



Swedish Centre for Nuclear Technology

# SKC

# Annual

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# Report 2014

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## Summary of 2014 – and a few more words ...

*'Change and adapt'* is perhaps the phrase that best describes SKC's activities and challenges during 2014. A new SKC contract period started in January. The tough situation that SKC's financiers face in the electricity market is reflected in a lower budget and a shorter contract period. In order to cope with the new situation, SKC has embarked on a journey of doing what its financiers are doing on a much larger scale:

- focus on what is important,
- cooperate,
- cut costs & increase efficiency, and
- improve communication.

### *Focus on what is important*

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 energy supply. The industry intends to run the ten Swedish nuclear power plants for another 10-30 years. All Swedish reactors have now reached or passed half of their planned lifetimes of fifty or sixty years. Ensuring safety is the major prerequisite to achieve the goal of life time extension. One of the main challenges today and in future is learning more about material ageing and degradation. As a response to the industry's need and demand, a large part of the SKC project funding has been allocated to material research. A new project called MÅBiL started in 2014. MÅBiL, which stands for academic research within material, ageing and fuel, consists 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.

It should be noted that the increased focus on material technology is primarily in research activities. Nuclear education continues to be dominated by traditional areas such as nuclear and reactor physics as well as thermal hydraulics.



### *Cooperate*

SKC has during the years been a cooperation between the nuclear industry on one side and the academia on the other. Cooperation among the academia or even between the different faculties of the same academy has not been among the characteristic strengths of SKC and always left more to wish for. With a new reality to relate to as a result of the tough situation in the electricity market, with campaigns to decrease costs and increase effectiveness ongoing in the industry, the question of cooperation among and within the academia should now be regarded as a long-term survivability issue, rather than an aesthetic ambition. SKC's financing partners have during the years demanded increasing cooperation among and within the academic partners – with limited results. Year 2014 however, has shown a positive trend with respect to cooperation. Within the framework of the project MÅBiL, with representatives from Uppsala University, KTH, Chalmers and experts from the industry, a comprehensive research collaboration has started in order to address some of the important challenges ahead regarding the safe and effective operation of the ageing fleet that produces a major part of Sweden's electricity needs. MÅBiL is in its start-up phase and it may still be somewhat early to judge it from a cooperation perspective - but what has been observed up to now is a harbinger of hope for future.

Another fruit of cooperation in 2014 was SKC's new information magazine. It was made possible through a real cooperation between SKC's partners who provided text, pictures and ideas for the magazine. The magazine contains articles on ageing, life time extension and gender/ethnic equality combined with interviews about what engineers work with in the industry. An electronic version of SKC's magazine can be downloaded from SKC's homepage.

### *Cut costs & Increase efficiency*

SKC's annual budget includes administrative costs which in 2014 was planned to amount to approximately 15% of the total budget. The lower total budget of SKC in the present contract period has motivated measures to be taken to reduce the administrative costs and thereby transfer more resources to research and education. As a result, SKC's year-end result for 2014 shows a surplus – despite a deficit in the beginning of the year. The cost cutting measures implemented in SKC have reduced the administrative costs for 2015/2016 to 10% of SKC's total budget. The surplus for 2014 in combination with reduced administration budget is going to be paid to the academia for research and education during 2015 and 2016.

The major contributor to the cost reductions in SKC's budget has been SKC's guidelines for communication, in accordance with which advertising in paper or digital media was eliminated – starting January 1<sup>st</sup> 2014.

### *Improve communication*

At the request of SKC board a communication plan was drafted early in 2014, and approved by the board later in the year. The communication plan provides guidelines for SKC's external and internal communication:

- *SKC's main target group:* students and researchers in academia.



- *Communication goals:* Fact-based information to, and information exchange with the target group. Networking and development of contact between the target group and employees with corresponding education in the industry.
- *Visibility:* Active participation in student fairs at KTH, Chalmers, and Uppsala university; through SKC homepage; SKC's new information magazine.
- *Publicity* – No *direct* activities to affect public opinion. No *direct* presence in mass media under the umbrella of SKC.

During 2014 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 Viktor Dykin at Chalmers for his work on noise applications in light water reactors. Kaur Tuttelberg received the prize for the best masters' thesis for his work on Monte Carlo reactor physics calculation. The prizes were awarded to the winners at the dinner ceremony of SKC's yearly symposium that was held at KTH on October 9-10 2014.

*And finally ...*

In less than a year from now the negotiations on renewing the SKC contract for a new period will be under way. With a large power reserve, decreasing demand, increasing introduction of production capacity in a shrinking market, and as a result low electricity prices, the economic challenges to be overcome by SKC's financiers will continue to grow for a few more years – necessitating further efforts to cut costs. SKC has played an important role as a bridge between universities, regulator and industry for more than two decades. In spite of the structural changes and financial challenges, SKC has a constructive role to play for many more years to come. Let's hope that when the moment of decision comes, SKC's financiers will envisage the continuation of this cooperation to be in the long-term interest of the nuclear industry.



Farid Alavyoon, SKC Director, 2015-03-12



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## SKC-Partners, Tasks and Goals

**Swedish Center for Nuclear Technology SKC** – (Svenskt Kärntekniskt Centrum [www.swedishnuclear.se](http://www.swedishnuclear.se)) was originally founded in 1992 (under the name of KTC, Kärntekniskt Centrum, at KTH). The center is a collaboration organizationally linked to the School of engineering sciences at KTH (KTH/SCI). Ending the earlier 6-year contract, the SKC collaboration entered a new 3-year contract on January the 1<sup>st</sup> 2014.

The partners in the SKC collaboration are the nuclear industry (financing parties)

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

and the educational centres

- KTH Royal Institute of Technology ( <http://www.kth.se/> )
- Chalmers University of Technology ( <http://www.chalmers.se/sv/Sidor/default.aspx> )
- Uppsala University ( <http://www.uu.se/> )

SKC supports education and research in disciplines applicable to nuclear technology.

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

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

An education program is also supported by financial contributions to senior positions at the universities.

Some areas of interest to the SKC partners within the research programs 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 reliable electricity production.

The overall goals of SKC are:

- ✓ 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.

Research on Gen. IV is not supported by SKC according to the directive of the SKC financing partners.



## Organization and funding

Svenskt Kärntekniskt Centrum – SKC – entered a new 3-year contract period on 1<sup>st</sup> of January 2014. The partners and organization are the same, except that SSM does no longer participate as a financier. The total volume for the three years is 32 300 000 SEK.

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

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

The contract states that the financiers should contribute 10.766 million SEK 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 2014, the advisory council consisted of:

- Per Brunzell, Chairman
- Mattias Olsson, Forsmarks Kraftgrupp AB
- Henrik Dubik, OKG AB
- Björn Forssgren, Ringhals AB
- Ingemar Jansson, Westinghouse Electric Sweden AB

SSM was not represented in the advisory council during 2014 although according to the SKC contract the regulator may have an observer in the council. Farid Alavyoon has attended the meetings as secretary.

During 2014, the SKC Board consisted of:

- Karl Bergman, Chairman, Vattenfall AB
- Lars Berglund, Forsmarks Kraftgrupp AB
- Andreas Roos, OKG AB
- Henric Lidberg, Ringhals AB
- Eva Simic, SSM – observer status
- Anders Andrén, Westinghouse Electric Sweden AB
- Leif Kari, KTH Royal Institute of Technology
- Måns Östring, Uppsala University
- Mats Viberg, Chalmers University of Technology

SSM was represented in the Board during 2014 according to the SKC contract that allows an observer status for the regulator. Farid Alavyoon attended the board meetings but has not participated in votings.



## SKC Financial statements 2014

The following table summarises the SKC financials for 2014:

### Revenues SEK

Payment Westinghouse Electric Sweden AB	2 833 666
Payment Forsmarks Kraftgrupp AB	2 380 000
Payment Oskarshamns Kraftgrupp AB	2 380 000
Payment Ringhals AB	3 173 666
<b>Sum Payment</b>	<b>10 767 332</b>
Payment French laboratory support	3 398 777
<b>Sum Payment</b>	<b>3 398 777</b>
<b>Sum incoming payments</b>	<b>14 166 109</b>

### Spending SEK

Payout Chalmers	2 610 000
Payout KTH	2 775 000
Payout UU	2 868 000
Payout SKC central administration	1 663 332
<b>Sum Payout</b>	<b>9 916 332</b>
Payout French laboratory support	3 859 559
<b>Sum Payout</b>	<b>13 775 891</b>

### Output Balance 2014 (transferred to 2015) SEK

Remaining funds SKC central administration	+383 720
Remaining funds French laboratory support	+701 437
Remaining funds transference account SKC	+851 000
<b>Sum remaining funds = input total</b>	<b>1 936 157</b>



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

Westinghouse	26.316%
Ringhals	29.474%
Forsmark	22.105%
OKG	22.105%

Comments:

1. At the end of 2013 SKC had a year end balance of -107 704 SEK. For French laboratory support the balance was +1 162 219 SEK.
2. The positive balance by the end of 2014 is due to the following reasons:
  - Savings in the administrative costs of SKC as a result of reducing marketing and eliminating advertising activities.
  - For 2014 an administrative cost of 250 kSEK was transferred from the French support to SKC's central administration.
  - Due to the late start of the project MÅBiL, an amount of 851 kSEK dedicated to the project was not paid to the academia in 2014. This amount is held in SKC's transferring account ( #46532) and will be paid to the academia in the first quarter of 2017.





## Winners of the Sigvard Eklund Prize in 2014



*Left to right, standing: Kaur Tuttelberg, Farid Alavyoon and Viktor Dykin. Picture from the prize ceremony at the old reactor hall R1 in Stockholm during the SKC Symposium 2014.*

Viktor Dykin, Chalmers University of Technology, was awarded the prize for the best **Ph.D. thesis** with the title: Noise applications on light water reactors with travelling perturbation. The work has been supervised by professors Christophe Demazière and Imre Pázsit.

The review committee described Viktor's work as follows:

“This very substantial original work in the field of nuclear reactor operation safety combines neutronics and thermal-hydraulics approaches to simulate the effect of propagating perturbations in Light Water Reactors. In particular, in the case of closed-loop systems, a reduced order model with four heated channels is successfully applied to study global and local instabilities in BWRs thanks to inclusion of the fundamental and both azimuthal modes. An example of application is given in the simulation of the Forsmark-1 instability event. Possible extension to Ringhals-1 is envisaged.

The work also presents important conclusions regarding the neutron noise diagnostics and their limits, and it explores two methods for the reconstruction of the axial void profile from the Monte Carlo simulated neutron noise in the case of bubbly flows, an important topic for reactor core management and surveillance.

The dissertation is clear and very well written and accompanied by a set of six journal papers and two conference papers published during the period 2009 – 2012.”



Kaur Tuttelberg was awarded the prize for the best **Masters' thesis**. Kaur is a student at the Talinn University of Technology, and did his Masters' thesis at the KTH Royal Institute of Technology under the supervision of Jan Dufek at the Nuclear Reactor Technology Division. The review committee motivated the choice of Kaur's thesis as the prize winner as follows:

“For contributions to the development of error estimation schemes in Monte Carlo criticality calculations, and specifically for innovative work on a method for improving the efficiency of such calculations in terms of optimal usage of computational time, and for high quality reporting and communication of the results, supported by publication of the material in refereed journals.”

*No* prize for the best **Bachelors' thesis** was awarded in 2014. The reason was that the reviewer and the SKC director Farid Alavyoon reached the conclusion that the submitted applications, though obviously good enough as thesis for the purpose of graduation, did not qualify for getting the Sigvard Eklund Prize.



## Appendix 1 - Chalmers University of Technology

### *Overview of Activities in 2014*



# CHALMERS

## *Sustainable Nuclear Energy Centre*

A new centre, called the Sustainable Nuclear Energy Centre (SNEC), was created on January 31, 2012 at Chalmers, and was formally inaugurated on October 8, 2012. This centre allows coordinating and structuring research, education, and communication about all aspects of nuclear energy and uses of radioactive elements in a comprehensive, responsible, and critical manner.

The main focus of the centre is on a Forum where researchers, MSc students, Ph.D. students, as well as industry members, meet to discuss and exchange ideas, information, and knowledge, thus contributing to a better networking between the industry, the academia, and its students.

The key feature of the Forum is that the industry representatives are in direct contact with Chalmers researchers, and can thus directly interact with them. It also creates a unique opportunity to discuss any issue with a variety of competences, thus favouring the actual problem formulation. Problem formulation and definition are often the most important steps towards a solution.

At present, the following research areas, each led by a senior scientist, are actively pursued at Chalmers:

- Computational and experimental fluid mechanics.
- Reactor physics and dynamics.
- Multi-physics and multi-scale modelling of nuclear systems.
- Deterministic safety analyses.
- Severe nuclear accidents.
- Fusion plasma physics.
- Radiation protection.
- Nuclear techniques.
- Particle and heavy ion Monte Carlo simulations.
- Degradation of nuclear materials.
- Non-destructive testing.
- Nuclear Safeguards.
- Nuclear fuel integrity management.
- Safety related to fuel coolant interactions.
- Novel nuclear fuel production.
- Separation/transmutation.
- Final repository.
- Technology assessment of nuclear expansion.
- Political aspects of spent nuclear fuel.

The Forum is mainly managed via a web-based platform used for assuring the proper dissemination of information within the centre and to the industrial SNEC members. The platform includes more than 120 users, gathering Chalmers researchers and students, as well as the representatives of the industrial partners supporting SNEC.

The 2014 industry members in SNEC include E-ON.



The coordination of SNEC is assured by a coordination group. Only the divisions at Chalmers being full SNEC members participate to the coordination group. The following Chalmers divisions/departments are participating to the coordination of SNEC:

- Div. of Nuclear Chemistry, Dept. of Chemical and Biological Engineering.
- Div. of Nuclear Engineering, Dept. of Applied Physics.
- Div. of Materials Microstructure, Dept. of Applied Physics.
- Div. of Advanced Non-destructive Testing, Dept. of Materials and Manufacturing Technology.
- Div. of Physical Resource Theory, Dept. of Energy and Environment.
- Div. of Fluid Dynamics, Dept. of Applied Mechanics.

The following Chalmers divisions/departments are participating to some extent to the Forum only, but are not full SNEC members:

- Dept. of Political Science (University of Gothenburg).
- Dept. of Literature, History of Ideas, and Religion (University of Gothenburg).
- Dept. of Mathematical Sciences, Chalmers.
- Div. of Materials and Surface Theory, Dept. of Applied Physics, Chalmers.
- Div. of Transport Theory, Dept. of Earth and Space Sciences, Chalmers.
- Div. of Dynamics, Dpt. of Applied Mechanics, Chalmers.
- Div. of Subatomic Physics, Dept. of Fundamental Physics, Chalmers.
- Fraunhofer Chalmers Centre.

Formal decisions are taken by a steering group, which is also responsible for the overall strategy of the centre. The departments having one of its divisions being a full SNEC member are represented in the steering group. The steering group also gathers one representative per industry member.

In 2014, the coordination group decided to focus the SNEC activities on a few and well-targeted events. Four main events were planned:

- A colloquium from Prof. Tomoko M. Nakanishi, from the University of Tokyo, Japan on March 11, 2014, with the title “Radiation and radioisotope studies in plants – including the radioisotope analysis at Fukushima”. This colloquium was co-sponsored by SNEC and by Gothenburg Physics Centre. The event was attended by people from the academia, and attracted about 40 persons, as well as some web-viewers.
- A seminar on ageing phenomena in nuclear power plants on May 8, 2014. The seminar was the results of a project financed by E-ON under the auspices of SNEC. This seminar was attended by about 50 persons, from the academia, the industry, and the regulatory bodies.
- An MSc/Ph.D. students – industry seminar, during which the students could first briefly present their projects, and could thereafter discuss the projects in more details via a poster session. This seminar was attended by about 30-40 persons, from the academia, the industry, and the safety authorities.
- The SNEC annual convention, held on November 25, 2014 on the theme “Sustainable nuclear education”, or how to maintain competences and knowledge in the nuclear area when the economic, political, and societal conditions have a strong influence on the future of the industry. More than 80 persons attended this event.

All SNEC events are recorded and some of them were even live-broadcasted. All events are available for on-demand viewing from the SNEC archive.



## Use of the SKC funding

The SKC funding is currently supporting three Divisions at Chalmers:

- Div. of Nuclear Chemistry, Dept. of Chemical and Biological Engineering.
- Div. of Nuclear Engineering, Dept. of Applied Physics.
- Div. of Materials Microstructure, Dept. of Applied Physics.

The facilities and tools available at these Divisions are as follows:

- A pulsed beam for variable energy slow positrons.
- A portable 14 MeV pulsed neutron generator.
- Access to all major system codes for neutronic and thermal-hydraulic calculations.
- Laboratories for  $\alpha$ ,  $\beta$ ,  $\gamma$  experiments and activity measurements.
- 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 18 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 Chalmers infrastructure Chalmers Materials Analysis Laboratory (CMAL) hosted by the Dept. of Applied Physics

The following Ph.D. projects were supported, either fully or partially, by SKC during 2014:

- Development of an integrated neutronic/thermal-hydraulic model using a CFD solver (Ph.D. student: Klas Jareteg; supervisor: Professor Christophe Demazière).
- Aging of reactor pressure vessel steel (Ph.D. student Kristina Lindgren; supervisor Professor Krystyna Stiller). The project is included in MÅBiL.

## Highlights of the year

Some of the highlights of the year are given below:

- A colloquium from Prof. Tomoko M. Nakanishi, from the University of Tokyo, Japan on March 11, 2014, with the title “Radiation and radioisotope studies in plants – including the radioisotope analysis at Fukushima”.
- The DREAM task force (Deterministic REActor Modelling) organized, for the second year in a row, an entirely web-based course in deterministic nuclear reactor modelling, which attracted 35 students: 9 of them were from Chalmers, and the other ones were from other universities in Sweden, Spain, Germany, Finland, and Brazil.
- Karin Rosenqvist, who graduated from the Nuclear Engineering master program, was one of the six recipients of the 2014 John Ericsson’s prize. The prize is attributed to students who got excellent grades during their studies, and who completed their education at a very high pace.
- A seminar on ageing phenomena in nuclear power plants on May 8, 2014. The seminar was the results of a project financed by E-ON under the auspices of SNEC.
- Ph.D. student Cheuk Wah Lau, from the Division of Nuclear Engineering, successfully presented and defended his Ph.D. thesis titled “Improved PWR Core Characteristics with Thorium-containing Fuel” on May 25, 2014.
- A novel research project titled "Development of Graphene-based Nuclear Fuel Cladding for Improved Safety" received 300 000 SEK from Ångpanneföreningen (ÅF).



- An MSc/Ph.D. students – industry seminar, during which the students could first briefly present their projects, and could thereafter discuss the projects in more details via a poster session.
- The Division of Nuclear Engineering hosted a tutorial/workshop with the title “Neutron noise techniques for reactor diagnostics” during the biannual topical meeting of the Reactor Physics Division of the American Nuclear Society (ANS), which was held between 28 September – 3 October 2014 in Kyoto, Japan.
- Lars Larsson completed his Ph.D. work in the research group Advanced non-destructive testing at the department of Material and Manufacturing Technology. In his thesis mathematical modelling of eddy current technique (EC) is used in order to simulate the non-destructive testing situation (NDT).
- The Fusion Theory research group at the Division of Nuclear Engineering received major grants from the Swedish Research Council (Vetenskapsrådet – VR). Prof. Tünde Fülöp was granted 10 000 000 SEK (2015-2018) for "Research for future fusion reactors: using or avoiding impurities" and 3 325 000 SEK (2015-2018) for "Runaway electrons in fusion plasmas". Dr. Istvan Pusztai was granted 3 200 000 SEK (2015-2018) for "Integrative modeling of transport barriers in fusion reactors" and 7 732 000 SEK (2015-2018) for "Integrative modeling of transport barriers in fusion reactors" (international career grant).
- Dr. Victor Dykin, researcher at the Division of Nuclear Engineering, received the 2014 Sigvard Eklund prize (Ph.D. category) from SKC for his Ph.D. thesis titled “Noise Applications in Light Water Reactors with Traveling Perturbations”.
- Mikael Andersson and Zsolt Elter, Ph.D. students at the Division of Nuclear Engineering, successfully presented their mid-term seminars on their Ph.D. projects, respectively titled “Influence of local spectral variations on control-rod homogenization in fast reactor environments, and convergence issues of the equivalence procedure” and “Investigation of fission chamber signals via theoretical models and numerical simulations”. Both Ph.D. students are currently stationed at CEA Cadarache, France and are working on the ASTRID project within a French-Swedish collaboration financed by the Swedish Research Council (Vetenskapsrådet – VR). The two seminars were organized at CEA Cadarache.
- Klas Jareteg, Ph.D. student at the Division of Nuclear Engineering, successfully presented, on November 24, 2014 his mid-term seminar on his Ph.D. project called FIRE – FIne mesh deterministic REactor modelling. The seminar was held in conjunction with reaching half of the Ph.D. study work.
- The SNEC annual convention, held on November 25, 2014 on the theme “Sustainable nuclear education”, or how to maintain competences and knowledge in the nuclear area when the economic, political, and societal conditions have a strong influence on the future of the industry.







Picture taken during the panel discussion organized at the SNEC annual convention. © Sabina Johansson

- Lovisa Bauhn, Ph.D. student at the Division of Nuclear Chemistry, presented her Licentiate thesis entitled "Homogeneous radiolysis studies using  $^{238}\text{Pu}$ " on December 15, 2014. Lovisa has developed a method for studying homogeneous alpha-radiolysis under final repository conditions, with the intention to determine the effect of dissolved bromide on the radiolytic yield of oxygen.
- SNEC got involved in the programme on Nuclear Materials organised by European Energy Research Alliance (EERA). The objective of this EERA JP on Nuclear Materials is to improve safety and sustainability of Nuclear Energy by focusing on materials aspects such as better knowledge of materials behaviour and development of innovative materials. This project is divided into in principle two parts, structural materials and nuclear fuel. Chalmers is involved in all aspects of JPNM.
- Fuel claddings from long term operation were investigated for the first time in the open literature using atom probe tomography by Ph.D. student Gustav Sundell (Redistribution of alloying elements in Zircaloy-2 after in-reactor exposure, JNM 454 (2014) 178).

In SKC-related subjects, the following Master theses were successfully presented during 2014:

- Patrik Fredriksson, Determination of Radial Power Profiles in Thorium-Plutonium Mixed Oxide Fuel Pellets.
- Albert Martin, New styrenic materials, a natural alternative to B in ABS.
- Yehya Alazem, Bioreduction of technetium, iodine and caesium in marine sediments.
- Fredrik Espegren, Lead/Bismuth - Fission Products Interaction.
- Yeyuan Josefsson, Software for calibration in Gamma-ray spectrometric in situ measurements.
- Janna Hempel, Oskar Lindgren, Development of a two-way fluid-structure interaction model for pipe system analysis.
- Shervin Shojaee, Modelling Stress Relaxation in Bolt Loaded CT-Specimens.
- Joakim Holmström, Anton Lundin, Analysis of Fast Pressure Transients using RELAP5 and TRACE.
- Björn Arkbörn, Alexander Engström, The Evolution of Regulatory Approaches in Nuclear Power Oversight - A comprehensive analysis and comparison of Sweden, Finland Canada and USA.



In SKC-related subjects, the following Licentiate theses were successfully presented during 2014:

- Emelie Nilsson, Lower hybrid current drive in the Tore Supra tokamak.
- Ivan Kajan, RuO<sub>4</sub> interaction with surfaces in the containment of nuclear power plant.
- Lovisa Bauhn, Homogeneous radiolysis studies using <sup>238</sup>Pu.
- Marcus Hedberg, Nitride fuel production by the internal sol gel process.

In SKC-related subjects, the following Ph.D. theses were successfully presented during 2014:

- Cheuk Wah Lau, Improved PWR Core Characteristics with Thorium-containing Fuel.
- Elin Löfström Engdahl, On the Diluent and Solvent Effects in Liquid-Liquid Extraction Systems based on Bis-triazine-bipyridine (BTBP) ligands.

## Master education

The Div. of Nuclear Engineering, Dept. of Applied Physics, Div. of Materials Microstructure, Dept. of Applied Physics, and the Div. of Nuclear Chemistry, Dept. of Chemical and Biological 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 Engineering. This master program is based on a contract between E.ON and Chalmers, and is also financially supported by SKC.

A vast majority of the master theses have been performed in collaboration with the nuclear industry.

As opposed to earlier courses in nuclear engineering, the program is more 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 2014:

- The master program was presented for students both at CHARM and later at information sessions preparing the students for selecting master programs.
- In 2012 and 2013, a guest lecturer from WANO (World Association of Nuclear Operators) was invited for two days to talk about safety culture. This was appreciated by the students and repeated autumn 2014.
- Within 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 2014. The exercise was in form of a two-and-a half day laboratory exercise on a small open pool reactor.
- A study trip to Oskarshamn was carried out during the spring 2014. Students both from the master program as well as bachelor students participated in the study trip.
- As mentioned previously a SNEC day for students and industry was arranged during the spring with participants from both E.ON and Chalmers as well as many other industry representatives. Many master thesis projects were presented.





- Guest lecturers from the industry have lectured during the spring in nuclear materials and nuclear safety assessment.
- During autumn 2014 a questionnaire was sent out to master students at the other master programs. Results were presented on the SNEC-day in the autumn. In short, the results show that the students choosing the master program in Nuclear engineering do so because they already have decided about their career path, while students at other master programs often want to have as many options as possible open. Thus if we want to attract more student we need to attract those students that want to have a broad education.  
The results also showed that the students were less dependent on lecturers than expected and more dependent on the general view of the development possibilities, both academic and technological, in the topic of the master program.

### Ph.D. education

The Doctoral School in Nuclear Engineering has on the average about 10 enrolled Ph.D. students. 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 Ph.D. 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 Engineering and corresponding to an advanced level can also be taken as Ph.D. courses. The resulting mix between MSc students and Ph.D. students favours discussions between the students, each having his/her own paradigm. This also creates a natural bridge between the MSc and Ph.D. educations, which will ultimately result in more students interested in pursuing an academic career.

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



## Publication statistics

Some data taken from the Chalmers Publication Library (CPL) about the 2014 publications from the Divisions getting some SKC financial supports are given below.

	Div. of Nuclear Chemistry	Div. of Nuclear Engineering	Div. of Materials Microstructure	Total
Number of peer-reviewed journal articles	15	49	14	78
Number of peer-reviewed conference articles	7	19	8	34
Number of Ph.D. theses	1	1	1	3
Number of Lic. theses	3	1	1	5
Number of MSc theses	-	5	-	5
Number of reports	-	7	-	7
Total number of publications	26	82	24	132

## Research project

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

*Ph.D. student: Klas Jareteg, Division of Nuclear Engineering, Chalmers University of Technology*

*Main supervisor: Professor Christophe Demazière*

*Assistant supervisors: Associate Professor Paolo Vinai and Professor Srdjan Sasic*

### Background

The core of a Light Water Reactor (LWR) involves many different physics problems, such as neutron transport, fluid dynamics and heat transfer. Inherently, all fields are coupled and to determine the state of the reactor all perspectives need to be considered concurrently.

In many of the currently applied methodologies, the coupled problem is divided in its constituent parts, and consequently solved in a segregated manner. Often the coupling is approximated by static or simplified expressions, whereas in other cases an a posteriori coupling is achieved by combining different tools. Such splitting approaches introduce approximations in terms of the interdependent parameters, and also represent an obstacle for highly resolved coupled calculations.

The reactor core is also a multiscale environment, with important phenomena ranging from the size of the reactor tank itself to scales relevant for the fuel pellet, and further smaller approaching particle



scales. Since fully resolved simulations on length scales smaller than the fuel pellet are still considered to be extremely heavy computations, the reactor core problem is commonly solved on larger scales. Unavoidably, such a coarsening introduces homogenization, not only in terms of geometrical details but also in the models used to represent the underlying physics.

In contrast, a fine-mesh tool able to resolve the finer scales would also allow resolved coupled calculations to be performed. Such a coupled tool could be used to assess the approximations in the coarser methods, as well as determining the fine scale, local behavior of the physics in the fuel bundles. Development of fine-mesh tools can give an important contribution to safety since they have the potential for reproducing the physical phenomena of a nuclear system with a higher degree of fidelity.

## Goals of the project

This project is aimed at developing models and implementing a high-resolution coupled tool for fine scale simulations of the reactor core. This includes formulating a fully consistent model, directly coupling the modeling of neutron transport in the core, of fluid dynamics in the moderator and of conjugate heat transfer between the moderator and the fuel pins.

The developed tool is aimed at better capturing the phenomena, both by resolving the physics and introducing a direct coupling on the fine levels. The primary target are LWRs, i.e. Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs), with BWRs representing the most interesting case due to the large fluid heterogeneities induced by the two-phase flow of concurrently appearing steam and liquid water.

A successful implementation of such a tool relies on the use of high performance computing (HPC), including efficient methods as well as the use of fully parallelized algorithms and solvers. Consequently, the computational aspects are also a major focus in the current project.

## Organization

The work is performed by Ph.D. student Klas Jareteg under the supervision of Professor Christophe Demazière and assisting supervision of Associate Professor Paolo Vinai (Division of Nuclear Engineering, Department of Applied Physics) and Associate Professor Srdjan Sasic (Division of Fluid dynamics, Department of Applied Mechanics). The members of the reference group are: Ninos Garis (SSM), Urban Sandberg (Ringhals), Henrik Eisenberg (OKG), Farid Alavyoon (Forsmark) and Erwin Müller (Westinghouse).

## Methodology

In the first stage of the project a coupled tool was implemented based on the open source C++ library OpenFOAM. The existing single-phase fluid dynamics and heat transfer solvers in the library were extended to suit the fuel assembly calculations and further complemented by a neutron diffusion solver for the neutronic calculations. This tool was applied to a lattice of 5x5 fuel pins, and used to determine the axial and radial dependencies of the neutron flux distributions, the moderator density and velocity and the temperature in the fuel as well as the moderator [1,4].

In the second stage of the project, a discrete ordinates solver for the neutronics was added to the coupled framework. This method allows for an angular dependence in the neutron flux, resulting in a more accurate prediction of the neutron distribution in heterogeneous lattices. The discrete ordinates solver was compared to the earlier diffusion solver using the coupled calculations of a heterogeneous 5x5 fuel assembly including burnable absorbers [5]. Furthermore, the framework was generalized to allow for more generalized computational meshes and material regions [2].



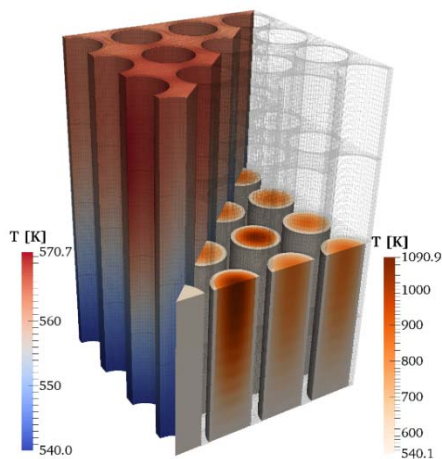


Figure 1. Moderator (left) and fuel (right) temperature for a transient case with an inlet temperature transient. [8]

In the current stage, the single-phase solver is complemented by a two-phase solver for the moderator. Starting with low void fractions, a solver based on a Population Balance Equation (PBE) is currently under development. The PBE is complemented by a two-fluid approach, and the coupled solvers allow for calculating the resolved vapor fractions and bubble size distributions [10]. In addition to the study of the PBE approach, numerical studies of the stability of the two-fluid formulation and implementation have been performed [3,7].

As a complement to the coupled steady-state solvers, the fourth stage of the project focuses on adopting the existing methodologies for transient simulations. A time-dependent neutron diffusion solver was added and combined with a single-phase transient CFD solver based on the PISO-algorithm. The solver has successfully been applied to a quarter of a system of 7x7 pins [8]. As an example, Figure 1 displays the system temperature for a case with an inlet temperature drop. Furthermore, Figure 2 shows probed values of the power level throughout the 10 seconds of transient, with the temperature drop occurring after 3 seconds. The transient solver gives the possibility to resolve the fine-mesh coupled behavior in the fuel assemblies, e.g. showing the effect of the different time scales for the different fields of physics. The transient solver is currently being extended with a transient discrete ordinates solver.

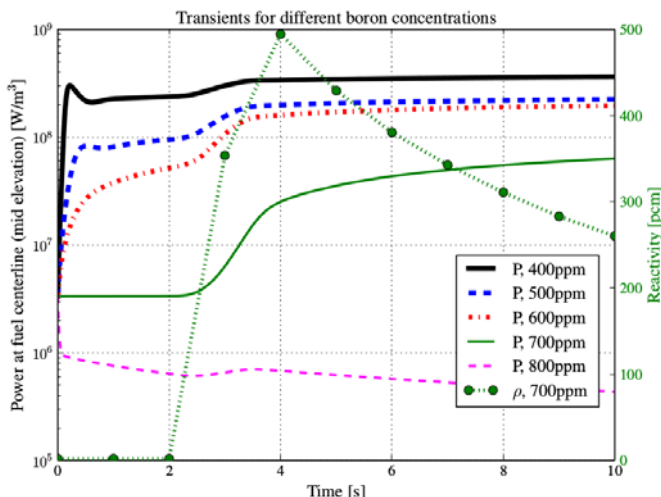


Figure 2. Power density at the fuel centerline at mid-elevation for five different boron concentrations. An inlet temperature ramp from 550 K to 540 K is applied between  $t=2.0$ s and  $t=3.0$ s. The system reactivity is displayed for ten time-steps for the 700 ppm boron case. [8]



## Publications

### Journal:

1. **K. Jareteg**, P. Vinai, C. Demazière. "Fine-mesh deterministic modeling of PWR fuel assemblies: Proof-of-principle of coupled neutronic/thermal-hydraulic calculations". *Annals of Nuclear Energy* 68.0 (2014), pp. 247 –256. ISSN : 0306-4549. DOI : <http://dx.doi.org/10.1016/j.anucene.2013.12.019>.
2. **K. Jareteg**, P. Vinai, S. Sasic, C. Demazière. "Coupled fine-mesh neutronics and thermal-hydraulics - modeling and implementation for PWR fuel assemblies". Accepted for publication in *Annals of Nuclear Energy*, Special Issue: "Multi-Physics Modeling of LWR Static and Transient Behavior" (2015)
3. H. Ström, S. Sasic, **K. Jareteg**, C. Demazière. "Behaviour and stability of the two-fluid model for fine-scale simulations of bubbly flow in nuclear reactors". *International Journal of Chemical Reactor Engineering* (2014). Submitted

### Conference (peer reviewed):

4. **K. Jareteg**, P. Vinai, C. Demazière. "Investigation of the possibility to use a fine-mesh solver for resolving coupled neutronics and thermal-hydraulics". M&C 2013, Sun Valley, Idaho (2013)
5. **K. Jareteg**, P. Vinai, S. Sasic, C. Demazière. "Influence of an S N solver in a fine-mesh neutronics/thermal-hydraulics framework". PHYSOR 2014, September 28 - October 3, Japan (2014)
6. C. Demazière, **K. Jareteg**. "Developing a course in nuclear reactor modelling and going from campus-based to web-based teaching". PHYSOR 2014, September 28 - October 3, Japan (2014)
7. H. Ström, S. Sasic, **K. Jareteg**, C. Demazière. "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) (2014)
8. **K. Jareteg**, R. Andersson, C. Demazière. "Development and test of a transient fine-mesh LWR multiphysics solver in a CFD framework". Accepted for M&C 2015, Nashville, Tennessee (2015)
9. E. Pettersen, C. Demazière, **K. Jareteg**, E. Schönfeldt T, B. Lauritzen. "Development of a Monte-Carlo based method for calculating the effect of stationary fluctuations". Accepted for M&C 2015, Nashville, Tennessee (2015)
10. **K. Jareteg**, S. Sasic, P. Vinai, C. Demazière. "Development of a Coupled Two-Fluid/DQMOM Methodology for Heated Bubbly Flows". Submitted to CMFF2015, Budapest, Hungary (2015)



## Appendix 2 - KTH Royal Institute of Technology

### *Overview of Activities Supported by SKC in 2014*

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 Professor (Waclaw Gudowski)
- 1 Assoc. Prof. (Pär Olsson)

Reactor Technology group:

- 1 Professor (Henryk Anglart)
- 1 Assist. Prof. (Jan Dufek)
- 2 Ph.D. students (Roman Thiele – 50% SKC, Mattia Bergagio – 50% SKC)

Solid Mechanics group:

- 1 Professor (Bo Alfredsson)
- 1 Assoc. Prof. (Jonas Faleskog)
- 1 Adj. Prof. (Pål Efsing)
- 2 Researchers (Carl Dahlsberg and Martin Öberg)
- 3 Ph.D. students (Michel Sedlak – 50% SKC; Rickard Shen – VAB/E.On/Fortum, Martin Bjurman – RAB/OKG/FKA)

#### Highlights and major research outcome

Ionut Anghel defended his Ph.D. thesis on March 28, 2014. The thesis title is “Experimental and Theoretical Study of Post-Dryout Heat Transfer in Annuli with Flow Obstacles”. Faculty opponent was Professor Dariusz Mikielewicz from Gdansk University of Technology. Dr Anghel’s work was fully financed by SKC.

Erdenechimeg Suvdantsetseg defended her thesis on August 18, 2014. The thesis title is “Neutronics and Transient Analysis of a Small Fast Reactor Cooled with Natural Circulation of Lead”. Faculty opponent was Professor Kim Yong Hee from KAIST, Korea. The thesis was funded by SKB.

Kaur Tuttelberg received the Sigvard Eklund’s Prize for the best Master Thesis in the nuclear field in Sweden during 2014. The title of the thesis is “STORM in Monte Carlo reactor physics calculations”. Kaur was supervised by Jan Dufek, Reactor Technology group.

Henryk Anglart published during 2014 one book within the field of nuclear engineering dedicated to international students at KTH:

*A Lexicon in Nuclear Engineering*, Warsaw University of Technology Publishing House, 402p, 2014.



Henryk Anglart served as a member of the technical program committee of the NUTHOS-10 conference, chaired a session and delivered a talk during the conference.

In collaboration with CEA, France, KTH/NRT continued research on the ASTRID and Jules Horowitz reactors.

Pål Efsing was invited lecturer at the Frédéric Joliot-Otto Hahn summer school, FJOH2014 in Cadarache with some 80 participating young engineers and Ph. D. students from all of Europe, India and China. In addition Efsing was invited as key-note speaker at the European Nuclear Society conference, ENS 2014 in Marseille in May to discuss knowledge preservation and retention in the aspect of ageing management of the current nuclear power plants.

Pär Olsson was invited to the American Nuclear Society annual meeting in Reno, in June 2014, to talk about the European materials science frameworks and radiation damage effects in steels. Pär Olsson was also invited to the MRS-Fall meeting in Boston, in December 2014, to talk about the work of his group on simulating irradiation induced embrittlement and swelling in structural materials. Pär Olsson was one of the faculty opponents for the Ph.D. thesis of Alexander Bakaev, University of Ghent, October 2014. Pär Olsson was the faculty opponent for the Ph.D. thesis of Chenwei He, University of Orleans, November 2014.

## Ph.D. education

### **The following Ph.D. Theses were completed during year 2014:**

Ionut Anghel: “Experimental and Theoretical Study of Post-Dryout Heat Transfer in Annuli with Flow Obstacles”, TRITA-FYS 2013:60, Ph.D. Thesis in Reactor Technology, KTH.

Erdenechimeg Suvdantsetseg: “Neutronics and Transient Analysis of a Small Fast Reactor Cooled with Natural Circulation of Lead”, TRITA-FYS 2014:29, Ph.D. Thesis in Reactor Physics, KTH.

### **The following Ph.D. and Licentiate projects were carried out during the year:**

Reijo Pegonen: “Development of new procedures for thermal-hydraulic analyses of the Jules Horowitz Reactor”, Ph.D. thesis project supported by VR.

Anders Riber-Marklund: “Acoustic leak detection in sodium applications”, Ph.D. thesis project supported by VR.

Roman Thiele: “Prediction of wall temperature characteristics with focus on thermal fatigue of nuclear materials”, Ph.D. thesis project partly supported by SKC and the THINS project.

Mattia Bergagio: “Experimental and analytical investigation of wall temperature characteristics with focus on thermal fatigue of nuclear materials”, Ph.D. thesis project partly supported by SKC.

Michel Sedlak: “Mechanical modelling of stress-corrosion cracking in sensitized stainless steel 316 in BWR water”, partly funded by SKC.

Rickard Shen: “Influence on Microstructure and Residual stress on Stress Corrosion Cracking in Nickel Based Alloys”, funded by Vattenfall, E.ON and Fortum.

Martin Bjurman: “Thermal ageing of cast and welded austenitic structures containing ferrite”.

Zhongwen Chang: “Multiscale modelling of irradiation enhanced diffusion phenomena in metals”.

Pertti Malkki: “Manufacture and characterisation of nitride fuels for use in light water reactors”. Supported by SKC.

Kyle Johnson: “Production and reprocessing methods for GenIV nuclear fuels”.





Antoine Claisse: “Thermomechanical performances of inert matrix nitride fuels in fast neutron reactors”.

Luca Messina: “Modelling of radiation induced embrittlement in nuclear reactor vessels”.

Karl Samulesson: “Internal corrosion in the cladding of the ASTRID reactor”.

## Undergraduate education

KTH divisions have been successfully running the Master’s Program in Nuclear Energy Engineering since 2007. The overview of the Master’s Program is available at KTH web site:

<https://www.kth.se/en/studies/master/kth/nuclear-energy-engineering/course-overview-1.268630>

During that time the program has gained high international reputation and the courses taught within the program have attracted many international and domestic students. The following major courses were given in 2014:

SH2600 Nuclear Reactor Physics, Major Course 9.0 credits, autumn, **28** students  
 SH2603 Radiation, Protection, Dosimetry and Detectors 6.0 credits, autumn, **33** students  
 SH2702 Nuclear Reactor Technology 8.0 credits, spring, **19** students  
 SH2773 Nuclear Power Safety 6.0 credits, spring, **24** students  
 KD2290 Reactor Chemistry 6.0 credits, spring, **7** students  
 SH2302 Nuclear Physics 8.0 credits, spring, **25** students  
 SH2604 Generation IV Reactors 6.0 credits, spring, **18** students  
 SH2605 Radiation Damage in Materials 6.0 credits, spring, **11** students  
 SH2610 Leadership for Safe Nuclear Power Industry 6.0 credits, autumn, **25** students  
 SH262V Elements of the Back-end of the Nuclear Fuel Cycle: Geological Storage in Precambrian Bedrock 7.5 credits, spring, **10** students  
 SH2701 Thermal-Hydraulics in Nuclear Energy Engineering 6.0 credits, autumn, **11** students  
 SH2703 Nuclear Reactor Dynamics and Stability 6.0 credits, spring, **16** students  
 SH2704 Monte Carlo Methods and Simulations in Nuclear Technology 6.0 credits, autumn, **16** students  
 SH2609 The Nuclear Fuel Cycle 6.0 credits, Autumn, **3** students  
 SH2608 Neutron Transport Theory and Reactor Kinetics 6.0 credits, autumn, **1** student  
 SH2602 Transmutation of Nuclear Waste 8.0 credits, autumn, **10** students  
 SH2774 Numerical Methods in Nuclear Engineering 6.0 credits, autumn, **3** students

In addition, nuclear technology is taught in the “Sustainable Power Generation” course, 9 ECTS given by the Energy Technology department.

At the Department of Solid Mechanics, no specific nuclear science related course has been given during 2014, but the Department is hosting approximately 25 under graduate students on a yearly basis. Courses in Solid Mechanics, Fracture Mechanics and Fatigue, Mechanical testing, Materials Mechanics, Finite Element modelling, Paper Mechanics and Fatigue, reliability and design at undergraduate/advanced level are given on a regular basis, whereas courses in more specialized areas such as Fatigue, Continuum Mechanics and Deformations Mechanisms are given when suitable.





## Master Theses

The following Master Theses have been completed during 2014:

Ante Hultgren, “Uncertainty Propagation Analysis for Low Power Transients at Oskarshamn 3 BWR”, KTH-Reactor Technology, TRITA-FYS 2014:37, June 2014 (in cooperation with Westinghouse).

Carl-Magnus Arvhult, “Validation of buoyant-mixing implementation in POLCA-T”, KTH-Reactor Technology, TRITA-FYS 2014:38, June 2014 (in cooperation with Westinghouse).

Johan Leduc: “On ageing management of nuclear power plants components”, KTH-Reactor Technology, TRITA-FYS 2014:50, February 2014 (in cooperation with AREVA).

Manuel Auliano: “Investigation and validation of void and pressure drop correlations in BWR fuel assemblies”, KTH-Reactor Technology, TRITA-FYS 2014:47, June 2014 (in cooperation with Westinghouse).

Kaur Tuttelberg: “STORM in Monte Carlo reactor physics calculations”, KTH-Reactor Technology, TRITA-FYS 2014:36, June 2014 (**Sigvard Eklund Prize for the best MSc thesis in 2014**).

Rafal Baranowski: “Investigation on debris related fuel failures in BWR supported by CFD simulations”, KTH-Reactor Technology, TRITA-FYS 2014:39, 2014 (in cooperation with Westinghouse).

Christina Ginopoulou: “Analysis of Design Uncertainties of the Hybrid Subcritical Research Reactor MYRRHA using Computer Simulation Codes DIF3D and DAKOTA”, KTH-Reactor Physics, December 2014 (in cooperation with SCK/CEN Belgium).

Niclas Lindbom: “An Investigation of Gas Atom Migration in Transition Metal- and Actinide Nitrides”, KTH-Reactor Physics, TRITA-FYS 2014:60, 2014, September 2014.

Elin Toijer: “Assessment of Primary Damage and Copper Precipitation in Cast Iron in Repository Conditions”, KTH-Reactor Physics, TRITA-FYS 2014:65, October 2014 (in collaboration with SSM).

Didier Bourgin: “Lattice physics mesh refinement study and its impact on full core nodal simulation results”, KTH-Reactor Physics, TRITA-FYS 2014:11 (in collaboration with Westinghouse).

## National and international projects

KTH is participating in numerous national, European and international cooperation projects. In 2014 several new project were initiated.

The Division of Reactor Technology was involved in the following European projects: NURES SAFE – on development of simulation tools for nuclear engineering applications; THINS – on development of thermal-hydraulics methods for new innovative nuclear systems; HPMC – on development of high performance Monte-Carlo methods.

The Department of Solid Mechanics has three on-going long term projects and one short-term project related to the nuclear industry and to the sponsors of SKC. These are:

- Modelling of stress corrosion cracking, with emphasis on initiation and short crack growth;
- Stress corrosion cracking in Alloy 690 and;
- Thermal ageing and decomposition of cast and welded austenitic materials;
- Continuum modeling of nodular cast iron using a porous plastic model with pressure-sensitive matrix—Experiments, model calibration & verification.

Of these, the program on modelling of Stress Corrosion Cracking has financial support, 60%, from SKC. The project on stress corrosion cracking in Alloy 690 is fully financed by the owners of the Swedish Nuclear Power Plants, Vattenfall, E.ON and Fortum as part of the agreement on the placement of Efsing at the department. The project on Thermal ageing is financed by SSM and the Swedish nuclear power plants materials utility group. Finally, the short-term project on nodular cast iron was financed by SKB.

Reactor Physics is involved with a number of EU projects: ASGARD, FREYA, MAXSIMA, ARCADIA, ESNII+, MARISA and MATISSE. On the national side, Wacław Gudowski is partly supported by SKC and so was the lic thesis of Pertti Malkki. SKB supports an activity on nitride fuel for transmutation purposes and Vattenfall supports a Ph.D. student (Luca Messina).



## Conferences and journal publications

The divisions actively participated in major international conferences within nuclear engineering field and also published in several reputed journals. The most important publications of the Reactor Technology group during 2014 are as follows:

- [1] Anghel I.G. and Anglart, H., "On post-dryout heat transfer in channels with flow obstacles," *Nuclear Engineering and Design*, vol. 270, pp. 351-358, 2014.
- [2] Pegonen R., Bourdon S, Gonner C. and Anglart, H., "A review of the current thermal-hydraulic modeling of the Jules Horowitz Reactor: A loss of flow accident analysis," *Nuclear Engineering and Design*, vol. 280, pp. 294-304, 2014.
- [3] Li, H. and Anglart, H., "CFD model of diabatic annular two-phase flow using the Eulerian-Lagrangian approach," *Annals of Nuclear Energy*, 77:415-424, 03/2015.
- [4] Pegonen, R., Edh, N., Angele, K. and Anglart, H., "Investigation of Thermal Mixing in the Control Rod Top Tube Using Large Eddy Simulations," *J. Power Technologies*, 2014.
- [5] Anglart, H., "Modelling of liquid film flow in annuli," accepted to *J. Power Technologies*, 2014.
- [6] Anglart, H., "Dry patch formation in diabatic annular two-phase flows," accepted to *J. Power Technologies*, 2014.
- [7] Anghel, I.G. and Anglart, H., "Wall temperature prediction in annuli with flow obstacles during post-dryout heat transfer," accepted to *J. Power Technologies*, 2014.
- [8] K. Tuttleberg and J. Dufek. Estimation of errors in the cumulative Monte Carlo fission source. *Annals of Nuclear Energy*, 72:151-155, October 2014.
- [9] J. Dufek and V. Valtavirta. Time step length versus efficiency of Monte Carlo burnup calculations. *Annals of Nuclear Energy*, 72:409-412, October 2014.
- [10] J. Dufek and J.E. Hoogenboom. Description of a stable scheme for steady-state coupled Monte Carlo-thermal-hydraulic calculations. *Annals of Nuclear Energy*, 68:1-3, June 2014.
- [11] A.R. Marklund and J. Dufek. Development and comparison of spectral methods for passive acoustic anomaly detection in nuclear power plants. *Applied Acoustics*, 83:100-107, January 2014.

In the Department of Solid Mechanics, Rickard Shen and Martin Bjurman has both published papers on their respective work at an international conference: Fontevraud 8 – contribution of materials investigation and operating experience to LWRs' safety, performance and reliability, in Avignon, France<sup>1,2</sup>. Shen has further published two papers in the open literature<sup>3,4</sup>.

- [1] Microstructural study of Alloy 690 base metal and HAZ from mockup components – influence of Ti(C,N) banding, R. Shen and P. Efsing, Fontevraud 8, September 15-18, 2014, Avignon, SFEN.
- [2] Localized deformation behaviour of thermally aged stainless steels castings, M. Bjurman, P. Efsing and D. Järdenäs, Fontevraud 8, September 15-18, 2014, Avignon, SFEN.
- [3] Experimental and theoretical investigation of three alloy 690 mockup components: base metal and welding induced changes, R Shen, B. Kaplan and P. Efsing, *International Journal of Nuclear Energy*, vol. 2014, Article ID 504927, 2014. doi:10.1155/2014/504927.
- [4] Effects of PWHT on the microstructure and mechanical properties of ERNiCrFe 7 all-weld metal, R. Shen et. al., accepted for publication in *Welding of the world*.
- [5] Effect of hydrogen on the oxide formation and CGR in CT specimens of Alloy 600 exposed in simulated PWR environment, J. Stjärnsäter, J. Chen, F. Lindberg, P. Ekström and P. Efsing, The Fontevraud 8, September 15-18, 2014, Avignon, SFEN.
- [6] Extended mechanical testing of RPV surveillance materials using reconstitution technique for small sized specimen to assist Long Term Operation" by May, Johannes; Rouden, Jenny; Efsing, Pål; Valo, Matti; Hein, Hieronymus, ASTM-STP-2013-0189.



The reactor physics group has published papers in international journals and at a number of conferences, mainly on neutronics, materials science issues and radiation damage:

- [1] Y. Zhang, J. Wallenius, "Upper limits to americium concentration in large sized sodium-cooled fast reactors loaded with metallic fuel", *Annals of Nuclear Energy*, 70 (2014) 180.
- [2] E. Suvdantsetseg, J. Wallenius "An assessment of prompt neutron reproduction time in a reflector dominated fast critical system: ELECTRA", *Annals of Nuclear Energy*, 71 (2014) 159.
- [3] D. Costa, G. Adjanor, C. Becquart, P. Olsson, C. Domain, "Vacancy migration energy dependence on local chemical environment in Fe-Cr alloys: A Density Functional Theory study", *J. Nucl. Mater.* 452 (2014) 425.
- [4] J.-B. Piochaud, T.P.C. Klaver, G. Adjanor, P. Olsson, C. Domain, C.S. Becquart, "First-principles study of point defects in an fcc Fe-10Ni-20Cr model alloy", *Phys. Rev. B* 89 (2014) 024101.
- [5] A. Bakaev, D. Terentyev, G. Bonny, T.P.C. Klaver, P. Olsson, D. Van Neck, "Interaction of minor alloying elements of high-Cr ferritic steels with lattice defects: An ab initio study", *J. Nucl. Mater.* 444 (2014) 237.
- [6] L. Messina, M. Nastar, T. Garnier, C. Domain, P. Olsson, "Exact ab initio transport coefficients in bcc Fe-X (X=Cr, Cu, Mn, Ni, P, Si) dilute alloys", *Phys. Rev. B* 90 (2014) 104203.
- [7] J. Ejenstam, M. Thuvander, P. Olsson, F. Rave, P. Szakalos, "Microstructural stability of Fe-Cr-Al alloys at 450-550 degrees C", *J. Nucl. Mater.* 457 (2014) 291.
- [8] P. Malkki, M. Jolkkonen, J. Wallenius, "Manufacture of fully dense uranium nitride pellets using hydride derived powders with spark plasma sintering", *J. Nucl. Mater.* 452 (2014) 548.



## Department of Solid Mechanics 2014

### *Staff directly involved in SKC activities during 2014*

2 Professor – 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%

### Ph.D. education

Michel Sedlak; Mechanical modelling of stress-corrosion cracking in sensitized stainless steel 316 in BWR water; partly funded by SKC.

Rickard Shen; Influence on Microstructure and Residual strain on Stress Corrosion Cracking in Nickel Based Alloys; funded by Vattenfall, E.On and Fortum

Martin Bjurman; Thermal ageing of cast and welded austenitic structures containing ferrite

### National Projects

The Department of Solid Mechanics has three on-going long term projects and one short-term project related to the nuclear industry and to the sponsors of SKC. These are:

- Modelling of stress corrosion cracking, with emphasis on initiation and short crack growth;
- Stress corrosion cracking in Alloy 690 and;
- Thermal ageing and decomposition of cast and welded austenitic materials;
- Continuum modeling of nodular cast iron using a porous plastic model with pressure-sensitive matrix—  
Experiments, model calibration & verification.

Of these, the program on modelling of Stress Corrosion Cracking has financial support, 75%, from SKC. The project on stress corrosion cracking in Alloy 690 is fully financed by the owners of the Swedish Nuclear Power Plants, Vattenfall, E.On and Fortum as part of the agreement on the placement of Efsing at the department. The project on Thermal ageing is financed by SSM and the Swedish nuclear power plants materials utility group. Finally, the project on nodular cast iron has been granted extended financing by SKB into 2015.



### The SKC funded Ph.D. project on IG-SCC

**Mechanical Modelling of Stress Corrosion Cracking in Sensitized Stainless Steel 316:** One of the main causes of degradation in stainless steel primary piping systems of nuclear reactor after some initial years of service, was Inter Granular Stress Corrosion Cracking, IG-SCC. The primary root causes for the degradation mode was identified as weld-induced sensitization in high carbon containing stainless steels, poorly maintained water chemistry with minor contaminants such as Chloride and Sulphur compounds, and cold work. As a, at that time, definite remedy for the sensitization issue low-carbon containing steels were introduced at the same time as better controlled and monitored water chemistry was implemented. However, currently there exist both laboratory evidence and findings in applications of SCC even at such ideal conditions, which illustrate that immune conditions does not exist. The plan for life extension of nuclear reactors increase the importance of understanding the mechanisms that initiate and propagate stress corrosion cracks in ultra-clean environment and stainless steel with residual stresses. Furthermore, the damage mode becomes even more detrimental if the material has been sensitized by heat-treatment for instance from welding or by cold work such as grinding.

The SCC damage features interaction of different physical processes. The coupled multi-physical properties involve fracture mechanics, diffusion and corrosion with degradation of local material properties, which all has to be facilitated in a complete damage model. Furthermore, the material structure influences the damage not only by guiding the crack to follow an intergranular path with branching but also through the in-homogenous and non-isotropic plastic deformation related to crystal-plasticity. The damage properties include a (at least from an engineering point of view) load threshold below which no damage occurs, a thermally activated crack propagation, stress and environmentally assisted kinetics and a stress intensity controlled crack extension. The reaction-rupture mechanism will take place in a narrow band where the locally resisted crack opening exceeds a critical value. The local cohesive zone parameters are controlled by a diffusion law for the passage of ions through the crack length. The cohesive model describes the local conditions at the crack tip including the corrosion detrimental effects on fracture resistance.

The SKC funded project on IG-SCC focuses on building a numerical model for the damage in sensitized stainless steel 316 in BWR water. The project work stated in August 2012 with identifying the physical descriptions for the individual parts of the damage: a cohesive model for macro and micro scale rupture, a microstructural grain structure for the micro-scale intergranular crack path, grain structure with random orientation of slip planes and slip systems for crystal-plasticity, a corrosion based degradation model for the cohesive elements, a diffusion model for ion transport in the crack with ion leakage and diffusion model into the degrading grain boundaries. The first two project years has been used to build numerical models for each of the damage parts and implement them into user coded finite elements with the requirement that they can be coupled into the multi-physical model. The fracture and the corrosion processes are treated by the cohesive element. The rate of degradation of fracture parameters, i.e. fracture energy and local traction resistance, due to corrosion is governed by diffusion through the crack and through the process zone. The oxide penetration along grain boundaries is implemented into a diffusion element that follows Fick's second law. The rate is governed by strain, time, ion concentration etc. The individual user elements are now combined into the multi-physical user code. The assembled oxides in the diffusion element in the process zone are now connected with the cohesive element through the degradation of the material parameters. Coding has been done with first versions of the cohesive element and the diffusion element. These elements are now connected into the multi-physics model and tried on a simple double-cantilever bend specimen. Thus, a first version of a working multi-physics model for some aspects of IG-SCC was finalized during 2014.

The Ph. D. student, Michal Sedlak, was during 2012 and 2013 jointly funded by SKC and the department of Solid Mechanics at KTH. For 2014, SKC increased its part of the total funding.



### Other projects of relevance to SKC

**Thermal ageing of cast and welded austenitic stainless steels:** Cast and welded stainless steels (SS) components have been shown to be sensitive to thermal ageing (TA) when exposed to nuclear power plant operating temperatures. During the solidification process of SS, a fine network of  $\delta$ -ferrite in an austenite matrix is formed. Diffusion causes spinodal decomposition of the  $\delta$ -ferrite as well as precipitation of secondary phases, affecting the structural integrity of components as well as the remaining service life by reducing mechanical and corrosion properties. The project goals are to microstructurally and mechanically characterize long term service-aged SS components with various manufacturing and aging history; model its macroscopic mechanical properties starting at a microstructural level; and find a small specimen mechanical testing technique targeting relevant parameters for TA of reactor components.

Microstructural and ageing characterization from macro- to nano-scale have been conducted during the first phase of the program, using LOM, SEM and APT-analysis. Mechanical characterization by hardness- and uniaxial tensile-tests was conducted, and (time dependent) elastic, plastic and fracture properties are analysed by fractography, EBSD and hardness measurements. These results have been reported at symposia and conferences relevant to the nuclear industry such as the SFEN-Fontevraud conference 2013.

Continued work on strain rate dependency, global and local plasticity interaction with the duplex microstructure. To investigate this are further EBSD-analysis, nano-indentation and finite element crystal plasticity modelling planned. These results will also be used to develop or evaluate the relevance of mechanical testing techniques from small sample volumes. Standard fracture mechanical testing is also planned for quantification and comparison purposes.

The Ph. D. student, Martin Bjurman, is an industrial student and has financial support from Studsvik, the Swedish nuclear power plants and the regulatory body SSM.

**Stress corrosion cracking in plastically strained Alloy 690;** Alloy 690 was developed to remedy the issue of stress corrosion cracking (SCC) in components made of the nickel base material Alloy 600 in pre-dominantly pressurized water reactors, PWRs. Alloy 690 has shown excellent resistance to SCC so far, but laboratory experiments have shown that it can crack by SCC at an alarming rate if the material has been subjected to considerable plastic straining. The straining may be results from the manufacturing processes utilized such as deliberate or unintentional cold working of the components, grinding procedures or welding.

In the industry, plastic strain assessments based on electron backscatter diffraction (EBSD) show that a relatively high level of plastic straining can be found in the heat affected zone (HAZ) as a result of deformation from welding. This level can be further increased if a repair weld is required. Laboratory crack growth experiments however indicate that weld induced deformation appears to be less detrimental than cold deformation by e.g. rolling, forging or uniaxial tension.

The project aims at identifying whether or not results from crack growth experiments on cold deformed Alloy 690 are relevant for weld deformed Alloy 690. As an initial step, component mockups were used for microstructural characterization of the base metal and HAZ of three different commercial Alloy 690 heats. Light optical microscopy and scanning electron microscopy were used together with thermodynamic calculations in order to identify the phases present and microstructural changes due to welding. In addition, the study revealed a connection between Ti(C,N) banding with effects on carbide morphology and grain size banding. The current work uses a combination of EBSD and nano-indentations to investigate the correlation between local plastic strain and local hardness for cold and hot strained Alloy 690.





The Ph. D. student, Richard Shen has worked on the project from 2011, and has published a number of papers in the open literature as well as reported on the progress of the project at several international symposia and workshops. The results are being added as an in-kind contribution to the current Finnish state funded program SAFIR under the subprojects SINI and NIWEL.

## Conferences and Publication

Dahlberg C., Faleskog J., Öberg M. "A continuum model for nodular cast iron incorporating experimentally observed strength differential effects, porous plasticity and ductile failure – Application to deep geological storage of nuclear waste in Sweden", European Conference on Fracture 20, Trondheim, 2014.

Shen RR, Zhou Z, Liu P and Chai G. 2014. "Effects of PWHT on the microstructure and mechanical properties of ERNiCrFe-7 all-weld metal", Welding in the World.

Shen RR, Kaplan B and Efsing P. 2014. "Experimental and theoretical investigation of three alloy 690 mockup components: Base metal and welding induced changes", International Journal of Nuclear Energy.

Shen RR and Efsing P. 2014. "Microstructural study of Alloy 690 base metal and HAZ from mockup components – Influence of Ti(C,N) banding", In Fontevraud 8. September 15–18, 2014, Avignon, France.

Bjurman M and Efsing P, "Localized Deformation Behaviour of Thermally Aged Stainless Steel Castings", In Fontevraud 8. September 15–18, 2014, Avignon, France.

## Undergraduate education

At the Department of Solid Mechanics, no specific nuclear science related course has been given during 2014, but the Department is hosting approximately 25 under graduate students on a yearly basis. Courses in Solid Mechanics, Fracture Mechanics and Fatigue, Mechanical testing, Materials Mechanics, Finite Element modelling, Computational Material Mechanics and Continuum Mechanics at undergraduate/advanced level are given on a regular basis, whereas courses in more specialized areas such as Fatigue and Deformations Mechanisms are given when suitable.



## Research project KTH

Measurement and prediction of wall temperature characteristics with focus on material ageing due to thermal fatigue

*Research leader: Professor Henryk Anglart*

*Ph.D. students: Mattia Bergagio and Roman Thiele, Division of Nuclear Reactor Technology, KTH, Stockholm*

## Background

During the 2008 refuelling outage at Oskarshamn 3 reactor it was found that one control rod extender was completely broken and several had incipient cracks. Shortly after a similar problem was identified at Forsmark 3 reactor, which is of similar design as Oskarshamn 3 reactor. Inspections and tests at both reactors revealed that about 37% of all control rod extenders suffered from cracks. Further investigations indicated that the damages to the control rods were due to the thermal fatigue phenomenon.

## Objectives and methodology

The objective of this project is to develop and validate numerical models to predict time and space characteristics of a temperature field during mixing of two streams corresponding to the situation observed in BWR control rods in Forsmark and Oskarshamn. This type of problems requires a detailed numerical approach that is able to resolve velocity and temperature fluctuations in a wide range of frequencies, typically from 0.2 to 10 Hz. In this project a conjugate heat transfer model with Large Eddy Simulation (LES) on the liquid side is developed and validated against detailed experimental data obtained in the KTH lab.

## Results in 2014

In 2014 the LES model developed in the previous year was applied to one of the cases measured in the lab. The preliminary results confirmed similar temperature fluctuations obtained in calculations (Fig. 1a) and in measurements (Fig. 1b). Currently experimental data have been obtained on the whole mixing surface for 5 different operational conditions. The experimental data are analyzed and heat flux information is retrieved using a new approach presented in papers submitted to the NURETH-16 conference [1,2].

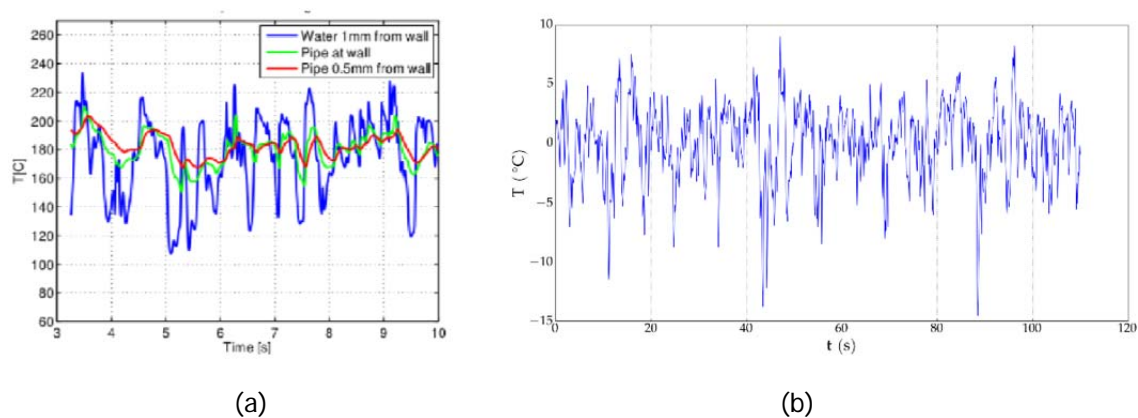


Fig. 1. Calculated (a) and measured temperature fluctuation in the mixing zone.





## References

- [1] H. Anglart, M. Bergagio, S. Hedberg, S. Rydström and W. Frid, "Measurement of wall temperature fluctuations during thermal mixing of non-isothermal water streams", paper submitted to NURETH-16 conf..
- [2] M. Bergagio, S. Hedberg, S. Rydström and H. Anglart, "Instrumentation for temperature and heat flux measurement on a solid surface under BWR operation conditions", paper submitted to NURETH-16 conf.



## Appendix 3 - Uppsala University

### *Overview of Activities in 2013*

### *Division of Applied Nuclear Physics*

#### Summary

As always, the Division of applied nuclear physics' ambition is to continuously develop its concepts in research and education. For example, the elements of interdisciplinary actions within the Nordic Academy for Nuclear Safety and Security (NANSS), the new research group dealing with novel nuclear technology physics group are all parts of a comprehensive strategy to create a stable and a high-quality research and education node that could serve and support the surrounding society. The increased collaboration within materials research and in particular the initiative taken by us, MÅBiL, is also a part of the strategy to make use of available funding as efficient as possible.

As noted in last year's Annual Report, the Division of applied nuclear physics today is a large research environment in which the research and education activities within nuclear technology are firmly anchored in the needs of the society as well as in the present scientific and didactic issues. Following the strategy outlined in earlier SKC reports, the areas below are in our focus for extensive research:

- Nuclear fuel diagnostics and core monitoring (Gen II, III, III+, IV).
- Nuclear data and Total Monte Carlo approach (experimental uncertainties and their propagation in core simulators and other relevant tools).
- Offering of nuclear expertise internationally (considering the fact that many developing countries now contemplate of initiating nuclear power programmes).
- Nuclear materials together with the Div. of materials theory (radiation assisted stress corrosion cracking and aging).
- Physics and design of nuclear energy systems (Gen III, III+, IV).
- Nuclear safeguards (more efficient and less intrusive technologies).

A determining factor for us to focus on these areas is the considerable international interest for our research and education we have gained. Presently there is collaboration with international parties such as UC Berkeley, Los Alamos National Laboratory LANL, Pacific Northwest National Laboratory PNNL, IAEA, CEA, NRG Petten, the World Nuclear University WNU among others. As a result of the collaboration with the WNU, Uppsala University will host the WNU Summer Institute 2015.

The SKC financed MÅBiL consortium was launched during 2014. This research collaboration involves researcher from Uppsala University, KTH and Chalmers with a twofold focus: 1. ageing of internal reactor parts and 2. accident tolerant fuels. Altogether MÅBiL comprises 21 researchers including 6 Ph.D. students. For a more detailed account on MÅBiL, please consult the MÅBiL Annual Report 2014.

The activities within NANSS have continued during 2014. During spring 2014 a course, "Myndighetskunskap" was given where the attendees came from all Swedish nuclear power plants. More courses are in the pipeline but the financial situation in the nuclear industry still is such that we have been forced to postpone these courses to 2015. NANSS will also be operative body for the WNU Summer Institute 2015 held in Uppsala.

With these introductory remarks we conclude that our activities during 2014 were successful. However, the strained situation of the nuclear industry creates worries about the future funding and we have therefore initiated processes to find complementary ways of financing our research and education.

For more information about the Division for Applied Nuclear Physics: <http://www.physics.uu.se/en>



## Education

Teaching and education continue to be areas of considerable importance for the Division of applied nuclear physics. The division is responsible for managing two engineering programs, the Bachelor of science in engineering programme with a specialisation in nuclear engineering, i.e., *Högskoleingenjörsprogrammet i kärnkraftteknik* (KKI), which is on its 5<sup>th</sup> year since the start in autumn 2010 and the Master of science in engineering programme with a specialisation in energy systems engineering, i.e., *Civilingenjörsprogrammet i energisystem* (ES), which is the largest master of science in engineering programme at Uppsala University. 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.

The collaboration with *Kärnkraftsäkerhet och Utbildning AB* (KSU) with UU providing higher education for the nuclear power industry has continued during 2014. The objective of the contract education is to secure competence building of existing and newly recruited personnel, primarily within reactor operation and radiation protection.

A new step was taken during the autumn of 2014 when ANP for the first time was involved in the annual re-training of the Forsmark 1 and 2 shift teams. The objective was to provide all shift team members with a one-day refresher course in primarily reactor and radiation physics. The one-day course, which was given on 9 occasions, received very positive reviews from the participants and it has been decided that also Forsmark 3 shift teams will participate in this course during the spring 2015. Also, the initiative was noticed by SSM and received favourable comments by inspectors, who attended the course on two occasions.

NANSS (Nordic Academy for Nuclear Safety and Security) was established in 2013 as a legal entity within UU. NANSS, which is operationally a part of the Division of applied nuclear physics will function as a hub and contact point between industry, university and external experts with the objective of fulfilling the need for higher education and competence building, primarily within the Swedis NPPs. During 2014 NANSS arranged its first course, *Myndighetskunskap inom kärnteknisk verksamhet*, with NPP staff participation and two more courses were developed, *Människa-teknik-organisation och Human Factors metoder ur ett säkerhetsperspektiv* and *Säkerhetsprinciper inom kärnteknikområdet*. These courses will be offered to industry during 2015.

### **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 a "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 2014 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

Recruitment activities require considerable effort, especially in view of the present public and political uncertainty about the future of nuclear power in Sweden. Recruitment activities are focused on arranging lunch seminars at several engineering colleges and universities around Sweden and also participation in student careers fairs, e.g., UTNARM, CHARM and LARM. Whenever possible these activities are conducted in collaboration with industry and SKC. Additionally, the programme is marketed through advertisements in various media such as educational supplements distributed with regular newspapers and also through mailings to students.

As shown in Table 1 below, since its inception in 2010 when the “nuclear renaissance” was at its peak, the programme experienced a decrease in student enrolment and in the following years the number of students has stabilized around approximately 10 full-time students per year. From our contact with students it is clear that students' choice of educational programs is heavily influenced by public opinion and debate and also the fact that “högskoleingenjörer” of all subjects are in high demand within Swedish industry in general, presently and for the foreseeable future. With that in mind it is important that the nuclear industry conveys a positive message to prospective students about the possibility of a career within the field. To some extent the low enrolment figures are compensated by a very low drop-out rate compared to other engineering programmes.

The students report a high degree of satisfaction with the quality of education. In the programme evaluation the class of 2013/2014, when questioned about their experience of the overall quality of the programme, gave the mark  $4.9 \pm 0.3$  on a scale from 1 (unacceptable) to 5 (excellent). The previous year the corresponding figure was  $4.7 \pm 0.5$ .

Table 1. Recruitment statistics for the period 2010-2014 (source: Verket för högskolestudier)

Study year	Applicants	1 <sup>st</sup> -hand applicants	Applicants admitted to the program	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 + 1 (Feb. 2015)



## Students' achievements

At the time of writing (February 2015) 39 students have successfully completed their Bachelors theses. A summary of the theses produced during 2014 is found at the end of this chapter. The students of the academic year 2013/2014 are exhibiting very good academic achievements with 5 out of 8 students having finished all their courses within the programme at the time of writing (Figure 1).

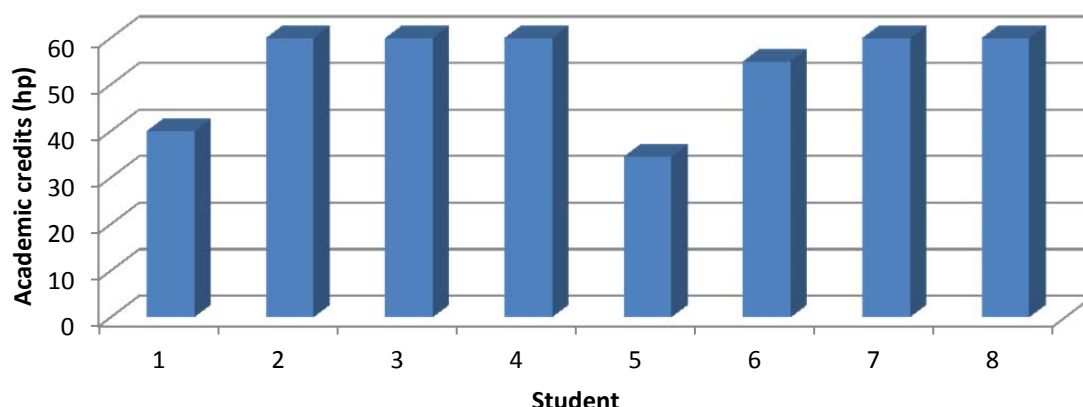


Figure 1: Student achievements for the academic year 2013/2014. The maximum academic credits possible are 60 hp.

## Employment

Almost without exception the students graduating from the Bachelors' programme have been employed within the nuclear industry. Of those students a large majority has taken up positions with the NPPs and we are happy to note that the interest among those students to pursue a career within NPP operation is continuously very high. Increasing the supply of candidates for this staff category was one of the original objectives of the programme.

## Contract education for the industry

Despite the fact that the Swedish nuclear industry have entered a period of cost down-sizing and low electricity prices resulting in a lower than usual number of course participants, the Division of applied nuclear physics provided industry 18 weeks of courses within the agreement with KSU. This is an increase by one week from the previous year.

## Students' theses during 2014

### Ph.D. theses

**Peter Andersson:** "Fast-Neutron Tomography using a Mobile Neutron Generator for Assessment of Steam-Water Distributions in Two-Phase Flows". Acta Universitatis Upsaliensis; 2014. Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology, 1146. Available at <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-222459>

**Peter Wolniewicz:** "Development of a Methodology for Detecting Coolant Void in Lead-cooled Fast Reactors by Means of Neutron Measurements". Acta Universitatis Upsaliensis; 2014. Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology, 1180. Available at <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-232252>



**Scott Holcombe:** "Gamma Spectroscopy and Gamma Emission Tomography for Fuel Performance Characterization of Irradiated Nuclear Fuel Assemblies". [Thesis]. Uppsala: Acta Universitatis Upsaliensis; 2014. Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology, 1201. Available at <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-235124>

Collaboration between Divisions of materials theory and Applied nuclear physics: **Lisa Bläckberg:** "Surface Coatings as Xenon Diffusion Barriers for Improved Detection of Clandestine Nuclear Explosions". Acta Universitatis Upsaliensis; 2014. Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology, ISSN 1651-6214 ; 1111. Available at <http://urn.nbn:se:uu:diva-215562>

### Licentiate theses completed

**Erwin Alhassan:** "Nuclear data uncertainty propagation for a lead-cooled fast reactor: Combining TMC with criticality benchmarks for improved accuracy". Available at <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-224687>

**Andrea Mattera:** "Characterization of a Neutron Source for Fission Yields Studies". Available at <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-238044>

### *Masters theses completed*

**Peter Höök:** "Utvärdering av beräkningskoden APROS för användning i inneslutningsanalyser". Available at <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-230357>

**Klas Sunnevik:** "Comparison of MAAP and MELCOR and evaluation of MELCOR as a deterministic tool within RASTEP", 2014-11-19

**Tom Bjelkenstedt:** "Optimization and design of a detection system based on transmission tomography with fast neutrons", 2014-05-08

**Carolin Holmkvist:** "Kvantifiering av osäkerheter i lyftkraftsmodellen"

**Fredrik Olsson:** "Estimating the fuel ion dilution in fusion plasmas using neutron emission spectrometry"

**Ludvig Svensson Sjöbom:** "Wiggling crystals for fun and profit - Improving sample alignment at the tandem accelerator".

### Masters diploma works in progress

**Magnus Ahnesjö:** "Tomographic Reconstruction of Sub-Channel Void measurements" – in collaboration with Westinghouse

**Sara Wiberg:** "Non-destructive assay methods for deep geological disposal of spent nuclear fuel" – in collaboration with SKB.

### Bachelors theses completed (KKI)

**Ammar Al-Bagdadi, Josef Abou-Soultan:** "Effektivisering av uppföljning av revisionstidplaner under revision", FKA

**Oskar Lidholm, Daniel Lundgren:** "Metod för identifiering av T-stycke med risk för termisk utmattning", FKA

**Mikael Tollman:** "Kärnkraftverks störningstålighet mot transienter", FKA.



**Christian Zackrisson, Magnus Zackrisson:** "System 348 - Rekombinator: Analys av reglerproblematik vid O2", OKG

**Bachelors diploma works in progress (KKI):**

**Mikael Haglund:** "Hantering av trender för processsystem och periodisk provning", OKG

**Ebrahim Raoufi:** "Metodik för kartläggning av risken för termisk utmattning i T-stycken", FKA

**Sören Bieling** (Projektarbete, 5 hp): "Rutherford Backscattering Spectrometry analysis of colloidal FePt-nanocrystals".

**Christian Zoller** (Projektarbete, 10 hp): "Analysis of HfO<sub>2</sub> and HfAlO layers".

**Tobias Tommikoski** (Projektarbete, 15 hp): "Model of Small Modular Fast Reactor (SMFR) in SERPENT".

**Qadir Nishada** (Projekt i tillämpad fysik, 15 hp): "Test of a Large Avalanche Photodiode (LAAPD) for Pulse-Shape Analysis and neutron-gamma Discrimination with Liquid Scintillator Detectors".

**Joel Blomberg,** David Gabro: "Simulering och beräkning av neutrondoser".

**Arya Tavana:** "An MCNP code simulation of a nuclear reaction chamber, and calculations of effective dose rates", 13/6-2014



## Research – Ph.D. student project

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

### STUNT

Ph.D. student: **Peter Andersson**

Main supervisor: Staffan Jacobsson Svärd

Assistant supervisor: Henrik Sjöstrand

## Background

Proper knowledge of the distribution of void and water in BWR fuel during reactor operation is important for fuel design and for optimization of the reactor operation. Accordingly, extensive research on two-phase flow and heat transfer is carried out at various experimental facilities, such as the HWAT loop at KTH in Stockholm and the FRIGG loop at Westinghouse in Västerås. There are several techniques for assessing void in these thermal-hydraulic test loops. Neutron tomography is a promising new alternative, without some of the drawbacks of e.g. gamma-ray tomography that was previously applied at FRIGG. Firstly, an accelerator-based neutron source may be used, which can be turned off when not used, and secondly, neutrons are more sensitive to the content of water/void in the object as compared to the construction material.

## STUNT Reference group

The STUNT project has a reference group with the following participants:

Stig Andersson, Westinghouse

Uffe Bergmann, Westinghouse

Jean-Marie Le Corre, Westinghouse

Henryk Anglart, KTH

Elisabeth Rudbeck, SSM

Jonas Lanthén, OKG

Jesper Ericsson FTB





## Milestones reached

The scientific and technological milestones reached during the course of this project include the following:

- An instrument concept has been developed using a 14 MeV neutron generator and a detector array of plastic scintillators. A prototype of has been assembled, see

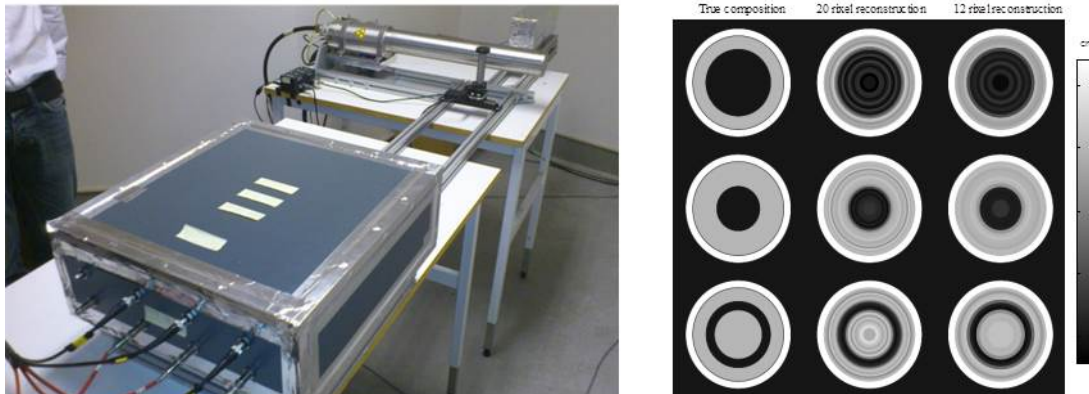


Figure 1. Left : The assembled FANTOM tomography system, including a portable neutron generator (back) and a detector array (front). Right: tomographic reconstructions of experimental data. Left column contains true attenuation profiles of polymer test objects inside cylindrical pipes, the middle and right columns are the reconstructed attenuation profiles with 0.5 respectively 1 mm rixels.

- Experimental validation of the instrument capabilities has been performed for artificial test-objects. These test objects have cylindrical symmetry, such as the vertical circular pipes of the HWAT test loop. The obtained performance was an image resolution of 0.5 mm with RMS errors of  $0.2 \text{ cm}^{-1}$ , which corresponds to 3.5 h of data collection, see

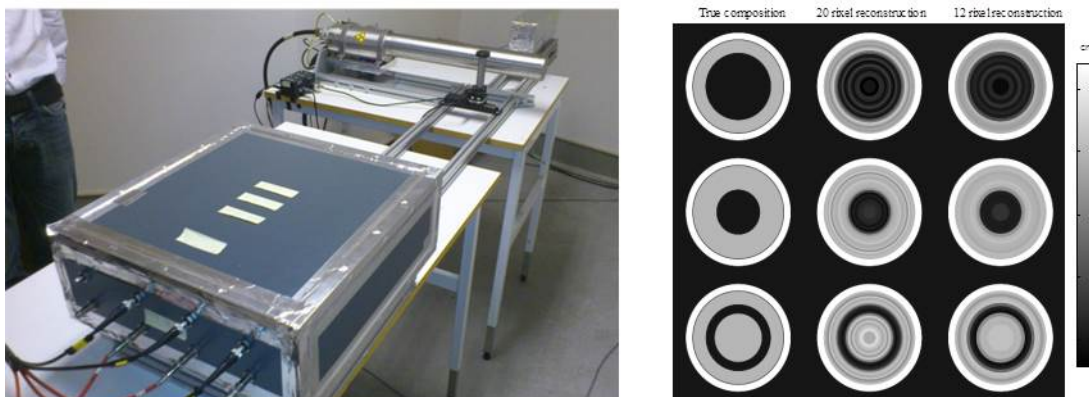


Figure 1. Left : The assembled FANTOM tomography system, including a portable neutron generator (back) and a detector array (front). Right: tomographic reconstructions of experimental data. Left column contains true attenuation profiles of polymer test objects inside cylindrical pipes, the middle and right columns are the reconstructed attenuation profiles with 0.5 respectively 1 mm rixels..

- Projections of the performance of a scaled-up version of the prototype instrument for full scale mock-ups of BWR quarter fuel-bundles have been made, where the achievable magnitude of the statistical uncertainties of 1.4 mm pixels is four void percent units, corresponding to 1 h of data collection time.
- In addition, methods for achieving unbiased transmission measurements of void fractions in dynamic two-phase flows have been developed and validated using simulated data.



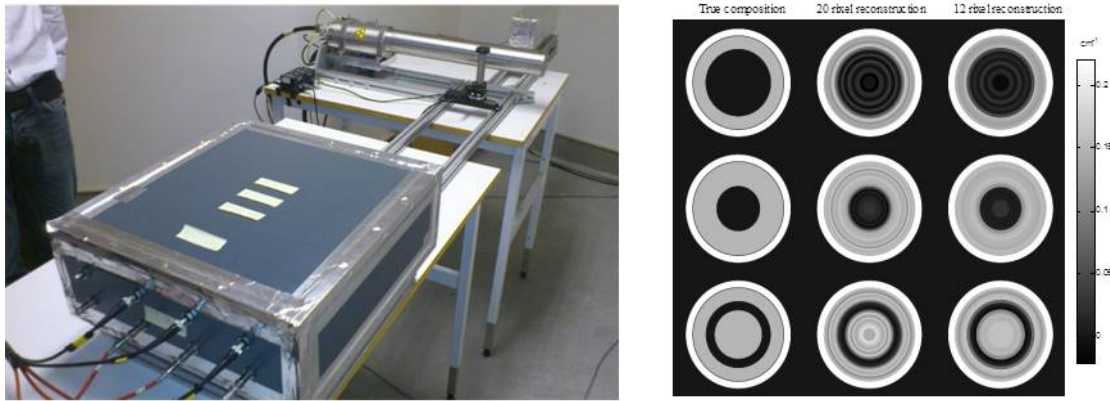


Figure 1. Left : The assembled FANTOM tomography system, including a portable neutron generator (back) and a detector array (front). Right: tomographic reconstructions of experimental data. Left column contains true attenuation profiles of polymer test objects inside cylindrical pipes, the middle and right columns are the reconstructed attenuation profiles with 0.5 respectively 1 mm rixels.

## Current status

In June 2014, Peter Andersson defended his Ph.D. thesis. The opponent was Dr. Bernhard Ludewigt from Lawrence Berkeley National Laboratory. Thereby, the project has ended.

## Advanced diagnostics of nuclear fuel based on tomographic techniques and high-resolution gamma-ray spectroscopy

Summary of Ph.D. project at Uppsala University for the SKC Annual report 2014

Ph.D. student: **Scott Holcombe**

Main supervisor: Ass. Prof. Staffan Jacobsson Svård

Assistant supervisor: Prof. Ane Håkansson

## Project overview

Nuclear fuel performance is of highest importance for safe and economic operation of commercial power plants. Therefore, extensive efforts are put into development and testing of new fuel designs, where the final steps include test irradiation in research reactors and irradiation of lead assemblies in commercial power plants. Among the strains that nuclear fuel has to be able to withstand are temperature and neutron flux transients, which may occur in accidental scenarios. Such transients can only be tested in a few research reactors in the world, e.g. at the HBWR of the OECD Halden Reactor Project (OECD-HRP). Among the fuel characteristics that are studied at such reactors are burnup, power and fission gas release distributions. However, with previous assay techniques such as gamma scanning, the assembly has to be cooled and disassembled before measurement of pin quantities, implying an inadequacy to measure short-lived fission products.

In this Ph.D. project, Scott Holcombe has developed a tomographic technique for fuel assessment, allowing for the characterization of all fuel rods in an assembly without disassembly. With this technique, fuel assemblies may be measured shortly after discharge from the reactor core, thus enabling the assessment of short-lived as well as long-lived products. A number of applications of this technique of value for the nuclear community have been identified; characterization of experimental fuel in research reactors; characterization of lead assemblies in commercial reactors; identification of leaking rods in commercial reactors, and; verification of assembly integrity in nuclear safeguards. The project was run in collaboration

with Westinghouse Electric Sweden AB (WSE) as a part of OECD-HRP, with Scott as a secondee in Halden. The project had financial support from the Swedish research council (VR).



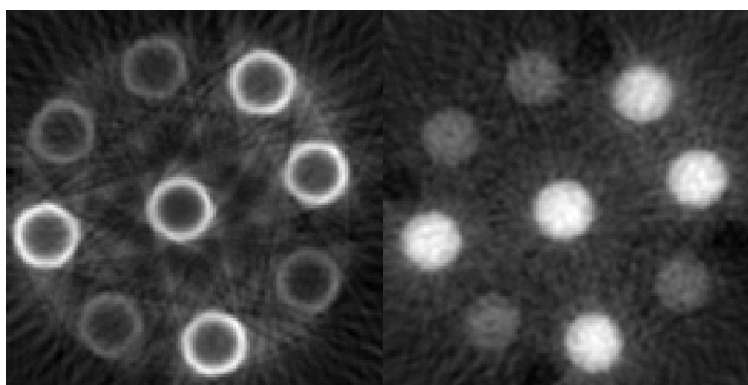
### Current status

In December 2014, Scott Holcombe defended his Ph.D. thesis. The opponent was Dr. Hans-Urs Zwicky from Switzerland. Thereby, the project has successfully ended.

### Milestones reached

The scientific and technological milestones reached during the course of this project include the following:

- A device for tomographic measurements on irradiated fuel at the HBWR research reactor in Halden has been designed, manufactured and assembled.
- The capability of the device has been demonstrated in an experimental campaign on HBWR driver fuel. The measured assembly comprised fuel rods with irradiation histories including periods of time with high linear heat generation rates. Accordingly, interestingly high levels of fission gas release and migration of volatile fission products were expected, which could be confirmed in the measurements. (See figure 1.)
- The potential use of tomography for materials analyses has been demonstrated by means of mapping the content of activation products in the structure materials. (See figure 2.)
- A methodology has been developed and demonstrated for analysing fission gas release during transients by measuring short-lived fission products. The method can be used in combination with tomographic measurements for analyses of ramp test fuel assemblies at the HBWR in between irradiations periods.
- A methodology has been developed and demonstrated for analysing the radial origin of released fission gases by means of analysing the isotopic content of short-lived fission gases in the plenum.
- A tomographic method has been suggested for identifying leaking fuel rods in a fuel assembly by means of mapping the fission gas content in the plenum region and identifying the fuel rod(s) from which fission gases have been expelled.



*Figure 1. Left: Distribution of the volatile fission product  $^{137}\text{Cs}$  in the fuel stack, showing its migration to the pellet surfaces. Right: Distribution of the gaseous product  $^{85}\text{Kr}$  in the gas plenum region, showing high levels of fission gas release from the pellets to the plenum. In both cases, five high-burnup rods and four low-burnup rods are easily identified.*



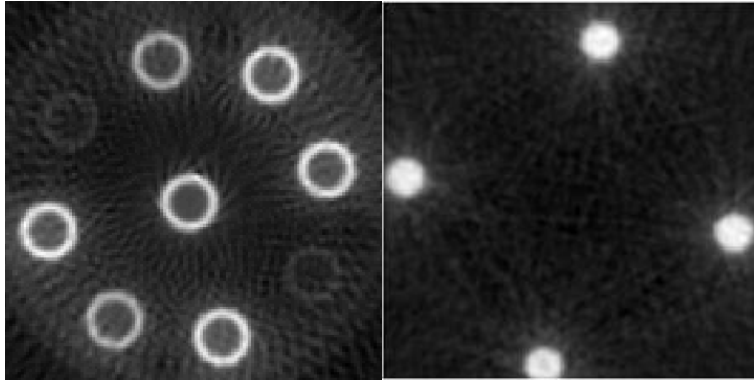


Figure 2. Left: Distribution of  $^{60}\text{Co}$  in the plenum region, showing neutron activation of the plenum springs. Right: Distribution of  $^{178}\text{mHf}$  in the plenum region, showing neutron activation of the tie rods. In both cases, the activation brings information of the composition of the structure materials. Note the absence of  $^{60}\text{Co}$  in the tie rods and the absence of  $^{178}\text{mHf}$  in the plenum springs as well as the different levels of  $^{60}\text{Co}$  content in the plenum springs.

### Reference group

The project had a reference group with the following participants:

Lars Hallstadius, Westinghouse

Christofer Willman, Westinghouse

Ane Håkansson, Uppsala University

Staffan Jacobsson Svärd, Uppsala University

In addition, support was given from additional employees of Westinghouse and OECD-HRP.

### Continuation of the project

After receiving his Ph.D., Scott Holcombe was employed by OECD-HRP to continue his research on fuel characterization. The tomographic device is now available for measurements of long-cooled HBWR fuel in the storage in the Halden bunker building. Once introduced by the reactor, the device will allow measurements to be performed on test fuel with short cooling times (1-2 days) enhancing the capabilities of e.g. fission-gas assessment significantly, while allowing for the fuel to be re-introduced into the core after measurement.

### Verification of nuclear fuel for safeguards purposes using non-destructive assay techniques for the future Swedish encapsulation facility

Ph.D. student: **Tomas Martinik**

Main supervisor: Dr. Sophie Grape

Assistant supervisor: Dr. Peter Jansson, Dr. Stephen J. Tobin (UU, Los Alamos National Laboratory)

Tomas continues his work within the Next Generation Safeguards Initiative Spent Fuel project (NGSI-SF) as a joint Ph.D. student between Uppsala University (UU) and Los Alamos National laboratory (LANL). This NGSI project began its effort in 2009 with the main objective of researching the potentials for new techniques and instruments applicable in future spent nuclear fuel (SNF) analysis. Originally 14 different non-destructive techniques were scrutinized in terms of their efficiency and applicability on determination of individual SNF characteristics. One of the techniques, the Differential Die-Away method, demonstrates potential to verify SNF parameters, judging from simulation results so far. Given the need to verify spent nuclear fuel before encapsulation in difficult-to-access storage, the DDA method has been suggested for potential future use. Thus, the effort has mainly focused on the design of an instrument which is expected

to be deployed in Swedish nuclear facilities – CLAB and possibly CLINK. Tomas has worked with the design on this prototype.





During the first half of 2014 Tomas finalized his first paper, which presents results on the performance of the instrument to asymmetrically burned SFA. The results in the paper allowed for a deeper understanding of certain aspects of the DDA functionality had not been studied before. The paper was submitted to Nuclear Instruments and Methods in March 2014, and is still under review.

Tomas stayed in total 5 months at LANL during 2014, researching mainly individual components of the DDA instrument and finalizing the design with respect to the Swedish requirements. Tomas's work consisted of thorough simulations, modelling, analysis of results as well as their interpretation and understanding. At the time of Tomas's departure from LANL, the prototype design had been almost finished and all the majority of the parameters of individual components were determined. A conference paper was written and presented at International Atomic Energy Agency's International Symposium in Vienna in October 2014. This paper contains comparison of practical DDA design for Sweden with former conceptual DDA design as well as other possible modifications and applications of DDA instruments which turned out of general understanding in DDA method.

Detailed results of Tomas's research on the prototype design are expected to be summarized in a paper and submitted for a publication in scientific journal during spring 2015. An abstract on the DDA prototype design has also been submitted to the ESARDA conference in 2015.

## 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 Svärd, Dr. Peter Jansson

The Digital Cherenkov Viewing Device (DCVD) is a valuable tool for IAEA inspectors when verifying the presence and integrity of irradiated nuclear fuel assemblies in storage pools. In spite of its current use, there are still a number of properties of Cherenkov light emission and detection not fully understood, and a better understanding together with improved analysis routines are expected to enhance its capabilities for safeguards assessments.

Erik Branger started his Ph.D. studies in November 2013, with a research focus on the DCVD and its performance for partial-defect verification of spent nuclear fuel assemblies. During his first year, he collaborated with the Centre for image analysis at Uppsala University regarding applications of image analysis to DCVD data. This work is aimed at investigating how general image analysis tools may be used to gain more information about spent nuclear fuel properties. It resulted in a report which was made available to the DCVD group as well as the Swedish Radiation Safety Authority.

Erik also updated a Geant4 simulation toolkit developed earlier for simulating the Cherenkov light emissions from irradiated nuclear fuel assemblies, to work with a more recent version of Geant4, and extended it to be able to simulate more cases of interest. This toolkit was then used to start simulating how the Cherenkov light emission is affected by various fuel parameters.

An international reference group meeting was held in September, with the reference group consisting of people responsible for the DCVD hardware and software design, representatives from safeguards authorities and professionals working with image analysis. The comments and suggestions from the participants on the research project gave many ideas about what the ongoing as well as future work. Erik Branger has also participated in a DCVD measurement course at CLAB. The course was arranged by the DCVD group and given for IAEA inspectors and its scope regarded practical aspects and the use of the instrument. In connection to this course, a measurement campaign was performed by Erik, in which actual as well as dummy fuel assemblies were measured.

Erik Branger has attended and presented research results at two international conferences during 2014. The first was the Institute for Nuclear Materials Management Annual Meeting in Atlanta, USA, where a presentation was given about improvements in DCVD measurement results with the use of image analysis techniques. The second was given at the International Atomic Energy Agency Safeguards Symposium, where a much appreciated and well received presentation was given on the possible unattended partial-defect use of the instrument.



## Massive Computational methodology for Reactor Operation – MACRO

Ph.D. student: **Erwin Alhassan**

Main supervisor: Bitr. univ. lekt. Henrik Sjöstrand.

Assistant supervisors: Univ. lekt. Michael Österlund, Prof. Stephan Pomp, Dr. Dimitri Rochman.

Erwin started his Ph.D. studies in 2011. He is using the Total Monte Carlo method (TMC) for assessing the impact of nuclear data uncertainties on reactor macroscopic parameters of the European Lead Cooled Training Reactor (ELECTRA). Uncertainties of plutonium isotopes and americium within the fuel, uncertainties of the lead isotopes within the coolant and some structural materials of importance have been investigated at the beginning of life. For the actinides, large uncertainties were observed in the  $k_{\text{eff}}$  due to nuclear data for Pu-238, 239, 240, while for the lead coolant, the uncertainty in the  $k_{\text{eff}}$  for all the lead isotopes – with the exception of Pb-204 – were large with significant contribution coming from Pb-208. The dominant contributions to the uncertainty in the  $k_{\text{eff}}$  came from uncertainties in the resonance parameters for Pb-208.

Methodologies for benchmark selection based the TMC method have also been developed. The method has been applied for nuclear data uncertainty reduction using integral benchmarks. From the results obtained, it was observed that by including criticality benchmark experiment information using a binary accept/reject method; a 40% and 20% reduction in nuclear data uncertainty in the  $k_{\text{eff}}$  was achieved for Pu-239 and Pu-240 respectively for the studied ELECTRA case.

These results were presented in his licentiate thesis in May 2014.

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

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

Main supervisor: Bitr. Univ. lekt. Henrik Sjöstrand

Assistant supervisor: Prof. Arjan Koning, Dr. Dimitri Rochman (NRG, The Netherlands), Prof. Klaes-Håkan Beijmer, 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.

During 2014 Petter has presented his work at various conferences and prepared an extensive manuscript on “Including experimental information in TMC using file weights from automatically generated experimental covariance matrices”. In short, a method for a mathematically stringent way to include experimental information in the TMC process is presented and discussed.

Notably, this work includes, besides researcher from applied nuclear physics and NRG, also researchers from the department of mathematics. This work may, furthermore, serve as seed for collaboration with PSI in Switzerland since Dimitri Rochman recently relocated to PSI.





## Neutron-induced nuclear reactions at intermediate energies

Ph.D. student: **Kaj Jansson**

Main supervisor: Bitr. Univ. lekt. Dr. Cecilia Gustavsson

Assistant supervisor: Prof. Stephan Pomp, Dr. Alexander Prokofiev

Kaj started during spring 2012 on the NFS project 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. Medley has been equipped with a low pressure gas system which was, together with a PPAC prototype, successfully tested. Due to delays in the construction of NFS in France, moving the setup to GANIL was postponed to the end of 2015 and first beam is expected early 2016.

During 2014 Kaj has also been working on analysing experimental data on the neutron standard  $\text{Li-6}(n,\alpha)$ . The data have been obtained at IRMM in Belgium with a Frisch-grid ionization chamber. The development work for NFS and the experimental data from IRMM will form the background for Kaj's licentiate thesis which will be presented in spring 2015.

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

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

Main supervisor: Prof. Stephan Pomp

Assistant supervisor: Dr. Mattias Lantz, Univ. lekt. Michael Österlund

Andrea started in spring 2011 on the ALFONS project. 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. Andrea presented his licentiate thesis in December 2014. In the design and characterization of the neutron source for IGISOL is presented. The neutron source, consisting of a 5 mm-thick water-cooled beryllium plate on which the incoming protons impinge, was simulated using different Monte Carlo codes (MCNPX and FLUKA). The high-energy part of the neutron spectrum was characterized in a measurement at the The Svedberg Laboratory in Uppsala. The results of the measurement show that the FLUKA simulation tends to underestimate the neutron yield at the highest energies, while MCNPX shows a better agreement with the experimental data.

A prototype of the proton-neutron converter was installed at the IGISOL-JYFLTRAP facility for a test-run in March, 2014. During this experiment no fission was induced, but the neutron source was tested for the first time and a pre-study was performed for the estimation of the neutron flux and energy spectrum at IGISOL. A first run with the neutron source and measuring fission yields from U-238 is planned for April 2014.

## Studies of independent fission yields from fast neutrons

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

Main supervisor: Dr. Mattias Lantz

Assistant supervisor: 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 TSL measurements for determining the neutron energy spectrum at IGISOL. Vasileios works in parallel with Andrea Mattera. His focus is, however, on the fission modelling and comparison of experimental data with theoretical calculations using the TALYS and GEF codes. Furthermore, Vasileios analysed experimental data on production of fission isomers taken in the spring of 2014. He will present his licentiate thesis in spring 2015.



## Surface Coatings as Xenon Diffusion Barriers for Improved Detection of Clandestine Nuclear Explosions

Ph.D. student: **Lisa Bläckberg**

Main supervisor: Prof. Mattias Klintenberg

Assistant supervisor: Dr. Henrik Sjöstrand, Dr. Anders ringbom (FOI)

This thesis investigates surface coatings as xenon diffusion barriers on plastic scintillators. The motivation for the work is improved radioxenon detection systems, used within the verification regime of the Comprehensive Nuclear-Test-Ban Treaty (CTBT).

One type of radioxenon detection systems used in this context is the Swedish SAUNA system. This system uses a cylindrical plastic scintillator cell to measure the beta decay from radioxenon isotopes. The detector cell also acts as a container for the xenon sample during the measurement.

One problem with this setup is that part of the xenon sample diffuses into the plastic scintillator material during the measurement, resulting in residual activity left in the detector during subsequent measurements. This residual activity is here referred to as the memory effect.

It is here proposed, and demonstrated, that it is possible to coat the plastic scintillator material with a transparent oxide coating, working as a xenon diffusion barrier. It is found that a 425 nm  $\text{Al}_2\text{O}_3$  coating, deposited with Atomic Layer Deposition, reduces the memory effect by a factor of 1000, compared an uncoated detector. Furthermore, simulations show that the coating might also improve the light collection in the detector. Finally, the energy resolution of a coated detector is studied, and no degradation is observed.

The focus of the thesis is measurements of the diffusion barrier properties of  $\text{Al}_2\text{O}_3$  films of different thicknesses deposited on plastic scintillators, as well as an evaluation of the expected effect of a coating on the energy resolution of the detector. The latter is studied through light transport simulations. As a final step, a complete coated plastic scintillator cell is evaluated in terms of memory effect, efficiency and energy resolution.

In addition, the xenon diffusion process in the plastic material is studied, and molecular dynamics simulations of the Xe- $\text{Al}_2\text{O}_3$  system are performed in order to investigate the reason for the need for a rather thick coating to significantly reduce the memory effect.

Lisa successfully defended her Ph.D. thesis: "Surface Coatings as Xenon Diffusion Barriers for Improved Detection of Clandestine Nuclear Explosions" on February 28.



*The following Ph.D. students are active within the research on Gen IV nuclear systems. Although outside the research framework of SKC, these projects are relevant from a general knowledge and competence building perspective:*

### Core Monitoring in Lead-Cooled Fast Reactors

Ph.D. student: **Peter Wolniewicz**

Main supervisor: Prof. Ane Håkansson

Assistant supervisors: Dr. Carl Hellesen, Dr. Peter Jansson, Ass. Prof. Staffan Jacobsson Svärd, Ass. Prof. Michael Österlund

In this project the capabilities of in-core and/or near-core detector systems for monitoring anomalies in core operation by means of changes in the neutron energy spectrum was investigated. In particular, Peter Wolniewicz has been working on the development of a methodology to detect coolant void in Lead-cooled Fast Reactors. The project has progressed significantly during 2014 and Peter successfully defended his Ph.D. thesis on October 31: "Development of a methodology for detecting coolant void in lead-cooled fast reactors by means of neutron measurements".

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

Ph.D. student: **Matilda Åberg Lindell**

Main supervisor: Dr. Sophie Grape

Assistant supervisors: Prof. Ane Håkansson, Ass. Prof. Staffan Jacobsson Svärd

Matilda Åberg Lindell studies nuclear safeguards for future Gen IV systems. The aims of this research project is specified to (1) develop methodologies for evaluating diversion resistance for Gen IV systems and (2) assign safeguards instrumentation to be used in sensitive parts of the fuel cycle.

Matilda has concluded her work on the first goal and she has finalized three publications on methodologies for evaluating diversion resistance in Gen IV systems.

During 2014 Matilda started to address the second goal. Here the focus will be put on verification of spent nuclear fuel at the reception area of a recycling facility because this is the last residence where the fuel's integrity is still intact. The work comprises investigations of different ways to analyse realistic gamma-ray spectra obtained from simulations, and possibly also later measurements performed at Clab. The potential of using advanced statistical methods such as multivariate analysis methods is currently investigated. The objective is to apply such methods to gamma-ray spectra in order to be able to verify and/or predict nuclear fuel characteristics such as burnup, initial enrichment and cooling time. Information on fuel characteristics can in turn be utilized to detect possible nuclear material diversions and other anomalies. Multivariate techniques may potentially increase the efficiency, regarding costs and detection ability, while keeping the safeguards implementations at low levels of intrusion to regular facility operations.

As a preparation for this part of the research project, Matilda arranged a successful study visit to the Rokkasho reprocessing plant in Japan with the purpose of studying the implementation of safeguards instrumentation in a current reprocessing facility under IAEA safeguards. Six participants from UU and SSM visited the facility during one week in February 2014. Matters of safeguards and reprocessing were discussed with representatives of the operating company, Japan Nuclear Fuel Limited, the IAEA, and the Japanese Nuclear Regulatory Authority. In June 2014, Matilda also visited Chalmers to examine their HPGe detector setup and discuss feasible chemical parameters of the advanced reprocessing method to be measured.



In addition to the produced publications and presentations, Matilda has presented her research at several occasions to the Swedish Radiation Safety Authority, and furthermore to safeguards staff from various companies within Swedish nuclear power industry. She has also presented her work at the annual GENIUS progress meetings.

## 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 Verma is a Ph.D. student within the Swedish-French collaboration on Gen IV research directed specifically to the ASTRID Sodium Fast Reactor, who started in November 2012. Her Ph.D. project is entitled “Core Diagnostics in the ASTRID Sodium Fast Reactor (CODIAS)”, and it is part of the framework program “Core physics, diagnostics and instrumentation for enhanced safety of the sodium cooled fast reactor ASTRID”, which is coordinated by Prof. Imre Pázsit at Chalmers.

The aim of the CODIAS project is to develop a simulation framework for evaluation of a neutron monitoring system in the prototype generation IV reactor ASTRID. During 2014 Vasudha, has implemented detailed models of the ASTRID reactor in the two Monte Carlo codes SERPENT and TRIPOLI-4. Using these models, Vasudha has evaluated the possibility for a neutron monitoring system to detect an inadvertent control rod withdrawal. This is considered to be a major accident scenario which could lead to local core melting.

The results from the simulations show that a neutron monitoring system is capable of detecting this situation at an early stage and also determine which control rod that has been inadvertently withdrawn. The use of two codes also gives an insight into the systematic uncertainties in the simulations, in addition to the statistical uncertainties. The results show that the codes agree qualitatively. However, there are significant differences between the two. These differences could possibly be attributed to the fact that the codes use different estimators for neutron transport and therefore have different inherent systematic uncertainties.

The results are presented in a paper written by Vasudha which will be submitted to a scientific journal shortly.

## Towards a functional room-temperature replacement of HPGe for efficient high-energy resolution gamma-ray spectroscopy

Ph.D. student: **Anna Shepidchenko**

Main supervisor: Prof. Mattias Klintonberg

Assistant supervisors: Prof. Susanne Mirbt, Prof. Ane Håkansson

The last part of Anna's research has concerned a more systematic study of the Cd vacancy and Te anti-site in CdTe. Differently charge states are investigated and new insights provided. By far the most important result from this part of Anna's work is that she is able to propose an explanation of the high resistivity in un-doped CdTe. This insight opens up for a development of completely new detector materials that may be used in a vast amount of applications within nuclear technology. This project must be considered to be highly successful and Anna will defend her Ph.D. thesis 2015-04-10.



## Publications and conferences

### Work published/accepted in scientific journals

Grape S, Jacobsson Svärd S, Lindberg B, "Partial Defect Evaluation Methodology for Nuclear Safeguards Inspections of Used Nuclear Fuel Using the Digital Cherenkov Viewing Device", Nuclear Technology, 186(1):90-98 (2014).

Qvist S, Greenspan E, "The ADOPT code for automated fast reactor core design", Annals of Nuclear Energy, 71:23-36 (2014).

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Qvist S, "Optimization method for the design of hexagonal fuel assemblies", Annals of Nuclear Energy. 2014;75:498-506. (2014).

Andersson P, Valldor-Blücher J, Andersson Sundén E, Sjöstrand H, Jacobsson Svärd S, "Design and initial 1D radiography tests of the FANTOM mobile fast-neutron radiography and tomography system", Nuclear Instruments and Methods in Physics Research Section A, 756:82-93 (2014).

Andersson, Peter; Jacobsson Svärd, Staffan; Andersson Sundén, Erik; Sjöstrand, Henrik, "Fast-Neutron Tomography using a Mobile Neutron Generator for Assessment of Steam-Water Distributions in Two-Phase Flows", Review of Scientific Instruments (2014).

Grape S, Jacobsson Svärd S, Hellesen C, Jansson P, Åberg Lindell M, "New perspectives on nuclear power - Generation IV nuclear energy systems to strengthen nuclear non-proliferation and support nuclear disarmament", Energy Policy, 73:815-819 (2014).

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S. Qvist, "Reactivity Swing as a function of Burnup for Uranium-Fuelled Fast Reactors", Nuclear Technology (Scheduled for publication in April 2015).

Henrik Sjöstrand, Erwin Alhassan, Junfeng Duan, Cecilia Gustavsson, Arjan Koning, Stephan Pomp, Dimitri Rochman, Michael Österlund, "Propagation of nuclear data uncertainties for ELECTRA burn-up calculations", Nuclear Data Sheets 118:527-30.

Dimitri Rochman, SC van der Marck, Arjan Koning, Henrik Sjöstrand, P. Helgesson Winfried Zwermann, "Efficient use of Monte Carlo: uncertainty propagation", Nuclear Science and Engineering 177 no. 3, 337.

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Erwin Alhassan, Henrik Sjöstrand, Junfeng Duan, Cecilia Gustavsson, Arjan Koning, Stephan Pomp, Dimitri Rochman, Michael Österlund: "Combining Total Monte Carlo and Benchmarks for nuclear data uncertainty propagation on an LFRs safety parameters", Nuclear Data Sheets 118, 542-544.

Junfeng Duan, Stephan Pomp, Henrik Sjöstrand, Erwin Alhassan, Cecilia Gustavsson, Michael Österlund, Arjan Koning, Dimitri Rochman, "Uncertainty study of nuclear model parameters for the  $n + {}^{56}\text{Fe}$  reactions in the fast neutron region below 20 MeV", Nuclear Data Sheets 118, 346-348, 2014.

A. Solders, et al., "Accurate fission data for nuclear safety", Nuclear Data Sheets 119 (2014) 338-341.

C. Gustavsson, et al., "Status report on the analysis of inelastic neutron scattering from carbon, Iron, yttrium and lead at 96 MeV", Nuclear Data Sheets, Volume 119, Pages 183-185.

A. Mattera, et al., "Characterization of a  $\text{Be}(p, xn)$  neutron source for fission yield measurements", Nuclear Data Sheets 119 (2014) 416-418.

V. Simutkin, et al., "Experimental neutron-induced fission fragment mass yields of  ${}^{232}\text{Th}$  and  ${}^{238}\text{U}$  at energies from 10 to 33 MeV", Nuclear Data Sheets 119, (2014) 331-333.

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Henrik Sjöstrand, Erwin Alhassan, Junfeng Duan, Cecilia Gustavsson, Arjan Koning, Stephan Pomp, Dimitri Rochman, Michael Österlund, "Propagation of nuclear data uncertainties for ELECTRA burn-up calculations". Nuclear Data Sheets 118:527-30, 2014.

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## Papers submitted during 2014

S. Qvist, B. W. Brook, "Potential for worldwide displacement of fossil-fuel electricity by nuclear energy in three decades based on extrapolation of regional deployment data", Submitted to PLOS One

S. Qvist, E. Greenspan, "Design space analysis for breed-and-burn reactor cores", Submitted to Nuclear Science and Engineering

S. Jacobsson Svärd, S. Holcombe, S. Grape, "Applicability of a set of tomographic reconstruction algorithms for quantitative SPECT on irradiated nuclear fuel assemblies", Submitted to Nuclear Instrumentation and Methods in Physics Research Section A.





S. Jacobsson Svärd, S. Holcombe, S. Grape, "Tomographic Reconstruction Algorithms for SPECT on Irradiated Nuclear Fuel Assemblies", Submitted to Nuclear Instrumentation and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment.

S. Holcombe, S. Jacobsson Svärd, L. Hallstadius, "A Gamma Emission Tomography Instrument for Characterizing Fuel Assemblies at the Halden Boiling Water Reactor", Submitted to Nuclear Instrumentation and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment.

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S. Qvist, B. W. Brook, "Environmental, economic and health impacts of phasing out nuclear power in Sweden", Submitted to Energy Policy.

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A. Al-Adili, K. Jansson, M. Lantz, A. Solders, C. Gustavsson, A. Mattera, A. V. Prokofiev, V. Rakopoulos, D. Tarrío, S. Wiberg, M. Österlund, S. Pomp, "Ion counting efficiencies at the IGISOL facility", The European Physical Journal A.

## Conference contributions

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Andersson, Peter; Bjelkenstedt, Tom; Andersson-Sunden, Erik; Sjöstrand, Henrik; Jacobsson-Svärd, Staffan; "Neutron tomography using mobile neutron generators for assessment of void distributions in thermal hydraulic test loops", 2014, WCNR-10, submitted.

Jansson P, Grape S, Tobin S, Liljenfeldt H, "Experimental Comparison between High Purity Germanium and Scintillator Detectors for Determining Burnup, Cooling Time and Decay Heat of Used Nuclear Fuel", The 40th Annual Waste Management (WM) Conference, Phoenix, Arizona, USA, March 2-6, 2014.

Qvist S, "The Autonomous Reactivity Control (ARC) System", International Congress on Advances in Nuclear Power Plants (ICAPP), Charlotte, NC, USA, April 6-9, 2014.

Branger E, Grape S, Jacobsson Svärd S, Wernersson E L, "Improved DCVD assessments of irradiated nuclear fuel using image analysis techniques", Institute of Nuclear Materials Management 55th Annual Meeting (INMM), Atlanta, Georgia, USA, July 20-24, 2014.

Holcombe S, Jacobsson Svärd S, Eitrheim K, Hallstadius L, "Gamma Emission Tomography for Characterizing Halden Boiling Water Reactor Fuel Assemblies: Instrumentation, Simulations, and Experimental Demonstration", Enlarged Halden Programme Group Meeting (EHPG), Røros, Norway, September 7-12, 2014.

Holcombe S, Jacobsson Svärd S, Eitrheim K, Hallstadius L. "Characterization of Nuclear Fuel Rods Operated at High Linear Heat Rates Using Nondestructive Gamma-ray Spectroscopy", 2014 Water Reactor Fuel Performance Meeting (TopFuel), Sendai, Japan, September 14-17, 2014.

Holcombe S, Jacobsson Svärd S, Hallstadius L, "Gamma Emission Tomography for Determining Pin-wise Percent Fission Gas Release in Fuel Assemblies at the Halden Boiling Water Reactor", 2014 Water Reactor Fuel Performance Meeting (TopFuel), Sendai, Japan, September 14-17, 2014.



S. Holcombe, S. Jacobsson Svärd, K. Eitrheim, L. Hallstadius, "Gamma Emission Tomography for Characterizing Halden Boiling Water Reactor Fuel Assemblies: Instrumentation, Simulations, and Experimental Demonstration", Enlarged Halden Program Group Meeting, Røros, Norway, September 2014.

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Branger E, Jacobsson Svärd S, Grape S, Wernersson E L, "Towards unattended partial-defect verification of irradiated nuclear fuel assemblies using the DCVD", IAEA Symposium on International Safeguards, Vienna, Austria, October 20-24, 2014.

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T. Martinik, V. Henzl, S. Grape, S. Jacobsson Svärd, P. Jansson, M. T. Swinhoe. and S. J. Tobin: "Characterization of Spent Nuclear Fuel with a Differential Die-Away Instrument", Proceedings of IAEA Symposium on International Safeguards, "Linking Strategy, implementation and People", Vienna, Austria, 2014, available online: [http://www.iaea.org/safeguards/symposium/2014/home/eproceedings/sg2014\\_eproceedings\\_online.pdf](http://www.iaea.org/safeguards/symposium/2014/home/eproceedings/sg2014_eproceedings_online.pdf) [2015-01-19]

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P. Jansson, S. Jacobsson Svärd, S. Grape, A. Davour, "Simulations and benchmarking", Presentation at the UGET project meeting in Washington DC, USA, May 2014.

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M. Åberg Lindell, A. Håkansson, P. Andersson, S. Grape, "Safeguarding advanced Generation IV reprocessing facilities: Challenges, R&D needs, and development of measurements", E-poster presentation at the IAEA Symposium on International Safeguards, Vienna, Austria, October 20-24, 2014.

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M. Åberg Lindell, ESNII+: Workshop on safety of the ESNII+ reactors, 22-23 May 2014, Stockholm.

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A. Mattera, H Penttilä, A Esposito, R Bedogni, V Rakopoulos, D Bortot, A Hjalmarsson, A Pola, A Al-Adili, MV Introini, B Valldor-Blücher, P Andersson, E Passoth, A Gentile, S Pomp, A Prokofiev, D Gorelov, M Lantz, A Solders, S Rinta-Antila, "Measurement of the energy spectrum from the neutron source planned for IGISOL", European Research Infrastructures for Nuclear Data Applications (ERINDA) workshop, CERN, Geneva, Switzerland, 1 - 3 Oct 2013.

Lantz M., Gorelov D., Al-Adili A., Jokinen A., Kolhinen V., Mattera A., Rinta-Antila S., Penttilä H., Pomp S., Rakopoulos V., Simutkin V., Solders A., "Development of a neutron converter for studies of neutron-induced fission fragments at the IGISOL facility", European Research Infrastructures for Nuclear Data Applications (ERINDA) workshop, CERN, Geneva, Switzerland, 1 - 3 Oct 2013.



## Additional information of interest to SKC

### 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
- Switzerland: CERN
- Thailand: Chiang Mai University
- Kenya: University of Nairobi
- USA: LANL, UCB, LBNL, LLNL, PNNL
- Norway: OECD Halden Reactor Project and IFE, Technical University in Trondheim
- IAEA
- The World Nuclear University

## Outreach

- A report on future electricity supply in Sweden was presented at Almedalsveckan in July: “Svensk elförsörjning i framtiden – en fråga med globala dimensioner : En tvärvetenskaplig rapport från Uppsala universitet”. The report is available at <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-233392>
- A debate paper was presented in Svenska Dagbladet: Håkansson A, Ottosson J, Qvist S, Grape S, Hellesen C, Lantz M, et al. IPCC förordar kärnkraft för att minska utsläppen. Svenska Dagbladet (SvD). 2014;11 nov.
- At the IAEA Symposium on International Safeguards in Vienna in October, Uppsala University participated with an exhibition, covering research and education with relevance for the nuclear field, and personnel from UU's central administration participated in several meetings with high officials of the IAEA.
- The courses in nuclear technology at Uppsala university have received international attention, e.g. in terms of the education given in nuclear safeguards, which was given attention in the IAEA report ”Sixth Biennial Report of the Secretary-General on Disarmament and Non-proliferation Education”.

## Additional achievements and commitments during 2014

- Sophie Grape has co-chaired the ESARDA working group of Training and Knowledge Management, with Karin Persson as an additional group member.
- Peter Jansson has been active in the ESARDA working group on Non-Destructive Assay.
- Matilda Åberg Lindell has participated in the ESARDA working group on Verification Technologies and Methodologies.
- Sophie Grape has been a member of Kärnavfallsrådet.
- On behalf of SSM, five of the division's researchers headed by Sophie Grape finalized a scrutiny assessment of three SKB reports describing their plans for encapsulation and final storage.
- Four of the division's teachers have implemented a system for supporting and following up students' progression in oral presentation within the bachelors program on nuclear power engineering, financed by UU funds for pedagogics development.



## Visions and Plans

The mission for the Division of applied nuclear physics 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. This particular matter was addressed in our report: “Svensk elförsörjning i framtiden – en fråga med globala dimensioner : En tvärvetenskaplig rapport från Uppsala universitet”. The report is available at <http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-233392>

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 universities will be instrumental. In particular when considering the future needs of the developing countries, 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.

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

## 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.

## Plans

### **Education**

- Making the bachelors nuclear engineering program a full three-year program.
- Offering “nuclear tracks” in several masters engineering programs.
- Continuing to train and educate personnel from nuclear industry and authorities within our contract education.
- Adding courses to the NANSS portfolio and direct these also for international stakeholders.

### **Research**

- Strengthening our collaboration with OECD Halden Reactor Project partly through the MÅBiL collaboration by:
  - setting up a research program within core and fuel diagnostics with experiments to be carried out at the HBWR,
  - setting up a research program within materials and aging with experiments to be carried out at the HBWR.
- Continuing our efforts to contribute to Gen IV research within our fields of expertise, a field of research that is attractive to students and young scientists:
  - European collaborations (ASTRID, MYRRHA, ELSY ...),
  - national collaborations to form a continuous Swedish Gen IV program,
  - researching on the system aspect of Gen IV from a safety-security perspective.
- Enhancing our contributions to Swedish and international safeguards research:
  - assessing and designing safeguards for future nuclear systems, including reactor designs with safeguards aspects taken into account,
  - providing technologies and methodologies for spent fuel assay, with particular focus on enhancing IAEA’s capabilities to detect partial defects.



- Intensifying our efforts to provide efficient assessment technologies for spent fuel prior to encapsulation and storage:
  - taking part in the design of new measurement system, making use of the latest research achievements in fuel assay,
  - performing experimental campaigns on spent fuel for evaluation purposes.







## Appendix 4 - MÅBiL Annual Report 2014



As a response to the new SKC strategy for research funding, discussions were initiated during 2013 with representatives from Uppsala University, KTH Royal Institute of Technology, Chalmers University of Technology and SKC Swedish Center for Technology to investigate comprehensive research collaboration between the universities with funding from SKC within a three year commitment. The aim was twofold: 1) to find a long sought research collaboration on the national level and 2) to address three research fields of particular interest for the nuclear industry. These fields are the following:

- (i) Studies of novel materials or combinations of materials with application to Accident Tolerant Fuels (ATF).
- (ii) Studies of materials and phenomena connected to material ageing.
- (iii) Studies of nuclear processes under regular and transient conditions related to point (i) and (ii) above.

After a period of fine tuning the concept MÅBiL was launched during second half of 2014 with the following participating entities:

Division of applied nuclear physics (UU)  
 Division of materials theory (UU)  
 Division of materials physics (UU)  
 Department of solid mechanics (KTH)  
 Reactor physics (KTH)  
 Applied physical chemistry (KTH)  
 Sustainable Nuclear Energy Centre, SNEC (Chalmers).  
 Westinghouse Electric Sweden

As stated in the research plan of MÅBiL, research is a dynamic activity where the output is hard to foresee. The work can deviate into dead ends or lead into completely new tracks, which were not considered initially. It is against this background the research conducted within MÅBiL shall be looked upon; as a way to address the above research fields and to generate general competence among a new generation of researchers in the field of nuclear technology.

The first MÅBiL meeting was held February 5 in Uppsala. It was an opportunity for, in particular, our young colleagues to meet and discuss common matters. It was decided at that meeting that the following "General Assemblies" of MÅBiL shall be held in connection with the Annual SKC Symposium.

This first Annual Report of MÅBiL is by necessity quite brief since several research activities have started late 2014 and in two cases started up in early 2015 due to, among others, difficulties to find Ph.D. students with adequate background. At any rate, it is my hope and belief that this Annual Report shall be the first one of a long row of reports in the future, filled with exciting research results.

*Ane Håkansson*





## *Research in brief*

### Uppsala University (UU)

#### **Fuel diagnostics**

Peter Andersson and Staffan Jacobsson Svärd

#### **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 with the aims to:

- Help developing analysis techniques.
- Perform analyses of gathered data from irradiation experiments.
- Participate in the development of Accident-Tolerant Fuels.
- Enable a knowledge transfer to the Swedish nuclear industry.

#### **Status**

Dr. Peter Andersson has been hired for the postdoc position and started on the 1st of February, 2015. A preliminary selection has been made of research topics within the HPR research program Fuel Safety and Operational Margins that are suited for this collaboration considering its scope and time extension. The selected topics are the following:

- Fuel behavior under LOCA conditions, including fuel fragment relocation and iodine and cesium release.
- Fission gas release mechanisms in high burn-up fuel.

An agreement has been settled with OECD-HRP, and Peter Andersson has been formally invited to Halden during his 2-year postdoc appointment.

#### **Plans**

The work on these topics will commence during the spring of 2015. Initially, focus will be on analyzing and reporting experiments already performed at OECD-HRP. In the autumn of 2015, the postdoc will participate in current experiments on the topics listed above.

#### *Contact persons in the Swedish nuclear industry*

Contacts will be taken with represents of the Swedish nuclear industry to receive feedback on the project plans and, in the coming years, to present results from the project. A list of suitable persons is being prepared, including represents from SSM, Westinghouse and the three power plants.



## Uppsala University (UU)

### Total Monte Carlo

Petter Helgesson (Ph.D. student), Henrik Sjöstrand and Stephan Pomp

During 2014, the Ph.D. student Peter Helgesson started working with the Måbil -TMC project. In this report, we give some background to the TMC method and summarize the achieved milestones.

### Background

In this project we connect macroscopic fuel and aging parameters to the fundamental nuclear physics processes by using the world leading nuclear model code TALYS and the Total Monte Carlo Method (TMC) method [1]. With a Talys base code package nuclear data libraries can be produced for all isotopes, reaction channels and secondary particle productions for the entire nuclide map. This, so called TENDL library, is in that respect superior to classical libraries such as ENDF/B-VII and JEFF. Furthermore, the TENDL library has the advantage that it can produce complete co-variance information. In the project we are using and improving the TENDL library to address material issues coupled both to fuel and aging performance, such as flux at the reactor vessel, gas production and PKA-spectrum. The goal is to quantify these parameters including their uncertainties. The project is inspired by the IAEA Coordinated Research Project: Primary Radiation Damage Cross Sections [2].

### Reached milestones 2014: materials

1. The goal was to publish methods that better takes into account the experimental differential data to calibrate the nuclear data and its uncertainties and to apply these methods for reactor relevant materials. An article in the Nuclear Data Sheets [3] has been published, in which, inter alia,  $^{56}\text{Fe}$  is examined.
2. At SKC's annual symposium, uncertainties in the effectiveness of using so-called "shielding assemblies" aiming to extend the life of pressurized water reactors were reported. The uncertainty was determined to be 2 %, but there are some indications that the uncertainty might be bigger and, consequently, we will continue to work with this application.

### Reached milestones 2014: fuel

The goal was to publish methods that better takes into account the experimental differential data to calibrate the nuclear data and its uncertainties and to apply them to today's fuel and study how the isotope vector and reactor parameters are affected for long burnup. In Reference [3] a  $^{235}\text{U}$  PWR rod with  $\text{UO}_2$  fuel was modeled with burn up to 61 MWd / kgU. The uncertainties due to nuclear data were examined for the whole fuel life-span and reported for the end of life. The results were also reported at the SKC annual meeting.

### References

- [1] A. Koning and D. Rochman, Nucl. Data Sheets 113,2841 (2012)
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- [3] P. Helgesson, H. Sjöstrand, A.Koning, D.Rochman, E.Alhassan, S.Pomp Incorporating experimental information in the TMC methodology using file weights Nuclear Data Sheets, Volume 123, 214–219, 2015



## Uppsala University (UU)

### ICEWATER

Erki Metsanurk (Ph.D. student), Mattias Klintenberg, Göran Possnert, Pål Efsing (KTH), Pär Olsson (KTH) and Mats Jonsson (KTH).

### IASCC

Proper design of an experiment for corrosion studies is essential for successful and reliable results:

*“Corrosion behavior is often the result of complicated interactions between the conditions of a metallic surface and the adjacent environment to which it is exposed. Therefore, there is no universal corrosion test for all purposes. Many investigators have traditionally avoided the use of statistical techniques because the added reliability did not seem to offset the effort and time required to become familiar with the methodology or to perform the calculations. Most often, the results must be interpreted in terms of relative rankings. Such interpretations can be subjective and depend much on the judgment of the investigator. Therefore, it is advisable, when planning a corrosion-testing program, to select the testing conditions carefully in order to produce ranking parameters with minimal influence from testing conditions while rich in engineering significance” [1].*

The onset of irradiation-assisted stress corrosion cracking (IASCC) depends on the material, stress, radiation and chemical environment. In order to emulate real-world situations all of those components must be sufficiently handled. Whereas the choice of material(s) to study is trivial, all other factors need considerably more attention.

In light water reactors (LWR) the material is irradiated by neutrons. Conducting experiments with neutrons is time-consuming and expensive. It has been shown that using a proton source can result in similar microstructure, radiation-induced segregation, hardening and susceptibility to IASCC as with neutrons resulting in considerably faster and more affordable experiments [2].

### Slow Strain Rate Testing

There are two options to induce stress in the material, either statically or dynamically. Over the years latter has become a standard way of studying IASCC for several reasons including faster onset of cracks which is essential for this project:

*“One problem often associated with tests for environmentally induced cracking conducted in the aforementioned manner (E.M.: static loading) is the amount of testing time required to initiate cracking and, in turn, the amount of time needed to conduct a proper evaluation of these types of phenomena. In some cases, the initiation time needed to produce cracking in some material environment situations is in excess of 10 000 hours (> 1 year). In order to reduce this initiation time, many investigators use aggressive, artificial solutions to chemically accelerate these tests. However, the problem often associated with tests conducted in these environments is one of producing test results that relate to real-world situations. These methods can often be used to screen one material from another, but their predictive capabilities are often in doubt.*

*Approximately 20 years ago (E.M.: from 1993), a new testing technique referred to as slow strain rate testing was first applied to the investigation of environmentally induced cracking of metals and alloys. In this test method, the specimen is not held at a constant load or deflection during the period of exposure. The slow strain rate test uses the application of dynamic straining of the specimen in the form of a slow, monotonically increasing strain to failure. The apparent advantage of slow strain rate testing over conventional techniques is the use of the dynamic straining to mechanically accelerate cracking. It is hoped that this technique will allow the use of more realistic environments and also reduce the total time requirement for evaluating various metallurgical or environmental parameters”[3].*



### Relevant excerpt from ASM Handbook:

*“An important method for accelerating the SCC process in laboratory testing involves relatively slow-strain-rate tension (SSRT) testing of a specimen during exposure to appropriate environmental conditions. In other words, the test specimen is stretched monotonically in axial tension at a slow rate until failure. This method is also known as constant extension-rate tensile (CERT) testing. The application of slow dynamic strain exceeding the elastic limit assists in the SCC initiation. This accelerated technique is consistent with the various proposed general mechanisms of SCC, most of which involve plastic microstrain and film rupture. Slow-strain-rate tests can be used to test a wide variety of product forms, including parts joined by welding. Tests can be conducted in tension, in bending, or with plain, notched, or precracked specimens. The principal advantage of slow-strain-rate testing is the rapidity with which the SCC susceptibility of a particular alloy and environment can be assessed” [4].*

### Water recirculation loop

To emulate chemical environment in LWRs it is necessary to control and measure water pressure, temperature, dissolved oxygen and hydrogen, electrochemical potential, conductivity and if needed other dissolved ions. An example of such system is depicted on Figure 1.

### Standards

A lot of previous experience has been written into official standards and guidelines to provide a framework for reliable and repeatable experiments. A list of most relevant documents for this project is:

- ASTM E6-09b. This terminology covers the principal terms relating to methods of mechanical testing of solids. The general definitions are restricted and interpreted, when necessary, to make them particularly applicable and practicable for use in standards requiring or relating to mechanical tests. These definitions are published to encourage uniformity of terminology in product specifications [5]
- ASTM G129-00. This practice covers procedures for the design, preparation, and use of axially loaded, tension test specimens and fatigue pre-cracked (fracture mechanics) specimens for use in slow strain rate (SSR) tests to investigate the resistance of metallic materials to environmentally assisted cracking (EAC) [6].
- ASTM E8/E8M-13a. These test methods cover the tension testing of metallic materials in any form at room temperature, specifically, the methods of determination of yield strength, yield point elongation, tensile strength, elongation, and reduction of area [7].
- ASTM G111-97. This guide covers procedures, specimens, and equipment for conducting laboratory corrosion tests on metallic materials under conditions of high pressure (HP) or the combination of high temperature and high pressure (HTHP) [8].
- ASTM E4-14. These practices cover procedures for the force verification, by means of standard calibration devices, of tension or compression, or both, static or quasi-static testing machines (which may, or may not, have force-indicating systems) [9].
- ASTM E1012-14. Included in this practice are methods covering the determination of the amount of bending that occurs during the application of tensile and compressive forces to notched and unnotched test specimens during routine testing in the elastic range. These methods are particularly applicable to the force levels normally used for tension testing, creep testing, and uniaxial fatigue testing [10].



## Window design

The challenge in designing the window lies in finding compromise between its strength and dimensions. A thick window with small diameter will ensure adequate rupture strength, but the protons will end up being stopped in it instead of the sample. Although a concave window would provide more strength compared to a flat one, it might not allow for small enough distance between it and the sample given the stopping distance of protons in water. There is a possibility that a "reverse" concave window akin to reverse buckling rupture disks will work, but this needs to be experimentally verified.

We have performed simulations for a flat window using SRIM to find stopping distance for protons and finite elements mechanical modelling to evaluate stress inside the window. The results for 150  $\mu\text{m}$  thick flat window are shown on Figures 2, 3 and 4. This type of window will allow adequate amount of space between it and the sample and allows for diameter of up to approximately 2 mm. The window would be incorporated into SSRT autoclave by a tube as shown on Figure 5.

Because the window will accumulate a respectable amount of damage over time it is necessary for it to be replaceable. Although the experiments performed in Michigan by Raiman et al [11] determined that a relatively thin window will hold the pressure, the irradiation times were much lower than expected in current project. Therefore it is necessary to perform initial tests to assess the possible failure of the window due to radiation damage.

## Meetings

There have been three meetings with different participants:

- UU (Discussion)
- UU, with A. and M. Caro regarding previous experiences from irradiation-corrosion experiments.
- KTH, with Martin Öberg regarding the design of an SSRT autoclave.

A meeting is planned in January 2015 with corrosion testing instrument manufacturer Cormet Oy at Vantaa, Finland.

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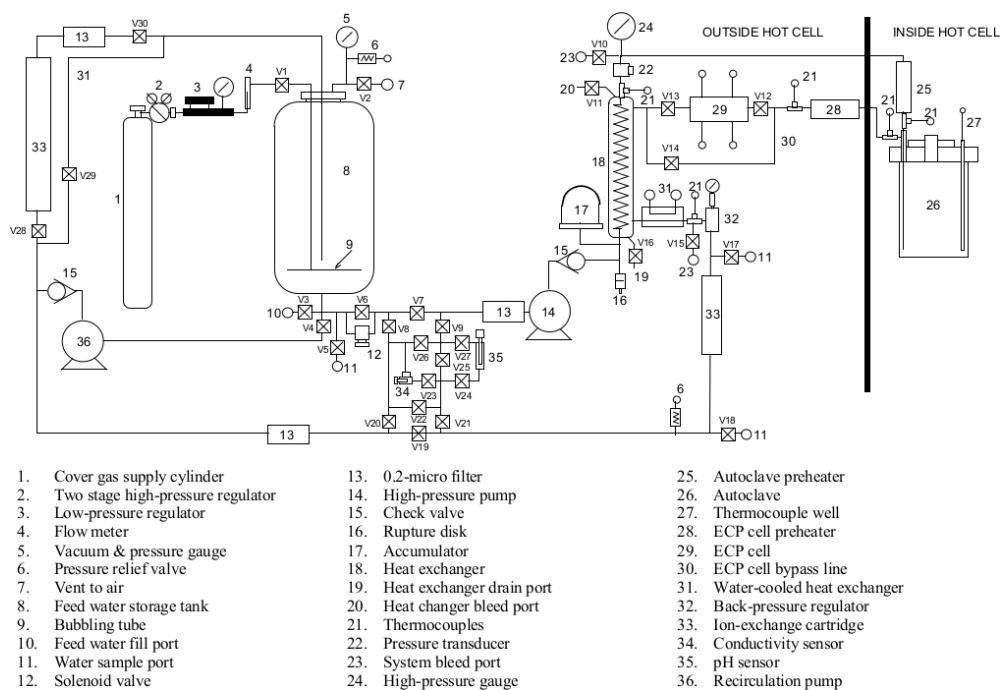


Figure 1. A schematic diagram of a water recirculation system.

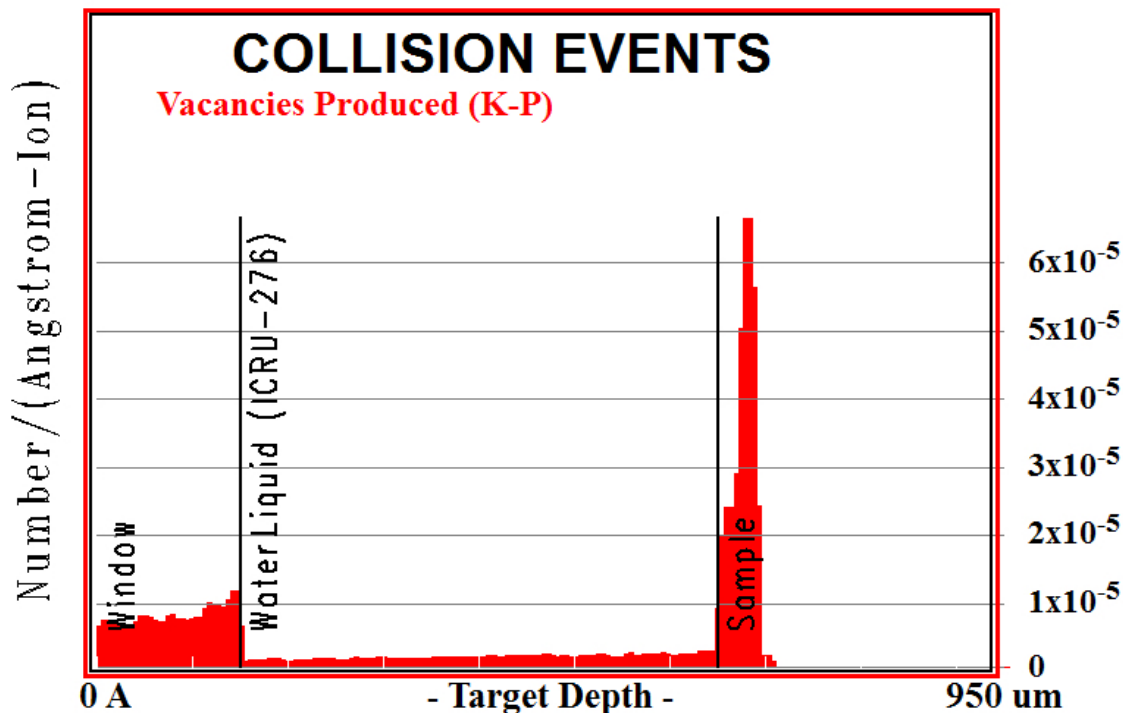


Figure 2. Damage distribution for 150  $\mu\text{m}$  m window, 500  $\mu\text{m}$  of water and the sample.



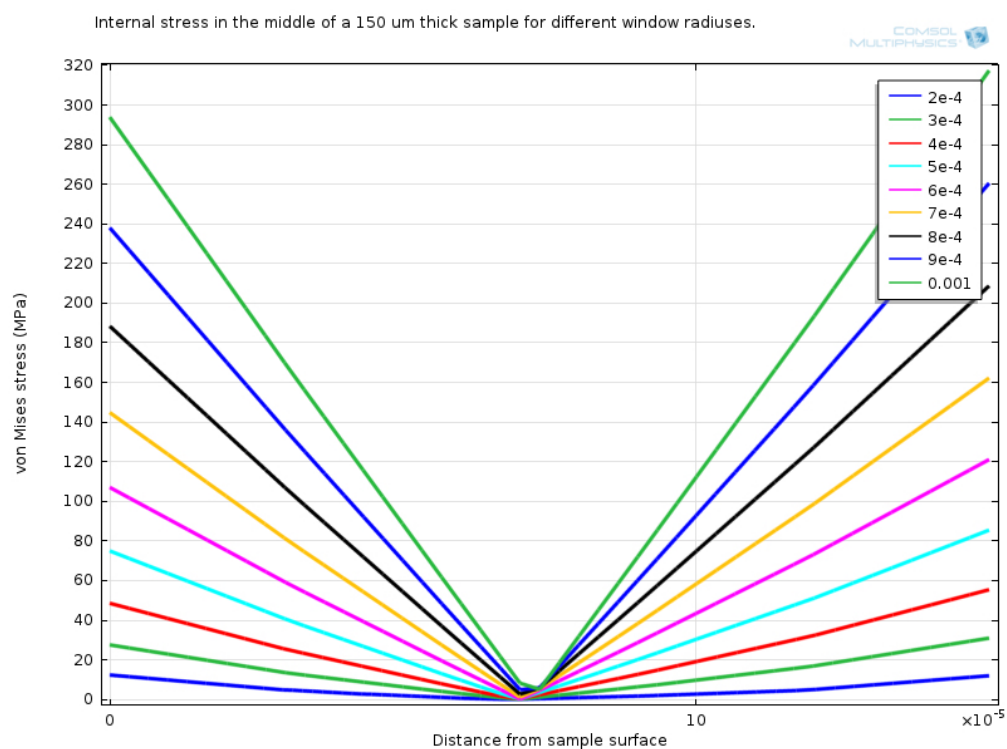


Figure 3. Internal stress in the middle of the sample vs sample radius for 150  $\mu\text{m}$  thick window and 12.8MPa pressure.

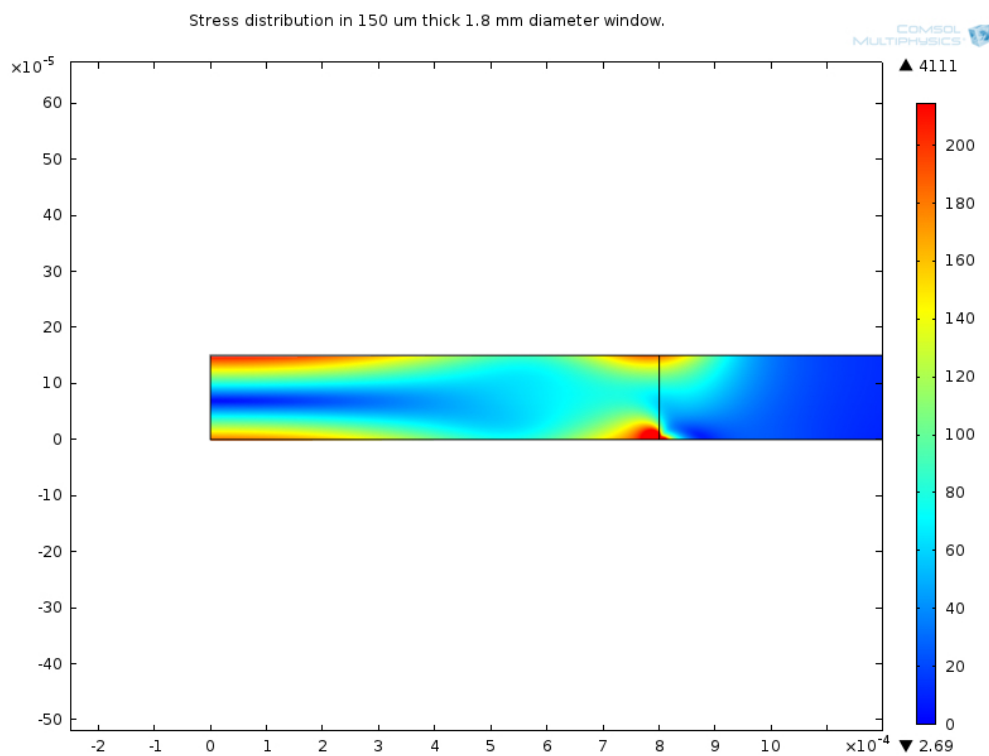


Figure 4. Internal stress for 150  $\mu\text{m}$  thick and 1.6 mm diameter flat window.







*Figure 5. SSRT autoclave. Description*



Uppsala University (UU)

## Amorphous metals for high-temperature applications

Lena Thorsson (Ph.D. student), Björgvin HJörvarsson

### Background

One approach to increasing the accident tolerance of nuclear fuel rods is applying thin film coatings on Zirconium based cladding materials. Such a coating could delay the fatal exothermic reaction between Zr and hot steam that produces hydrogen gas and eventually might cause explosions and reactor core melting in case of an accident. Among other candidate coating materials, amorphous metals have been mentioned as potentially having an interesting combination of physical properties, such as good corrosion resistance and non-brittle or elastic behaviour in certain alloy specific temperature ranges. Thanks to the lack of grain boundaries, amorphous metals are also discussed as efficient barriers for atom transport from the surrounding environment to the zirconium alloy compared to crystalline materials.

### Status

Ph.D. student Lena Thorsson started work in this project in July 2014. The initial phase comprised a thorough literature survey to map and compile current knowledge regarding high temperature behaviour of amorphous metal alloys. Focus of the survey was on:

- Describing general thermal behaviour for amorphous alloys including mechanisms special for this group of materials
- Compiling existing high temperature alloys and their thermal properties
- Describing corrosion properties of these alloys

The resulting report was finalised and submitted to Måbil in December 2014. In summary, it was concluded that certain amorphous alloys have been demonstrated to maintain their properties, that is, to display a glass transition temperature  $T_g$ , up to 1200-1450 °C.  $T_g$  corresponds to the maximum operating temperature and is an alloy dependent property which roughly correlates to the melting temperature  $T_m$  of the alloy as  $T_g = 0,67 \cdot T_m$  for a good glass forming metal according to Turnbull's criteria. It was also concluded that existing amorphous alloys with interesting high temperature properties tend to be based on high melting elements such as W, Re, Ta, and Mo.

### Plans

During spring 2015, work has been initiated in the thin film laboratory to create and evaluate alloys intended to maintain their amorphous properties at high temperatures, aiming in the range of 1700 °C when Zr softens. First alloys to be evaluated will be Mo-based due to Molybdenum's small neutron cross section in combination with a high melting point. Based on Turnbull's criteria it is thought that if an amorphous alloy with melting point around 2600 °C could be created, it would be interesting to evaluate that alloy further with the specific nuclear industry application in mind.



## KTH

**Irradiation-assisted stress corrosion cracking**

New Ph.D. student announced in February 2015, P. Olsson, M. Jonsson, P. Efsing, Erki Metsanurk (Ph.D. student, UU), Mattias Klintenberg (UU)

**Background**

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 behaviour, considering all environmental factors, very challenging [1]. 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 [2,3]. In order to better understand the complex aspects of IASCC, investigation of the intergranular stress corrosion cracking (IGSCC) mechanisms must be made. The assumed mechanism of IGSCC is that exposure to water allows the oxide to penetrate along grain boundaries (the rate is governed by strain, time etc.). The oxide weakens the grain boundaries mechanical strength and the boundaries will eventually crack due to the applied stress leaving new virgin material exposed. This process will repeat itself and cracks will grow.

SKC partially supports a Ph.D. student (M. Sedlak), under the supervision of B. Alfredsson and P. Efsing, whose project consists in developing a computational model of IGSCC. The computational model of the assumed mechanism has to solve a multi-physics problem by coupling fracture mechanics, corrosion and material properties at the microscopic level in a physically motivated way. The equations of motion are used as starting point and are then coupled to cohesive laws to get the fracture mechanics properties, Fick's second law to model corrosion as a diffusion process and crystal plasticity to incorporate the properties of slip planes in crystals. The coupled problem is then solved numerically using the finite element method.

Irradiation mechanisms can be incorporated in the model by making the grain boundaries weaker and/or by changing the oxidation rate/depth due to the amount of irradiation. Both in the case of pure IGSCC without radiation effects and for the extended situation, that includes degradation due to radiation; the model requires data for new material micro-scale damage parameters. Such will have to be determined through modelling and experiments done at both micro- and macro-scale, both from the point of view of crystalline radiation damage and from the point of view of chemistry. The ICEWATER experiment will provide first of a kind data for the IASCC phenomenon and the efforts described in this project will be directly in aid of the ICEWATER project. The measurements performed there will be used to validate models here developed and the studies here described will help understand and interpret the mechanisms that are studied in the experiment. A very close link will exist between these two projects.



## Research proposal

We propose to investigate the mechanisms underlying irradiation-assisted stress corrosion cracking. The complex interplay of local water chemistry, mechanical loading and irradiation effects has yet to be explained to any satisfaction. Combining the expertise in radiation chemistry (Jonsson), fracture and materials mechanics (Efsing) and radiation damage (Olsson) could provide sufficient impetus to unveil part of the IASCC mechanisms.

We propose to study the effects of irradiation on grain boundary cohesion and on the crack tip region, which limits the crack growth rate, using atomistic methods in order to provide input data to the finite element continuum models. For the grain boundaries, quantum mechanical atomistic methods are well suited to address the mechanisms considering the scale to which the problem can be reduced. The role of the local chemistry at the crack tip can be treated either at a fully quantum mechanical level or using semi-empirical approximation methods and then be coupled to focused experiments. The theoretical work will be carried out in close collaboration with the experimental work projected in the ICEWATER project.

In addition, experimental work will be carried out to study the reactivity (kinetics) of aqueous radiolysis towards the materials to be used in the ICEWATER experiments. The reactivity studies will be accompanied by surface characterization and quantitative analysis of the aqueous solutions (using ICP-OES). The aim of these studies is to build a foundation for predictive modeling of the surface chemistry involved in irradiation-assisted stress corrosion cracking. In parallel with these experimental studies, a code for interfacial radiation chemistry is being developed. The development of this code relies on accurately determined rate constants for the individual reactions involved, the reaction mechanism and on an accurate description of the energy deposition in the two-phase system. The latter is currently under investigation in other projects at the division of Applied Physical Chemistry. The code will be used in planning and evaluating the ICEWATER experiments along with the theoretical work mentioned above.

## Plan

### Grain boundary cohesion

The effect of irradiation on grain boundary (GB) cohesion will be studied using a multi-scale modelling approach, where the basic interaction parameters (the thermodynamics) and the diffusion parameters (the kinetics) will be calculated *ab initio*, using state of the art electronic structure techniques, coupled with higher scale atomistic and mean field models developed over the years by the Reactor Physics group in strong collaboration with national and international partners (Linköping, Uppsala, EDF, CEA, SCK-CEN, ...) e.g. [4-11]. Aspects of the radiation enhanced and/or induced diffusion of solutes that can weaken the GB cohesion have been started in the Ph.D. thesis work of L. Messina at Reactor Physics, sponsored by Vattenfall [12,13]. The effect of irradiation on the GB cohesion can be directly used as input in the IGSCC model currently under development.

### Crack tip growth

The growth of a crack tip can be modelled using hybrid atomistic models combining electronic structure detail, where local chemical composition can be flexibly arranged without loss of transferability or precision, and semi-empirical classical interatomic detail, where billions of atoms and close to realistic strain rates are achievable. The effect of radiation induced defects on crack tip growth can thus be addressed in a direct fashion, and provide input parameters to the fracture mechanics modelling code under development. The effect of Be and Li on the crack growth rate will be investigated. Continuous dialogue with M. Jonsson and P. Efsing will ensure that the most appropriate local chemistry and most important interactions are considered.



## Reactivity studies

Studies of the reactivity of aqueous radiolysis products towards solid oxide materials and metals have been performed by the Nuclear Chemistry group for more than one decade [14-16]. These studies are mainly performed using aqueous powder suspensions of the material of interest. In the experiment, the oxidant (added) concentration is monitored as a function of reaction time. The results of the experiments are used to elucidate the reaction mechanism and to determine the kinetic parameters. In addition to monitoring the oxidant concentration, the solid powder is characterized before and after the exposure to the oxidant. A complete study of one material usually requires 1-2 months of full time work.

## Radiation induced corrosion studies

Radiation induced corrosion studies will be carried out parallel with the reactivity studies mentioned above. In these studies, we mainly use a gamma source (Cs-137) and irradiate powder, foils and larger objects immersed in aqueous solution. By adjusting the composition of the aqueous solution it is possible to make more selective studies on the effects of specific radiolysis products. The metal ion concentrations in the solution are measured using ICP-OES and the solid samples are characterized using SEM, XRD, Raman spectroscopy and XPS before and after exposure. In combination with the reactivity studies, these experiments are used to resolve the overall mechanism of radiation induced corrosion of the material in question. A complete study of one material takes 1 month of full time work (if there are no problems).

## Code development

A code for radiation chemistry in heterogeneous systems is currently being developed in an ongoing Ph.D.-project. This code will be applicable for radiation induced corrosion of any material provided the mechanism and kinetics of corrosion is known. The aim of the experimental studies mentioned above is to provide data for such systems. As data becomes available, they will be incorporated in the model and the irradiation experiments mentioned above will be used as a first benchmark. The development of this model (for corrosion of the materials of interest in this project) will be strongly connected to the modeling approaches of P. Olsson and P. Efsing with the final aim of developing a combined model to be used for simulation of IASCC in nuclear reactors.

The results of the above activities will be continuously discussed in view of the ICEWATER experiments and both M. Jonsson and P. Olsson are involved in the planning of the ICEWATER design and experiments.

## Milestones

- (M9) Literature survey and state-of-the-art
- (M17) GB cohesion properties and irradiation effects
- (M24) Oxidation reactivity
- (M32) Chemical influence on crack tip growth rate
- (M41) Radiation induced corrosion
- (M48) Full parameterizations for Fracture Mechanics and Radiation Chemistry codes
- (M54) Dissertation

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## Chalmers

### Production of water compatible nitride based nuclear fuel

Aneta Sajdova (Ph.D. student), Teodora Retegan, Christian Ekberg

#### Background and general considerations

Uranium nitride based nuclear fuel has been shown to display chemical compatibility with liquid metal coolants such as sodium and lead. UN interaction with heated water has resulted in hydrolysis and mechanical degradation of the examined pellets.

UN doped materials produced by the internal sol gel technique offers a possibility to produce and investigate nitride materials more compatible with water. The non-powder based mixing technology used in sol gel may offer a method for production of very homogeneous materials.

The basic principle of the internal sol gel process is a heat induced gelation of a sol caused by thermal degradation of hexamethylenetetramine. This allows for possible co polymerization/precipitation of metallic ions.

The internal sol gel process was originally developed in the KEMA laboratories in the Netherlands as a method for preparation of uranium oxide kernels. The process starts from an acid deficient uranium nitrate solution. This solution is cooled to around 0 °C and urea is added to the sol. The addition of urea is made in order to complex the uranyl ions and prevents premature gelation of the sol. Secondly HMTA is dissolved in the sol. The sol is then dripped into an immiscible heat carrier such as silicone oil. The heat carrier is kept at a temperature ranging from about 50 - 100 °C. In contact with the heated oil the urea will decomplex from the uranyl ions. The heat also causes the HMTA to degrade. The HMTA degradation consumes H<sup>+</sup> ions in the solution. When the H<sup>+</sup> concentration decreases the uranyl hydrolysis equilibrium will be shifted. Uranyl mono- di- and trimer ions will begin to react with water and form long uranyl hydroxide chains releasing more H<sup>+</sup> into the solution. The driving force in the internal sol gel process is thus the removal of H<sup>+</sup> in the solution by HMTA degradation. The uranyl hydroxide microspheres can then be converted into UO<sub>2</sub> microspheres by heat treatment in reducing conditions.

Production of nitride fuel is also possible by internal sol gel processing. If elemental carbon is added to the sol it will be gelled within the formed microspheres. Heat treatment at temperatures about 1400 - 1700 °C in N<sub>2</sub> or N<sub>2</sub> + H<sub>2</sub> gas of the microspheres can be used to convert the uranium oxide microspheres to uranium nitride by carbothermal reduction. During carbothermal reduction the carbon is used to remove the oxygen in the material as CO during nitride formation. UN can form solid solution with other actinide nitrides but unlike these who only occur as mononitride the uranium displays stable sesquinitrides (U<sub>2</sub>N<sub>3</sub> and UN<sub>2</sub>) at temperatures below roughly 1000 °C. Heating and cooling between room temperature and about 1000 °C during carbothermal reduction should therefore be performed in argon or Ar + H<sub>2</sub> atmosphere.

Uranium nitride degradation in water at high temperature is facilitated by hydrolysis, producing uranium dioxide and ammonia. The produced ammonia increases the pH in the water and when the pH becomes high enough the mechanical integrity of the fuel pellet fails. Countermeasures to such degradation could include addition of more water resistant nitrides in the fuel pellet composition. Possible candidates to be examined as nitride stabilizers could include the nitrides of Thorium, Iron and Titanium. Thorium could be of interest since it like other actinide nitrides forms solid solutions with UN but is considered being a softer ion and possibly increases the cohesive strength in the nitride crystal structure. TiN forms solid solutions with UN and is potentially more stable towards hydrolysis than UN making it an interesting candidate for doping purposes. Iron based nitrides could be of interest since iron hydroxides may form protective coatings of the pellet during hydrolysis. This is true for also other metal nitrides such as AlN, but iron based hydroxides may provide better barrier properties during elevated pH conditions.



## Project plan

Even if the fact that degradation takes place it is still unclear how and at what temperature. Is it pitting reactions or more general surface reaction or following grain boundaries. In order to make more insoluble nitride, knowledge about the physical degradation process is vital. Therefore this project will start by making non doped UN material for further degradation investigation. For the sol gel part a working method for uranyl sols is already established. The pressing and sintering characteristics of UN pellets produced from microspheres should also at least to some extent be investigated in order to obtain pellets of suitable density and porosity. A dual path could possibly be followed for production of doped UN. One slower path could be to start from the beginning and add different suggested materials to the sol and co-gelate. In order to get a quicker feeling for which elements to focus upon it could be of interest to produce UN microspheres which are then milled into powder and blended with commercially purchased nitrides of the desired elements. The downside might be higher oxygen inclusion in the commercial material (not uncommon in ZrN for example). The gain is that pellets (powder pressed of course) faster can be produced and tested in contact with water. It could be a quicker way to screen a larger number of additions compared to making every composition from scratch by sol gel.

The degradation investigations cannot be done in a normal autoclave due to the ammonium formation and thus water composition change. Flowing water will be needed to simulate the fact that in a reaction a very large water volume is available compared to the fuel volume making actual chemical changes small. For this purpose a dedicated facility will have to be constructed.

The time plan for the Ph.D. student will be that up to licentiate degree. The degradation process will be studied in detail as well as preliminary scoping studies of effects of some inclusions. After the licentiate exam, the most promising candidates for actually low solubility nitrides will be investigated in detail and the optimal compositions will be determined.



## Chalmers

**Ageing of Reactor Pressure Vessel Steel Welds**

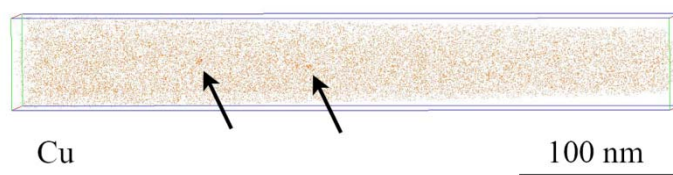
Kristina Lindberg (Ph.D. student), Mattias Thuvander and Pål Efsing (KTH)

The reactor pressure vessel (RPV) is a life-limiting component of a nuclear reactor. Neutron radiation during operation makes the RPV steel embrittled, the higher dose the larger effect. This is important to consider when looking at prolonging the operational time of a reactor. Since the microstructural changes during irradiation are on a very small scale (i.e. nanometer precipitates) atom probe tomography (APT) is a suitable technique for investigation of the neutron radiation effect.

So far, unirradiated reference material has been run in the atom probe, in order to find suitable parameters and for the Ph.D. student to learn the technique and data evaluation. The expected distribution for most elements before irradiation is random. This is also generally found for most elements. However, there is a small tendency for Cu to precipitate even before irradiation, as can be seen in Figure 1. Since Cu is supersaturated in the matrix, this happens during the cooling of the steel during fabrication. A line of V and Mo rich carbides is also found along something that is probably a line defect (dislocation).

The next step is to characterize the irradiated steels (with doses up to corresponding to 80 years in the reactor) using APT. Emphasis will be on MnNiSi-rich precipitates, late blooming phases, and their evolution after high doses.

The material, irradiated in Halden, has recently been shipped from VTT to Chalmers. We are currently investigating suitable procedures for the study, considering that the samples are somewhat active. Probably we will use FIB lift-out techniques, so that most of the work can be carried out on very small samples. In addition to studies of the effect of irradiation, a part of the project will deal with heat treatment of irradiated material, to see if the material can be restored.



*Figure 3. APT reconstruction showing the Cu distribution. Each dot represents a Cu atom. Two small clusters are present even before irradiation.*

