SKC
Swedish Centre for Nuclear Technology

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SKC 16-01

Annual Report 2015

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Summary and highlights of 2015

SKC had a year of dramatic changes on personal level as well as coupled to the entire energy landscape. In April the former Director of SKC, Farid Alavyoon, suddenly passed away. His work to establish the new three-year agreement was important and helped keeping up the pace within SKC during the entire 2015. We would all like to acknowledge his enthusiasm for nuclear power and to bring research forward in a stable way. It was an enormous loss to the community and Farid is missed by all of us.

On a more general level, the costs for nuclear power production have increased, and the prize for electricity has decreased. This has led to decisions for earlier closure of two nuclear power plants in Oskarshamn (O1 and O2) and two in Ringhals (R1 and R2). What this means to the Swedish nuclear programme needs to be considered when focusing on national research and competence building. Could this mean more focusing on decommissioning issues, and how does this affect the educational programmes?

Other major factors in the energy landscape include the energy commission work with several hearings in 2015 to collect the national situation regarding energy production/consumption, and the global climate agreement following the COP21 Meeting in Paris in December.

Goals and focus

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. Ensuring safety is the major prerequisite to achieve the goal of life time extension. One of the main challenges today and in the future is learning more about material ageing and degradation. This focus has for example involved new departments at the universities, such as the Materials Microstructure division at Chalmers, see Appendix 1, and the Materials Physics and Materials Theory divisions at Uppsala University, see Appendix 3.

Regarding education, several levels are needed to pursue the future need in the nuclear industry. Master programmes at the universities are popular, and the quality of the courses is very high, when looking at independent studies and surveys, see for example in Appendix 2 from KTH. The classical courses are also more and more going towards e-learning, which makes courses more accessible as well as easier to manage.

The Bachelor programme of Uppsala University (see Appendix 3) has been appreciated by the nuclear industry. Another approach to education is the contract education for ongoing knowledge improvement of professionals in the field. This is ongoing for example at Uppsala in the NANSS framework.

As a response to the industry's needs and demands of research, a large part of the SKC project funding has been allocated to material studies in a new project called **MÅBiL**.

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.

During 2015, 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 Klara Insulander Björk and Cheuk Wah Lau at Chalmers for their work on the usage of thorium fuel in light water reactors. Giulio Imbalzano, KTH, received the prize for the best masters' thesis for his work on material modelling. Johan Larsson, UU, received the prize for best bachelor thesis for work on documentation of maintenance simulator training. The prizes were awarded to the winners at the dinner ceremony of SKC's yearly symposium, this year held in Sigtuna, on October 8-9.

And finally …

The present contract is about to end, and by the end of the year a new agreement is hopefully in place. With a large power reserve, no increase in electric demand and low electricity prices, the economic challenges to be overcome by SKC's financers will continue to grow for a few more years. Another mayor challenge is how to keep a strong national nuclear competence to allow for continuous operation of the Swedish nuclear industry. This will be of main focus in the near future.

SKC is intended to continue serving as a bridge between universities and industry even in a time of structural changes and financial challenges. The aim now is to give the opportunity for SKC's financers to ensure the cooperation on the long-term, as the most beneficial to the nuclear industry, with a new agreement.

Hans Henriksson, SKC Director, 2016-03-18

Contents

SKC-Partners, Tasks and Goals

Swedish Centre for Nuclear Technology SKC – (**S**venskt **K**ärntekniskt **C**entrum www.swedishnuclear.se) was originally founded in 1992 under the name of KTC, Kärntekniskt Centrum, at KTH. The centre is a collaboration administrated at the School of engineering sciences at KTH (KTH/SCI). The SKC collaboration entered the present three-year contract on January 1, 2014.

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

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

and academy

- Chalmers University of Technology (www.chalmers.se)
- KTH Royal Institute of Technology (www.kth.se)
- Uppsala University (www.uu.se)

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

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

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

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

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

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

Organization and funding

SKC runs according to three-year contract periods of which the present contracts started January 1, 2014. The total volume for the three years is 32.3 MSEK.

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

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

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

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

During 2015, the Advisory Council consisted of:

- Per Brunzell, Chairman
- Mattias Olsson, Forsmarks Kraftgrupp AB
- Henrik Dubik, Oskarshamns Kraftgrupp AB (was replaced be Georg Lagerström in November 2015)
- Björn Forssgren, Ringhals AB
- Ingemar Jansson, Westinghouse Electric Sweden AB

The Swedish Radiation Safety Authority, Strålsäkerhetsmyndigeten (SSM), was represented in the Advisory Council during 2015 by Nils Sandberg as observer. Hans Henriksson has attended a meeting as secretary, held September 18, 2015.

During 2015, the SKC Board consisted of:

- Karl Bergman, Chairman, Vattenfall AB
- Jan Greisz, Forsmarks Kraftgrupp AB
- Andreas Roos, Oskarshamns Kraftgrupp AB
- Henric Lidberg, Ringhals AB
- Eva Simic, Stråsäkerhetsmyndigheten – observer status
- Anders Andrén, Westinghouse Electric Sweden AB
- Leif Kari, KTH Royal Institute of Technology
- Åsa Kassman Rudolphi, Uppsala University (formally replacing Måns Östring as of 3 Dec 2015)
- Mats Viberg, Chalmers University of Technology

SSM was represented in the Board according to the SKC contract that allows an observer status for the regulator. Four meetings were held in 2015. Hans Henriksson attended the board meetings held September 23, and December 3 2015, but has not participated in votings. Hans Henriksson has also an observer position in the SSM Research Board, and attended two meetings in 2015.

SKC Financial statements 2015

The following table summarises the SKC financials for 2015:

Revenues, SEK

Payment Forsmarks Kraftgrupp AB	2 380 000
Payment Oskarshamns Kraftgrupp AB	2 380 000
Payment Ringhals AB	3 173 002
Payment Westinghouse Electric Sweden AB	2 833 002
Sum Payment	***10 766 004***
Payment French laboratory support	3 519 172
Sum Payment	**3 519 172**
Sum incoming payments	**14 285 176**

Spendings, SEK

Payout Chalmers	3 207 000
Payout KTH	3 550 000
Payout UU	3 380 000
Payout SKC central administration	1 080 000
Sum Payout	***11 217 000***
Payout French laboratory support	0
Sum Payout	**11 217 000**

Output Balance 2015 (transferred to 2016), SEK

Remaining funds SKC central administration	*638 046*
Remaining funds French laboratory support	*3 826 660*
Remaining funds transference account SKC	*400 664*
Sum remaining funds = input total	***4 865 370***

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

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

Comments:

1. At the end of 2014 SKC had a positive year-end balance of 1 936 157 SEK. For French laboratory support the positive balance was 701 437 SEK.

2. The positive balance by the end of 2015 is due to the following reasons:

   - Savings in the administrative costs of SKC as a result of reducing marketing and eliminating advertising activities.
   - For 2015 an administrative cost of 250 000 SEK was transferred from the French support to SKC's central administration.

- The cost of the French laboratory support for 2015 was invoiced in January 2016, and to a lower cost than expected, resulting in a positive balance of 3 826 660 SEK, of which 1 100 270 SEK will be paid in 2016.

   - Due to the late start of the project MÅBiL in 2014, an amount of 851 000 SEK dedicated to the project was not paid to the academia in 2014. This amount is held in SKC's transferring account and will be paid to the academia in the end of the present agreement or first quarter of 2017.
   - Due to late start for one Ph.D. project of MÅBiL in 2015, 375 000 SEK is held in the transferring account and will be paid to the academia in the end of the present agreement or first quarter of 2017.

Winners of the Sigvard Eklund Prize

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

The Director of SKC handed over the Sigvard Eklund Prize in three categories, best Bachelor, best Master and best Doctoral thesis, during the SKC symposium in Sigtuna October 8, 2015.

Left to right: Cheuk Wah Lau, Giulio Imbalzano, Hans Henriksson, Klara Insulander Björk, and Johan Larsson at the prize ceremony at Sigtunahöjden, Sigtuna, during the SKC Symposium 2015.

The prize for best Bachelor thesis, 25 000 SEK, was given to Johan Larsson, Uppsala University, for his thesis: ***"Dokumentation av underhållssimulatorer för utbildning i vardagssäkerhet"***.

The prize for best Master thesis 2015, 35 000 SEK, was given to Giulio Imbalzano for his thesis: ***"First principle calculations of the residual resistivity of defects in metals".***

The prize for best Doctoral thesis 2015, 50 000 SEK, was divided between Klara Insulander Björk and Cheuk Wah Lau for their work on Thorium in today's reactors. The theses are entitled: **"Thorium fuels for Light Water Reactors"** and **"Improved PWR Core Characteristics with Thorium-containing Fuel"**, respectively.

Appendix 1 - Chalmers University of Technology

CHALMERS

Sustainable Nuclear Energy Centre

Overview of Activities in 2015

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

The main occasions for networking are the events arranged by SNEC during 2015. These have been:

- A student/industry seminar, involving both M.Sc. and Ph.D. students, was arranged on 2015-06-15. The students briefly presented their projects, and could thereafter discuss them in more detail via a poster session. This seminar was attended by 35 persons, from the academia, the industry, and the safety authorities.
- M.Sc. thesis project proposals from the industry were presented to the M.Sc. students in connection with a networking event.
- A workshop for community building and for spawning new research project ideas was arranged 2015-11-26, gathering 11 senior researchers from all SNEC's participating divisions. Six project embryos were conceived, and first steps have been taken to bring these forward to potentially interested industry partners.
- The 17th meeting on Reactor Physics in the Nordic Countries (RPNC2015) was held in Gothenburg, May 11-12. The meeting attracted a large number of attendees with 51 registered participants, 36 submitted abstracts and 36 corresponding technical presentations.

The SNEC coordinator (Stina Rydberg) and director and scientific leader (Christian Ekberg) made a journey to SNECs stakeholders (Oskarshamns Kraftgrupp AB, Studsvik Nuclear AB, Svafo AB, SKB AB, Vattenfall AB and Westinghouse Electric AB). The main questions that were discussed with the partners were what the industry would see as the ideal form of a nuclear technology research center, and how it could be financed. The conclusion was that the industry would prefer a national research center, which could act as a single contact point for the industry and to synchronise and optimise the use of available research funding. Such a center, it was perceived, should best be financed by and overhead cost on research projects.

Use of the SKC funding

The SKC base 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 SKC funding has been split between these divisions and used as follows:

Division of Nuclear Engineering

Kostnadsslag	***Utfall***	***Kommentar***
Personalkostnader	812 574,43	*varav 396 522,19 kr för Anders Nordlund och 415 993,66 kr för Klaes Jareteg*
Utrustning	11 499,00	*Dator*
Köpta tjänster	175 785,04	
Resor & Konferenser	69 744,36	
OH	463 284,07	
Förbrukn.mtrl & övriga kostnader	33 405,00	
Totalt	***1 566 291,90***	

Division of Materials Microstructure

Mostly supported through the MÅBiL project.

Kostnadsslag	***Utfall***	***Kommentar***
Personalkostnader	481 655,51	*Kristina Lindgrens lön, varav kurs/utbildning 800 kr SEM-skolan*
Utrustning	9 899,25	*Aktivitetsmätare*
Köpta tjänster	168 952,83	*Mikroskopikostnader, varav Torben Pingel 4 200 kr resten Kristina Lindgren*
Resor & konferenser	9 206,75	*varav Mattias Thuvander 6077,92 resten Kristina Lindgren*
OH	230 810,62	
Totalt	***900 524,96***	

Division of Nuclear Chemistry

Kostnadsslag	*Utfall*	*Kommentar*
Personalkostnader	129 941,38	*del av Stefan Allards lön*
Doktorand	403 767,16	*Aneta Sajdovas lön 80%*
	18 016,33	*Kemikalier och lab material*
Resor & konferenser	8 651,44	*Stefan Allard, Teodora Retegan Aneta Sajdova Stockholmsresa*
OH	341 573,48	
Totalt	***901 949,79***	

Activities and common resources

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

- A pulsed beam for variable energy slow positrons.
- Access to all major system codes for neutronic and thermal-hydraulic calculations.
- Laboratories for α, β, γ experiments and activity measurements.
- A hot cell laboratory for γ activity.
- A special laboratory for research on advanced nuclear fuels (collaboration with KTH), including both a SEM and XRD facility.
- Several irradiation sources including a 18 kGy/h ^{60}Co and ^{137}Cs facilities ranging from 50 Gy/h and down to 1 Gy/h.
- An Atom Probe Tomography Instrument.*
- Three Transmission Electron Microscopes.*
- Two Scanning Electron Microscopes.*
- Two Focused Ion Beam Workstations.*

*Managed by the infrastructure unit at the Dept. of 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).
- Accident tolerant nitride based fuel (Ph.D. student: Aneta Sajdova; supervisor: Professor Christian Ekberg).
- Ageing of Reactor Pressure Vessel Steel Welds (Ph.D. student: Kristina Lindgren; supervisor: Associate Professor Mattias Thuvander)

Education

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 programme in Nuclear Engineering. This master programme 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 collaboraton with the nuclear industry.

As opposed to earlier courses in nuclear engineering, the programme 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 programme. 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 2015:

- A SNEC-day for students and industry was arranged during the spring with participants from both industry and Chalmers. Many master thesis projects were presented.
- The master programme was presented for students both at CHARM and later at information sessions preparing the students for selecting master programmes.
- As previous year a guest lecturer from WANO (World Association of Nuclear Operators) was invited for two days to talk about safety culture in October.
- As part of a French-Swedish agreement regarding exchange of nuclear services as part of the European Spallation Source, the students for the master programme have been to a research reactor in Saclay, France in spring 2015. The exercise was in form of a two-and-a-half day laboratory exercise on a small open pool reactor.
- A project, Le@rn, is progressing with the goal of converting some key courses in the master programme to web based courses with flipped-classroom approach. Within this project two courses are converted to flipped-classroom. These web based courses will be offered to SKC. Feedback from the students shows that the web-based flipped-classroom course format is much appreciated.
- The name of the master programme has now changed to "Nuclear science and technology" to emphasize that the master programme also gives a good foundation for an academic career.

SKC-relevant courses

The following SKC-relevant courses were given (number of students in parenthesis):

- Nuclear Materials TIF265, 7.5 ECTS (9)
- In-service inspection technologies MTT065, 7.5 ECTS (10)
- Introduction to nuclear reactors TIF215, 7.5 ECTS (17)
- Physics of nuclear reactors TIF210, 7.5 ECTS (8)
- Applied nuclear engineering TIF195, 7.5 ECTS (6)
- Noise techniques in nuclear systems TIF245, 7.5 ECTS (1)
- Nuclear reactor safety TIF250, 7.5 ECTS (5)
- Nuclear chemistry I KBT192, 7.5 ECTS (14)
- Nuclear Chemistry II KBT168, 7.5 ECTS (8)
- Radioecology and radioanalytical chemistry KBT216, 7.5 ECTS (2)
- Chemistry of Lanthanides, Actinides and Super-Heavy Elements KBT171 (4)

The following courses were also offered, but they were not chosen by any students:

- Radiopharmaceutical chemistry KBT221, 7.5 ECTS
- Solvent Extraction KBT196, 7.5 ECTS

Ph.D. education

A specific Doctoral School in Nuclear Engineering is available at Chalmers. The Doctoral School was designed in such a way that students with various backgrounds could be accepted to the Doctoral School. This corresponds to the fact that nuclear engineering is by essence a cross-disciplinary area, and consequently might attract students with various backgrounds (physics, chemistry, mechanical engineering, electrical engineering). Such a mix of students within one single Doctoral School creates a very rich and stimulating environment for the students during their 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 M.Sc. students and Ph.D. students favours discussions between the students, each having his/her own paradigm. This also creates a natural bridge between the M.Sc. 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.

Completed theses

In SKC-related subjects, the following Master theses were successfully presented during 2015:

- Rasmus Andersson, Transient fine-mesh multiphysics in nuclear fuel assemblies
- Markus Nybeck, Investigation of Deviations Between Measured and Calculated Peaking Factors at Ringhals 3
- Roger Hurtig, Construction of a generic PSA model for Swedish BWRs
- Athanasios Stathis, Analysis of a Load Step Test at Ringhals 4 NPP using RELAP5 Code
- Cecilia Fager, Structural Characterization of Oxide Films Formed on Stainless Steel of Type 304L in Simulated PWR Primary Water
- Erik Karlsson, Differentiation of Radionuclides on Surfaces using Autoradiographic Methods

In SKC-related subjects, the following Licentiate theses were successfully presented during 2015:

- Alberto Ghione, Improvement of the nuclear safety code CATHARE based on thermal-hydraulic experiments for the Jules Horowitz Reactor
- Jenny Halleröd, Phenyl Trifluoromethyl Sulfone as Diluent in a Grouped ActiNide EXtraction Process

In SKC-related subjects, the following Ph.D. theses were successfully presented during 2015:

- Klara Insulander Björk, Thorium fuels for light water reactors (Sigvard Eklund Prize winner)
- Petty Cartemo, Radiation Detection Techniques for the Enhancement of Nuclear Safety
- Gustav Sundell, Atomic Scale Degradation of Zirconium Alloys for Nuclear Applications
- Erik Lindgren, Detection and 3-D positioning of small defects using 3-D point reconstruction, radiography, and tracking
- Anders Rosell, On model assisted probability of detection in eddy current evaluation

Reorganisation

The former division of nuclear engineering has now merged into a larger division with the name Subatomic and plasma physics. We hope for better visibility for the students and more cooperation within the nuclear science field with this new organization.

Planned activities for 2016

- SNEC will work to establish the nation-wide nuclear technology research center that the industry requested during the tour undertaken in June.
- SNEC will follow up on the research project embryos spawned during the workshop in November 2015. One project plan has already been drafted, and potentially interested industry representatives have been contacted for meetings.
- SNEC will arrange the SNEC-day on 2016-02-04, a conference on the consequences of the early decommissioning of Swedish reactors. Almost 100 participants will attend the event.
- SNEC will arrange a M.Sc./Ph.D./industry seminar in June, possibly in collaboration with SKC, making the event national.
- SNEC will co-arrange the SKC symposium in Gothenburg in October.
- The M.Sc. programme will continue during 2016, comprising essentially the same courses as in 2015.
- The Ph.D. students that have been involved in the Swedish-French collaboration and stationed in France for 2-3 years (Mikael Andersson, Szolt Elter, Alberto Ghione) will return to Chalmers to complete their Ph.D. studies during 2016.
- A 100% web-based course in nuclear reactor modelling will be offered.

Appendix 2 - KTH Royal Institute of Technology

Overview of activities in 2015

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

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

Staff directly involved in SKC activities

Reactor Physics group:

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

Reactor Technology group:

- 1 Professor - Henryk Anglart
- 1 Assoc. Prof. - Jan Dufek
- 2 Ph.D. students - Roman Thiele – 50% SKC and Mattia Bergagio – 50% SKC

Solid Mechanics group:

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

Highlights and major research outcome

Preliminary efforts have been made to develop on-line versions of the main courses in the Master programme. Short video presentations (so-called video-pitches) of the programme are now available on YouTube (see e.g. https://www.youtube.com/watch?v=EIoHfjwpVYo).

In addition, several master theses were supervised; one of which received the Sigvard Eklund’s prize for the best thesis in the nuclear field during 2015.

Jan Dufek has become a docent at KTH and he has been promoted to Associate Professor (“Lektor”).

Roman Thiele defended his Ph.D. thesis on December 9, 2015. The thesis title is "*Mechanistic Modelling of Wall-Fluid Thermal Interactions for Innovative Nuclear Systems*".

Major archival publications

I. Mickus, J. Dufek, and K. Tuttelberg. Performance of the explicit Euler and predictor-corrector based coupling schemes in Monte Carlo burnup calculations of fast reactors. Nucl. Technol. 191(2):1-6, August 2015

K. Tuttelberg and J. Dufek. Neutron batch size optimisation methodology for Monte Carlo criticality calculations. Ann. Nucl. Energy, 75:620–626, January 2015.

H. Li and H. Anglart. CFD model of diabatic annular two-phase flow using the Eulerian-Lagrangian approach. Ann. Nucl. Energy, 77:415-424, 2015.

R. Pegonen, S. Bourdon, C. Gonnier and H. Anglart. Hot fuel element thermal-hydraulics in the Joules Horowitz Reactor. Nucl. Eng. Des. 300:149-160, 2016.

Major conference presentations

Jan Dufek. Development of advanced Monte Carlo burnup methods within the HPMC project. The 17th meeting on Reactor Physics in the Nordic Countries Chalmers University of Technology, Gothenburg, Sweden, May 11-12, 2015.

Ignas Mickus and Jan Dufek. Comparative study of the explicit Euler and predictor-corrector based coupling schemes in Monte Carlo burnup calculations of fast and thermal reactors. The 17th meeting on Reactor Physics in the Nordic Countries Chalmers University of Technology, Gothenburg, Sweden, May 11-12, 2015.

Pegonen R., Bourdon S, Gonnier C. and Anglart, H., "Hot fuel element thermal-hydraulic modelling in the Jules Horowitz reactor nominal and LOFA conditions," Proc. 16th Int. Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-16), Chicago, Il., USA, Aug. 30 – Sept. 4, 2015.

Bergagio M., Hedberg S., Rydström S. and Anglart, H., "Instrumentation for temperature and heat flux measurement on a solid surface under BWR operating conditions," Proc. 16th Int. Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-16), Chicago, Il., USA, Aug. 30 – Sept. 4, 2015.

Anglart H, Bergagio M., Hedberg S., Rydström S. and Frid, W., "Measurement of wall temperature fluctuations during thermal mixing of non-isothermal water streams," Proc. 16th Int. Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-16), Chicago, Il., USA, Aug. 30 – Sept. 4, 2015.

Anglart H., "Current trends in CHF predictions: from correlations to simulations," Proc. Int. Seminar on Subchannel Analysis (ISACC-2015), Shenzhen, China, Dec. 6-8, 2015.

Master Theses and examination

Reported number of theses from Nuclear Engineering and Solid mechanics during 2015:

Number of Master theses: 32
Number of Bachelor theses: 123 (of which 3 related to nuclear engineering)
Licentiat exams: 8
Ph.D. exams: 10

Fixed funding

During 2015 the fixed funding has been used to support teaching in the nuclear engineering field. The main goal has been to continue providing high quality teaching within the Master Programme and in particular, in the core areas of nuclear engineering such as:

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

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

Prof. W. Gudowski, Reactor Physics	555 kkr
Prof. H. Anglart, Reactor Technology	555 kkr
Assoc. Prof. J. Dufek, Reactor Technology	390 kkr

The fixed funding has been used according to the planned budget for year 2015.

Education

Report on educational activities in Nuclear Energy Engineering (TNEEM)

- **Programme Director – Waclaw Gudowski**

The Master Programme in Nuclear Energy Engineering (TNEEM) is developing really well and reaches new achievements. After Swedish national assessment of all master programmes at Swedish universities in 2013, when TNEEM got the highest grade (MHK) – as only one of 5 master programmes at KTH, we can report further achievements.

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

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

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

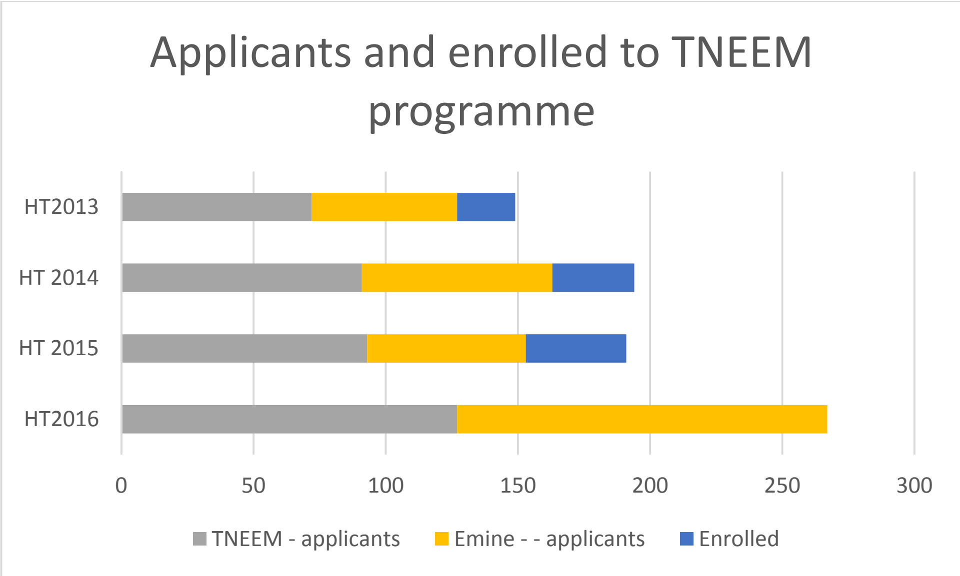


Figure 1. Development of TNEEM programme in terms of applicants and enrolled students.

Table 1 lists the courses offered in the TNEEM programme. The number of elective course offered at TNEEM is really impressive, students have a choice of over 140 credits out of which they need to choose only about 40 credits, it means in reality that students have an offer of more than 4 courses for every one they need to choose. A really exceptional possibility for the students to form their elective part of education and to focus on subjects they are particularly interested in.

In 2015 and in coming years particular efforts have been and will be put on E-learning platform development. The ambition is that by years 2017-2018 the entire master programme will be offered in the frame of E-learning technology.

E-learning development strategy for TNEEM

During 2015 an E-learning strategy has been formulated and developed by/at KTH. This strategy is based on 3 pillars:

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

This part of the strategy aims at two important objectives: promotion of the TNEEM programmes for potential applicants and aids for navigation through the entire programme, in particular helps to select elective courses. This is being done through:

a) Short video presentation of the entire programme in a 4-5 minute video clip
b) Each course is video presented and described by the course lecturer. Videos are recorded in a studio with slides, animation and/or other demonstration items.

The step of this development is under completion and can be viewed at YouTube clicking at any links in Table 2.

Table 1: List of TNEEM compulsory and elective courses

		Code	Course Title	ECTS
Compulsory	Year 1	MJ2405	1. Sustainable power generation	9
		SH2600	2. Reactor Physics	9
		SH2603	3. Radiation, Protection, Dosimetry and Detectors	6
		SH2702	4. Nuclear Reactor Technology	8
		SH2773	5. Nuclear Power Safety	6
	Year 2	AK2030	6. Theory and Methodology of Science (Natural and Technological Science)	4.5
		SH2007	7. Research Methodology in Physics	3
		SH2609	8. The Nuclear Fuel Cycle	6
		SH203X	9. Master Thesis	30
Elective	Year 1	KD2290	10. Reactor chemistry	6
		MJ2411	11. Renewable Energy Technology	6
		SH2302	12. Nuclear physics	8
		SH2604	13. Gen IV reactors	6
		SH2605	14. Radiation damage in materials	6
		SH2610	15. Safety Leadership in Nuclear Technology	6
		SH262V	16. Geological Storage of Spent Nuclear Fuel – Summer Course	7.5
		SH2701	17. Thermal Hydraulics in Nuclear Energy Engineering	6
		SH2703	18. Nuclear Reactor Dynamics and Stability	6
		SH2704	19. Monte Carlo simulations in nuclear technology	6
	Year 2	SH2602	20. Transmutation of nuclear wastes	8
		SH262V	21. Geological Storage of Spent Nuclear Fuel – Summer Course	7.5
		SH2608	22. Nuclear Reactor Kinetics and Noise Analysis	6
		SH2610	23. Safety Leadership in Nuclear Technology	6
		SH2704	24. Monte Carlo Simulations in Nuclear Technology	6
		SH2705	25. Reactor simulator, simulations of reactor kinetics and reactor dynamics	6
		SH2772	26. The Chemistry and Physics of Nuclear Fuels	8
		SH2774	27. Numerical Methods in Nuclear Engineering	6
		EF2200	28. Plasma Physics	6
		ED2220	29. Experimental Fusion Plasma Physics	6

Table 2. List and links to TNEEM video clips

Programme Presentation	https://www.youtube.com/watch?v=EIoHfjwpVYo
SH2610 – Leadership for Safety	https://www.youtube.com/watch?v=qwzFbitbN8w
SH2773 – Nuclear Power Safety	https://www.youtube.com/watch?v=j8s7jPRB6cs
SH2600 – Reactor Physics	https://www.youtube.com/watch?v=tUasI7-f8aM
SH2302-Nuclear Physics	https://youtu.be/fsUFqunobTg
SH2702 Nuclear Reactor Technology	https://www.youtube.com/watch?v=v1qowRnCN-s
SH262V – Geological Spent Fuel	https://www.youtube.com/watch?v=fljb8Tr55G4
SH2604 Gen- IV Reactors	https://www.youtube.com/watch?v=VvCQIno2WEo
SH2703Nuclear Reactor Dynamics	https://youtu.be/nItU9bGe8Sc
SH2704 Monte Carlo Methods -	https://youtu.be/Qaj35dShA_Q
KD2290 Reactor Chemistry	https://youtu.be/TmkDQhfsGeo
SH2605 Radiation Damage	https://youtu.be/qBVYphsRtuw
EF2200 Plasma Physics	https://youtu.be/FS1-whSip4g

Pillar II: Support and E-learning for the registered TNEEM Programme students

The main objective of this part of E-learning strategy is to support, optimized and radically improve **the campus based educational process.** Deliverables and measurable objectives of those efforts will be enhanced learning pace, better through-put of the programme students and higher average grades.

All TNEEM lectures at KTH will be video recorded and accessible for the programme students after the "physical lectures" (or even before if so decided by the lecturer) in order to give students the chance to either review the lectures once more, to repeat lecture moments they did not understand well and give the chance for students who missed particular lectures to "post-factum" participate virtually in the lectures.

Learning will be significantly enhanced through off-class activities based on internet **"Exerciser module"** supporting processes of home assignments, problem solutions and electronic examinations.

The **"Exerciser module"** has been developed in 2015 based on cooperation with MapleSoft and pilot implemented for the course in Nuclear Reactor Physics – see below. Further implementation is planned for 2016-2017.

Laboratory exercises will be modelled and simulated using E-learning platform through a special module of **interactive laboratory simulations. Interactive laboratory simulations** will be obligatory before conducting the laboratory exercises in "real space". Moreover students will have a chance to re-simulate real exercises in case of experimental errors and/or misses in the laboratory.

Pillar II will also help TNEEM to preselect courses and start **MOOC** activities.
Funding for part of those broad activities in Pillar II has been assigned locally at KTH by the School of Science, hardware system has been selected and it is under procurement at KTH.

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

Further development of E-learning platform and its strategy implies development of **distance education "on-demand" for non-academic stakeholders.**
This Pillar III, accessible only for our contractors, will be a tailored merger of Pillar I and II and specially developed distance education courses. Pillar III will follow development of Pillars I and II.

Development of E-learning tools for the course: Nuclear Reactor Physics, SH2600.

In the Fall Semester of 2015 an E-learning approach has been implemented in the Nuclear Reactor Physics Course SH2600 at KTH.
38 students registered for Nuclear Reactor Physics did 9 “Week Assignments” each week of the course, for 9 weeks. On January 15, 2016 33 students made the first at KTH fully electronic examination based on developed “Exerciser” Maple TA platform.
Students got 8 questions with some “sub-questions” to be solved during 5 hours. Each question has been individualized, there were different problem parameters or conditions for each and every student. The risk of cheating and copying the results has been drastically minimized. Once the students submitted the final answers they got immediately the final exam results. A very important pedagogical and educational progress has been achieved – a “zero time” delay between the exam and information about the results.
The results of the exam are presented at Fig. 2

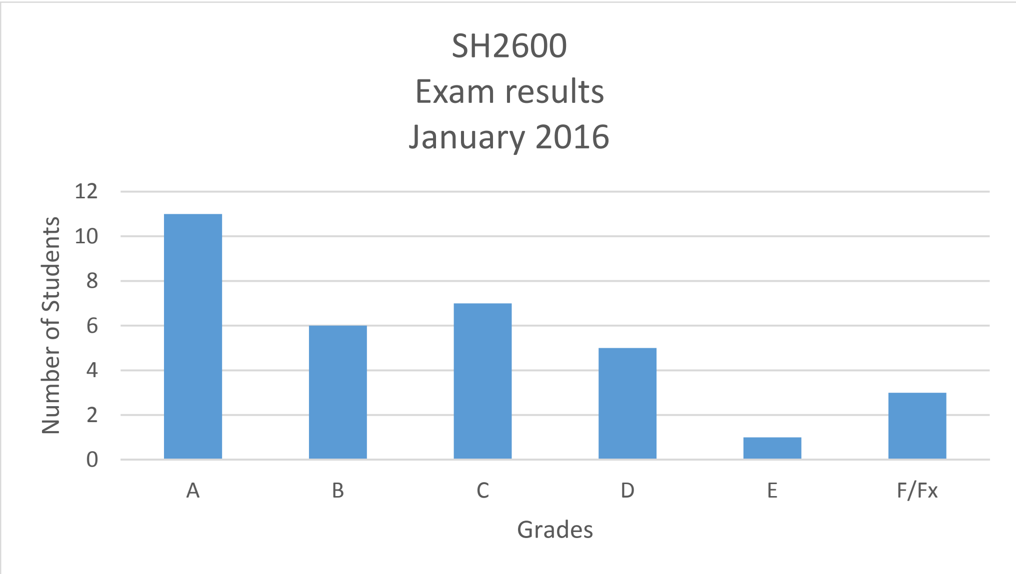
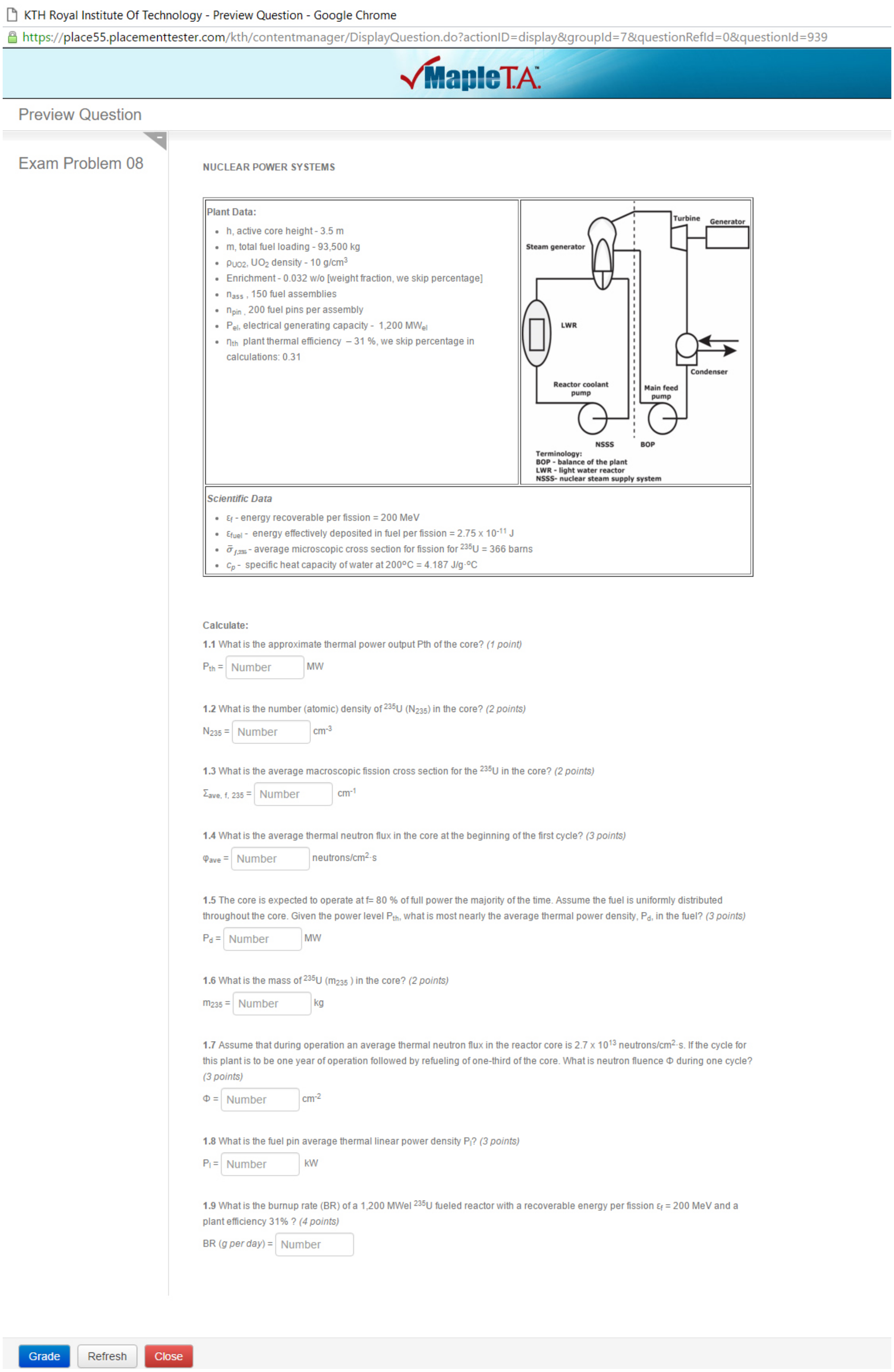


Figure 2. Results of the exam in Nuclear Reactor Physics - 2016

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

Figure 3 shows an example of the examination question in the E-learning platform.



KTH Royal Institute Of Technology - Preview Question - Google Chrome

https://place55.placementtester.com/kth/contentmanager/DisplayQuestion.do?actionID=display&groupId=7&questionRefId=0&questionId=939

MapleT.A.

Preview Question

Exam Problem 08

NUCLEAR POWER SYSTEMS

Plant Data:

- h, active core height - 3.5 m
- m, total fuel loading - 93,500 kg
- ρ_{UO2}, UO_2 density - 10 g/cm^3
- Enrichment - 0.032 w/o [weight fraction, we skip percentage]
- n_{ass} , 150 fuel assemblies
- n_{pin} , 200 fuel pins per assembly
- P_{el}, electrical generating capacity - 1,200 MW_{el}
- η_{th} plant thermal efficiency – 31 %, we skip percentage in calculations: 0.31

Scientific Data

- ε_f - energy recoverable per fission = 200 MeV
- ε_{fuel} - energy effectively deposited in fuel per fission = 2.75 x 10^{-11} J
- $\bar{\sigma}_{f,235}$ - average microscopic cross section for fission for ^{235}U = 366 barns
- c_p - specific heat capacity of water at 200°C = 4.187 J/g·°C

Calculate:

1.1 What is the approximate thermal power output Pth of the core? *(1 point)*

P_{th} = Number MW

1.2 What is the number (atomic) density of ^{235}U (N_{235}) in the core? *(2 points)*

N_{235} = Number cm^{-3}

1.3 What is the average macroscopic fission cross section for the ^{235}U in the core? *(2 points)*

$\Sigma_{ave, f, 235}$ = Number cm^{-1}

1.4 What is the average thermal neutron flux in the core at the beginning of the first cycle? *(3 points)*

φ_{ave} = Number neutrons/cm^2·s

1.5 The core is expected to operate at f= 80 % of full power the majority of the time. Assume the fuel is uniformly distributed throughout the core. Given the power level P_{th}, what is most nearly the average thermal power density, P_d, in the fuel? *(3 points)*

P_d = Number MW

1.6 What is the mass of ^{235}U (m_{235}) in the core? *(2 points)*

m_{235} = Number kg

1.7 Assume that during operation an average thermal neutron flux in the reactor core is 2.7 x 10^{13} neutrons/cm^2·s. If the cycle for this plant is to be one year of operation followed by refueling of one-third of the core. What is neutron fluence Φ during one cycle? *(3 points)*

Φ = Number cm^{-2}

1.8 What is the fuel pin average thermal linear power density P_l? *(3 points)*

P_l = Number kW

1.9 What is the burnup rate (BR) of a 1,200 MWel ^{235}U fueled reactor with a recoverable energy per fission ε_f = 200 MeV and a plant efficiency 31% ? *(4 points)*

BR (*g per day*) = Number

Grade Refresh Close

Figure 3. An example of the examination question in E-learning platform

There is a clear strong incentive for the teachers to develop an E-learning platform for home assignments and examinations, in spite of a significant and pretty high "initial threshold":

"Having 35 students on the course, 9 home assignments with 8 problems each, gives about 2500 problems to assess and grade. Assuming 5 minutes required for each problem over 200 hours of assessment work – ***5 weeks of teachers work done instantly by the computer!***

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

Number of students complaining about final exam grading was very standard and not different than for conventional exams – about 10-15 %.
The forts and most important conclusion: E-learning creates really huge opportunities to improve and modernize our pedagogy on reasonable costs of teacher's work.

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

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

a) This course has been designed and organized by the Royal Institute of Technology (**KTH**), the Center for University Studies Research and Development (**Nova - Oskarshamn**) and by the Swedish Nuclear Fuel and Waste Management Company (**SKB**) and supported by the Linnaeus University and the University of Illinois at Urbana-Champaign.
b) The course consists of a combination of classroom lectures and field excursions and work The unique feature of the course is that the students visit Clab (an interim geological repository for spent fuel), the Laxemar Site (study area for bedrock and surface geology), the Äspö Hard Rock Laboratory (research laboratory for geological spent fuel disposal), and the Canister Laboratory (development center for spent fuel encapsulation technology).
c) The course is heavily sponsored and funded by the local Oskarshamn community and SKB
d) A comprehensive multimedia report has been produced including video recorded lectures and students presentations. Click the link
https://www.dropbox.com/s/e3vnhn2r7fgzx4c/SH262V-extra.zip?dl=0
for the report, unzip and enjoy the report with all multimedia features.
e) For 2016 a dedicated text book is under preparation funded by SKB and Oskarshamn.

The course gained a very good international reputation having many international students, see Fig. 4 for details.
The student evaluation of this course is also exceptionally good as presented at Fig. 5.

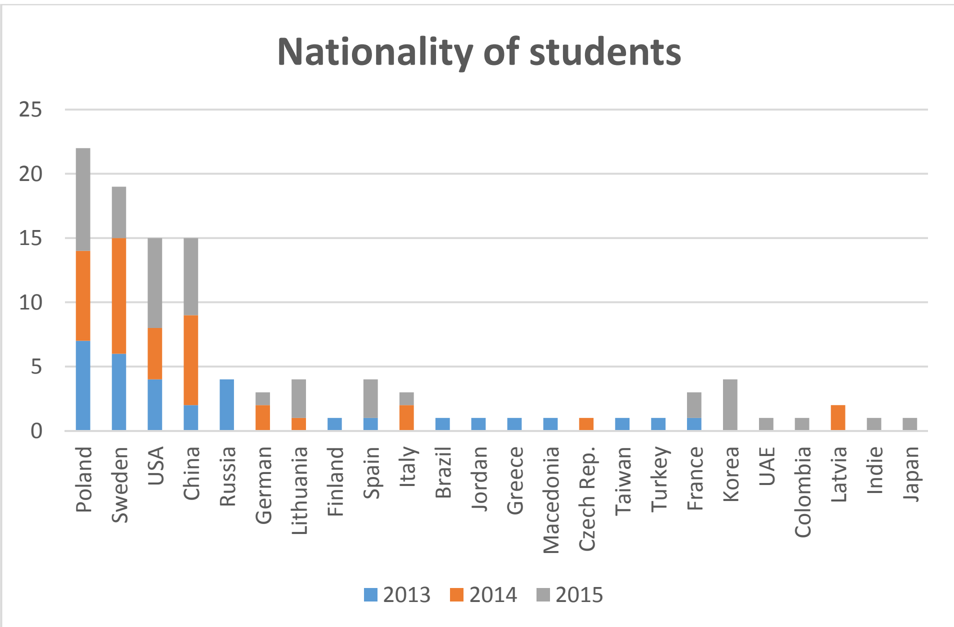


Figure 4. Nationality of the students of the Summer Course SH262V in the years 2013-2015

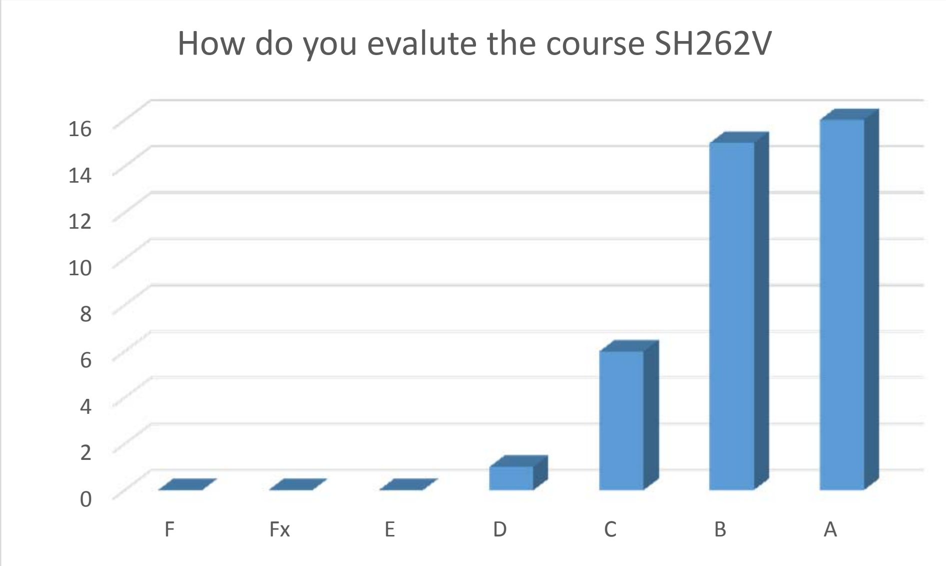


Figure 5. Students' evaluation of the course SH262V

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

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

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

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

Final exam, a presentation of important safety topics, has been conducted at the hall of old reactor R1 at KTH, video recorded and re-viewed with the students. Student presentations can be viewed by clicking at links below

Table 3 SH2610-2015 – Exam presentations

Group 7	https://youtu.be/EJxoAwOxAos
Group 6	https://youtu.be/DolkFFLpo8A
Group 5	https://youtu.be/_NLCfoMa4VU
Group 4	https://youtu.be/i0srlQeCr6E
Group 3	https://youtu.be/wFhKvQV4E_o
Group 2	https://youtu.be/qcUbwYnlef8
Group 1	https://youtu.be/_K-ECtNbDqc

2. Initiating further development of the course: Reactor simulator, simulations of reactor kinetics and reactor dynamics – SH2705

In cooperation with Fortum Keilaniem, a Finnish energy company, a project has been started to develop internet-based nuclear reactor simulator based on APROS – Advanced Process Simulation Software. Course SH2705 is offered today as a stand-alone nuclear reactor simulator studies and applications, but will be in a near future developed for internet based student use and fully integrated into KTH E-learning platform.

Final conclusion:

In 2015 and in coming years particular efforts have been and will be put on E-learning platform development. The ambition is that by years 2017-2018 the entire master programme will be offered in the frame of E-learning technology and become one of the most modern Mater Programmes of KTH and in Europe.

Master Theses

The following Master Theses have been completed during 2015:

Student	Title	Reference	Examiner
Anna Kramarz	Modelling and simulation of gas stratification and mixing in a containment	Trita: 2015;82	Henryk Anglart
Boel Morenius	Data acquisition and post-processing of a high time resolution local phase signal at the Westinghouse FRIGG facility	Trita: 2015;37	Jan Dufek
Ignas Mickus	Quantitative Approach to APROS Code Validation Against TALL-3D Experimental Data	Trita: 2015;56	Henryk Anglart
Jennifer Arnesson	Implemented for Loss of Coolant Accident, Evaluated using Latin Hypercube Sampling	Trita: 2015;41	Chong Qi
Jonathan Wäng	Valdiation of the Critical Flow Models in POLCA-T	Trita: 2015;38	Henryk Anglart
Jurij Kotchoubey	POLCA-T Neutron Kinetics Model Benchmarking	Trita: 2015;59	Waclaw Gudowski
Lukasz Filich	Modeling and Simulation of Thermal Stratification and Mixing induced by Steam Injection through Spargers into Large Water Pool	Trita: 2015;32	Henryk Anglart
Lway Bassim Al-Maeeni	Sub-cooled nucleate boiling flow cooling experiment in a small rectangular channel	Trita: 2015;49	Jan Dufek
Patrik Sirén	Identification of Silicon Phases in Highly Dense Uranium Nitride Pellets	Trita: 2015;77	Janne Wallenius
Timothy Ekelund	Severe accident assessment of a small lead cooled reactor	Trita: 2015;73	Janne Wallenius

Research Project funding and outcome during 2015

The project funding has been used according to the project descriptions provided below.

Development and validation of CFD models to predict propagation of temperature oscillations in solid walls

- Ph.D. student: Roman Thiele
- Prof. Henryk Anglart

Funds spending

During year 2015, the project has been partially supported by SKC with 300 kkr. The provided funds have been spent as specified in the budget.

Activities within the project under 2015

In this project a Large Eddy Simulation (LES) model with conjugate heat transfer to solid walls has been developed and implemented in the OpenFOAM CFD code. The numerical results have been compared to experimental data obtained in the companion project (Project 2 described below) and good agreement has been obtained. The calculated Fourier spectrum of wall temperature oscillations has a peak at 0.17 Hz, which is in a good agreement with the measured spectrum having peak at 0.16 Hz (see figure below).

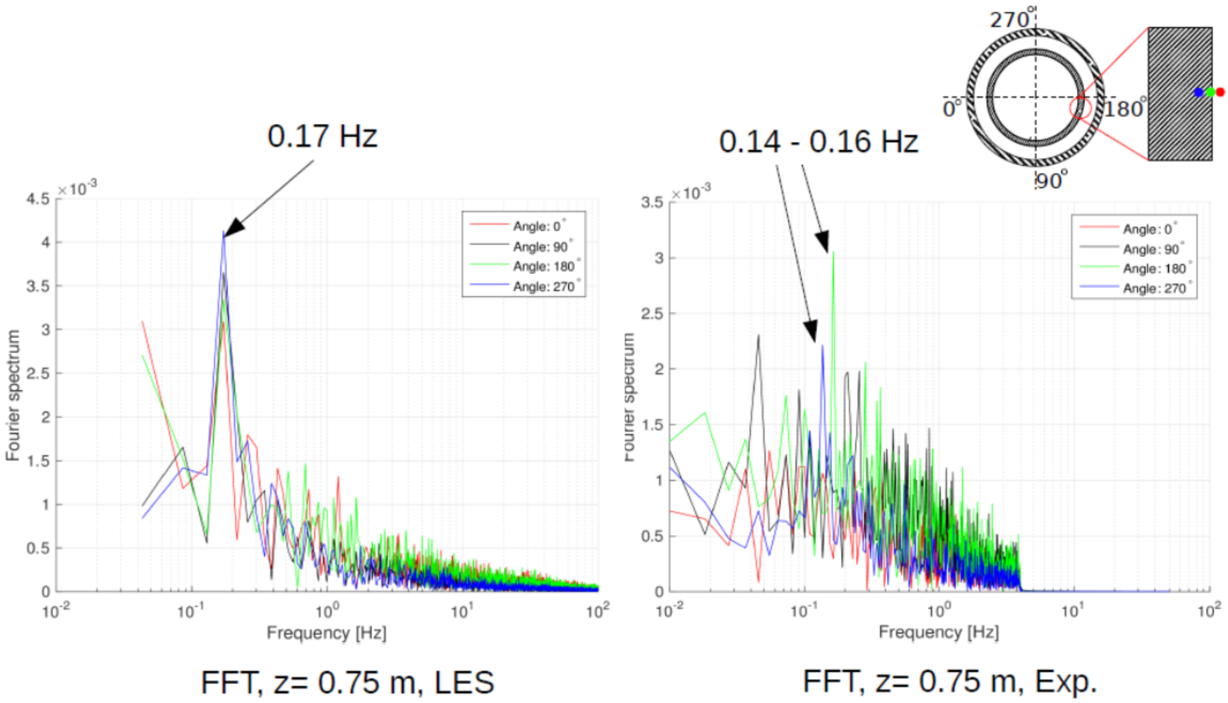


Figure 1: The calculated (left) and measured (right) Fourier spectrum of the wall temperature oscillations during turbulent mixing in a cylinder at BWR conditions.

The following milestones have been achieved within the project:

I. A numerical methodology has been developed to predict thermal interactions between fluid and solid walls, relevant for thermal fatigue analyses.
II. It has been shown that the methodology provides wall temperature fluctuations which are in agreement with experimental data.
III. It has been demonstrated that the new methodology is applicable to study thermal fatigue issues in BWR applications.

Planned activities

The work performed in this project has been finished, however, it is planned that a further, related analytical work will be performed in the Reactor Technology group (see Project description of Mattia Bergagio below).

Publications and presentations:

1. R. Thiele, Ph.D. Thesis: Mechanistic Modelling of Wall-Fluid Thermal Interactions for Innovative Nuclear Systems, KTH, Stockholm, Sweden 2015
2. R. Thiele, M. Bergagio, and H. Anglart, "Large Eddy Simulations of Thermal Mixing in an Annulus with Conjugate Heat Transfer," submitted to Nuclear Engineering and Design.
3. Ph.D. Thesis presentation, KTH, 2015-12-09.

Experimental investigation of propagation of temperature oscillations in solid walls

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

Funds spending

During year 2015, the project has been partially supported by SKC with 300 kkr. The provided funds have been spent as specified in the budget.

Activities within the project under 2015

The experimental data on thermal mixing of water at BWR lower plenum conditions (pressure 7 MPa, temperature 276 °C) with crude water (temperature 60/150 °C) has been processed and analyzed (see figures 2 and 3 below). In total 10 experimental cases obtained at different flow rates and temperatures of water streams have been analyzed. For each case the wall temperature was measured during about 120 seconds at more than 50 locations in the mixing region. The accuracy of the wall temperature measurements is shown to be better than 1.5 K. The spectral analysis of the temperature signal indicates that significant energy of the signal is within frequency of 0.05 to 1 Hz. These results confirm that the obtained experimental data are highly relevant to the thermal fatigue conditions that may occur in a reactor.

Milestones achieved during 2015

I. The experimental data have been post-processed (filtered and de-trended) to make them useful for a spectral analysis and for a comparison with numerical results.
II. Temperature fluctuation intensity has been evaluated.
III. The spectral analysis of the measured temperature fluctuation has been performed.

Publications and presentations

1. H. Anglart, M. Bergagio *et al*. "Measurement of wall temperature fluctuations during thermal mixing of non-isothermal water streams," presented at NURETH-16, Chicago, 2015.
2. M. Bergagio *et al*. "Instrumentation for temperature and heat flux measurement on a solid surface under BWR operating conditions," presented at NURETH-16, Chicago, 2015.

Planned publications

1. M. Bergagio and H. Anglart, "Thermal Mixing of Water at Elevated Pressure. Part 1 – Experimental Results," to be submitted to the *International Journal of Heat and Mass Transfer*
2. M. Bergagio and H. Anglart, "Thermal Mixing of Water at Elevated Pressure. Part 2 – Mixing Intensity and Spectral Analysis," to be submitted to the *International Journal of Heat and Mass Transfer*

Planned activities during 2016

I. Continue development of best-estimate CFD approach, applicable to thermal fatigue analyses at nuclear reactor conditions.
II. Write two journal papers.
III. Write and present the licentiate thesis.

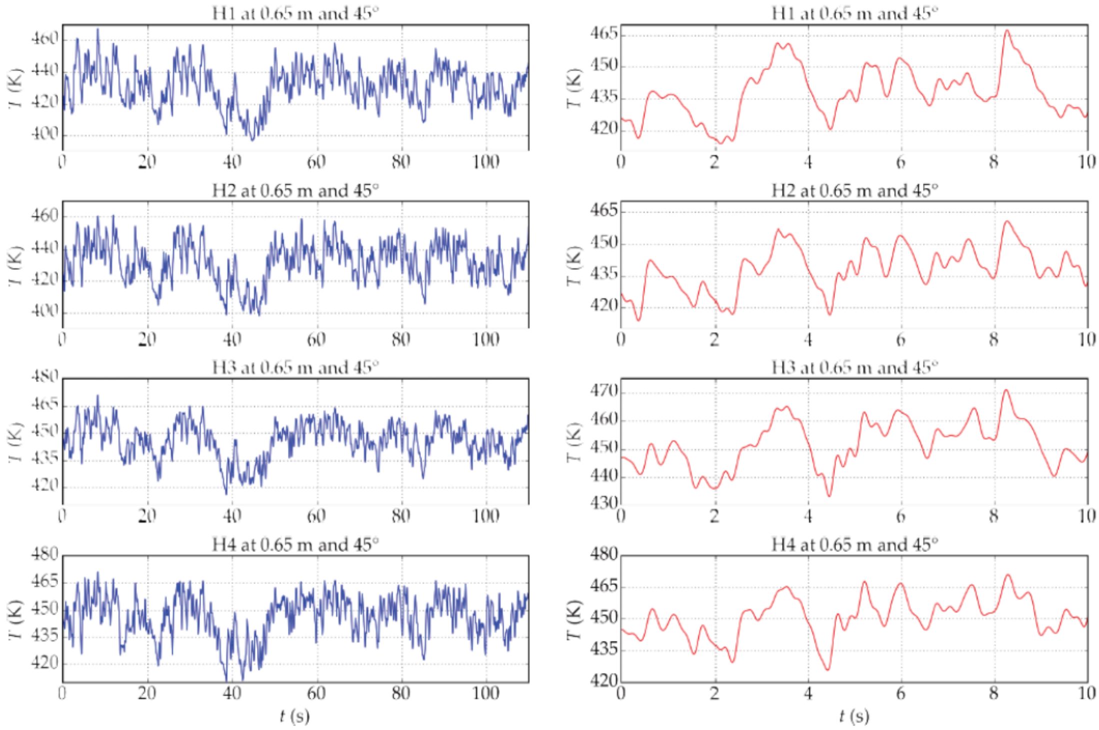


Figure 2: The measured wall temperature oscillations at various termocouples for Case 1 during 120 seconds (left) and first 10 seconds (right).

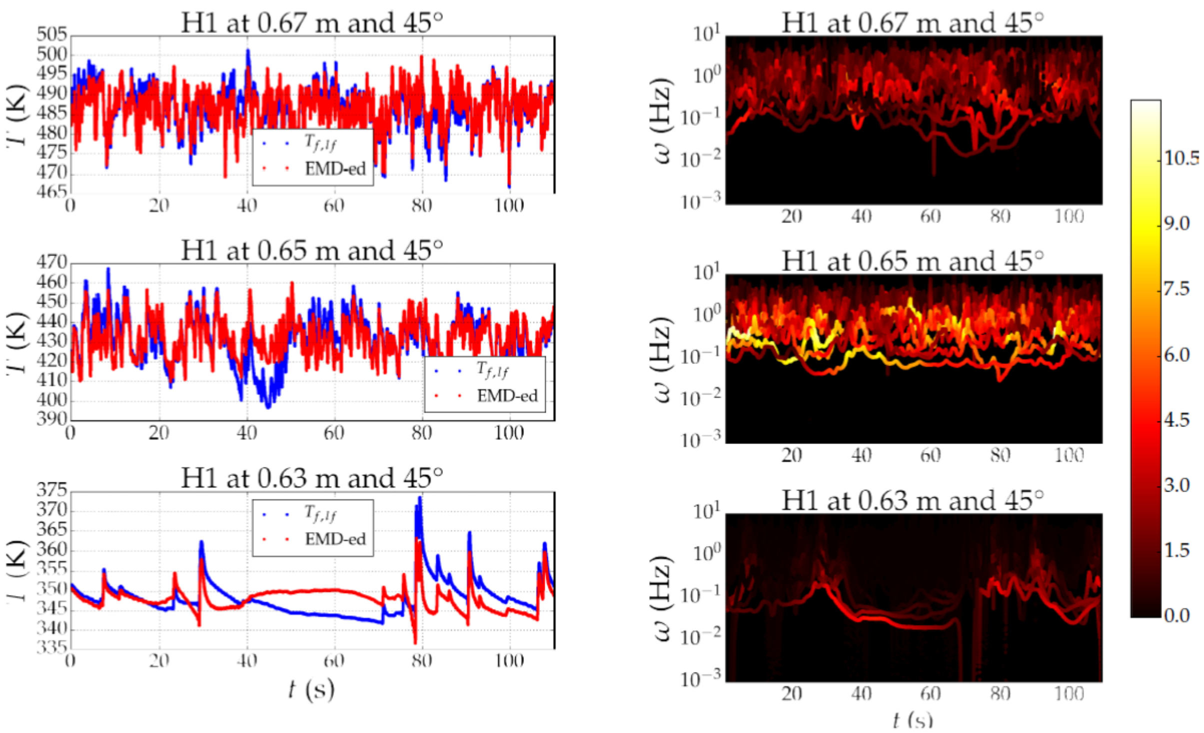


Figure 3: Measured temporal wall temperature variations for Case 1 and for different vertical locations (left) and the corresponding Hilbert-Huang transformation of the signal indicating its energy for different frequency levels.

Mechanical modelling of inter-granular stress corrosion cracking in sensitized austenitic stainless steel

- Ph.D. Student: Michal Sedlak
- Main supervisor: Prof. Bo Alfredsson
- Assistant supervisor: Prof. Pål Efsing

Funds spending 2015

Salary costs: Michal Sedlak 80% and Bo Alfredsson 10% within the project. Total salary cost 886 200 kr. Financial budget: 600 kkr from SKC and 286 kkr from KTH in-kind. No deviation from budget.

Coupling to other projects in 2015

The Swedish Nuclear Utilities Materials group (MG) is co-financing a coupled project to the Ph.D. study on development of mechanical property data for the material utilized in the study. This study will be performed "in-house" by Sedlak with support from the personnel at the Mechanical Lab at the department of Solid Mechanics. The budget for this project was 100 kkr for 2015. Work is progressing.

Activities within project in 2015

The numerical model in FEM has been finalized with a fracture mechanical portion that can alter the character of the grain boundaries from ductile to brittle behavior. Sedlak has created a numerical loop to take into account the degradation effects on the fracture mechanical properties of the oxide formation in the grain boundaries.

In the end of 2015, the fracture mechanical properties and the numerical model has been reviewed and scrutinized. The fracture mechanical properties have been reviewed using a J-integral model with variable energies to represent the transition from brittle to ductile fracture.

The first paper on the subject of fracture mechanical analysis of the system including IGSCC propagation has been initiated. The different processes will be compared to analytical solutions of the diffusion equations, train functions, and variations of the exponential equations.

Practical work on experimental verification of the model has been initiated. Precursory tests on J_{1C} has been conducted. Further tests are foreseen in the beginning of 2016.

The objective is to have a modular model that incorporates all of the proposed influential effects according to figure 1. In figure 2, a simplified schematic of the process is given. In figure 3, the model, applied to a double cantilever beam element is described. The objective of the modular model is that further models, such as influence of irradiation on mechanical properties, and enhanced local chemistry model etc. can be incorporated in future steps to refine the model further.

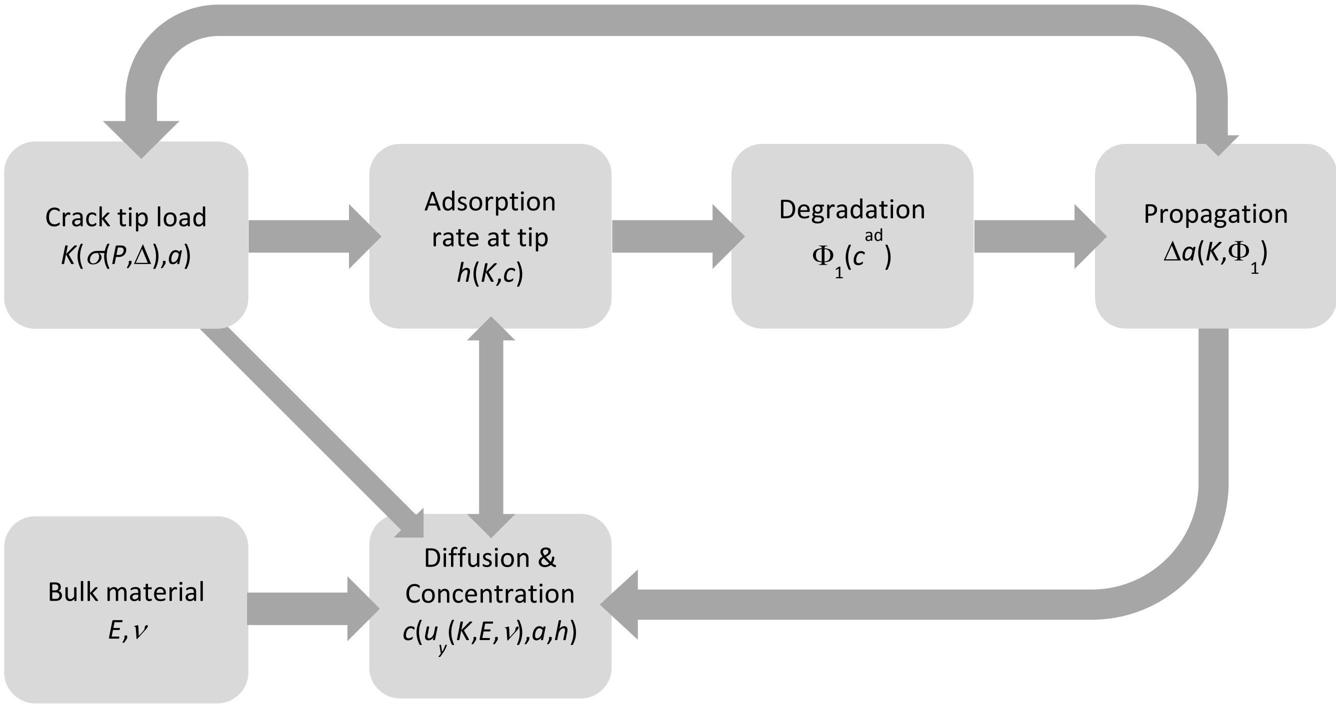


Figure 4: Mechanical modelling of IG-SCC: Couplings between physical processes.

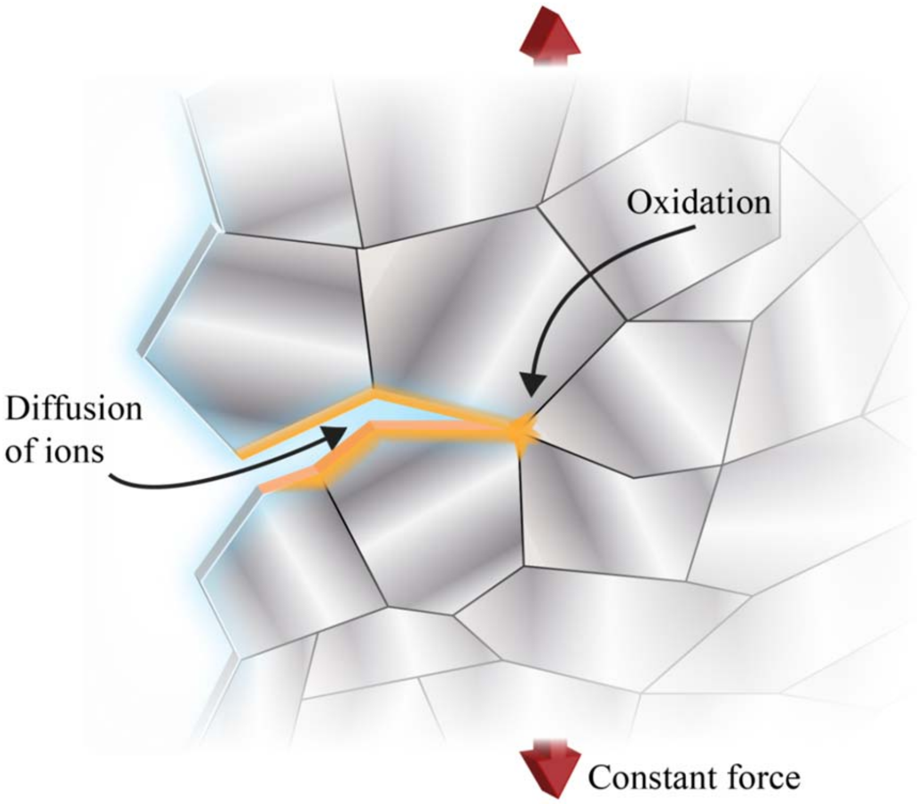


Figure 5: Schematic figure of the bulk material undergoing constant loading and diffusion of ions into the crack.

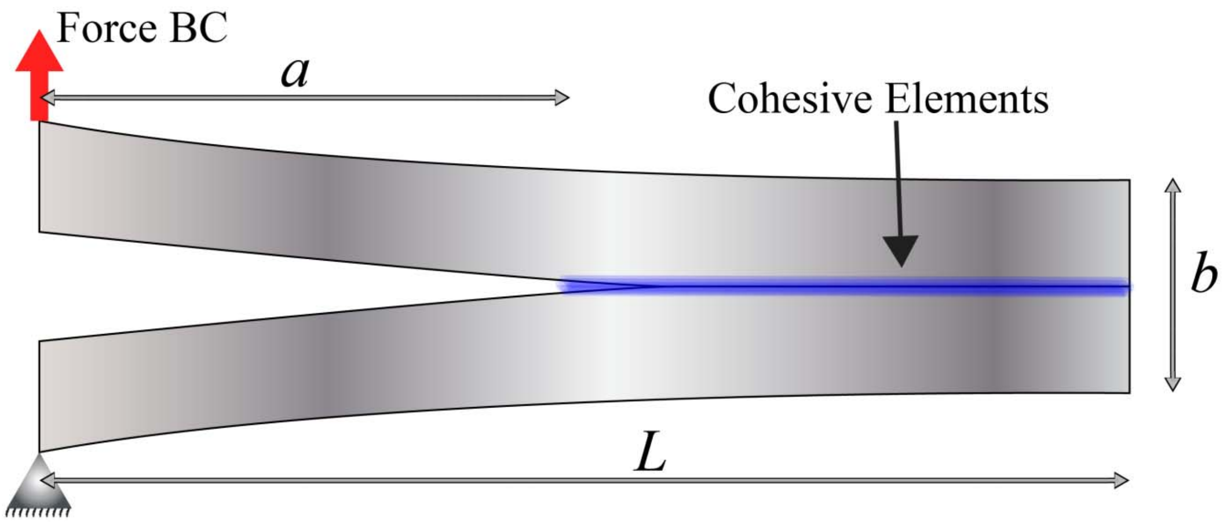


Figure 6: The DCB model, showing the locations for boundary conditions and loads.

Milestones reached

- The coupled modular numerical model is finalized.
- Matlab scripts for data extraction finished.
- Model generator for various and variable specimen geometries

Presentations and Publications

- Public presentation at Svenska Mekanikdagarna, SMD, in Linköping 10 – 12 juni 2015 and at the 17th Conference on Environmental Degradation of Materials in Nuclear Power Systems in Ottawa, Canada 9 – 13 augusti 2015.
- The Conference contribution to the ENVDEG 2015 reviewed and made available in the *proceedings to conference*. (Paper distributed to SKC in conjuction to reporting 2015 Q3.)

Planned activities 2016

- Experimental verification of the IG-SCC model, including accelerated IG-SCC for 316.
- 1st half-year 2016: Paper 1 on fracture mechancial properties with-in the model. Paper 2 on the behaviour of th coupled model for descrubing IGSCC. Licentiat presentation Michal Sedlak.
- 2nd half-year 2016: Paper 3 on experimental and numerical modeling.
- Paper 4: IG-SCC effects of crystal structure and gradient plasticity with the grain structure.
- Ph.D. Thesis defense for Michal Sedlak planned for 2017

Appendix 3 - Uppsala University

UPPSALA
UNIVERSITET

Overview of activities during 2015

The main research on nuclear technology is performed in the Division of applied nuclear physics at Uppsala University, with an ambition 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), leading to direct use of contract education in industry and surrounding society.

The increased collaboration within materials research through MÅBiL (se Appendix 4 below), is also a part of the strategy to make use of available funding as efficient as possible.

The division of applied nuclear physics focus on research and education activities within nuclear technology on:

- 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).
- Nuclear expertize 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 hosted the WNU Summer Institute 2015 (see below) which was a success with over 80 participants from 37 nations, most being young professionals within nuclear industry and national authorities.

Ane Håkansson

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 programmes, the Bachelor of science in engineering programme with a specialisation in nuclear engineering, i.e., H*ögskoleingenjörsprogrammet i kärnkraftteknik* (KKI), which is on its 6th 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 one of the large master of science in engineering programmes at Uppsala University. Also, during 2015 it was decided that the responsibility of managing the candidate programme in physics, i.e., *Kandidatprogrammet i fysik* should be transferred to the division of applied nuclear physics. Michael Österlund, Matthias Weiszflog and Henrik Sjöstrand respectively, have been appointed managers for three educational programmes. In addition to courses within these programmes, division staff also provides courses in nuclear technology, energy physics and technical thermodynamics within the framework of other UU engineering programmes.

Due to the reorganisation of *Kärnkraftsäkerhet och Utbildning AB* (KSU), which has taken place during the last couple of years, the KSU board decided not to renew the agreements with Uppsala University regarding higher education for the nuclear power industry and the Bachelors' programme in nuclear engineering. The agreements, which expired during 2015, were originally signed in 2003 and 2009 respectively. They have resulted in a very fruitful collaboration between academy and industry providing industry with continued education for primarily NPP staff and an influx of fresh engineering graduates with a solid knowledge of nuclear technology as has been reported in previous SKC annual reports.

Following the expiration of the agreements, a new agreement was signed in early 2015 between Uppsala University and the three nuclear power plants (FKA, OKG and RAB) regarding continued activities within higher education and the Bachelors' programme. The objective of the contract education is to ensure the continued education and competence building of existing and newly recruited personnel, whereas the objective of the Bachelors' programme is to supply the industry with graduating engineering students with a solid knowledge of nuclear technology, well suited to take on positions within the nuclear power plants primarily within operations and maintenance. The collaboration with KSU AB concerning teaching materials, simulator training for course participants and Bachelor students continues in the same way as before.

A work has been initiated to revise courses, primarily within the Bachelors' programme in order to be able to provide opportunities for NPP staff to participate in such courses as part of their continued education. First and foremost this entails adopting teaching methods and revision of course syllabuses in order to make the courses available as distance teaching courses. This work will primarily be performed during 2016 with an objective of offering the first distance teaching courses during 2017.

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 Swedish NPPs.

Because KSU AB is no longer responsible for handling admissions and other administrative matters regarding higher-education courses it has been decided that NANSS should take on the role of handling those higher education courses that are within the framework of the higher education agreement with the NPPs. An advisory board with participants from the NPPs and Uppsala University will provide advice and guidelines for what courses should be made available and also advice on when different courses should be offered. Consequently, during 2015 a web portal has been developed, *www.nanss.uu.se* , were available courses are presented and where prospective course participants can register their participation in the courses on offer. Karin Person continues as project leader for NANSS and Michael Österlund remains as director of studies for nuclear contract education.

Master of Science engineering

The number of students within the programmes of Master of Science engineering was practically unchanged from 2014 according to (for each course):

- Energifysik I and II in the Teknisk Fysik programme, year 4: 33 students
- Kärnkraft teknik och system in the Energisystem programme, year 4: 16 students
- Framtida nukleära system in the Energysystem programme, year 4: 6 students
- Energisystemfysik in the System i teknik och samhälle progr, year 3: 38 students
- Tillämpad reaktorfysik (also as contract education course), year 4: 6 students

Thus, in total 99 students were presented to nuclear technology in the regular education at Uppsala University in 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 2015 students have made study visits to FKA, OKG and RAB, the SKB facilities in Oskarshamn, the Westinghouse nuclear fuel fabrication plant in Västerås, Siemens Turbo machinery in Finspång (steam turbines) and ABB in Ludvika (generators and transformers).

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

Recruitment

Prospective students are very sensitive to information conveyed in different media on the future of nuclear power. Also, statements by the power companies themselves about the prospects of nuclear power have a significant influence on student's choice of programmes and courses. Consequently recruitment requires considerable effort on a scale quite different from other engineering programmes. Following interviews with programme students it has been decided to focus the recruitment activities on arranging lunch seminars at several engineering colleges and universities around Sweden and on participation in student careers fairs, e.g., UTNARM, CHARM and LARM. Whenever possible these activities are conducted in collaboration with industry and SKC. Additionally, the programme is marketed through advertisements in 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 has experienced a decrease in student enrolment associated with the aftermath of the Fukushima accident, the strong political focus on renewable energy sources and the discussions and decisions about premature closure of reactors in Sweden. From our contact with students it is clear that students' choice of educational programmes 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. To some extent the low enrolment figures are compensated by a very low drop-out rate compared to other engineering programmes.

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

Study year	Applicants	1st-hand applicants	Applicants admitted to the programme	Students registered at start of first semester	Students active at end of semester 2
2010/2011	80	47	34	21	19
2011/2012	57	26	36	12	11
2012/2013	60	29	36	14	12
2013/2014	46	22	21	10	8
2014/2015	45	19	14	9	9
2015/2016	64	16	15	7	6+1 (Jan. 2016)

The students report a high degree of satisfaction with the quality of education. In the programme evaluation the class of 2014/2015, when questioned about their experience of the overall quality of the programme, the gave the mark 4.9 ± 0.3 on a scale from 1 (unacceptable) to 5 (excellent). On the question on whether the students would recommend other students to enrol in the programme or not, the response was 5.0 ± 0.0 on a scale from 1 (not recommended) to 5 (highly recommended).

Students' achievements

At the time of writing (January 2016) 41 students have successfully completed their Bachelors theses. A summary of the theses produced during 2015 is found at the end of this chapter. The students of the academic year 2014/2015 are exhibiting average academic achievements (Figure 1). It is notable that several students have not yet completed their diploma thesis. This is mostly due to the fact that during 2015 very few diploma works were made available to the Bachelors' students from industry, forcing students to eventually take on diploma works within the university itself. We expect most of these theses to be completed during 2016. We are happy to report that one of the 2014/2015 students, Johan Larson, was awarded the 2015 Sigvard Eklund prize for the best diploma work on the Bachelors' level.

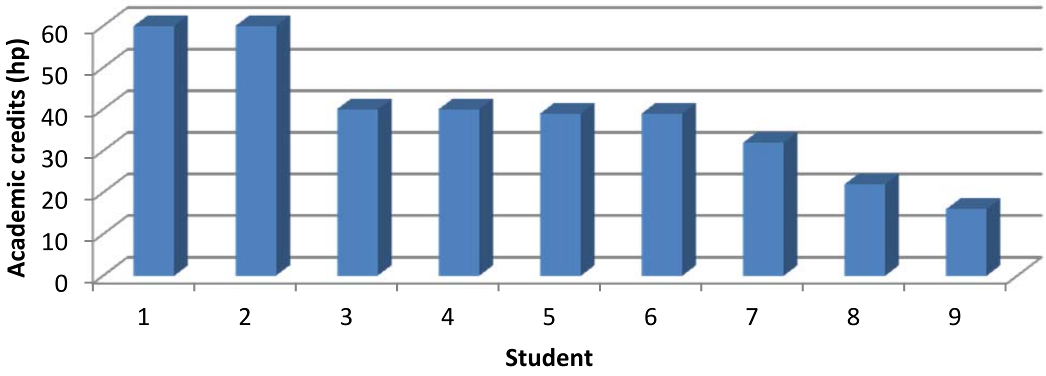


Figure 1: Student achievements for the academic year 2014/2015. The maximum academic credits possible are 60 hp.

Employment

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

Contract education for the industry

We are happy to report that during 2015 the Division of applied nuclear physics provided industry with 15 weeks of contract education courses within the agreements on higher education. This is decrease by three week from the previous year, which is caused by a reduction in the number of course participants from industry. For the academic year 2015/2016 18 weeks of courses are planned (January 2016).

Table 2: Contract education courses provided on one or more occasions during 2015

Course	Credits / duration
Tillämpad reaktorfysik	5 hp
Myndighetskunskap	5 hp
Fördjupad strålskyddsutbildning (FS1)	6 hp
Värme- och strömningslära (operatörsutbildning OKG)	1 w
Reaktorfysik (operatörsutbildning, FKA, OKG)	1 w
Teoretisk återträning av skiftlag (FKA)	1 d/team

The World Nuclear University Summer institute 2015 in Uppsala

During July and August 2015 Uppsala University co-organized the WNU Summer Institute together with the World Nuclear University. The Summer Institute which took place over a period of six weeks in Uppsala between July 4 to August 14 in Uppsala attracted over 80 participants from 37 nations, most being young professionals within nuclear industry and national authorities. Unfortunately, the Swedish nuclear industry was represented by only one summer institute participant.

The Summer Institute, which was a huge success, included lectures on a wide range of topics ranging from reactor physics to nuclear law. It also included a one week technical tour to the nuclear power plants in Barsebäck, Forsmark, Oskarshamn and Ringhals as well as study visits to the Westinghouse fuel factory in Västerås, SKC’s Äspö laboratory and the newly inaugurated proton therapy centre, Skandionkliniken, in Uppsala.

Lecturers from Uppsala University contributed to the curriculum together with more than 40 experts from all over the world. Also many high-ranking officials and corporate leaders gave lectures and presentations during the Summer Institute, e.g., Hans Blix, Janice Dunn Lee (deputy director general, IAEA), Agneta Rising (CEO, WNA), Jacques Régaldo (chairman, WANO), William W. Magwood (director general, NEA), Kirill Komarov (vice president, ROSATOM) and many more. The Summer Institute received widespread attention including coverage in international media and Sveriges Radio.

Development of teaching in the nuclear field

- UU is one of about 25 organizations behind an EU project called ANNETTE, which was granted during 2015. The project covers the development of an “Advanced Master” training programme for professionals in the nuclear business. The project is coordinated by ENEN (the European Nuclear Education Network), and will run during 2016-2019.
- Sophie Grape is chairing the working group of Training and Knowledge Management in ESARDA (European Safeguards Research and Development Association), with Karin Persson as an additional group member. The TKM group is also a suitable platform for the development of a safeguards course within the ANNETTE project.
- During 2015, the system used for supporting and following up students’ progression in oral presentation within the bachelors programme on nuclear power engineering was evaluated. The system was implemented during 2014, financed by UU funds for pedagogics development, and used for the first year 2014/2015. The evaluation showed that the students experience that the system supports them in their development of skills in oral presentation. The system and the evaluation was presented at a the 5th conference on development of Swedish engineering education (5:e Utvecklingskonferensen för Sveriges Ingenjörsutbildningar) in November.

Student's theses during 2015

Ph.D. theses

Erwin Alhassan: "Nuclear data uncertainty quantification and data assimilation for a lead-cooled fast reactor : Using integral experiments for improved accuracy". Uppsala: Acta Universitatis Upsaliensis; 2015. Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology, 1315.

Licentiate theses

- **Tomas Martinik:** "Development of Differential Die-Away Instrument for Characterization of Swedish Spent Nuclear Fuel". Available at http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-268143. (has not yet been presented orally).
- **Petter Helgesson**: "Experimental data and Total Monte Carlo : Towards justified, transparent and complete nuclear data uncertainties". Uppsala universitet; 2015.
- **Kaj Jansson**: "Improving the Neutron Cross-section Standards ^{238}U(n,f) and ^{6}Li(n,a) : Measurements and Simulations". Polacksbackens repro; 2015.

Masters theses completed

- **Magnus Ahnesjö**: "Tomographic Reconstruction of Sub-Channel Void measurements" – in collaboration with Westinghouse. Dr. Peter Andersson.
- **Daniel Constanda**: "Control Rod Effect at Partial SCRAM: Upgrade of Plant Model for Forsmark 2 in BISON After Power Uprate" – in collaboration with Forsmarks Kraftgrupp. Reviewer: Dr. Staffan Qvist.
- **Tobias Lindström**: "SPARC fast reactor design: Design of two passively safe metal-fuelled sodium-cooled pool-type small modular fast reactors with Autonomous Reactivity Control". Dr. Staffan Qvist.
- **Henrik Liljenfeldt**: "Applying fast calorimetry on a spent nuclear fuel calorimeter" – in collaboration with SKB. Reviewer: Dr. Peter Jansson.
- **Joakim Nordlander**: "Dimensionell stabilitet i PWR-patroner i Ringhals" – in collaboration with Vattenfall Nuclear Fuel. Reviewer: Dr. Peter Jansson.
- **Joel Blomberg**: "Sensitivity study of control rod depletion coefficients" – in collaboration with Westinghouse. Reviewer: Dr. Andreas Solders.

Masters diploma works in progress

- **Sara Wiberg**: "Non-destructive assay methods for deep geological disposal of spent nuclear fuel" – in collaboration with SKB. Dr. Peter Jansson.
- **Moa Skan**: "TIP deviations in Forsmark 1" – in collaboration with Forsmarks Kraftgrupp. Reviewer: Ass. Prof. Staffan Jacobsson Svärd.

Bachelors theses completed (KKI)

- **Olof Lantz**: “Virtualiserad testmiljö. Utvärdering av virtualiseringsprogramvaror”,
- ISRN UTH-INGUTB-EX-KKI-2014702-S.

- **Johan Larsson**: “Dokumentation av underhållssimulatorer för utbildning i vardagssäkerhet”, ISRN UTH-INGUTB-EX-KKI-2015/03-S.

- **Sam Samuelsson**: “Införandet av snabbreaktorer i Sverige”, ISRN UTH-INGUTB-EX-KKI-2015/04-SE.

- **Ann-Caroline Wiberg**: “Evaluation of how the LUCOEX results can be utilized by less-advanced programs”, ISRN UTH-INGUTB-EX-KKI-2015/01-SE.

Bachelors diploma works in progress (KKI):

- **Mikael Haglund**: ”Hantering av trender för processystem och periodisk provning”, OKG, OKG.

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

- **Victor Ericsson, Olof Eriksson**: “Arbetsmetodik för konfigurering av layouter i FKAs övervakningssystem”, FKA.

- **Niklas Grundberg, Wu Ming**: “Undersökning av egenskaper hos ABWR”, Supervisor Dr. Carl Hellesen. Industry Maria Fernroth, FKA.

- **Carl Hemmingsson, Emil Rostedt**: “Modellering av PRISM-reaktor”, Supervisor Dr. Staffan Qvist.

Other Bachelors theses completed

- **Benjamin Eriksson**: “Neutron field characterization using TFBCs and comparison to Monte Carlo Simulations”. Andrea Mattera

Personnel

Recruitment of senior personnel

Dr. Staffan Qvist was hired as a researcher to continue his postdoc research on Gen IV systems. Staffan started his new position in August 2015.

Dr. Peter Andersson started a postdoc position on fuel diagnostics in the beginning of 2015. Peter performs research within the OECD Halden Reactor Project in Norway as part of the MÅBiL project.

Recruitment of Ph.D. students

No new Ph.D. student positions have been opened during 2015.

Promotion of senior personnel

Dr. Sophie Grape was appointed a docentship after presenting her docent lecture on "Kärnämneskontroll - Världssamfundets strategi för att förhindra kärnvapenspridning" on November 13, 2015.

Dr- Henrik Sjöstrand was appointed a docentship after presenting his docent lecture on "Göra el av kärnavfall, en strålande idé?" on April 15, 2015.

Dr. Henrik Sjöstrand and **Dr. Cecilia Gustavsson** have been promoted to senior lecturers.

Research projects within SKC

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:

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

- Ph.D. student: **Petter Helgesson**
- Main Univ. lekt. Henrik Sjöstrand
- Assistant Prof. Arjan Koning (IAEA, Vienna), Dr. Dimitri Rochman (PSI, Switzerland), Prof. Klaes-Håkan Bejmer, Prof. Stephan Pomp

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

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

During 2015, there has been an increased emphasis on aging parameters, and in this work, he connects macroscopic fuel and aging parameters to the fundamental nuclear physics processes by using the nuclear model code TALYS and the Total Monte Carlo Method (TMC) method. With a TALYS based code package, nuclear data libraries can be produced for the entire nuclide map, with all reaction channels and secondary particle production.

During 2015 Petter has investigated ^{59}Ni, since the two-step thermal neutron reaction sequence ^{58}Ni(n,γ)^{59}Ni(n,α)^{56}Fe, (Q-value = 5,1 MeV) results in non-linear He production rates and is an important contribution to the He production in steel in thermal spectrum. The reaction sequence is also a significant contribution to the damage energy. He is also investigating the hydrogen producing reaction sequence: ^{58}Ni(n,γ)^{59}Ni(n,p)^{59}Co, (Q-value = 1.9 MeV). Currently, existing evaluated data has no uncertainty information, neither for ^{59}Ni(n,α)^{56}Fe nor ^{59}Ni(n,p)^{58}Co reactions, in the thermal region.

To improve the He production prediction and to provide nuclear data uncertainty estimates, new ^{59}Ni cross section data has been produced. As opposed to existing evaluated data (for nuclides in general) the helium and hydrogen production cross sections have been produced using relevant resonance parameters using R-matrix theory with the Reich-Moore approximation. A re-evaluation of the thermal cross sections including experimental correlations has also been performed during 2015. The lack of well-documented measurements on the cross sections in the resonance region makes the actual values of the resonance parameters very uncertain. The cross-sections are generated from average unresolved resonance parameters and sampled with a high uncertainty, after which they are adjusted to the experimentally known thermal cross sections and their uncertainties. The cross-sections will soon be published in ENDF-6 format, including so-called random files, for usage by the nuclear community.

The new development of ^{59}Ni cross-sections also address some critical issues when it comes to the processing of the data and a contact with A. Kahler (who develops NJOY) has been established.

To check the performance of the random files they have been tested on an MCNP-6 model. The results were compared to He and H production rates in a reference case. It was found that the inclusion of ^{59}Ni increased the helium production rate by a factor of 4.9+/- 0.8. The uncertainty of 0.8 is due to nuclear data uncertainties. It was also found that there were some discrepancies between the results obtained with these new files and the result which was obtained using ENDF/B- VII.1.

During 2015, Petter has also continued to work on statistical stringent ways to include experimental information in TMC using file weights from automatically generated experimental covariance matrices.

The methods developed were tested on both uranium and plutonium fuels as well as on the famous Jezebel benchmark and the Ringhals shielding assemblies.

The work has been presented at IAEA coordinated research project (CRP) on "Primary Radiation Damage Cross Sections", in scientific journals and at different international conferences during 2015. In October 2015, the work was also presented in Petters licentiate thesis.

Fuel diagnostics within MÅBiL

- Postdoc: **Dr. Peter Andersson**
- Participating researchers: Staffan Jacobsson Svärd, Division of Applied Nuclear Physics, Department of Physics and Astronomy, Uppsala University and Scott Holcombe OECD Halden Reactor Project, Norway

Background

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

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

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

Project description and status

The *MÅBIL* sub-programme *Fuel diagnostics* started in February 2015 with the assignment of Peter Andersson on a postdoc position which is 50% funded by SKC. In the first year, the focus has been on non-destructive measurements of irradiated nuclear fuel using gamma spectroscopy and gamma tomography. An important part of this work has been the development and evaluation of qualitative and quantitative reconstruction methods for emission tomography of nuclear fuel.

The recently installed custom-made tomography instrument for irradiated nuclear fuel at the Halden reactor (HRP) has been characterized and new applications are continuously being explored. The instrument has exquisite spectroscopic capabilities, thanks to the use of a HPGe detector, and gives unique opportunities to quantify the amount and the spatial distribution of numerous gamma-emitting fission, activation and decay products in irradiated nuclear fuel bundles. During the first year of the project, the tomography instrument has been used in experimental research on several world-leading applications, such as;

- Validation of power and burnup profiles calculated with a core simulator (here in terms of HELIOS calculations for a HRP-fuel rig);
- Evaluation of fission gas contents in rod plenums, used to derive fission gas release;
- Examination of the fuel relocation and packing density in a LOCA test rod .

Details such as a higher burnup on the outskirts of the fuel rig, rod internal burnup distribution and migration of Cesium at high fuel temperatures can be deduced, as illustrated in Figure 1.

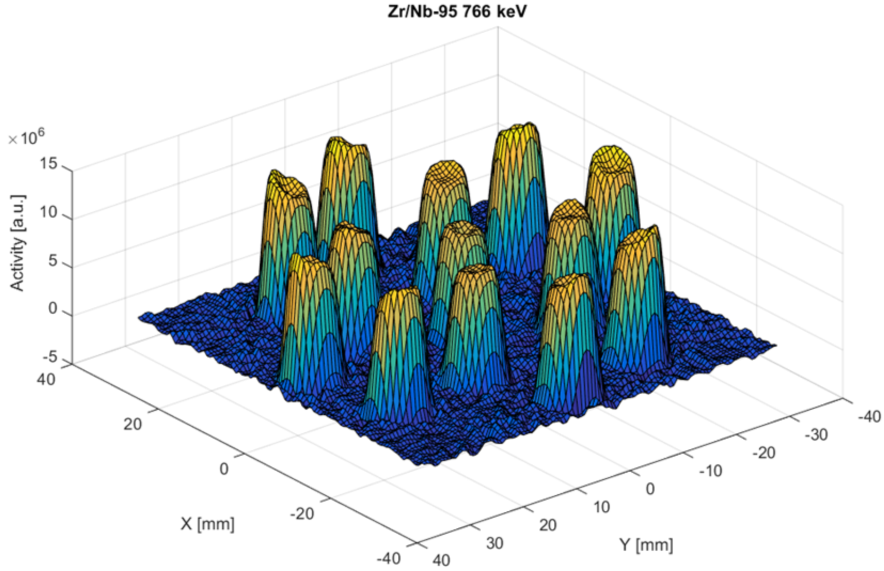


Figure 1. Example of tomographic reconstruction (Zr-96 inventory) in a 13 pin HRP driver fuel. Note the various features of the distribution that are visible, such as higher power (and therefore higher inventory) in periphery of the rods and towards the outside of the bundle.

In addition, recent studies have shown that the fragmentation and relocation of fuel in rods that have undergone a LOCA transient test can be mapped using tomography. In the LOCA tests performed at the HBWR, a single fuel rod is exposed to the conditions of a LOCA transient. It typically undergoes ballooning, fuel relocation, cladding burst and fuel fragment dispersion during this transient. These important features can be assessed non-destructively using the gamma tomography setup of OECD-HRP, which can give a detailed view of the nuclear fuel location and packing fraction inside the expanded cladding. The gamma emission tomography system is the only available technique that may provide these data on-site, prior to the transport of the test rig to external PIE facilities. One may note that such transport requires the fuel to be moved into a horizontal orientation, which may alter the fuel fragment distribution and deteriorate such assessment. The first experimental campaign using the tomography system for this purpose was started in the end of 2015 and it continues into 2016. The preliminary results are highly promising.

Fulfilling of projects goals

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

The results obtained so far show that these goals can be reached within the project. Firstly, measurements of fission gas release have been executed, and the data are currently undergoing analysis to evaluate the achievable precision in this type of assessment. Secondly, tomographic measurements have been performed of test rods subjected to LOCA in the HBWR, and preliminary results indicate that ballooning and failure of cladding as well as cracking and relocation of pellet material can be assessed with this technique. Scientific papers are currently under preparation, according to the list below. In the end, the experimental techniques developed within MÅBiL are expected to be highly useful in the analyses of irradiation tests of new fuel types such as ATF, once these are made available for this type of assessment.

<u>Plans</u>

Several other applications are considered, such as the measurement of Plutonium build-up and fission gas release. Additional applications for this new and unique data collection instruments are also explored.

The following Ph.D. students perform research within nuclear safeguards. They were partly financed by SKC funding until 2013, whereas they currently receive parts of their funding directly from SSM:

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

- Ph.D. student: **Tomáš Martiník**
- Main Dr. Sophie Grape
- Assistant supervisors: Dr. Peter Jansson, Prof. Ane Håkansson

Tomáš Martiník is a joint Ph.D. student between Los Alamos National Lbaoratory and Uppsala University, working within the so-called Next Generation Safeguards Initiative (NGSI). Within NGSI several non-destructive methodologies are researched, one of them is the active neutron assay technique called Differential Die-Away (DDA), which Tomáš works with. Tomáš has recently been working on the development of a prototype instrument for deployment in the future encapsulation facility for verification of irradiated nuclear fuel. It is planned that the prototype should be manufactured and tested in the Clab facility.

Studies of Cherenkov light emission and detection for nuclear safeguards purposes

- Ph.D. student: **Erik Branger**
- Main Dr. Sophie Grape
- Assistant supervisors: Ass. Prof. Staffan Jacobsson Svärd, Dr. Peter Jansson

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

Other research projects

A number of research projects have been carried out within the division during 2015 that are funded from other sources than SKC. A short account of some major research projects are described below:

Neutron-induced nuclear reactions at intermediate energies

- Ph.D. student: **Kaj Jansson**
- Main Univ. lekt. Dr. Cecilia Gustavsson
- Assistant Prof. Stephan Pomp, Dr. Alexander Prokofiev, Dr. Ali Al-Adili

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 middle of 2016 and first beam is expected at the end of 2016.

During 2015 Kaj has also been working on analysing experimental data on the neutron standard Li-6(n,alpha). The data have been obtained at IRMM in Belgium with a Frisch-grid ionization chamber. Kaj has also started participating in the development of the VERDI spectrometer (2E-2v instrument) at the IRMM.

The development work for NFS formed the background for Kaj's licentiate thesis, presented in 2015.

Measurements of independent fission yields from a fast neutron spectrum

- Ph.D. student: **Andrea Mattera**
- Main Prof. Stephan Pomp
- Assistant Dr. Mattias Lantz, Univ. lekt. Michael Österlund

Andrea started working on the AlFONS project in spring, 2011. AlFONS, co-financed by SSM and SKB, aims at measuring independent fission yields in thermal and fast neutron spectra at the IGISOL facility in Jyväskylä, Finland. Andrea defended his licentiate thesis in December 2014. In the thesis the design and characterization of a neutron source for IGISOL is presented. This source will facilitate neutron induced fission yield measurements at IGISOL through the Be(p,n)-reaction.

In 2015 a dedicated ion-guide, for collection of the products, for neutron induced fission was developed in Jyväskylä and in April and March the combined neutron converter and ion guide was tested in two runs with natural Uranium. In these runs the proton beam current was limited to 10 uA due to technical problems with the cyclotron. Nevertheless, the runs successfully proved that the setup work and that we can separate fission products by mass, even though the extracted intensities were very low.

During the run in April we also made characterization measurements of the neutron field using TFBC-detectors and TOF for which Andrea was responsible. The measurement was successful, but due to limited time resolution, using a different cyclotron as proton source, it is not possible to extract accurate energy spectra from the TOF data. As we have more beam time allocated for this experiment it will be repeated once we have the main cyclotron available.

Lately, Andrea's work has been focused on the comparison of the fission models of different codes. The main focus is the incorporation of the fission code GEF into TALYS. Andrea will present his thesis in the fall 2016.

Studies of independent fission yields from fast neutrons

- Ph.D. student: **Vasileios Rakopoulos**
- Main Dr. Mattias Lantz
- Assistant Prof. Stephan Pomp, Dr. Andreas Solders

Vasileios joined the division in spring 2012 to work on the AlFONS project together with Andrea Mattera. He has been involved in the tests of the ion guide and neutron field characterizations in Jyväskylä in 2015. Vasileios works in parallel with Andrea Mattera. His focus is comparison of experimental data with theoretical calculations using the TALYS and GEF codes. At present, Vasileios is analysing experimental data on isomeric yield ratios from proton induced fission on uranium and thorium. The data were taken in several experiments between 2010 and 2014. In one of the experiments there were also data taken through gamma spectroscopy, which will be compared with the data taken with the Penning trap.

Isomeric yield ratios can be used to extract spin states of the fission fragments before neutron emission. This information can, in turn, guide the development of fission models and in particular neutron emission. Vasileios will present his licentiate thesis in spring 2015, based on the work with isomeric yield ratios.

Unattended Gamma Emission Tomography for Partial-Defect Verification (UGET)

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

The International Atomic Energy Agency (IAEA) initiated a support programme project in 2012, which was executed during three years; 2013-2015. It comprised researchers from Sweden (UU) and the U.S. (PNNL, LLNL and LANL) as well as participants from Finland, EC, IAEA and SSM. The capabilities for Gamma Emission Tomography for unattended verification of nuclear fuel assemblies were evaluated, and a final report is currently under preparation. Funding was granted by SSM via the Swedish Support Programme to the IAEA.

Characterization of Spent Fuel in connection to Encapsulation and Final Reposition

- Responsible researcher: **Dr. Peter Jansson**

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

Multivariate analysis for use in nuclear safeguards

- Participating senior researchers: **Ass. Prof. Sophie Grape, Dr. Carl Hellesen**

This SSM-funded project is currently being defined and a postdoc will be hired during 2016. In this project, the possibilities to use multivariate analysis of the signals from different sets of nuclear measurement techniques will be explored, with the aim to enhance the analysis capabilities within nuclear safeguards.

Fission observables and particle emission

- Principal Investigator: **Dr. Ali Al-Adili**

Experimental efforts are put into understanding fission dynamics and correlations between the characteristics of fission fragments and neutron/gamma emission. The investigations of various fission reactions are in collaboration with the colleagues at the JRC-IRMM.

Previously the U-234(n,f) reaction has been studied as a function of incident neutron energy. Currently, a Frisch grid ionization chamber is used in conjunction with neutron detectors to measure the prompt fission neutron multiplicity and spectrum. The aim is to perform a systematic study of the changes in neutron emission as a function of fragment mass and excitation energy, in various fissioning systems. The impact of such study is eminent on fission modelling as well as for nuclear applications. A first feasibility test has been performed on U-235(n_{th},f).

These activities have been financially supported via the CHANDA scientist programme (total of 21 weeks of visits to IRMM).

Development of best estimate coupled codes with uncertainty assessment capabilities design for the safety analysis of LWRs

- Principal Investigator: **Dr. Augusto Hernandez Solis**

During 2015, the main task of this research focused in the development of generic best estimate codes, which are also able to perform uncertainty analysis on transient scenarios of coupled neutronic and thermal-hydraulic calculations of LWRs. For this purpose, the Total Monte Carlo (TMC) method was applied. The deterministic code, known as CORE SIM-TH, was developed as a joint collaboration between the reactor physics group at Chalmers University and the reactions group at Uppsala University. Thus, a scheme was developed to apply the TMC method and utilize both deterministic and Monte Carlo (MC) codes (such as SERPENT) for uncertainty analyses purposes, as depicted in the figure below.

Also, the TMC method was applied to academic neutron transport codes recently developed, such as the OpenMOC case. This code utilizes state-of-the art numerical methods to solve the multi-group neutron flux at any domain within a fuel assembly, or at the core level. The main idea of this project is to develop tools that even tough are based on best estimate methods, could be easy to use and understood by students while teaching the TMC method at university courses.

The work has been was presented at international conferences during 2015. Also a research report was written.

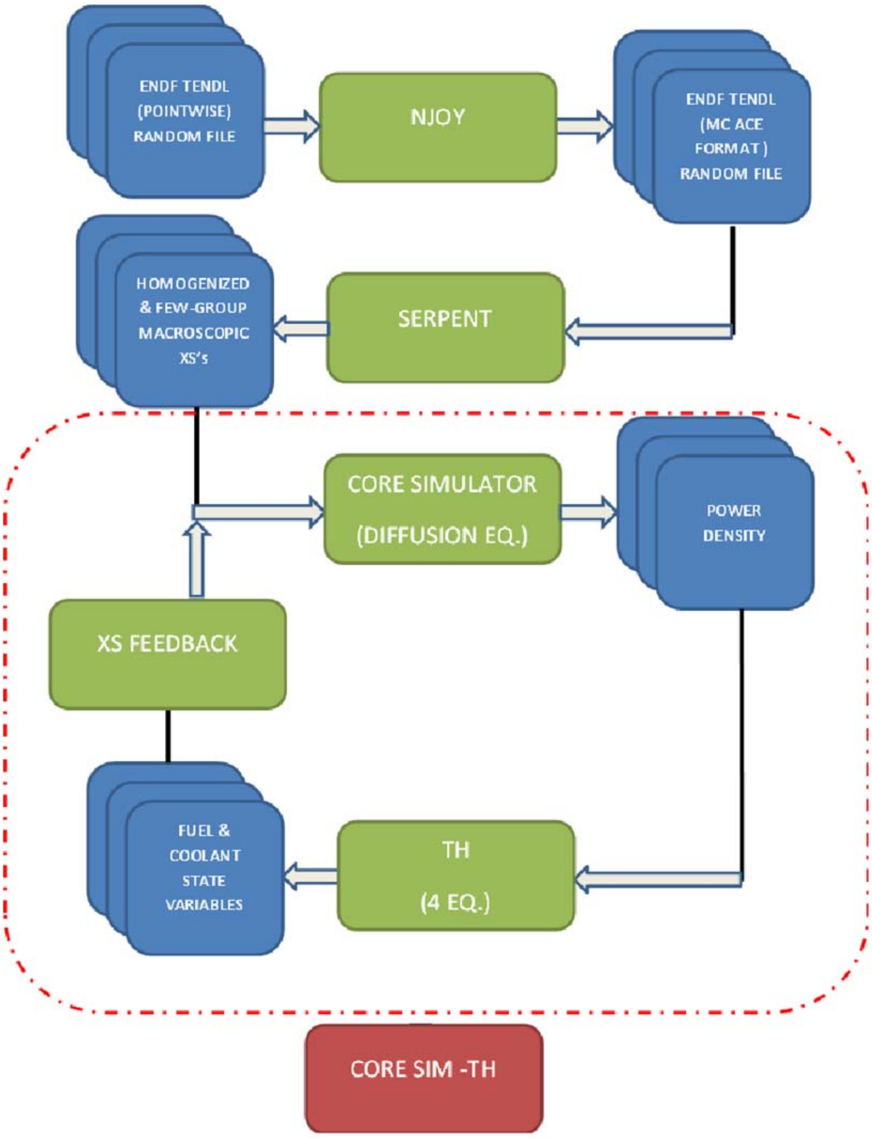


Figure 1. Scheme to apply the Total Monte Carlo (TMC) method and utilize both deterministic and MC codes (such as SERPENT) for uncertainty analyses purposes.

Research projects with relevance to SKC, outside present scope

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

Instrumentation and safeguards evaluations of a Generation IV reprocessing facility

- **Ph.D. student: Matilda Åberg Lindell**
- Main Dr. Sophie Grape
- Assistant supervisors: Prof. Ane Håkansson, Dr. Peter Andersson

Matilda is working with nuclear safeguards issues related to the future Generation IV nuclear fuel cycle. Her focus was during the first years to investigate methodologies for detecting diversion of sensitive material. After the licentiate thesis, the purpose was to continue with multivariate data analysis in order to identify misuse and diversion of sensitive material from the recycling facility associated with a Generation IV nuclear reactor. Matilda has been on sick leave for the majority of 2015 and the project has for that reason been idle.

Core Diagnostics in the ASTRID Sodium Fast Reactor (CODIAS)

- **Ph.D. student: Vasudha Verma**
- Main Dr. Carl Hellesen
- Assistant supervisors: Ass.Prof. Staffan Jacobsson Svärd, Prof. Ane Håkansson, Dr. Peter Jansson, Ass. Prof. Michael Österlund

Vasudha is working on developing an advanced neutron monitoring system for Generation IV sodium cooled fast reactors (SFR). The first part of her Ph.D. project has been focused on investigating how a neutron profile monitor can be used to detect anomalies in the reactor operation as early as possible. The profile monitor consists of an array of ex-core fission chambers located in the radial neutron shield.

The project is also includes investigations of the possibility to install self-powered neutron detectors (SPND) inside the core of an SFR. SPNDs have been used extensively in light water reactors. This is however the first time their use is investigated for SFRs.

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

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

This VR-funded project is currently being defined and a postdoc will be hired during 2016 to work in collaboration with French CEA for a period of 2 years.

Research on Gen IV systems

- Responsible researchers: **Dr. Carl Hellesen** and **Dr. Staffan Qvist**

The project is focused on the transient safety of Sodium cooled Fast Reactors (SFR) in severe accidents. A part of the project studies the behaviour of different types of SFR cores under such accident scenarios. The goal is to optimize the core design. The second part of the project is focused on further improving the safety of SFR cores using a novel safety system called ARC. The goal here is to demonstrate that an SFR equipped with the ARC system can survive even the most severe types of accidents.

MAssive Computational methodology for Reactor Operation – MACRO

- Ph.D. student: **Erwin Alhassan**
- Main Univ. lekt. Henrik Sjöstrand.
- Assistant supervisors: Univ. lekt. Michael Österlund, Prof. Stephan Pomp, Dr. Dimitri Rochman (PSI, Switzerland).

Erwin started his Ph.D. studies in 2011. He has been 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_{eff} due to nuclear data for Pu-238, 239, 240, while for the lead coolant, the uncertainty in the keff 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_{eff} came from uncertainties in the resonance parameters for Pb-208.

During 2015 an accept/reject method and a method of assigning file weights based on the likelihood function has been developed for uncertainty reduction using criticality benchmark experiments within the TMC method. From the results obtained, it was observed that by including criticality benchmark experiment information significant reductions in nuclear data uncertainty in the k_{eff} was achieved for Pu-239 and Pb -208 respectively for the studied ELECTRA case.

During 2015, Erwin has also developed a method for selecting benchmark for code validation for specific reactor applications. The method was applied to the ELECTRA reactor. And finally, during the year, he has developed a method for combining differential experiments and integral benchmark data for nuclear data adjustments and applied for the adjustment of neutron induced 208Pb nuclear data in the fast energy region.

These results were presented in his Ph.D. thesis which he defended in December 2015.

Publications and conferences

Work published/accepted in scientific journals

The following scientific papers were published or scheduled for publication during 2015:

S. Jacobsson Svärd, S. Holcombe, S. Grape, "Applicability of a set of tomographic reconstruction algorithms for quantitative SPECT on irradiated nuclear fuel assemblies", *Nuclear Instruments and Methods in Physics Research Section A*, **783**, pp. 128-141 (2015).

T. Martinik, V. Henzl, S. Grape, S. Jacobsson Svärd, P. Jansson, M. T. Swinhoe, S. J. Tobin, "Simulation of differential die-away instrument's response to asymmetrically burned spent nuclear fuel", *Nuclear Instruments and Methods in Physics Research Section A*, **788**, pp. 79-85 (2015).

P. Andersson, T. Bjelkenstedt, E. Andersson Sundén, H. Sjöstrand, S. Jacobsson Svärd, "Neutron Tomography Using Mobile Neutron Generators for Assessment of Void Distributions in Thermal Hydraulic Test Loops", *Physics Procedia*, **69**, pp. 202-209 (2015).

S. Holcombe, S. Jacobsson Svärd, L. Hallstadius, "A Novel gamma emission tomography instrument for enhanced fuel characterization capabilities within the OECD Halden Reactor Project", *Annals of Nuclear Energy*, **85**, pp. 837-845 (2015).

P. Wolniewicz, A. Håkansson and P. Jansson, "Detection of coolant void in lead-cooled fast reactors", *Annals of Nuclear Energy*, **85**, pp. 1096-1103 (2015).

S. Qvist, "Reactivity Swing as a function of Burnup for Uranium-Fuelled Fast Reactors", *Nuclear Technology*, **190** (1), pp. 11-27, (2015)

S. Qvist, "Optimization method for the design of hexagonal fuel assemblies", *Annals of Nuclear Energy*, **75**, pp. 498-506 (2015).

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", *PLOS One*, **10** (5), e0124074 (2015).

S. Qvist, B. W. Brook, "Environmental and health impacts of a policy to phase out nuclear power in Sweden", *Energy Policy*, **84** (1), pp. 1-10 (2015).

E. Suvdantsetseg, S. Qvist and E. Greenspan, "Preliminary transient analysis of the Autonomous Reactivity Control system for fast reactors", *Annals of Nuclear Energy*, **77**, pp. 47-64 (2015).

S. Qvist, E. Greenspan, "Design and performance of 2D and 3D-shuffled breed-and-burn cores", *Annals of Nuclear Energy*, **85**, pp. 93-114 (2015).

S. Qvist, E. Greenspan, "Design space analysis for breed-and-burn reactor cores", Scheduled for publication in *Nuclear Science and Engineering*, **183** (2016).

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Gorelov D, Eronen T, Hakala J, Jokinen A, Kankainen A, Kolhinen V, et al. Erratum to : "Measuring independent yields of fission products using a penning trap". Bulletin of the Russian Academy of Sciences: Physics. 2015;79(10):1315-1315.

Helgesson P, Sjöstrand H, Koning A, Rochman D, Alhassan E, Pomp S. Incorporating Experimental Information in the Total Monte Carlo Methodology Using File Weights. Nuclear Data Sheets. 2015;123(SI):214-219.

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Jansson K, Gustavsson C, Al-Adili A, Hjalmarsson A, Andersson Sundén E, Prokofiev A V, et al. Designing an upgrade of the Medley setup for light-ion production and fission cross-section measurements. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 2015;794:141-150.

Michel R, Hansmann D, Neumann S, Glasser W, Schuhmacher H, Dangendorf V, et al. Excitation functions for the production of radionuclides by neutron-induced reactions on C, O, Mg, Al, Si, Fe, Co, Ni, Cu, Ag, Te, Pb, and U up to 180 MeV. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms. 2015;343:30-43.

Paradela C, Calviani M, Tarrío D, Leal-Cidoncha E, Leong L S, Tassan-Got L, et al. High-accuracy determination of the 238U/235U fission cross section ratio up to ~1 GeV at n_TOF at CERN. Physical Review C. Nuclear Physics. 2015;91:024602-.

Pomp S, Al-Adili A, Alhassan E, Gustavsson C, Helgesson P, Hellesen C, et al. Experiments and Theoretical Data for Studying the Impact of Fission Yield Uncertainties on the Nuclear Fuel Cycle with TALYS/GEF and the Total Monte Carlo Method. Special Issue on International Workshop on Nuclear Data Covariances April 28 - May 1, 2014, Santa Fe, New Mexico, USA. Nuclear Data Sheets. 2015;123(SI):220-224.

Papers submitted during 2015:

E. Branger, S. Grape, S. Jacobsson Svärd, E. L. Wernersson, "Studies of Cherenkov light production for verification of irradiated nuclear fuel assemblies in wet storage", Submitted to *Annals of Nuclear Energy*.

T. Martinik, V. Henzl, S. Grape, P. Jansson, "Design of a Prototype Differential Die-Away Instrument proposed for Swedish Spent Nuclear Fuel Characterization", Submitted to *Nuclear Instruments and Methods in Physics Research Section A*.

Alhassan E, Sjöstrand H, Helgesson P, Österlund M, Pomp S, Arjan J K, et al. Selecting benchmarks for reactor simulations: an application to a Lead Fast Reactor. Annals of Nuclear Energy. 2015.

Planned publications

"Validating nuclear fission codes with integral nuclear observables", nuclear data sheets.

Conference contributions

C. Jammes, P. Filliatre, et. al. (incl. V. Verma, C. Hellesen and S. Jacobsson Svärd), "Progress in the development of the neutron flux monitoring system of the French GEN-IV SFR: simulations and experimental validations", 4th International Conference on Advances in Nuclear Instrumentation Measurement Methods and their Applications (ANIMMA), Lisbon, Portugal, April 20-24, 2015.

E. Branger, S. Grape, P. Jansson, S. Jacobsson Svärd, "Improving the prediction model for Cherenkov light generation by irradiated nuclear fuel assemblies in wet storage for enhanced partial-defect verification capability", 37th Annual Symposium on Safeguards and Nuclear Materials Management (ESARDA), Manchester, UK, May 18-21, 2015.

T. Martinik, V. Henzl, S. Grape, P. Jansson, M.T. Swinhoe, A.V. Goodsell M.T. Swinhoe, A.V. Goodsell, S. Grape, S. Jacobsson Svärd, P. Jansson and S. J. Tobin, "Development of Differential Die-Away Instrument for Characterization of Swedish Spent Nuclear Fuel", 37th Annual Symposium on Safeguards and Nuclear Materials Management (ESARDA), Manchester, UK, May 18-21, 2015.

A. Davour, S. Jacobsson Svärd and S. Grape, "Image analysis methods for partial defect detection using tomographic images on nuclear fuel assemblies", 37th Annual Symposium on Safeguards and Nuclear Materials Management (ESARDA), Manchester, UK, May 18-21, 2015.

S. Jacobsson Svärd, P. Andersson, A. Davour, S. Grape, S. Holcombe and P. Jansson, "Tomographic determination of spent fuel assembly pin-wise burnup and cooling time for detection of anomalies", 37th Annual Symposium on Safeguards and Nuclear Materials Management (ESARDA), Manchester, UK, May 18-21, 2015.

T.A. White, S. Jacobsson Svärd, L.E. Smith, V. Mozin, P. Jansson, A. Davour, S. Grape, H. Trellue, N.l Deshmukh, R.S. Wittman, T. Honkamaa, S. Vaccaro and J. Ely, "Passive Tomography for Spent Fuel Verification: Analysis Framework and Instrument Design Study", 37th Annual Symposium on Safeguards and Nuclear Materials Management (ESARDA), Manchester, UK, May 18-21, 2015.

S. Grape, K. Persson, E. Andersson Sundén, "Building a Strategy for ESARDA - Education, Training and Knowledge Management", 37th Annual Symposium on Safeguards and Nuclear Materials Management (ESARDA), Manchester, UK, May 18-21, 2015.

K. Ianakiev et.al. (incl. P. Jansson), "Underwater Testing of Detectors and Electronics Hardware for Spent Fuel Measurements", 37th Annual Symposium on Safeguards and Nuclear Materials Management (ESARDA), Manchester, UK, May 18-21, 2015.

P. Jansson, P. Andersson, T. White and V. Mozin, "Monte Carlo simulations of a Universal Gamma-Ray Emission Tomography Device", 37th Annual Symposium on Safeguards and Nuclear Materials Management (ESARDA), Manchester, UK, May 18-21, 2015.

T. Martinik, S. Grape, P. Jansson and V. Henzl, "Development of Differential Die-Away Instrument for Characterization of Swedish Spent Nuclear Fuel", 37th Annual Symposium on Safeguards and Nuclear Materials Management (ESARDA), Manchester, UK, May 18-21, 2015.

V. Duc, A. Favalli, B. Grogan, and P. Jansson, ”Determination of Initial Enrichment, Burnup, and Cooling Time of Pressurized-Water-Reactor Spent Fuel Assemblies by Analysis of Passive Gamma Spectra Measured at the CLAB Interim Fuel Storage Facility in Sweden”, Institute of Nuclear Materials Management (INMM) 56th annual meeting, Indian Wells, California, USA, July 12-16, 2015.

S. Grape, S. Jacobsson Svärd, P. Jansson, M. Österlund, “Students’ Approaches to Learning from Other Students’ Oral Presentations”, 5:e Utvecklingskonferensen för Sveriges Ingenjörsutbildningar, Uppsala, Sweden, November 18-19, 2015.

P. Jansson, M. Österlund, S. Jacobsson Svärd and S. Grape, “A platform for feed-forward and follow-up of students' progression in oral presentation within a study programme, 5:e Utvecklingskonferensen för Sveriges Ingenjörsutbildningar, Uppsala, Sweden, November 18-19, 2015.

Al-Adili A, Alhassan E, Gustavsson C, Helgesson P, Jansson K, Koning A, et al. Fission Activities of the Nuclear Reactions Group in Uppsala. In: Scientific Workshop on Nuclear Fission Dynamics and the Emission of Prompt Neutrons and Gamma Rays, THEORY-3: . Scientific Workshop on Nuclear Fission Dynamics and the Emission of Prompt Neutrons and Gamma Rays, THEORY-3. 2015. 64p. 145-149.

Alhassan E, Sjöstrand H, Rochman D, Helgesson P, J. Koning A, Österlund M, et al. REDUCING A PRIORI 239Pu NUCLEAR DATA UNCERTAINTY IN THE keff USING A SET OF CRITICALITY BENCHMARKS WITH DIFFERENT NUCLEAR DATA LIBRARIES. In: : . The 17th meeting on Reactor Physics in the Nordic Countries Chalmers University of Technology, Gothenburg, Sweden, May 11-12, 2015. 2015.

Helgesson P, Sjöstrand H, J. Koning A, Rochman D. New 59Ni data including uncertainties and consequences for gas production in steel in LWR spectraNew 59Ni data including uncertainties and consequences for gas production in steel in LWR spectra. In: : . WONDER2015. 2015.

Helgesson P, Sjöstrand H, J. Koning A, Rochman D, Alhassan E, Pomp S. TOWARDS TRANSPARENT, REPRODUCIBLE AND JUSTIFIED NUCLEAR DATA UNCERTAINTY PROPAGATION FOR LWR APPLICATIONS. In: : . The 17th meeting on Reactor Physics in the Nordic Countries Chalmers University of Technology, Gothenburg, Sweden, May 11-12, 2015. 2015.

Hernandez Solis A. On the importance of the spatial dependence of gap properties in the design of modern fast reactor cores. In: : . 17th meeting on Reactor Physics in the Nordic Countries. 2015.

Hernandez Solis A. Development of an in-house coupled neutronic and thermal-hydraulic code for the steady-state analysis of LWRs. In: : . 17th meeting on Reactor Physics in the Nordic Countries. 2015.

Hernandez Solis A, Sjostrand H, Alhassan E, Helgesson P. DRAG-MOC: A tool for the study of uncertainty analysis through OpenMOC. In: : . WONDER 2015. 2015.

Hernandez Solis A, Sjostrand H, Alhassan E, Helgesson P. DRAG-MOC: A tool for the study of uncertainty analysis through the deterministic OpenMOC transport code. In Reactor physics meeting PHYSOR 2016. 2016.(accepted for presentation 2016)

Hong Q, Platt S, Prokofiev A V, Passoth E. Detailed Geant4 simulations of the ANITA and ANITA-CUP neutron facilities. In: : . 15th European Conference on Radiation and Its Effects on Components and Systems (RADECS), Moscow, Sept. 14-18, 2015. 2015.

Lantz M, Al-Adili A, Gorelov D, Kolhinen V S, Mattera A, Penttilä H, Pomp S, et al.Fission yield measurements at IGISOL, CNR*15 - 5th International Workshop on Compound-Nuclear Reactions and Related Topics, Tokyo, 19-23 October 2015.

Sjöstrand H, Helgesson P, Alhassan E, Pomp S. NUCLEAR DATA UNCERTAINTY QUANTIFICATION FOR THE NUCLEAR FUEL CYCLE USING THE TMC METHOD. In: : . The 17th meeting on Reactor Physics in the Nordic Countries Chalmers University of Technology, Gothenburg, Sweden, May 11-12, 2015. 2015.

Other conferences, reports and books

V. Fedchenko (editor), "The new nuclear forensics: Analysis of nuclear materials for security purposes" Great Britain: Oxford University Press (2015)

The book includes two chapters written by Sophie Grape: "*Gamma spectroscopy as a tool of non-destructive nuclear forensic analysis*" and "*Basic facts and definitions related to measurement*".

Pomp S, Lantz M, Solders A, Mattera A, Rakopoulos V, Al-Adili A, et al. Accurate FissiOn data for Nuclear Safety (AlFONS) : Final Report. 2015. TK Report, 2015/01.

INDC(NDS)-0691 Distr. AC/AD/FE/G/J/PR/RD , Summary Report of the Second Research Coordination Meeting of the IAEA CRP no. F44003 Primary Radiation Damage Cross Sections IAEA Headquarters, Vienna, Austria 29 June - 2 July 2015 (co-authored).

Hernandez Solis A, THE TOTAL MONTE CARLO (TMC) METHOD APPLIED TO THE IN-HOUSE COUPLED CORE SIMULATOR CORE SIM – TH FOR THE UNCERTAINTY ANALYSIS OF THE NOVEL RBWR, Internal report.

Networking and collaborations

Research collaboration

- 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, PSI
- Thailand: Chiang Mai University
- Kenya: University of Nairobi
- USA: LANL, UCB, LBNL, LLNL, PNNL, ANL, ORNL
- Norway: OECD Halden Reactor Project and IFE, Technical University in Trondheim
- IAEA
- The World Nuclear University
- EU: CHANDA (35 partners)
- RADSAGA network project with about 25 participating organizations from academy and industry
- Nordic Academy for Nuclear Safety and Security, NANSS
- National and international Gen IV efforts (GENIUS and ASTRID)
- ENEN (European Nuclear Education Network): Via the ANNETTE project on the development of training for professionals in the nuclear business for an "Advanced Master" degree, UU has strengthened the collaboration with about 25 European organizations active in this project.
- ESARDA (European Safeguards Research and Development Association): UU is very active in this Europe-wide research association; Sophie Grape is chairing the ESARDA working group of Training and Knowledge Management, with Karin Persson as an additional group member, while Peter Jansson is co-chairing the ESARDA working group on Non-Destructive Assay, with Staffan Jacobsson Svärd as an additional group member.
- SKB, LANL: Research regarding nuclear fuel characterisation related to the back-end of the nuclear fuel cycle has been performed in close collaboration between Uppsala University, SKB AB and Los Alamos National Laboratory.
- Lead of MÅBiL project with participants from UU, KTH and Chalmers

Outreach

General

- Sophie Grape is a member of Kärnavfallsrådet.
- Papers on energy policy, published by Staffan Qvist and claiming that nuclear power is an important contributor to solve the climate issue, gained large interest from media, such as:
  - Interview on BBC in December
  - Debate in Dagens Nyheter (see e.g. James Hansen's article "Straffskatt på klimatvänlig kärnkraft är en förfärlig idé", referring to Qvist).
  - Attention in international media, e.g. in Forbes, Discovery Channel, ZMESience, RealClearScience and Reddit.
  - Invitation to a workshop on energy supply in Sweden at Chalmers/Göteborgs Universitet
- We had a visit from the French ambassador on November 2nd, covering current research projects in collaboration with French researchers.
- On November 4th, we arranged a thematic evening for students within the Physics Programme at UU on tomographic methods used in support of the nuclear industry.
- Nine meetings with policy makers and the non-nuclear industry.
- February 18: Young Generation.

Mass media

- February 12, debate article Uppsala Nya Tidning.
- February 24, Second Opinion.
- April 23, Expressen
- November 18, Ny Teknik
- December 7, Forskning.se: ”Älskade, hatade kärnkraft – finns du kvar 2050?

Popular science

- March 19-21, SciFest 2015
- March 23, Skolbesök
- November 4 ,”Tema Ljus” for Bachelors students
- November 13, Sveriges Kärntekniska Sällskap, study visit to Uppsala
- November 28, ”Ljusdagen”, Gustavianum, Uppsala

Other meetings / seminars

- April 22, SKGS seminar about Energikommissionen
- September 3, Radioecology meeting Sweden-Japan, Stockholms universitet
- September 18,seminar by Energikommissionens
- September 25 Radiophysics / radiobiology / radioecology-meeting at SSM
- October 6, seminar by Energikommissionen
- October 27, visit by six physics teachers from Borlänge interested of Gen IV.
- October 28, study visit in the radioekologylab, University of Tokyo, Japan
- November 3, seminar by Kärnavfallsrådets
- November 19-20, SSM:s forskningsdagar
- November 24, attending a panel debate at the Svenskt Näringsliv + WNA seminarium: ”Nuclear Energy in a Global Perspective”

Recruitment

September 23, ”Jobba med kärnkraft” visited Uppsala

Additional information and commitments during 2015

- NESSA - A neutron facility at Uppsala University. Applied Nuclear Physics plan to purchase a high-intensity neutron generator has commenced during 2015. The neutron generator will be situated in the FREIA hall of the Ångström laboratory and is tentatively called NESSA, NEutron Source in UppSAla. NESSA is planned to be used both as a part of research and education as well as an irradiation facility. NESSA can be used for both detector development and material studies. The division is currently investigating the possibilities for co-funding of NESSA with different partners.

- Together with World Nuclear University, we arranged Summer Institute 2015 in Uppsala.

Visions and Plans

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

Among the plans for the research on experimental techniques used for the characterization of nuclear fuel and its performance during normal and accidental conditions, one can mention that a request has been sent to SSM for UU to become a so-called “academic member” of OECD-Halden Reactor Project. This would facilitate the availability of OECD-HRP data to the UU research and enable postdocs and Ph.D. students to become secondees within the Swedish HRP membership, provided that this is supported by the Swedish HRP member organizations. In the longer term, we want to establish stronger collaborations and networking between academic and industrial organizations that are active within the research on fuel and reactor safety, nationally as well as internationally. We foresee that a national collaboration may attract funding from authorities as well as industry and optimize the research performed by the actors within this field. The long-term visions are to bring forward accident-tolerant fuels and demonstrate and evaluate their performance under normal and accidental conditions.

Nuclear data underpin all of Nuclear Science and Technology and the division conducts extensive research in the field of nuclear data. The aim of the research is to provide the whole core physical knowledge for different applications adequately. Hence, we improve microscope measurement of nuclear observables at a several state of the art European nuclear facilities, contribute to the development of model codes for calculations of nuclear reactions, and develop methods for propagation of uncertainties, from the microscopic to the macroscopic scale. To have a combined knowledge of measurements, modelling and application simulations is a unique competence of the division and something we intend to continue to build on. This allows us to addresses both new and more mature fields within the nuclear community, e.g. radiation damage modelling in MåBiL, transient analysis of LWRs, and fuel cycle calculations.

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

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

Appendix 4 - MÅBiL Annual Report 2015

Summary

MÅBiL is an initiative to perform research on Materials, Ageing management and advanced Fuel at all three participating academia: Chalmers University of Technology,
KTH Royal Institute of Technology and Uppsala University. The aim is to to find a long sought research collaboration on the national level and to address research fields of particular interest for the nuclear industry. The main topics include:

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.

This annual report from the MÅBiL consortium shows that the somewhat faltering beginning of MÅBiL now has turned into a vivid research activity where all initially proposed projects progress very well and in some cases even lay ahead schedule. Due to this fact there are ideas to adjust the plans for at least one project during 2016, which will be addressed in discussions with the SKC.

I feel confident that 2016 will be a successful year for MÅBiL and in particular we can anticipate a number of scientific articles submitted for publication during the year.

Ane Håkansson,
Uppsala University, Applied Nuclear Physics

Research in brief

Ageing of Reactor Pressure Vessel Steel Welds

- **Research leader: Mattias Thuvander, Division of Materials Microstructure, Department of Physics, Chalmers**
- **Ph.D.-student: Kristina Lindgren**
- **Participants: Krystyna Stiller (Chalmers) and Pål Efsing (KTH)**

Finances

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

Project activities

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

The project started in July 2014 and during 2014 un-irradiated reference materials were studied. Early in 2015 irradiated samples were received from VTT, Finland, where mechanical testing has been undertaken. The samples had been irradiated in the Halden reactor to levels corresponding to operation for about 20, 28 and 63 years, respectively. These samples are identical to the RPV welds of R4. The samples were in the shape of 0.3x0.3x15 mm3, intended for making APT samples by electropolishing. However, the activity was regarded to be too high for this procedure, and instead an approach had to be chosen. Hereby a small piece (0.3x0.3x1 mm3) was cut from the original samples, and samples for APT have been produced using a focused ion beam (FIB) lift-out technique. This approach has the advantage of minimizing radiation and also that a large number of APT analyses can be made.

During 2015 a large number (to get good statistics) of APT analyses of the sample series from Halden, together with one surveillance sample, have been made and a fairly good understanding of the evolution of the particles has emerged, including the evolution of number density, size distribution and chemical composition. Experiments to study annealing of the samples, in order to restore the ductility, have also been started. In addition to the irradiated samples, analyses have also been made on welds from a pressurizer (exchanged at Ringhals after ca. 28 years of operation), to try and understand the reason for their embrittlement. In this case the ageing is purely thermal, but it is clear that nano-sized precipitates form at these relatively low temperatures (345°C), also without irradiation, after long enough time. The precipitates are mainly found along dislocations, which also contain segregated Mo. Samples from the pressurizer have also been sent to Manchester University for TEM studies.

<u>Plans</u>

The APT investigations of the Halden samples are finished, and next the results will be compiled and two journal papers are to be written. We will also compare the microstructural results with the mechanical properties measured by VTT, and hopefully the results can be modeled (cooperation with Pär Olsson/KTH will be sought). We also need to decide how the results from the pressurizers will be used. During 2016, the annealing experiments, including annealing, hardness measurements and APT analyses, will be finished.

Later on, materials retrieved from Barsebäck RPV will be analyzed. Cooperation with the ICEWATER project is anticipated. Probably APT analysis will be used to ascertain that the irradiation has affected the microstructure.

Milestones

M18: Investigation of Halden samples
M23: Submit paper to Microscopy&Microanalysis, Participate at APT&M
M24: Investigation of annealing of Halden samples
M26: Investigation of pressurizer samples
M28: Licentiate thesis
M35: Modelling of precipitate evolution
M40: Investigation of ICEWATER samples
M45: Investigation of Barsebäck samples
M54: Ph.D. thesis

Publications

So far, no publications have been finalized. The following two papers, with tentative titles, journals and authors, are planned for the first half of 2016.

1. Evaluation methods for characterization of nano-sized precipitates in irradiated reactor pressure vessel steel welds, K. Lindgren, P. Efsing, K. Stiller and M. Thuvander, Microscopy and Microanalysis.

2. Evolution of irradiation induced precipitates in reactor pressure vessel steel welds, K. Lindgren, P. Efsing, K. Stiller and M. Thuvander, Journal of Materials Science.

Total Monte Carlo (TMC) method applied to neutronics

- **Research leader: Henrik Sjöstrand, Division of Applied Nuclear Physics, Department of Physics and Astronomy, Uppsala University**
- **Ph.D.-student: Petter Helgesson**
- **Participants: Andreas Mattera, Augusto Hernadez Soilis, Erwin Alhassan**

Finances

The funds from SKC have been used for covering 80% of the cost of the Ph.D. student. The funds have been spent in accordance with budget.

Project activities

During 2015, there has been an increased emphasis on aging parameters, and in this work, Petter Helgesson connects macroscopic fuel and aging parameters to the fundamental nuclear physics processes by using the nuclear model code TALYS and the Total Monte Carlo Method (TMC) method.

During 2015 Petter has investigated ^{59}Ni, since the two-step thermal neutron reaction sequence ^{58}Ni(n,γ) ^{59}Ni(n,α) ^{56}Fe, (Q_value = 5,1 MeV) results in non-linear He production rates and is an important contribution to the He production in steel in thermal spectrum. The reaction sequence is also a significant contribution to the damage energy. He is also investigating the hydrogen producing reaction sequence: ^{58}Ni(n,γ) ^{59}Ni(n,p) ^{59}Co, (Q_value = 1.9 MeV). Currently, existing evaluated data has no uncertainty information, neither for ^{59}Ni(n,α) 56Fe nor ^{59}Ni(n,p)^{58}Co reactions, in the thermal region.

To improve the He production prediction and to provide nuclear data uncertainty estimates, new ^{59}Ni cross section data has been produced. As opposed to existing evaluated data (for nuclides in general) the helium and hydrogen production cross sections have been produced using relevant resonance parameters using R-matrix theory with the Reich-Moore approximation.

A re-evaluation of the thermal cross sections including experimental correlations has also been performed during 2015. The lack of well-documented measurements on the cross sections in the resonance region makes the actual values of the resonance parameters very uncertain. The cross-sections are generated from average unresolved resonance parameters and sampled with a high uncertainty, after which they are adjusted to the experimentally known thermal cross sections and their uncertainties. The cross-sections will soon be published in ENDF-6 format, including so-called random files, for usage by the nuclear community.

The new development of ^{59}Ni cross-sections also address some critical issues when it comes to the processing of the data and a contact with A. Kahler (who develops NJOY) has been established.

To check the performance of the random files they have been tested on an MCNP-6 model. The results were compared to He and H production rates in a reference case. It was found that the inclusion of ^{59}Ni increased the helium production rate by a factor of 4.9 +/- 0.8. The uncertainty is due to the uncertainty in nuclear data. It was also found that there were some discrepancies between the results obtained with these new files and the result which was obtained using ENDF/B- VII.1.

During 2015, Petter has also continued to work on statistical stringent ways to include experimental information in TMC using file weights from automatically generated experimental covariance matrices. The methods developed were tested on both uranium and plutonium fuels as well as on the famous Jezebel benchmark and the Ringhals shielding assemblies.

The work has been presented at IAEA coordinated research project (CRP) on “Primary Radiation Damage Cross Sections”, in scientific journals and at various international conferences during 2015. In October 2015, the work was also presented in Petters licentiate thesis.

Augusto Hernandez has developed a tool that allows for calculation of uncertainty in important fuel parameters during transients. This was also listed in the general goals of the TMC-fuel project.

New methods to couple TALYS and GEF have been developed. This will allow to improved fission gas production data and other fission observables.

An article describing how to integrate integral experiments has been submitted and accepted in Progress of Nuclear Energy.

Plans

As mention in the sections above, there has been a focus on the He production during 2015. This was envisaged for 2016. Methods for including integral benchmarks have been developed however not been applied on structural relevant materials so far. Methods have already been developed and tested for transient analysis. Fission gas production under burn-up and some SiC calculations are yet to be completed. As general comment, the project is processing very well; however, there has been some restructuring in the time table between 2015 and 2016.

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

Lic. Thesis

Helgesson P. Experimental data and Total Monte Carlo : Towards justified, transparent and complete nuclear data uncertainties. [Thesis]. Uppsala universitet; 2015.

Publications

Publications (submitted, accepted and published during 2015):

Journal articles

1. Alhassan E, Sjöstrand H, Helgesson P, Österlund M, Pomp S, Arjan J K, et al. On the use of integral experiments for uncertainty reduction of reactor macroscopic parameters within the TMC methodology. Progress of nuclear energy. 2016;88:43-52.
2. Helgesson P, Sjöstrand H, J. Koning A, Rydén J, Rochman D, Alhassan E, et al. Sampling of systematic errors to estimate likelihood weights in nuclear data uncertainty propagation. Elsevier; Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 2016;807:137-149.
3. Helgesson P, Sjöstrand H, Koning A, Rochman D, Alhassan E, Pomp S. Incorporating Experimental Information in the Total Monte Carlo Methodology Using File Weights. Nuclear Data Sheets. 2015;123(SI):214-219.
4. Pomp S, Al-Adili A, Alhassan E, Gustavsson C, Helgesson P, Hellesen C, et al. Experiments and Theoretical Data for Studying the Impact of Fission Yield Uncertainties on the Nuclear Fuel Cycle with TALYS/GEF and the Total Monte Carlo Method. Special Issue on International Workshop on Nuclear Data Covariances April 28 - May 1, 2014, Santa Fe, New Mexico, USA. Nuclear Data Sheets. 2015;123(SI):220-224.

Conference contributions

1. Al-Adili A, Alhassan E, Gustavsson C, Helgesson P, Jansson K, Koning A, et al. Fission Activities of the Nuclear Reactions Group in Uppsala. In: Scientific Workshop on Nuclear Fission Dynamics and the Emission of Prompt Neutrons and Gamma Rays, THEORY-3: . Scientific Workshop on

Nuclear Fission Dynamics and the Emission of Prompt Neutrons and Gamma Rays, THEORY-3. 2015. 64p. 145-149.

2. Alhassan E, Sjöstrand H, Rochman D, Helgesson P, J. Koning A, Österlund M, et al. REDUCING A PRIORI 239Pu NUCLEAR DATA UNCERTAINTY IN THE keff USING A SET OF CRITICALITY BENCHMARKS WITH DIFFERENT NUCLEAR DATA LIBRARIES. In: : . The 17th meeting on Reactor Physics in the Nordic Countries Chalmers University of Technology, Gothenburg, Sweden, May 11-12, 2015. 2015.
3. Hernandez Solis A, Sjostrand H, Alhassan E, Helgesson P. DRAG-MOC: A tool for the study of uncertainty analysis through the deterministic OpenMOC transport code. In: Reactor physics meeting PHYSOR 2016. 2016. (accepted ORAL)
4. Helgesson P, Sjöstrand H, J. Koning A, Rochman D. New 59Ni data including uncertainties and consequences for gas production in steel in LWR spectraNew 59Ni data including uncertainties and consequences for gas production in steel in LWR spectra. In: : . WONDER2015. 2015.
5. Helgesson P, Sjöstrand H, J. Koning A, Rochman D, Alhassan E, Pomp S. TOWARDS TRANSPARENT, REPRODUCIBLE AND JUSTIFIED NUCLEAR DATA UNCERTAINTY PROPAGATION FOR LWR APPLICATIONS In: : . The 17th meeting on Reactor Physics in the Nordic Countries Chalmers University of Technology, Gothenburg, Sweden, May 11-12, 2015. 2015.
6. Hernandez Solis A. Development of an in-house coupled neutronic and thermal-hydraulic code for the steady-state analysis of LWRs. In: : . 17th meeting on Reactor Physics in the Nordic Countries. 2015.
7. Hernandez Solis A, Sjostrand H, Alhassan E, Helgesson P. DRAG-MOC: A tool for the study of uncertainty analysis through OpenMOC. In: : . WONDER 2015. 2015.
8. Sjöstrand H, Helgesson P, Alhassan E, Pomp S. NUCLEAR DATA UNCERTAINTY QUANTIFICATION FOR THE NUCLEAR FUEL CYCLE USING THE TMC METHODIn: : . The 17th meeting on Reactor Physics in the Nordic Countries Chalmers University of Technology, Gothenburg, Sweden, May 11-12, 2015. 2015.

Other scientific publications

1. INDC(NDS)-0691 Distr. AC/AD/FE/G/J/PR/RD
2. Summary Report of the Second Research Coordination Meeting of the IAEA CRP no. F44003 Primary Radiation Damage Cross Sections IAEA Headquarters, Vienna, Austria 29 June - 2 July 2015 (co-authored)
3. Hernandez Solis A, THE TOTAL MONTE CARLO (TMC) METHOD APPLIED TO THE IN-HOUSE COUPLED CORE SIMULATOR CORE SIM – TH FOR THE UNCERTAINTY ANALYSIS OF THE NOVEL RBWR, Internal report

Planned publications 2016:

1. PROPAGATION OF NEUTRON-REACTION COVARIANCE DATA THROUGH MULTI-PHYSICS MODELS OF NOVEL LIGHT WATER REACTORS, Nuclear data sheets
2. Including experimental information in TMC using file weights from automatically generated experimental covariance matrices, Progress of Nuclear Energy
3. THE IMPACT OF THE RETROACTIVE METHOD FOR RESONANCE PARAMETER UNCERTAINTIES, IN PARTICULAR FOR HELIUM PRODUCTION DUE TO NI-59 IN STAINLESS STEEL, Nuclear data sheets

Irradiation assisted stress corrosion cracking

- **Research leader: Pär Olsson and Mats Jonsson, Reactor Physics and Nuclear Chemistry, KTH**
- **Ph.D.-student: Elin Toijer**
- **Participants: Pål Efsing, KTH**

Finances

Since Elin was hired in April 2015 we have not used all the funds awarded for that year, but only 75%.

Planerade publikationer:

Ab initio study of phosphorous segregation to grain boundaries in fcc metals and alloys, Planned for Phys. Rev. B.

Project activities

Elin is working at Reactor Physics with modelling of grain boundaries in order to produce a model for grain boundary decohesion due to radiation accelerated diffusion. She is presently focusing on perfect grain boundaries in model metals and is adding in phosphorous impurities.

At Nuclear Chemistry Elin has performed reactivity experiments on austenitic steels. She is making good progress and has developed her knowledge and skills in the relevant chemistry that she didn't have with her in her diploma.

She has finished several courses relevant for her thesis work and is following the individual study plan.

The project is progressing according to plan.

Plans

Elin continues working at both fronts and we have had constructive discussions with Solid Mechanics about how her studies can be used, additionally, as important parameters for the crack initiation model developed there by Michal Sedlak. During 2016 we will intensify the collaboration between the three departments.

Publications

Planned: Ab initio study of phosphorous segregation to grain boundaries in fcc metals and alloys, Planned for Phys. Rev. B

Theoretical and Experimental Studies of Uranium Nitrides

- **Research leader: Christian Ekberg and Teodora Retegan, Nuclear Chemistry, Chalmers**
- **Ph.D.-student: Aneta Sajdova**

Finances

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

Project activities

Introduction

This project, started at Chalmers in February 2015, with the aim to study the degradation process of uranium nitride fuel under the condition of Light Water Reactor (high temperature and high pressure) and then use this knowledge for manufacturing low solubility fuels. The main task consists of the two parts (a., b.), whereby the initial research was focused on the pure uranium nitride (UN) production by sol gel method.

a. UN hydrolysis studies
b. Investigating the possible dopants (e.g. Th, Ti, anticorrosion elements) in order to increase the UN insolubility in hot water

A literature review was carried-out in June 2015 and the first series of experiments were performed between February and September 2015 and presented at SKC symposium in October 2015. The experimental work for 2015 is concluded within this report.

Background

Uranium nitride is one of several fuel types suggested for use mainly in "Generation four nuclear reactors" but also in the current Light Water Reactors (LWRs). The motivation is foremost based on its high melting point, high thermal conductivity and high fissile atom density. On the downside, uranium nitride is incompatible with water – it hydrolyses, dissolves and undergoes a mechanical erosion ted in hot water. The hydrolysis process of pure UN is not yet well understood and thus various parameters are being studied, e.g. the initial temperature and pressure of the reaction, the structure of reaction products and the effect of fuel characteristics (composition, density and porosity etc.) on the reaction mechanism and kinetics. An experimental setup for dissolution studies on both pure UN (reference) and doped UN was designed with attempt to simulate real temperature (280 °C) and pressure (70 atm) conditions in the Boiling Water Reactor (BWR) core.

Experimental results and discussion

The experimental work so far was directed to developing the method for pure UN production based on sol gel. The process follows three steps:

1. Uranyl Nitrate Hexahydrate (UNH) production (from uranium metal)
2. Uranium oxide formation by internal sol-gel technique
3. Uranium oxide reduction to uranium nitride by carbothermal reduction

Ad. 1

Uranyl Nitrate Hexahydrate was produced by immersing the uranium metal in concentrated (68 wt%) nitric acid occasionally bubbled with oxygen. Self-grown crystals of UNH were then formed and collected. To enhance the effectivity of and to consume the waste some modifications were tried (heat controlled evaporation of mother liquor, lower concentration of nitric acid, no bubbling with oxygen). The crystals formed in each modified process were collected with intention to analytical proof of the same constitution (hexahydrate). Powder X-ray diffractometry (available at the department) was not suitable for the measurement, therefore a single crystal X-ray crystallography was chosen as a proper method. Several crystal samples are planned to be send for analytical testing to University of St Andrews.

Ad. 2

The internal sol-gel technique followed by carbothermal reduction was chosen for the preparation of uranium nitride. The composition of product (air dried microspheres) is assumed to be hydrated uranium trioxide ($UO_2(OH)_2$ or 2 UO_3 . 2 H_2O or $2UO_3$. NH_3 . 3 H_2O (Vaidya 2008)). The original internal sol-gel technique was designed to utilize the two different uranium sources (in order to obtain Acid Deficient Uranyl Nitrate solution and therefore utilize less gelating agents). The technique was then adjusted to allow working with one single uranium source only (a metal rod). This simplification offers the possibility of direct connection to the recyclation of used nuclear fuel, since the recyclation product is formed as metal nitrate and can be subsequently processed in the internal sol-gel step to form nuclear fuel again. For the carbothermal reduction - carbon is needed to reduce the metal oxide into metal nitride. Therefore “uranium + carbon microspheres” with even distribution of uranium and carbon (confirmed by SEM with EDS) were prepared by internal sol-gel. A water insoluble form of carbon was used in the process – carbon nano powder and thus a surfactant must have been added to enhance the solubility and homogeneity of formed suspension. To avoid impractical working with a suspension an alternative method to be tried in the future could on the contrary utilize a water soluble form of carbon (e.g. sugars, polyacrylonitrile), where a necessary adjustment of gelating chemicals concentration is expected.

Ad. 3

Carbothermal reduction was firstly performed in the Thermal Technology LLCTM Graphite heater furnace (up to 2500 °C) and secondly in the tube furnace (up to 1500 °C) as it was believed in significant undesired carbon contribution from the graphite heater as this had previously been observed at KTH. Nevertheless, this assumption was later refuted since no considerable difference in carbon content was measured by SEM EDS on the surface versus on inside of the beads. Carbothermal reduction was performed on the samples with various Carbon/Uranium (C/U) molar ratio. It was assumed to observe a clear trend in the final carbon content of products for different initial carbon content in the products formed under the same conditions (temperature, heating rate, reaction time and atmosphere). According to the reactions below the stoichiometric C/U ratio is 2.5. The samples with stoichiometric amount of carbon were prepared together with other samples containing either under- or over-stoichiometric amount of carbon (C/U = 2.25 or 2.75).

$UO_3 + 0{,}5\ C \rightarrow UO_2 + 0.5\ CO_2$ (g) (S.K. MUKERJEE 1990)

$UO_2 + 2\ C$ (s) $+ 0.5\ N_2 \rightarrow UN + 2\ CO$ (g) (S.K. Mukerjee 1991)

The elected reaction conditions are listed in Table 1. Molybdenum crucible was used when worked with the graphite furnace. The heating rate in the graphite furnace was set as follows: 15 °/min from room to 200 °C; 2 °/min from 200-500°C; 10 °/min from 500-1450 °C. The slow rate of 2 °C/min was to protect the spheres from being cracked or burst for the maximal amount of gaseous CO is formed between 200 and 500 °C (Beatty 1976). The cooling rate of 15 °/min was applied from 1450 °C to ambient temperature. Argon and nitrogen inlet overpressure was 1 Bar and gas flow 0.1 L/min was constant during the reaction. An alumina boat was used as a sample holder in the tube furnace. This furnace was heated with the constant rate of 10 °/min and cooled with the rate of 10 – 15 °/min. Argon and nitrogen inlet overpressure was around several thousand Pa, gas flow 0.5 L/min was steady during the reaction. During experiment no.7 it was planned to use N_2+5%H_2 mixture as the reaction gas but in reality argon was set by mistake. In experiments no. 4 and 6 vacuum was applied during heating up to 1450 °C to enhance releasing the gaseous products.

All the products were analysed by XRD (in the box with low oxygen atmosphere), SEM with EDS and some of them with elemental analyser (total oxygen and nitrogen content). The results are listed in Table 2. A UC molar fraction, wt% of carbon and a lattice parameter were calculated by Vegard´s law. A designation “up” in experiment no. 12 refers to the upper part of the pellet, “down” refers to the down part of the pellet as it was placed on the tungsten plate in the furnace during the sintering.

The best result (experiment no. 12, pellet down side) was obtained with six times higher carbon content 0.595 wt% compared to the maximal allowed amount - the pure UN contains 5,56 wt% nitrogen with allowed carbon content 0.099 wt% (0.001 g carbon per 1 g uranium) and lattice parameter 4.880 Å. The certain variances can be seen from the data in Table 2 e.g. experiment no. 12 the different composition of the upper and down part of the pellet (experiment 12). The upper side of pellet seemed to be affected by the significant carbon contribution from the graphite heater since debris were formed that fell onto the pellet surface. This could have been caused by a large break in the graphite heater which was later found.

Table 1: carbothermal reduction experimental conditions

experiment	*initial molar ratio carbon/uranium*	*heating; cooling; reaction*	*reaction time [hr]*	*reaction temperature [°C]*	*furnace type*
1	2,75	Ar; Ar; N_2	6	1450	graphite
2	2,75	Ar; Ar; N_2	6	1450	graphite
3	2,75	Ar; Ar; N_2	6	1450	graphite
4	2,75	vacuum; Ar; N_2 and N_2+5%H_2	0,5 + 4,75 + 0,5	1450	graphite
5	2,5	Ar; Ar; N_2	6	1450	graphite
6	2.5	vacuum; Ar; N_2	0,5 + 5,5	1450	graphite
7	*2,25*	*Ar then N_2+5%H_2; Ar; Ar*	*6*	*1450*	*graphite*
8	2,25	Ar; Ar; N_2	6	1500	tube
9	2,25	Ar; Ar; N_2	10	1500	tube
10	2,5	Ar; Ar; N_2	6	1500	tube
11	2,5	Ar; Ar; N_2	10	1500	tube
12 (pellet)	2,75 (up)	Ar; Ar; N_2	6	1800 (sintering)	graphite
	2,75 (down)	Ar; Ar; N_2			

No clear trend in the carbon content in products was tracked. However, the conclusion was drawn: the higher the temperature the less carbon in the product (1450 °C versus 1800 °C) or for lower temperatures the longer the reaction time the lower carbon content (experiments 8 - 9 and 10 - 11). The chosen temperature 1450 °C seems to be too law and it is believed to gain purer nitride (0.335 wt% carbon) with increased temperature 1800 °C (Hunt, Silva et al. 2014).

The data on elemental analysis for experiments 1-3 are not in good agreement with the theoretical values - too much nitrogen was measured. No reasonable explanation besides inaccurate calibration of the instrument was found.

Table 2: the analytical data on carbothermal reduction products

experiment	***UC** fraction [mol%]*	*wt% carbon*	*estimated composition*	*lattice parameter **a** [Å] (XRD, fcc)*	***oxygen** [wt%]*	***nitrogen** [wt%]*	*furnace type*
1	15,2	0,725	$UN_{0,848}C_{0,152}$	4,892 ± 0,001	0,701 ± 0,007	5,607 ± 0,02	graphite
2	16,5	0,794	$UN_{0,835}C_{0,165}$	4,893 ± 0,001			graphite
3	18,4	0,886	$UN_{0,816}C_{0,184}$	4,895 ± 0,002			graphite
4	54,7	2,688	$UN_{45,3}C_{54,7}$	4,924 ± 0,013	not measured	not measured	graphite
5	17,7	0,852	$UN_{82,3}C_{17,7}$	4,894 ± 0,003	not measured	not measured	graphite
6	83	4,146	$UN_{17}C_{83}$	4,946 ± 0,040	not measured	not measured	graphite
7	*70 + UC_2*	*3,471*	*$UN_{0,30}C_{0,70}$ + UC_2*	*4,936 ± 0,001*	*not measured*	*not measured*	*graphite*
8	15,7	0,755	$UN_{0,843}C_{0,157}$	4,893 ± 0,002	0,763 ± 0,019	4,847 ± 0,035	tube
9	14,3	0,687	$UN_{0,857}C_{0,143}$	4,891 ± 0,002	not measured	not measured	tube
10	17,2	0,828	$UN_{0,828}C_{0,172}$	4,894 ± 0,002	0,645 ± 0,032	4,922 ± 0,202	tube
11	14,4	0,692	$UN_{0,856}C_{0,144}$	4,892 ± 0,001	not measured	not measured	tube
12 (pellet)	21,8	1,052	$UN_{0,782}C_{0,218}$	4,897 ± 0,004	not measured	not measured	graphite

Hydrolysis experiments set-up

The hydrolysis of UN most likely follows the reaction below (G.A. Rama Rao 1991):

$2\ UN\ (s) + 4\ H_2o\ (g, l) \rightarrow 2\ UO_2\ (s) + 2\ NH_3\ (g, l) + H_2\ (g)$

$3\ UN\ (s) + 2\ H_2O\ (g, l) \rightarrow UO_2\ (s) + U_2N_3\ (s) + 2\ H_2\ (g)$

Therefore these suggestions for product detection were done:

• NH_3 (g) trapped in H_2SO_4 as $(NH_4)2SO_4$, titration with NaOH (Na_2SO_4 + NH_3. H_2O, increase in pH) or by MS

• NH_3 (l) pH electrode submerged in liquid phase in situ

• H_2 (g) by MS

• *solid residue* U_2N_3 by TGA (burn in the air to U_3O_8) or gravimetry, or elemental analysis

• *solid residue* UO_2 by TGA (burn in the air to U_3O_8) or gravimetry, or elemental analysis

An instrument for hydrolysis experiments a "dissolver" was designed (figure 1). The sample will be put into the reactor vessel (PARR autoclave, 100 ml) which will then be filled with water, sealed, de-aired by argon and pressurized by heating up to 70 atm (cca 280 °C). The sample will be placed and fixed in either of the two positions, a bottom one for aqueous phase reaction an upper one for the reaction with steam. The sampling (gaseous samples) could be done by argon overpressure.

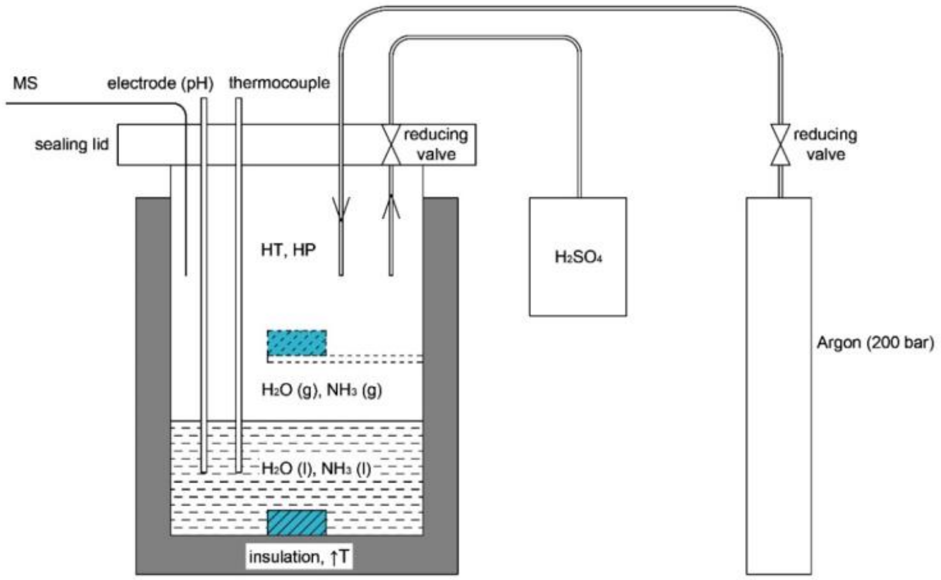

Figure 1: simplified dissolver design of the static model

The limitation presented here is the little volume of reactor vessel. Thus the only feed water (and later steam) for the reaction must be brought into the system before the reaction starts. That restricts the possible amount of samples to be analysed during the reaction.

Therefore a dynamic variant (figure 2) with the reactor vessel volume 2 L was purposed, where the circulating water/steam loop was suggested as constant feed for the reaction and for the sampling purposes. However no technicians were found so far to carry out such instrument installation.

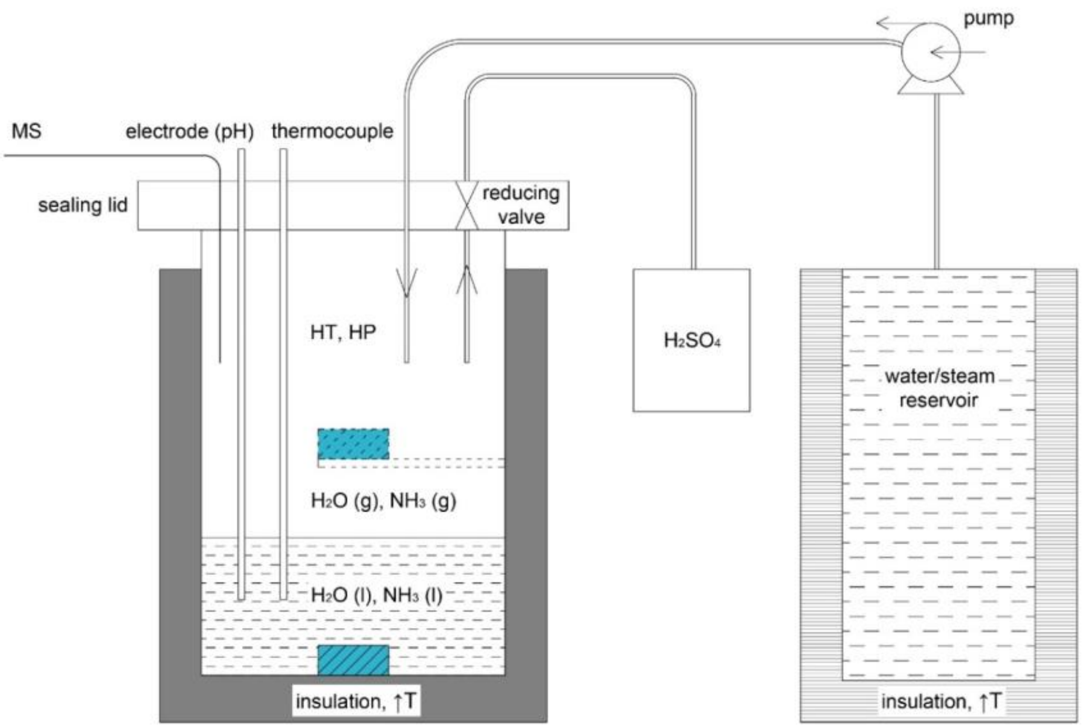

Figure 2: simplified dissolver design of the dynamic model

Plans

Current method

Whereas no pure uranium nitride was produced so far by the chosen sol gel technique, some additional modifications must be done. A production of pure UN by carbothermal reduction from powder UO_2 + carbon was tried (this process for plutonium led to promising results) leading to sesquinitride formation instead of mononitride. Therefore, the decomposition of sesquinitride into mononitride and nitrogen by heat will be tried as a second step. To modify sol gel, a dissolvable form of carbon can be utilized to yield more homogenous beads (some carbon spots were found on inside the beads after carbothermal reduction). Also a higher temperature and/or hydrogen presence during the thermal treatment could be examined, even though the undesired sintering on the beads surface will most likely occur due to higher temperature.

Another approach

Since it seems hard to minimize the final carbon content only by adjusting the initial amount of carbon, other method could be tested using less carbon plus another reductant – metals (Th, Ti, Mg or some of the anti-corrosion elements i.e. chromium, Ni, Nb) The idea behind is to already produce a doped material for solubility test studies (where the metals would be in form of oxides and uranium in form of nitride). Either uranium dioxide powder will serve as starting material or hydrated uranium trioxide in the form of beads produced by sol gel (followed with grinding and blending with metal). In case of successful pure UN production from UO2 powder, the blending of uranium dioxide powder with metal dopants will be tried which could subsequently lead to overall nitride formation for both uranium and the added metal.

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Nuclear Fuel Diagnostics

- **Research leader: Dr. Peter Andersson (postdoc), Division of Applied Nuclear Physics, Department of Physics and Astronomy, Uppsala University**
- **Participants: Staffan Jacobsson Svärd, Division of Applied Nuclear Physics, Department of Physics and Astronomy, Uppsala University and Scott Holcombe OECD Halden Reactor Project, Norway**

Finances

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

By the end of 2015, 42% of the total SKC project grants had been used. This is well in agreement with the fraction of time spent within the project so far, which is 46%. At present, Peter Andersson is on 80% parental leave, and thus there will be a prolongation of the project with a time corresponding to the parental leave. Accordingly, the use of the project funding will continue several months into 2017, depending on the level of Peter's parental leave during 2016.

Project activities

Background

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

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

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

Project description and status

The *MÅBIL* sub-programme *Fuel diagnostics* started in February 2015 with the assignment of Peter Andersson on a postdoc position which is 50% funded by SKC. In the first year, the focus has been on non-destructive measurements of irradiated nuclear fuel using gamma spectroscopy and gamma tomography. An important part of this work has been the development and evaluation of qualitative and quantitative reconstruction methods for emission tomography of nuclear fuel.

The recently installed custom-made tomography instrument for irradiated nuclear fuel at the Halden reactor (HRP) has been characterized and new applications are continuously being explored. The instrument has exquisite spectroscopic capabilities, thanks to the use of a HPGe detector, and gives unique opportunities to quantify the amount and the spatial distribution of numerous gamma-emitting fission, activation and decay products in irradiated nuclear fuel bundles. During the first year of the project, the tomography instrument has been used in experimental research on several world-leading applications, such as;

- Validation of power and burnup profiles calculated with a core simulator (here in terms of HELIOS calculations for a HRP-fuel rig);
- Evaluation of fission gas contents in rod plenums, used to derive fission gas release;
- Examination of the fuel relocation and packing density in a LOCA test rod.

Details such as a higher burnup on the outskirts of the fuel rig, rod internal burnup distribution and migration of cesium at high fuel temperatures can be deduced, as illustrated in Figure 1.

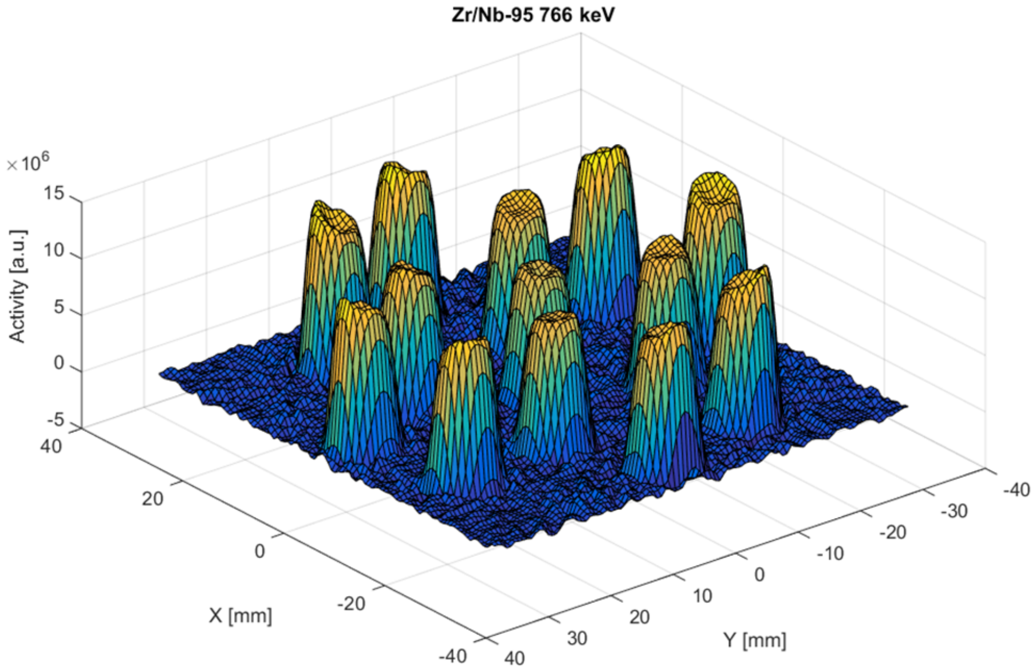

Figure 2. Example of tomographic reconstruction (Zr-96 inventory) in a 13 pin HRP driver fuel. Note the various features of the distribution that are visible, such as higher power (and therefore higher inventory) in periphery of the rods and towards the outside of the bundle.

In addition, recent studies have shown that the fragmentation and relocation of fuel in rods that have undergone a LOCA transient test can be mapped using tomography. In the LOCA tests performed at the HBWR, a single fuel rod is exposed to the conditions of a LOCA transient. It typically undergoes ballooning, fuel relocation, cladding burst and fuel fragment dispersion during this transient. These important features can be assessed non-destructively using the gamma tomography setup of OECD-HRP, which can give a detailed view of the nuclear fuel location and packing fraction inside the expanded cladding. The gamma emission tomography system is the only available technique that may provide these data on-site, prior to the transport of the test rig to external PIE facilities. One may note that such transport requires the fuel to be moved into a horizontal orientation, which may alter the fuel fragment distribution and deteriorate such assessment. The first experimental campaign using the tomography system for this purpose was started in the end of 2015 and it continues into 2016. The preliminary results are highly promising.

Fulfilling of projects goals

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

The results obtained so far show that these goals can be reached within the project. Firstly, measurements of fission gas release have been executed, and the data are currently undergoing analysis to evaluate the achievable precision in this type of assessment. Secondly, tomographic measurements have been performed of test rods subjected to LOCA in the HBWR, and preliminary results indicate that ballooning and failure of cladding as well as cracking and relocation of pellet material can be assessed with this technique. Scientific papers are currently under preparation, according to the list below. In the end, the experimental techniques developed within MÅBiL are expected to be highly useful in the analyses of irradiation tests of new fuel types such as ATF, once these are made available for this type of assessment.

Plans

Several other applications are considered, such as the measurement of Plutonium buildup and fission gas release. Additional applications for this new and unique data collection instruments are also explored.

Publications

The following manuscripts are currently being worked on:

1) P. Andersson, "The emission tomography reconstruction code UPPREC for detailed, quantitative reconstructions of irradiated nuclear fuel rods and assemblies"
2) P. Andersson; S. Holcombe, S. Jacobsson Svärd, "Demonstration of quantitative gamma emission tomography capabilities for measurements of nuclear fuel at HRP"
3) A. Davour, S. Jacobsson Svärd, P. Andersson, S. Grape, S. Holcombe, P. Jansson, M. Troeng "Applying image analysis techniques to tomographic images of irradiated nuclear fuel assemblies"
4) P. Andersson, S. Holcombe, T. Tverberg, "Inspection of a LOCA test rod at the Halden Reactor Project using gamma emission tomography"
5) S. Holcombe; S. Jacobsson Svärd; P. Andersson, "Gamma emission tomography for fission gas release quantification"

Amorphous metals for the nuclear industry

- **Research leader: Björgvin Hjörvarsson Division of Materials Physics, Department of Physics and Astronomy, Uppsala University**
- **Ph.D. student: Lena Thorsson**

Finances

The funds from SKC have been used for covering 100% of the cost of the Ph.D. student. The funds have been spent in accordance with budget.

Project activities

Background
One approach to increasing the accident tolerance of nuclear fuel rods is applying thin film coatings on zirconium based cladding materials, which could delay the well-known fatally exothermic H_2-producing reaction between Zr and hot steam. 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.

Ph.D. student Lena Thorsson started work in this project in July 2014. The initial literature survey was submitted to MÅBiL in December 2014. In summary, it was concluded that certain amorphous alloys have been demonstrated to maintain their properties up to a T_g of 1200-1450 °C. The glass transition temperature 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 $T_g = 0.67^* T_m$ 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.

Project progress
During 2015, thin film samples of two- and three-component alloys in the Mo-Zr-Si system have been created by combinatorial sputtering and thereafter evaluated. This Mo-based alloy system was selected due to the small neutron cross-section and high melting temperature of molybdenum. The manufacturing method results in thin film samples with continuous compositional gradient material. The samples have been evaluated as-manufactured using x-ray diffraction analysis (XRD) and more specifically using methods XRR (to analyse thickness and roughness of films) and GIXRD (to analyse the microstructure for crystallinity vs amorphicity). All samples have been manufactured and evaluated at room temperature conditions. The analyses results for 55 compositions are summarized in Figure 1 where amorphous microstructures are indicated with blue marks and crystalline with red marks. Hitherto, compositions with Mo-content ranging between approximately 40 and 80 at% appear amorphous.

<u>Plans</u>
To conclude the first test cycle of the study, the samples will be heat-treated at high temperatures and re-evaluated for amorphicity during Q1-Q2 2016. The aim of this testing is to find the transition temperatures T_x and T_g for these compositions, or, in other words, to investigate whether the amorphous properties of these compositions persevere at temperatures 1000-1700 °C. The temperature range is selected considering the intended application, which would require an amorphous coating to maintain its properties at temperatures as high as 1700 °C when the zirconium cladding softens. Additionally, method development of nanoindentation analyses of mechanical properties have been initiated and will be carried out if deemed fruitful. Table 1 summarizes these plans in terms of tasks and milestones for the period 2015-2016.

A subsequent second test cycle could be planned based on the results of the first test cycle. By exchanging or adding some elements to the alloy system, for example adding known glass forming elements or refractory elements to the Mo-Zr-Si alloys, high-temperature properties could be improved in an iterative process comprising sample manufacturing and evaluation. Hence, research would lead to increased understanding of amorphous alloys' high temperature properties but also form a knowledge base for further material development with the intended application in mind.

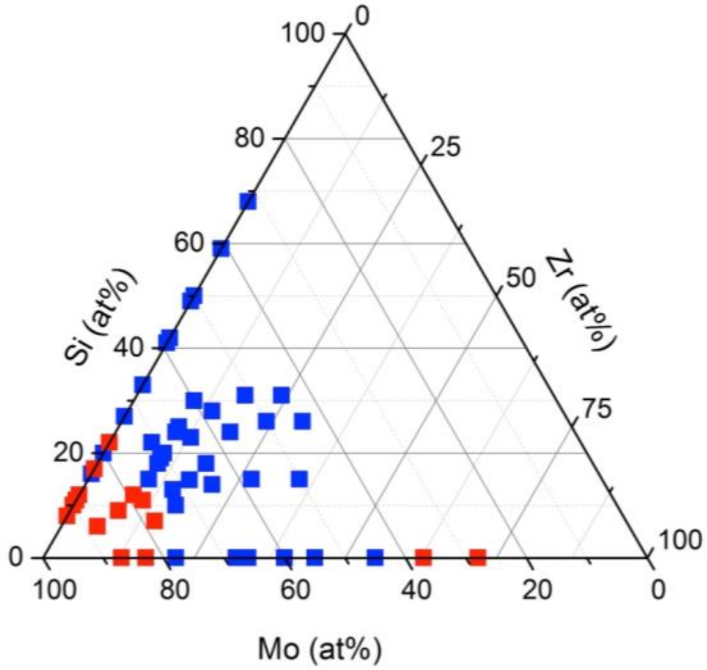

Figure 1. Amorphous (blue marks) and Crystalline (red) microstructures of 55 compositions of binary and ternary alloys in the Mo-Zr-Si system according to GIXRD analyses of thin film samples at room temperature.

Milestones

Table 1. Amorphous metals for the nuclear industry: milestones 2015-2016

Task	Milestone	Status
First cycle of sample manufacturing and evaluation of microstructures at room temperature conditions	Finding limits of amorphous compositional range at RT	Finalised and reported at SKC meeting Oct 2015
High-temp heat treatments and subsequent re-evaluation of microstructures	Finding T_x, Tg, and amorphous compositional range at HT	Started; involving a thesis worker
Nanoindentation measurements for mechanical properties	Results	Method development initiated
Publications	First publication	Final stages

ICEWATER

- **Research leader: Mattias Klintenberg, Division of Materials Theory, Department of Physics and Astronomy, Uppsala University**
- **Ph.D. student: Erki Metsanurk**
- **Participants: Pål Efsing, KTH**

Finances

The grant provides salary for one Ph.D. student.

Project activities

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

Construction
The target environment for IASCC tests will be flowing high-temperature water (320 °C). In order to achieve that the pressure inside the system needs to be at least 113 bar. We do this by pumping water using high-performance liquid chromatography pump capable of pressures up to 350 bar. The water flows through a small-diameter stainless steel coil which is placed inside a ceramic heater with maximum power of 550 W. The water is subsequently cooled down using tube-in-tube heat exchanger and finally passes through back-pressure regulator.

Controller
In order to monitor the pressure and temperatures of both hot and cooled water and control the HPLC pump, we built a custom controller. It has two inputs for K-type thermocouples and one 4-20 mA current loop receiver for the pressure transducer. There is a data port for communication with the pump which is done over CAN bus. The controller is connected to a PC for sending commands and logging data. A PID controller keeps the temperatures at desired levels.

Window tests
We selected two different types of materials for a window through which the proton beam will enter the test cell, 50µm 316L stainless steel and 75 µm Sandvik Hiflex.
To perform the burst tests in a safer manner we started instead with a thin copper foil.



Figure 1. (a) ICEWATER (b) Some window test results (c) Performing tests

Initially a Swagelok VCR fitting was used as a window holder, but the tests suggested that the smooth surfaces were allowing the window to slip resulting in wide variance for burst pressures. We fixed that by machining the fittings so that the grip was improved. By reducing the diameter down to 2 mm, both types of steels held up to pressures over 200 bars at room temperature.

BLEVE tests: BLEVE is an acronym for boiling liquid expanding vapour explosion. Those tests were conducted to determining the system's behaviour when the window bursts. When the super-heated water in the system is bought down to atmospheric pressure, there is a chance that a local over-pressure in the system can exceed the nominal pressure and be harmful to the equipment. We performed initial assessment of that at temperatures around 120 °C and burst pressures of 60 bar.

Plans

Continue improving the current system.
Perform irradiation tests to assess buildup and the magnitude of activity in the material.
Add capability to monitor (and possibly control) the water chemistry.
Design a loading mechanism for the sample.