample holding and loading cell was designed. The process consisted of five iterations each of which improved the design in order to fulfill the specifications and to remove obvious flaws. The design was made using Solidworks 3D CAD design software. In addition, the stress in the cell and temperature at the pull rod seal was simulated using Comsol FEM software.

Measurement of electrochemical parameters such as electrochemical corrosion potential (ECP), dissolved oxygen and hydrogen (dO and dH), pH etc is important to quantify the experimental conditions. However, it has turned out that these kinds of measurements are non-trivial, and since it is possible that the development of the sensors, especially the ECP one which is also one of the most important parameters, could take another project to fulfill, we have currently postponed the measurement part as in principle it does not interfere with designing and using the miniaturized loading cell to induce IASCC in stainless steel samples.

Through discussions during attended conferences, two issues with the current design were identified and work was started on resolving these: Friction between the pull rod and the pull rod seal and temperature increase in the window and between the window and the sample.

### Nuclear fuel diagnostics

During 2016, the focus has been on non-destructive measurements of irradiated nuclear fuel using gamma tomography.

New methods have been developed for the quantitative, high resolved reconstruction of gamma-emitting nuclides in cross-sectional images of fuel assemblies using the gamma tomography technique.

We participated in the ongoing HRP LOCA test series, by performing and analysing the measurements of the relocated fuel distribution using gamma tomography. The inspection which was proposed and planned by us was executed in the beginning of 2016. Preliminary qualitative reconstructions were performed and the analysis tools have also been modified in order to account for the nonhomogeneous attenuation distribution of relocated fuel fragments, to allow for quantitative reconstructions.

The fission gas release fraction has been studied in a HRP fuel assembly using the tomographic reconstruction of  $^{85}\text{Kr}$  in the fuel plenum and the  $^{137}\text{Cs}$  in the fuel stack. The concentration of  $^{85}\text{Kr}$  in the fuel was calculated based on the  $^{137}\text{Cs}$  concentration corrected for differences in e.g. fission yield and half-life to estimate the fraction of produced fission gas that had been released. The results were in good agreement with benchmark data collected using the conventionally used technique of single-rod gamma scanning.

### Irradiation assisted stress corrosion cracking

Within the framework of the experimental part of the project, we have been conducting a study of the reaction between the radiolysis product  $\text{H}_2\text{O}_2$  and 304L type austenitic steel. Both the kinetics and the mechanisms of this reaction is studied.

The modeling of impurity and defect diffusion (and energetics) near grain boundaries is advancing well, although the quite extensive computational load has led to some delays (there has been some competition between students to use the supercomputers). Elin has been successfully developing codes and methods to pre-process her supercomputer simulations.

We have been planning an experimental campaign on radiation induced crack growth between the three pillars of the project (reactor physics, applied physical chemistry and solid mechanics). These studies will, however, require additional funding to commence.



## Publications

During 2016, the following publications have been made by the project participants:

### Publications in peer reviewed journals

P. Helgesson, Sjöstrand H., J. Koning A., Rydén J., Rochman D., Alhassan E., Pomp S.; "Sampling of systematic errors to estimate likelihood weights in nuclear data uncertainty propagation"; Journal: Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment; Vol: 807; Publisher: Elsevier; DOI: 10.1016/j.nima.2015.10.024; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-265321>; (2016)

P. Helgesson, H. Sjöstrand, A.J. Koning, J. Rydén, D. Rochman, E. Alhassan, S. Pomp, Combining Total Monte Carlo and Unified Monte Carlo: Bayesian nuclear data uncertainty quantification from auto-generated experimental covariances, Progress in Nuclear Energy, Volume 96, April 2017, Pages 76-96, ISSN 0149-1970, <http://dx.doi.org/10.1016/j.pnucene.2016.11.006>.

P. Helgesson, H. Sjöstrand, Uncertainty driven nuclear data evaluation including thermal (n, $\alpha$ ): applied to  $^{59}\text{Ni}$ , (prepared and reviewed by SKC during 2016, submitted to NDS 2017)

K. Lindgren, P. Efsing, K. Stiller and M. Thuvander, "On the analysis of clustering in an irradiated low alloy reactor pressure vessel steel weld", Microscopy and Microanalysis. Accepted in January 2017.

K. Lindgren, M. Boåsen, P. Efsing, K. Stiller and M. Thuvander, "Evolution of precipitation in reactor pressure vessel steel welds under neutron irradiation", Journal of Nuclear Materials. Submitted in December 2016.

Davour A., Jacobsson Svärd S., Andersson P., Grape S., Holcombe S., Jansson P., Troeng M.; "Applying image analysis techniques to tomographic images of irradiated nuclear fuel assemblies"; Journal: Annals of Nuclear Energy; Vol: 96; DOI: 10.1016/j.anucene.2016.05.024; Permalink: <http://urn.kb.se>

Andersson P., Holcombe S.; "A computerized method (UPPREC) for quantitative analysis of irradiated nuclear fuel assemblies with gamma emission tomography at the Halden reactor"; Submitted to Annals of Nuclear Energy, 2016. [3] Andersson P., Holcombe S., Tverberg T.; "Inspection of LOCA Test Rod IFA-650.15 Using Gamma Emission Tomography"; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-283654>; (2016)

Andersson P., Holcombe S., Tverberg T.; "Inspection of a LOCA Test Rod at the Halden Reactor Project using Gamma Emission Tomography"; Conference: Top Fuel; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-303810>; (2016)

Holcombe S., Andersson P., Jacobsson S., Hålistadius L.; "Determination of the Rod-wise Fission Gas Release Fraction in a Complete Fuel Assembly Using Non-destructive Gamma Emission Tomography"; Journal: Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment; Vol: 837; DOI: 10.1016/j.nima.2016.08.061; Permalink: <http://urn.kb.se>

### Conference contributions

P. Helgesson et al., Novel nuclear data evaluation combining sampling of experimental uncertainty components and TALYS parameters - Applied to helium production due to  $^{59}\text{Ni}$  in stainless steel, Oral and poster presentation at ND2016, International Conference on Nuclear Data for Science and Technology, 11-16/9 Bruges Belgium.

#### Other Scientific

Helgesson P., Sjöstrand H.; "Justified and complete gas-production cross sections with uncertainties for Ni-59 and consequences for stainless steel in LWR spectra"; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-313642>; (2016)

Helgesson P., Sjöstrand H., Rochman D., Koning A.; "Ni-59 cross section evaluation : covariance focus"; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-313641>; (2016)



Helgesson P.; "Evaluation of the Ni-59 cross sections including thermal (n,alpha), (n,p) and complete uncertainty information"; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-313638>; (2016)

K. Lindgren; Licentiate thesis: Radiation Induced Precipitation in Reactor Pressure Vessel Steel Welds, Chalmers, 2016.

## Projects

### Ageing of Reactor Pressure Vessel Steel Welds

Research leader: Mattias Thuvander, Division of Materials Microstructure, Department of Physics, Chalmers

PhD-student: Kristina Lindgren

Participants: Krystyna Stiller (Chalmers) and Pål Efsing (KTH)

### Finances

The funds from SKC have been used for covering 80% of the cost of the Ph.D. student. Costs for instruments and supervision have been covered by Chalmers. The funds have been spent in accordance with budget.

### Project activities

The reactor pressure vessel (RPV) is a life-limiting component of a nuclear reactor. Neutron irradiation during operation decreases the ductility of the RPV most important mechanism for making the brittle is the formation of nanometre-sized consisting of Ni, Mn, Si and Cu, see Figure particular, welds are affected as they often higher concentrations of the listed In the R3 and R4 reactors, the Ni- and Mn- are higher than in most other reactors, studies of these important. The aim of this to study ageing of RPV steel welds, both the neutron irradiation and purely thermal better understand the mechanisms of and to provide a basis for predicting the of RPVs. Since the microstructural changes irradiation are on a very small scale, atom tomography (APT) is the most suitable technique for this study.

The project started in July 2014 and during irradiated reference materials were studied. 2015 irradiated RPV samples were received VTT, Finland, where mechanical testing has undertaken. The samples had been irradiated in the Halden reactor to levels corresponding to operation for about 20 years, respectively. These samples are to the RPV welds of R4. During 2015 a large (to get good statistics) of APT analyses of sample series from Halden, together with surveillance sample, have been made.

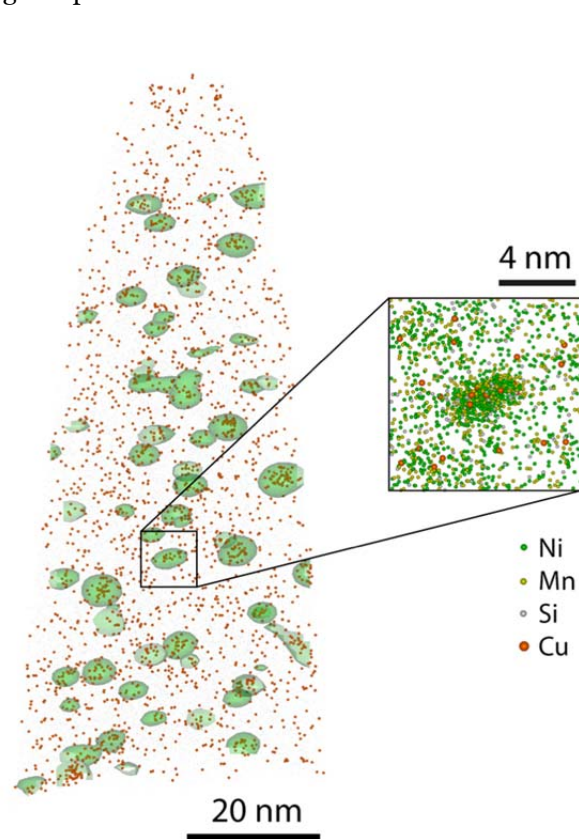


Figure 2. An atom probe tomography reconstruction of an irradiated reactor pressure vessel steel of surveillance material. Green surfaces correspond to 12.43 at% of Ni, Mn and Si. Orange dots correspond to Cu atoms. The enlarged volume is  $10 \times 10 \times 10 \text{ nm}^3$ .

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In 2016, the results from the irradiated RPV material have been further analysed and summarised in two journal papers, included in the licentiate thesis that was presented in November. The first paper (no. 2 in the publications list below) is mainly concerned with the APT methodology (cluster analysis - how to define and compare the clusters in the materials). The second paper (no. 3) is concerned with the microstructure and hardness of the RPV welds. It was found that the cluster number density and size increase with fluence, as expected. There was no sign of so called "late blooming precipitates" i.e. sudden changes of cluster characteristics leading to sudden embrittlement after long times of irradiation. The influence of flux was discussed in the comparison of the materials irradiated in Halden and the surveillance material. It was found that the high flux Halden materials have smaller clusters with a higher number density. However, the increase in hardness follows the same trend for surveillance and Halden materials, i.e. the smaller size of the clusters is compensated by the larger number density. The methods and results have also been presented at two conferences. A collaboration with KTH (Magnus Boåsen) was initiated, on post irradiation annealing (PIA) of the RPV steels, aiming at combining our microstructural studies with investigations of the recovery of the mechanical properties.

In addition to the irradiated samples, analyses have also been made on welds from a pressurizer (exchanged at Ringhals after ca. 28 years of operation), to try to understand the reason for their embrittlement. In this case the ageing is purely thermal, but it is clear that nano-sized precipitates form even at these relatively low temperatures (345°C), also without irradiation, after long enough time. The precipitates are mainly found along dislocations, which also contain segregated Mo, see Figure 2. Samples from the pressurizer have also been sent to Manchester University for TEM studies. In 2016, APT analysis of the thermally aged RPV head (320°C for 20 years) have been performed to compare with the pressurizer. No Cu-rich clusters were found, explaining the non-existent change in hardness for this particular part of the RPV.

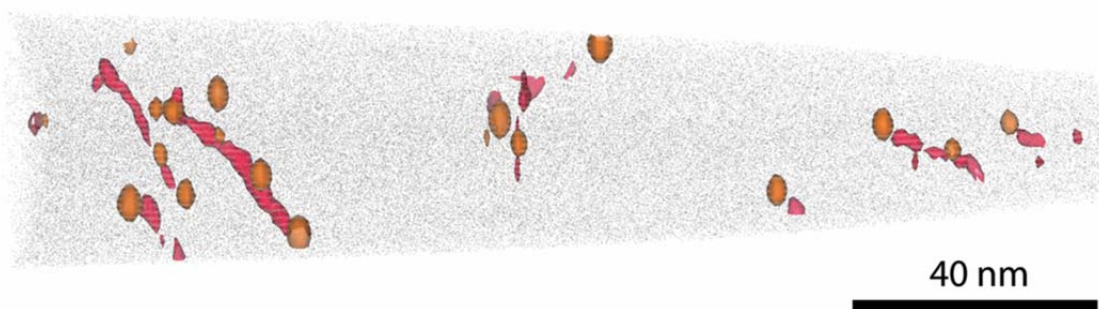


Figure 3. Atom probe reconstruction of a pressurizer weld, thermally aged for 28 years at 345°C. Cu clusters (also enriched in Ni, Mn and Si) are found on dislocation lines, enriched in Mo, Mn and C. The orange surfaces correspond to 1.1 at% Cu, the red surfaces to 1.6 at% Mo.

## Plans

The APT investigations of the pressurizer will be presented in a paper. An application for small angle neutron scattering (SANS) of the pressurizer will be written and hopefully SANS results will be included in the paper. The collaboration with Boåsen (KTH) will be continued on the pressurizer material. During 2017, the PIA RPV material will arrive to Chalmers and APT analyses will be performed on these, to be summarised in a journal paper. Later on, materials retrieved from Barsebäck RPV will be analysed. Cooperation with the ICEWATER project is anticipated. Probably APT analysis will be used to ascertain that the irradiation has affected the microstructure.

## Milestones

M18: Investigation of Halden samples - Done

M23: Submit paper to Microscopy&Microanalysis, Participate at APT&M - Done

M24: Investigation of annealing of Halden samples - On-going

M26: Investigation of pressurizer samples - Done

M28: Licentiate thesis - Done



M40: Investigation of ICEWATER samples

M45: Investigation of Barsebäck samples

M54: PhD thesis

### Publications

1. Licentiate thesis: Radiation Induced Precipitation in Reactor Pressure Vessel Steel Welds, 2016.
2. On the analysis of clustering in an irradiated low alloy reactor pressure vessel steel weld, K. Lindgren, P. Efsing, K. Stiller and M. Thuvander, Microscopy and Microanalysis. Accepted in January 2017.
3. Evolution of precipitation in reactor pressure vessel steel welds under neutron irradiation, K. Lindgren, M. Boåsen, P. Efsing, K. Stiller and M. Thuvander, Journal of Nuclear Materials. Submitted in December 2016.

### Planned publications: (tentative titles and authors)

4. Cu-rich precipitates in a thermally aged pressurizer, K. Lindgren, M. Boåsen, K. Stiller, P. Efsing, M. Thuvander.
5. Cluster evolution during post irradiation annealing of high Ni & Mn, low Cu reactor pressure vessel steel weld, K. Lindgren, M. Boåsen, K. Stiller, P. Efsing, M. Thuvander.

### Conference contributions

1. APT&M 2016, Gyeongju, South Korea (Oral presentation)
2. NuMat 2016, Montpellier, France (Oral presentation)

### Amorphous metals for the nuclear industry

Research leader: Björgvin Hjörvarsson, Division of Materials Physics, Department of Physics and Astronomy, Uppsala University

Ph.D. student: Maciej Kaplan

### Finances

Grant provides two years of salary for one Ph.D. student.

### Project activities

#### Background

Amorphous metals are continuing to be interesting as an approach of enhancing the accident tolerance of nuclear fuel rods. The main challenge of amorphous metals is their thermal stability, which is mainly defined by the glass transition temperature ( $T_g$ ) and crystallisation temperature ( $T_x$ ). The behaviour of the thermal stability is still an open question, however, there are several criteria one can follow. Alloys which contain elements with a high melting point generally exhibit a higher thermal stability than alloys which consist of elements with lower melting points. Furthermore, alloys consisting of minimum three elements, a negative enthalpy of mixing ( $\Delta H_{mix}$ ) and a significant size mismatch between the elements are said to increase glass forming ability and thermal stability. What is also interesting is that additions of metalloid elements (such as Si), often times significantly enhances





glass forming and thermal stability of amorphous alloys. This is probably due to large size mismatch and localisation of electrons, the latter of which may cause embrittlement of the alloy. However, it is possible that other, thus far unknown, reasons also have an influence on this matter.

Following Lena Thorssons departure the project halted in mid 2016. Maciej Kaplan was employed in late September to continue the development of amorphous alloys. Alloys containing of elements with a high melting point is continuing to be a key aspect in the work.

### Project progress

The Mo-Si-Zr system was evaluated with respect to thermal stability in early 2016 by MSc. Student Maciej Kaplan. The thesis can be found on DiVA portal under the name "Thermal Stability of Amorphous MoSiZr Thin Films". In short, the Mo-Si-Zr-alloy remained amorphous at temperatures up to 1073 K, which is high in comparison to many other alloys. Evaluation was done by iterating heat treatments in vacuum and ex-situ GIXRD and XRR. Oxidation was also observed, despite heat treatments in vacuum, however, its behaviour was not investigated further.

After employing Maciej Kaplan, the work started with searching for a new material system to investigate. A scan of the periodic table was made with respect to atomic size and mixing enthalpy of elements, from binary through ternary to quaternary. The aim of this was to identify a material system which would be purely metallic with a significant size mismatch and  $\Delta H_{mix}$  as close to zero as possible. The reasoning behind this "neutral"  $\Delta H_{mix}$  is a minimisation of the thermodynamic drive force for crystallisation, hence increasing  $T_g/T_x$ . Consequently, the Zr-Nb-Cr-Mo system was chosen for investigation, which is also chosen to have a small neutron cross section. It is expected to have a higher thermal stability than other conventional amorphous Zr-alloys, such as Zr-Co-Al-Ag or Zr-Cu-Fe-Al. Subsequently, roughly 60 thin film (~80-100 nm) samples of the Zr-Nb-Cr-Mo-alloy were manufactured by combinatorial sputtering. The as-grown samples are currently being characterised by GIXRD (for structural analysis) and XRR (for thickness analysis). No crystallinity has been found in any of the thin samples which have been analysed thus far.

Samples for evaluation of mechanical properties have been grown, however, problems with crystallinity and adhesion to substrate were observed.

### Plans

Initial characterisation with respect to structure, thickness and composition will be finalised in march 2017. Composition will be evaluated using XPS analysis. Subsequently, the samples will undergo thermal tests. This time, however, a new method will be used to characterised the thermal stability. A resistivity setup will be developed, since iterations of heat treatments and ex-situ XRD measurements are very time consuming. This should give a more accurate picture of the crystallisation event and increasing the time efficiency for testing thermal stability of amorphous samples.

A new attempt of growing samples for mechanical evaluation will also be performed. Slight modifications to the process might improve adhesion and crystallinity problems. If successful, these samples will be subject to mechanical evaluation using nanoindentation.



## Milestones

Table 1: Amorphous metals for the nuclear industry: milestones for 2017-2018

Task	Milestone	Status
Evaluation of microstructure at room temperature conditions of the Zr-Nb-Cr-Mo samples	Mapping the compositional region where samples are amorphous at room temperature.	Started; finished during March 2017
Development of a resistivity setup for thermal evaluation of amorphous materials	A new tool for evaluation of thermal stability with greater insight and efficiency of the crystallisation event	Start planned in April 2017
Evaluation of thermal stability in the amorphous Zr-Nb-Cr-Mo system using resistivity measurements	Finding $T_g/T_x$ with respect to the composition	Start as soon as setup is developed
Manufacturing of samples for mechanical evaluation	Finding the mechanical properties of the amorphous alloy	Start planned in March/April 2017
Mechanical evaluation using nanoindentation measurements	Finding mechanical properties with respect to composition	Starting when samples are ready
Publication	First publication	Starting as soon as data is available

## Interim Project

Aneta Sajdova\*, Teodora Retegan, Christian Ekberg  
 Chalmers University of Technology  
 Department of Chemistry and Chemical Engineering  
 Nuclear Chemistry and Industrial Materials Recycling

## List of contents

1. Summary
2. Background
3. Experimental results and discussion
4. Hydrolysis experiemnts set-up
5. Future work
6. References

### 1. Summary

The project started at Chalmers in February 2015 and it's goal is to develop a uranium nitride (UN) fuel with resistivity towards water for use in Light Water Reactors (LWRs). In order to make UN water insoluble, it was suggested to protect it's structure by doping it with selected metals which are known or used in other areas for their anti-corrosion characteristics. The main focus was put on firstly, a material production by internal sol gel technique (followed by carbothermal reduction) and secondly, on the behavior studies of such material in water. At first by simple testing in boiling water at normal pressure and later under high temperature and high pressure to imitate the real conditions in LWR during an accident e.g. a cladding rupture.



During 2015 the main work aimed at the pure UN production by sol gel/carbothermal reduction at various conditions (reaction time, temperature, pressure, atmosphere, gas flow rate) and at designing an instrument that would be used for the water behavior studies in later stage of the project. In spite of trying numerous variants of uranium nitride production, the most products contained residual carbon in form of uranium carbide. An uneven carbon distribution in the sol gel products leading to heterogeneous reaction extent could have been a possible explanation. Therefore a water soluble source of carbon was suggested instead of so far used carbon nano powder (CNP) for the sol gel process.

In 2016, mainly an internal sol gel method with use of a water soluble source of carbon – glucose was investigated and resulted in a manufacture of series of UN doped materials (U-Cr, U-Al, U-Ni and U-Th). An analogical set of materials was also produced with use of CNP. The preliminary experiments were performed with those materials by testing them in boiling water at normal pressure.

Besides, a production of a pure and/or doped UN material by ammonolysis was done. The product contained only a residual amount of carbon which was well below the allowed limit.

The experimental data were presented in April 2016 on the RANC-2016 (International conference on radioanalytical and nuclear chemistry), in August 2016 on the NRC9 (Ninth international conference on nuclear and radiochemistry), in October 2016 at SKC symposium and in November 2016 at the CARAT fuel subgroup meeting.

## 2. Background

Uranium nitride is among several fuel types that can replace a currently used UO<sub>2</sub> in LWRs. It is also suggested for use in future “Generation four nuclear reactors”. The main advantages of UN compared to UO<sub>2</sub> are higher thermal conductivity, higher fissile atom density and comparably high melting point (Youinou et al., 2014). On the downside, uranium nitride is incompatible with water – it hydrolyses (Rama Rao et al., 1991), dissolves and undergoes a mechanical erosion in hot circulating water. The hydrolysis process of pure UN that leads to UO<sub>2</sub> and NH<sub>3</sub> formation (Dell et al., 1967) and the mechanism is not yet well understood. Thus, various parameters of this reaction are being studied, e.g. the starting temperature and pressure, the exact structure of reaction products and also the effect of a fuel composition: density, porosity etc. on the reaction mechanism and reaction kinetics.

## 3. Experimental results and discussion

The experimental procedure consisted of the following steps:

1. Internal sol gel production of doped material: with use of glucose or carbon nano powder
2. Carbothermal reduction and sintering
3. Hydrolysis test in boiling water at normal pressure

Only a selected data were chosen as examples to keep an adequate extent of this report.

### Ad. 1 - glucose process

Goal: to achieve a homogeneous distribution of carbon in samples

The internal sol gel process was adjusted to suit our requirements, meaning that an Acid Deficient Uranyl Nitrate (ADUN) (Jeong et al., 2005) preparation was eliminated in order to use just one uranium source. A starting material - Uranyl Nitrate Hexahydrate (UNH) was produced from uranium metal by dissolving it in concentrated nitric acid. Since no other uranium source is needed in the procedure, both economical and time demands are positively affected. Moreover, such modification would allow a direct connection to the current reprocessing process of a spent nuclear fuel which is also based on dissolving the fuel in the nitric acid and forming uranyl nitrate. A feed solution was prepared according to desired composition by dissolving metal nitrates in water together with glucose (for more details see table 1) and put on a cooling bath. Glucose was used here to serve a double purpose: as a complexing agent of metal cations (replacing urea) and as a source of carbon.



Hexamethylentetramin (HMTA) was then added in the sol and then after the complete dissolution of HMTA the sol was transferred into a column filled with a heated silicon oil to form spheres of gel. The spheres were then washed in a petroleum ether to remove the silicon oil and aged in ammonia solution to complete the gelation and to remove the by-products (Idemitsu et al., 2003). An average shape together with a diameter of spheres were examined by SEM Hitachi TM 3000 microscope. The carbon and metal distribution both on the surface and in the bulk of air dried spheres was determined by Energy Dispersive X-ray Spectroscopy (EDS) with use of Quantax 70 software.

Table 1. The composition of sols for the internal sol gel process of uranium-chromium, uranium-nickel, uranium-aluminum and uranium-thorium materials production.

/... molar ratio	x = Cr	x = Ni	x = Al	x = Th
U [mol/L]	0,98	1,03	1,01	1,00
x [mol/L]	0,12	0,06	0,11	0,05
U wt%	97,2	96,6	98,8	94,0
x wt%	2,8	3,4	1,2	6,0
x vol%	9,8	8,4	7,4	8,9
x mol%	11,7	12,5	10,0	6,1
C/U	2,52	2,49	2,89	12,60
C/M*	2,24	2,36	2,60	12,00
HMTA/M	1,90	1,84	2,27	1,81
HMTA/H+	0,90	0,92	1,08	0,86

\*vol% calculated for Cr<sub>2</sub>O<sub>3</sub>, NiO and Al<sub>2</sub>O<sub>3</sub> \*\*M = uranium + metal(x)

The main advantage of this process is, that less compounds (glucose, HMTA) are used compared to initial method (surfactant, CNP, urea, HMTA). Both carbon and metals (e.g. U/Cr system on Fig 1) were homogeneously distributed all through the sample in all four cases and that is considered to be a necessary condition for a complete conversion of oxide to nitride in the following carbothermal reduction step.

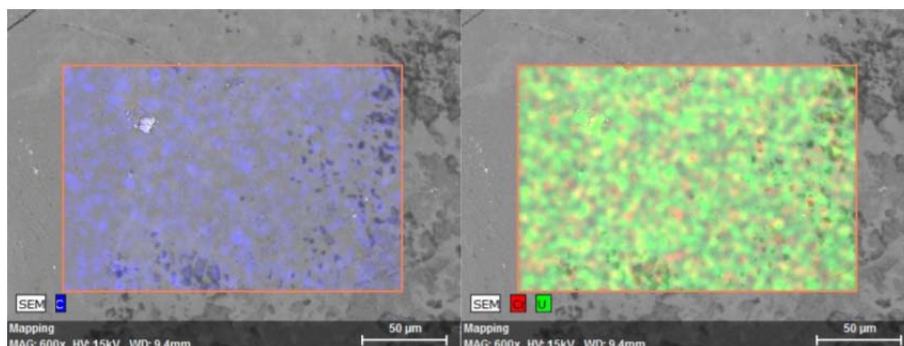


Figure 1: SEM/EDS mapping of carbon and metal distribution on uranium-chromium sample



### Ad. 1 - carbon nano powder process

A feed solution was prepared according to desired composition (table 2) by dissolving metal nitrates in water together with non-ionic surfactant and CNP. Urea was then added to a sol and finally HMTA.

Table 2. The composition of sols for the internal sol gel process of uranium-chromium, uranium-nickel, uranium-aluminum and uranium-thorium materials production.

/... molar ratio	x = Cr	x = Ni	x = Al	x = Th
U [mol/L]	1,5	1,51	1,51	2,5
x [mol/L]	0,19	0,18	0,22	0,13
U wt%	97,3	97,2	98,5	95,1
x wt%	2,7	2,8	1,5	4,9
x vol%	9,5	7,0	8,9	7,4
x mol%	11,3	10,6	11,9	5
C/U	2,49	2,48	2,50	2,72
C/M*	2,21	2,22	2,18	2,59
HMTA/M*	1,69	1,70	1,66	1,80
UREA/M*	1,28	1,29	1,25	1,42
HMTA/H <sup>+</sup>	0,80	0,85	0,78	0,86

\*vol% calculated for Cr<sub>2</sub>O<sub>3</sub>, NiO and Al<sub>2</sub>O<sub>3</sub> \*\*M = U+x

The main disadvantage of this process is, that carbon in the product form aggregates. Also, because of CNP leaks into ammonia during aging step, it is not possible to control the amount of carbon in the product. But metals (e.g. U/Cr system on Fig 2) were homogeneously distributed all through the sample in all four cases.

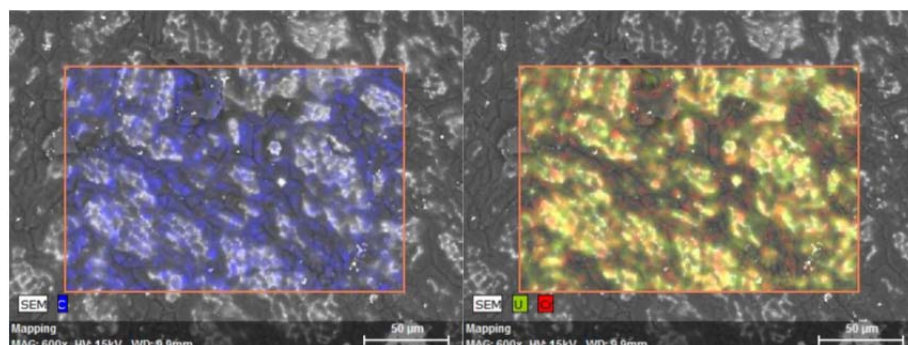


Figure 2: SEM/EDS mapping of carbon and metal distribution on uranium-chromium sample

### Ad. 2

The carbothermal reduction of air dried spheres was performed in a high temperature graphite heated furnace in the mixture of nitrogen and hydrogen at 1500 °C for 6 hours. The product after thermal treatment was examined by SEM/EDS (e.g. Fig 3) in order to evaluate a metal distribution and the microstructure of spheres. One portion was also grinded into a fine powder to perform an XRD measurement and to detect the crystallographic structure of a sample and verify a solid solution formation during the thermal treatment.

The samples were then pressed into a green pellet, either from intact microspheres or from a fine powder made of spheres. The green pellets were then sintered in argon at 1800 °C for 6 hours. The mass and the dimensions of the pellets were then measured to estimate the density.



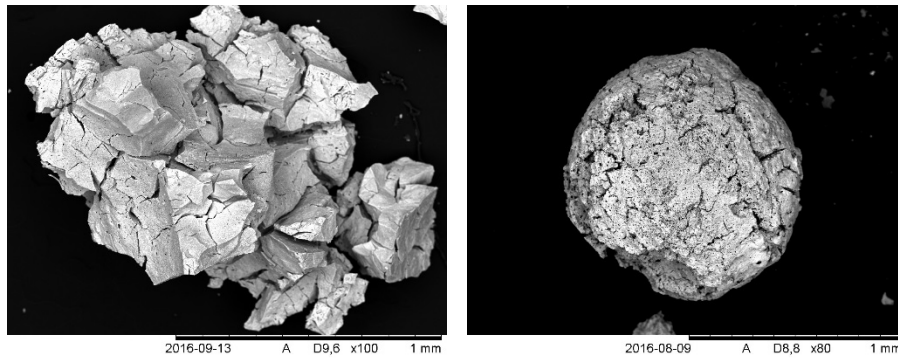


Figure 3: A SEM photo of uranium-chromium sample after carbothermal reduction (left – glucose process, right – CNP process)

A desired UN phase was formed in all samples during the carbothermal reduction (e.g. Fig 4, 5). Other metal nitrides (CrN) were also identified by XRD together with oxide structures ( $\text{UO}_2$ ,  $\text{UO}_3$ ,  $\text{Cr}_2\text{O}_3$ ). Doping metals chromium nickel and aluminum didn't remain evenly distributed after the reaction re-localized (Uranium-thorium spheres were not yet tested).

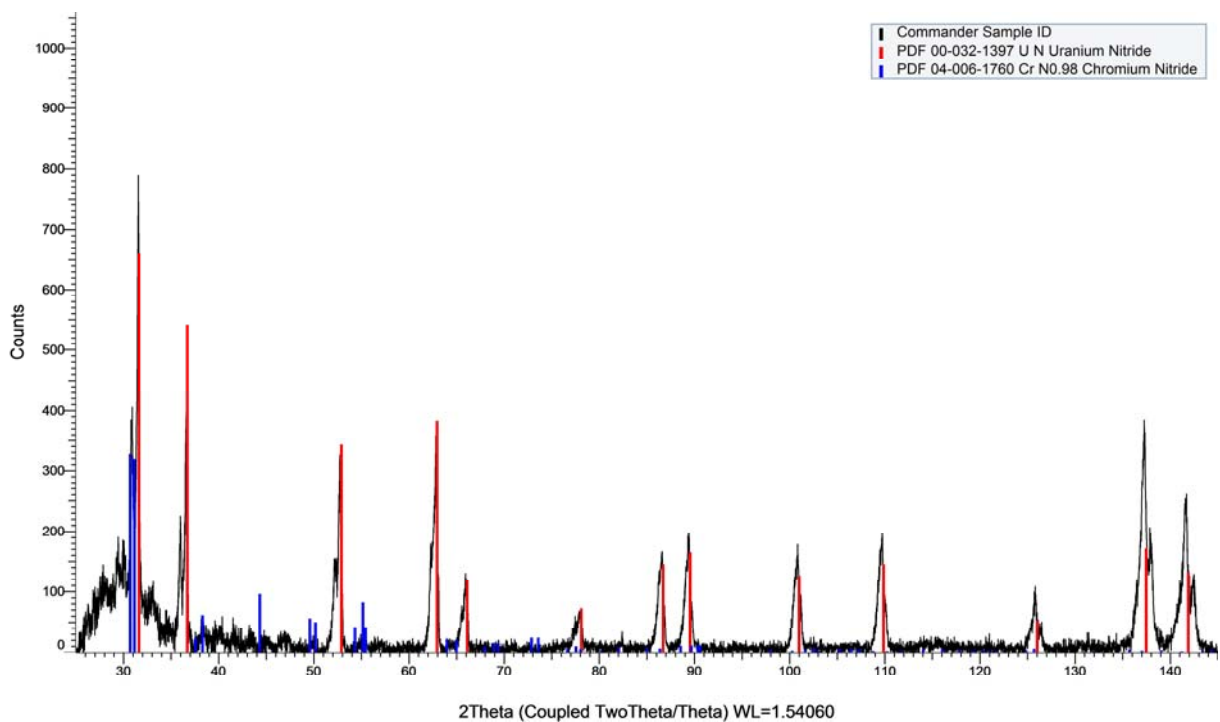


Figure 4. The XRD pattern of U-Cr sample after carbothermal reduction, the major phases correspond to uranium and chromium nitrides.





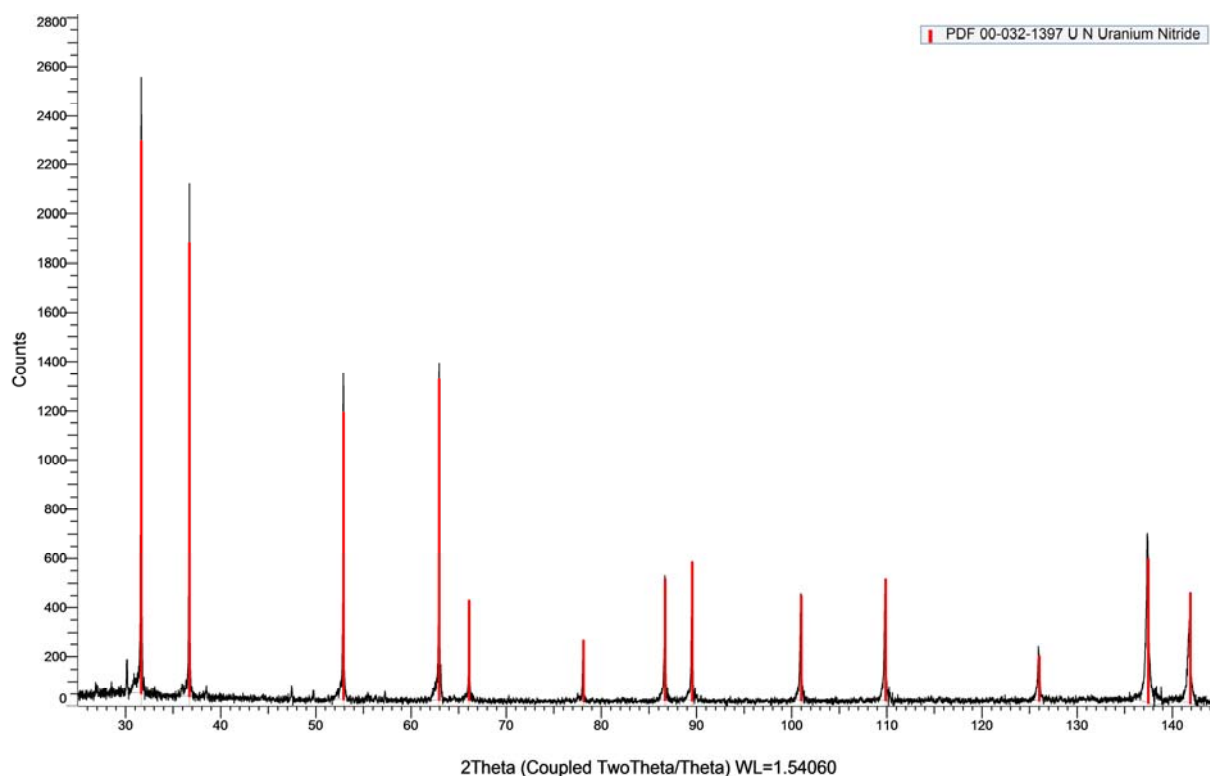


Figure 5. XRD pattern of U-Ni sample after carbothermal reduction, the phase corresponds UN.

The high theoretical density in produced pellets wasn't reached yet (table 3). Also, during the sintering the doping metals reacted in the material in different ways, e.g. chromium content significantly decreased on the surface, nickel was located along the grain boundaries and found in metallic form and aluminum formed an aggregate on the rim of the pellet.

Apart from this, nickel was confirmed as a sintering agent, U-Ni pellet shrinkage was the biggest. And in case of U-Cr microspheres prepared by "glucose process" (Fig. 3 left), a binder (Zinc Stearate) must have been used to be able to press a green pellet.

Table 3: The calculated densities and shrinkage of pellets U/Cr, U/Ni, and U/Al.

U-Cr	TD of UN	40 %	TD of UO <sub>2</sub>	59%	shrinkage	6 %
U-Ni	TD of UN	57%	TD of UO <sub>2</sub>	138%	shrinkage	23 %
U-Al	TD of UN	51%	TD of UO <sub>2</sub>	75%	shrinkage	18 %

### Ad. 3

The pellets were put on a glass holder and hanged roughly in the middle height of glass beaker containing deionized water. The beaker was heated up to boiling and stirred to ensure an equal temperature in the entire volume.

A pure uranium nitride pellet was used as a reference sample. This pellet collapsed after 2 hours of boiling. A bubble formation from the pellet surface was observed signaling either degassing of pores or gaseous ammonia formation.

U-Cr pellet was boiled for 5 hours without collapsing (Fig 6), U-Al and U-Ni pellets dissolved after a few minutes in boiling water. This indicates a clear improvement in corrosion resistance of U-Cr material.





Figure 6. U-Cr pellet before (left) and after a dissolution test (right).

XRD pattern of the U-Cr pellet revealed a uranium oxide and uranium nitride phase on the surface together with  $\text{Cr}_2\text{O}_3$  phase.

#### 4. Future work

A further research of selected dopants or their mixtures (Cr, Ni, Th) will be executed. A deeper study of chromium protecting mechanism will be done. Nickel will be used as a co-dopant (e.g. U-Cr-Ni) to better the densification of such material. Also a sintering at lower temperatures by e.g. spark plasma sintering technique will be tried to prevent from chromium losses. Dissolution tests of possible water resistive materials will be performed in the dissolver at high temperatures and high pressures.

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### Irradiation Assisted Stress Corrosion Cracking

#### Research leaders

Pär Olsson, Reactor Physics, KTH

Mats Jonsson, Applied Physical Chemistry, KTH

Ph.D. student or PostDoc worker: Elin Toijer

Other participants: Bo Alfredsson, Pål Efsing: Solid Mechanics, KTH



## Finances

The SKC funds have been used to cover the salary of the PhD student and some travels. The SKC funds have covered about 80% of the total cost of the project.

## Project activities

### *Overview*

Irradiation-assisted stress corrosion cracking (IASCC) is one of the potentially life limiting phenomena of components in light water reactors today as suggested in time limiting ageing mechanism analyses, TLAA, at various power plants. The decrease of critical stress for onset of crack initiation, and the time dependent degradation of the mechanical strength of the metallic components can severely limit the lifetime of reactor vessel internal components. The combined effect of persistent radiation, aggressive water chemistry and applied primary and secondary strains are the underlying factors for the cracking. The water chemistry for the reactor internals is, relative to other reactor components, affected by the irradiation primarily through radiolysis, by changing the corrosion potential through formation of radiolytic radicals and molecules that can be either reducing or oxidizing. At the same time, the component material is affected by the irradiation by the introduction of point defects. Their diffusion evolves the microstructure of the material. Numerous radiation induced phenomena are activated simultaneously, such as radiation-induced segregation, dislocation loop formation, subsequent hardening, swelling and irradiation induced creep. Taken together, the radiolysis and the microstructure evolution opens up new pathways for cracking that would not appear in the absence of a corrosive chemical or a radiation environment. The underlying mechanisms for IASCC are not satisfactorily understood and make predictions on the cracking behavior, considering all environmental factors, very challenging. Even the stress corrosion cracking evident in the absence of irradiation is not entirely consensually understood, although the common crack growth mechanism seems to be a reasonable candidate.

### *Activities in 2016*

Within the framework of the experimental part of the project, we have been conducting a study of the reaction between the radiolysis product H<sub>2</sub>O<sub>2</sub> and 304L type austenitic steel. Both the kinetics and the mechanisms of this reaction is studied. This part of the project is expected to finish soon and result in a publication, to be submitted early 2017.

The modeling of impurity and defect diffusion (and energetics) near grain boundaries is advancing well, although the quite extensive computational load has led to some delays (there has been some competition between students to use the supercomputers). Elin has been successfully developing codes and methods to pre-process her supercomputer simulations. Publication is planned for 2017.

We have been planning an experimental campaign on radiation induced crack growth between the three pillars of the project (reactor physics, applied physical chemistry and solid mechanics). These studies will, however, require additional funding to commence.

Elin has been finishing her course work in good time and according to plan.

## Plans

Description of plans for 2017 (relating to milestones not yet reached).

Soon a series of experiments with the aim of clarifying the effects different anions have on radiation induced reaction on oxide surfaces will be started. We will also begin by studying how chloride and bicarbonate affects reactions on ZrO<sub>2</sub>.

The study of impurity and defect diffusion to grain boundaries is nearing completion and should be ready for publication during 2017.

## Publications

Nothing published yet.



## Nuclear Fuel Diagnostics

**Research leader:** Dr. Peter Andersson (Researcher), Division of Applied Nuclear Physics, Department of Physics and Astronomy, Uppsala University

**Participants:** Dr. Staffan Jacobsson Svärd and Prof. Ane Håkansson, Division of Applied Nuclear Physics, Department of Physics and Astronomy, Uppsala University and Scott Holcombe OECD Halden Reactor Project, Norway

### Finances

Project funding was granted by SKC with in total 1030 kkr over three years (2014-2016). In agreement with the application granted by SKC, the funding is used to cover 50% of the expenses for a 2-year postdoc researcher within MÅBiL. Following the announcement of a postdoc position in 2014, Peter Andersson was hired and started his 2-year postdoc appointment on February 1<sup>st</sup> 2015. The project is co-funded by grants from FKA and by internal UU funding.

By the end of 2016, 69% of the total SKC project grants had been used. This has been affected by the fact that the postdoc used parental leave during the period and thus there will be a prolongation of the project with a time corresponding to the parental leave. Presently, Peter Andersson back on 100 %. Accordingly, the use of the project funding will continue several months into 2017.

## Project activities

### Background

The OECD Halden Reactor (OECD-HRP) is a world-leading laboratory for research on nuclear fuel and reactor materials. The unique HBWR reactor enables studies of nuclear fuel behavior during normal operation as well as transient and accident scenarios, such as LOCA. The closed loops used in the reactor even allow fuel ruptures during the tests. Uppsala University has established a collaboration with OECD-HRP, which covers the following topics:

- Take part in developing analysis techniques
- Perform analyses of collected data from irradiation experiments
- Participate in the evaluation of Accident-Tolerant Fuels

A recent collaboration project resulted in the construction and demonstration of a tomographic measurement device, designed specifically for use at OECD-HRP, which has now been brought into use and started to produce data on test fuel from the HBWR.

### Project description and status

The MÅBiL sub-programme Fuel diagnostics started in February 2015 with the assignment of Peter Andersson on a postdoc position which is 50% funded by SKC. During 2016, the focus has been on non-destructive measurements of irradiated nuclear fuel using gamma tomography.

New methods have been developed for the quantitative, high resolved reconstruction of gamma-emitting nuclides in cross-sectional images of fuel assemblies using the gamma tomography technique. These methods have been incorporated in an analysis code, UPPREC. The code uses an iterative process, where the important attenuation distribution of the gamma rays in the fuel is first neglected to perform a naïve reconstruction. Subsequently, this is used for localization of rod positions with the template matching technique [1], to allow for the attenuation correction in the response function used by the reconstruction code. Using the improved description of the gamma transport, a new reconstruction less affected by systematic errors can be performed, where in turn structural components of the assembly may be localized and accounted for, finally achieving a quantitative image of the reconstructed nuclide concentration in the assembly, where all important attenuating structures are



correctly accounted for. The methods used have been presented in a draft submitted to *Annals of Nuclear Energy* in the end of 2016 [2]. See a demonstration reconstruction in *Figure 4*.

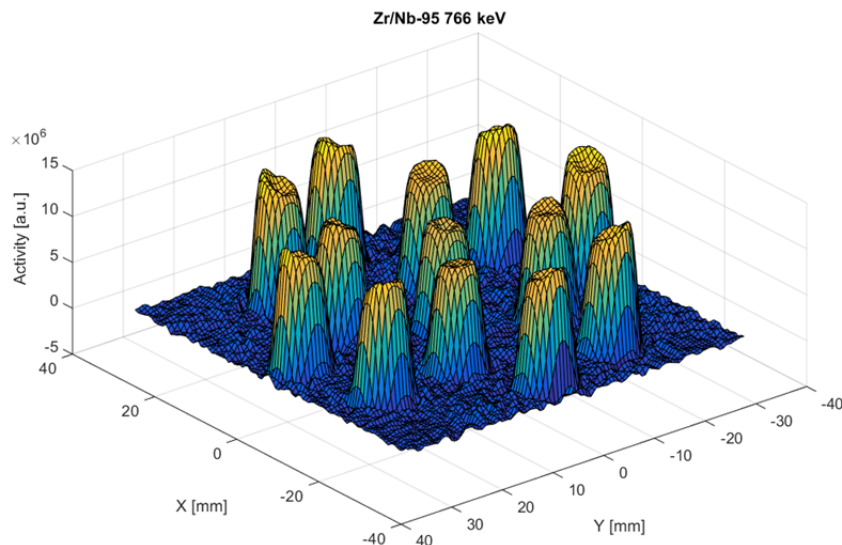


Figure 4. Example of tomographic reconstruction (Zr-96 inventory) in a 13 pin HRP driver fuel. Note the various features of the distribution that are visible, such as higher power (and therefore higher inventory) in periphery of the rods and towards the outside of the bundle.

We participated in the ongoing HRP LOCA test series, by performing and analysing the measurements of the relocated fuel distribution using gamma tomography. The inspection which was proposed and planned by us was executed in the beginning of 2016. Preliminary qualitative reconstructions were performed and the analysis tools have also been modified in order to account for the nonhomogeneous attenuation distribution if relocated fuel fragments, to allow for quantitative reconstructions. The subsequent quantitative analysis is still ongoing. The preliminary qualitative results have been presented at EHPG Sandefjord [3] and TopFuel Boise [4]. The technique has been integrated in the LOCA series for the future tests.

The fission gas release fraction has been studied in a HRP fuel assembly using the tomographic reconstruction of  $^{85}\text{Kr}$  in the fuel plenum and the  $^{137}\text{Cs}$  in the fuel stack. The concentration of  $^{85}\text{Kr}$  in the fuel was calculated based on the  $^{137}\text{Cs}$  concentration corrected for differences in e.g. fission yield and half-life to estimate the fraction of produced fission gas that had been released. The results were in good agreement with benchmark data collected using the conventionally used technique of single-rod gamma scanning. Tomography has the potential to speed up the measurements, as compared to single rod scanning, and in addition it requires less manual handling of the fuel. The results were presented in NIM A [5].

### Fulfilling of projects goals

The goals stated for the fuel diagnostics project in the MÅBiL application for 2014-2016 was to support the research and development of techniques for evaluation of fuel performance in connection to irradiation testing. Special focus was put on developing experimental techniques for future assessments of Accident-Tolerant Fuels (ATF), stated explicitly in terms of; (1) Fission gas release from fuel during transients, and; (2) Fuel behaviour during accident conditions, such as LOCA.

The results so far show that the goals have largely been reached within the project. Firstly, new methodology for measurements of fission gas release have been tested, analysed and presented in a scientific journal. Secondly, tomographic measurements have been performed of test rods subjected to LOCA in the HBWR, and preliminary results indicate that ballooning and failure of cladding as well as cracking and relocation of pellet material can be assessed with this technique. The technique has been included in the plans for the future LOCA tests, and further refinement of the method to get quantitative data packing fraction estimates is underway. In the end, the



experimental techniques developed within MÅBiL are expected to be highly useful in the analyses also of irradiation tests of new fuel types such as ATF, once these are irradiated and available for this type of assessment.

## Plans

A new focus in 2017 will be on the usage of Gamma Emission Tomography for identification of leaking fuels rods in PWR fuels at commercial reactors. The feasibility and requirements on the setup will be investigated and potentially demonstrated. Parallel to that, current activities continue (i.e. development of quantitative reconstruction methods, implementation of GET in the LOCA test series at HRP.)

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- [2] Andersson P., Holcombe S.; "A computerized method (UPPREC) for quantitative analysis of irradiated nuclear fuel assemblies with gamma emission tomography at the Halden reactor"; Submitted to Annals of Nuclear Energy, 2016. [3] Andersson P., Holcombe S., Tverberg T.; "Inspection of LOCA Test Rod IFA-650.15 Using Gamma Emission Tomography"; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-283654>; (2016)
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## Nuclear data uncertainty propagation with Total Monte Carlo for fuel – method development and applications

Ph.D. student: **Petter Helgesson**

Main supervisor: Univ. lekt. Henrik Sjöstrand

Assistant supervisors: Prof. Arjan Koning (IAEA, Vienna), Dr. Dimitri Rochman (PSI, Switzerland), Prof. Klaes-Håkan Bejmer, Prof. Stephan Pomp

Petter Helgesson started his Ph.D. studies in August 2013 in collaboration with Nuclear Research and Consultancy Group (NRG) in Petten, the Netherlands. A detailed description of the aims of this project is found in the previous annual report.

Petter works within the MÅBiL project, and his results hitherto are also reported in the MÅBiL Annual Report.

During 2016, there has been a continued emphasis on aging parameters, and in this work, Petter Helgesson connects macroscopic fuel and aging parameters to the fundamental nuclear physics processes by using the nuclear model code TALYS and the Total Monte Carlo Method (TMC) method.

During 2016 Petter has continued investigated  $^{59}\text{Ni}$ , since the two-step thermal neutron reaction sequence  $^{58}\text{Ni}(n,\gamma)^{59}\text{Ni}(n,\alpha)^{56}\text{Fe}$ , ( $Q_{\text{value}} = 5,1 \text{ MeV}$ ) results in non-linear He production rates and is an important





contribution to the He production in steel in thermal spectrum. The reaction sequence is also a significant contribution to the damage energy. He is also investigating the hydrogen producing reaction sequence:  $^{58}\text{Ni}(n,\gamma)^{59}\text{Ni}(n,p)^{59}\text{Co}$ , ( $Q_{\text{value}} = 1.9 \text{ MeV}$ ). Currently, existing evaluated data has no uncertainty information, neither for  $^{59}\text{Ni}(n,\alpha)^{56}\text{Fe}$  nor  $^{59}\text{Ni}(n,p)^{58}\text{Co}$  reactions, in the thermal region.

To improve the He production prediction and to provide nuclear data uncertainty estimates, new  $^{59}\text{Ni}$  cross section data has been produced. As opposed to existing evaluated data (for nuclides in general) the helium and hydrogen production cross sections have been produced using relevant resonance parameters using Multi Level Breit Wigner approximation.

The lack of well-documented measurements on the cross sections in the resonance region makes the actual values of the resonance parameters very uncertain. The cross-sections are generated from average unresolved resonance parameters and sampled with a high uncertainty, after which they are adjusted to the experimentally known thermal cross sections and their uncertainties. The cross-sections have been produced in ENDF-6 format, including so-called random files, for usage by the nuclear community.

To check the performance of the random files, they have been tested on an MCNP-6 model. The results were compared to He and H production rates in a reference case. It was found that the inclusion of  $^{59}\text{Ni}$  increased the helium production rate by a factor of  $5.2 \pm 0.3$ . The uncertainty is due to the uncertainty in nuclear data. It was also found that there were some discrepancies between the results obtained with these new files and the result which was obtained using ENDF/B- VII.1. The results have also been validated against experimental transmission data.

The results have been accepted for JEFF.3.3 T2 (Joint Evaluated Fission and Fusion File test version 2). The results were presented at ND2016, and a full article has been written and reviewed by SKC and was submitted beginning 2017.

The work has during 2016 been presented at the IAEA Nuclear Reaction Data and Uncertainties for Radiation Damage Technical Meeting, at ND2016, JEFF Co-ordination Group Meeting.

During 2016, Petter has also continued to work on statistical stringent ways to include experimental information in TMC. For this, collaboration with Los Alamos has been started. In this work, different techniques to evaluate nuclear data have been evaluated. This will allow us to choose the best approach when assessing nuclear data for a wide range of quantities. The work has had some emphasis on the prompt fission neutron spectrum, which plays an important role in e.g. pressure vessel dosimetry. The work has been accepted for presentation at the International Symposium on Reactor Dosimetry 2017.

## Publications (submitted, accepted and published during 2016)

### Journal articles

Helgesson P., Sjöstrand H., J. Koning A., Rydén J., Rochman D., Alhassan E., Pomp S.; "Sampling of systematic errors to estimate likelihood weights in nuclear data uncertainty propagation"; Journal: Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment; Vol: 807; Publisher: Elsevier; DOI: 10.1016/j.nima.2015.10.024; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-265321>; (2016)

P. Helgesson, H. Sjöstrand, A.J. Koning, J. Rydén, D. Rochman, E. Alhassan, S. Pomp, Combining Total Monte Carlo and Unified Monte Carlo: Bayesian nuclear data uncertainty quantification from auto-generated experimental covariances, Progress in Nuclear Energy, Volume 96, April 2017, Pages 76-96, ISSN 0149-1970, <http://dx.doi.org/10.1016/j.pnucene.2016.11.006>.

P. Helgesson, H. Sjöstrand, Uncertainty driven nuclear data evaluation including thermal (n, $\alpha$ ): applied to  $^{59}\text{Ni}$ , (prepared and reviewed by SKC during 2016, submitted to NDS 2017)



### Conference contributions

P.Helgesson et al., Novel nuclear data evaluation combining sampling of experimental uncertainty components and TALYS parameters - Applied to helium production due to  $^{59}\text{Ni}$  in stainless steel, Oral and poster presentation at ND2016, International Conference on Nuclear Data for Science and Technology, 11-16/9 Bruges Belgium.

#### Other Scientific

Helgesson P., Sjöstrand H.; "Justified and complete gas-production cross sections with uncertainties for Ni-59 and consequences for stainless steel in LWR spectra"; Permalink:

<http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-313642>; (2016)

Helgesson P., Sjöstrand H., Rochman D., Koning A.; "Ni-59 cross section evaluation : covariance focus";

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Helgesson P.; "Evaluation of the Ni-59 cross sections including thermal (n,alpha), (n,p) and complete uncertainty information"; Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-313638>; (2016)

Griffin P., Sjöstrand H., Simakov S.; "Nuclear Reaction Data and Uncertainties for Radiation Damage : Summary Report of the Technical Meeting, IAEA Headquarters, Vienna, Austria 13 – 16 June 2016 (INDC(NDS)-0719)";

Permalink: <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-301968>; (2016)

### Continuing activities

The project is planned to continue according to the plan, with the modification to focus on structural materials such as Ni and Fe instead of Si.

### Planned publications 2017

Petter Helgesson, Denise Neudecker, Roberto Capote, Henrik Sjöstrand, Donald L. Smith, and Michael Grosskopf, ASSESSMENT OF NOVEL TECHNIQUES FOR NUCLEAR DATA EVALUATION, International Symposium on Reactor Dosimetry, 2017-05-07/2017-05-12 (Santa Fe, New Mexico, United States)

The Impact of the Retroactive Method for Resonance Parameter Uncertainties and Consequences for LWR Aging Parameters, Journal publication

