# SKC Annual Report 2011

Swedish Centre for Nuclear Technology

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SKC 12-01

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## Summary of 2011

The success in 2009 with the GENIUS project, resulting in 36 MSEK until 2012, was followed up in 2010 with an even larger step forward for Swedish nuclear technology in the university sector. A contract on 11.3 MEUR has been signed on cooperation with France. This framework comprises work packages on access to training reactors in Saclay for Swedish students, transfer of nuclear physics experimental research equipment to the GANIL laboratory in Caen, as well as access for Swedish PhD students to the research centres in Cadarache and Marcoule. For the latter, the work will be focused on development of the Jules Horowitz Reactor, a new materials testing reactor presently being built, and to safety studies and fuel development related to the sodium-cooled fast reactor ASTRID, planned to go critical in 2022.

The year 2011 has to some extent been devoted to preparations for this large project. During the year, student groups from all the SKC universities have visited Saclay for experimental training. This is administrated by SKC, whereas the research part of the programme will be administered by the Swedish Research Council (Vetenskapsrådet). An announcement of research funding was issued during the autumn 2011, and the final distribution of funding is expected in late March 2012.

The nuclear education has grown steadily in Sweden during the recent years. 2011 has to some degree been a year of consolidation. The educational programs that have been initiated during the recent years have now found their forms and come into steady operation. One very positive sign of this consolidation is that several new positions for professors, lecturers and researchers have been filled. This has reduced the workload that often is very high in expansions at academia, due to the tedious process to recruit new staff.

The Fukushima event in March 2011 hampered the student recruitment, but it seems not to have lead to permanent damage of the situation in education and education in Sweden. For instance, the Masters' program at Chalmers still filled its seats, and very little hostility towards nuclear power has been detected in student contacts.

The Sigvard Eklund price to the best PhD thesis of the year was awarded to Chi Tranh Tran for his work on severe accidents. Martin Lundgren won the price for the best masters´ thesis for his work on irradiation effects on materials. Finally, Katja Göller was awarded the price in the new Bachelors' thesis class for work on oxide-film thickness measurements.

# Contents

# SKC-Partners, Tasks and Goals

*By Jan Blomgren,*
*Director of SKC*

SKC – Swedish Center for Nuclear Technology or Svenskt Kärntekniskt Centrum in Swedish – has been active since 1992 in providing support to education and research within the nuclear power area. From the first of January 2008 the SKC partners have entered a new six-year period of support to KTH, Chalmers and Uppsala University for senior positions at these universities and for research projects.

The partners are:

- Swedish Radiation Safety Authority (SSM, Strålsäkerhetsmyndigheten)
- Forsmark Kraftgrupp AB
- Ringhals AB
- OKG AB
- Westinghouse Electric Sweden AB

and the three universities:

- Kungliga Tekniska Högskolan (KTH)
- Chalmers Tekniska Högskola AB
- Uppsala Universitet

SKC is active within three research programs:

1) Nuclear Power Plant Technology and Safety
2) Reactor Physics and Nuclear Power Plant Thermal Hydraulics
3) Materials and Chemistry

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

Within the research programs the focus is on the areas of primary interest to the SKC partners, as shown in the following list:

- Thermal-Hydraulics
- Core Physics
- Core and Plant Dynamics
- Chemistry
- Material physics and engineering
- Safety & Severe Accidents
- Reactor Diagnostics
- Detectors and measurement
- Safeguards
- Fuel Technology

SKC shall provide long-term support to securing knowledge and competence development at an academic level for the Swedish nuclear technology programs. This shall be a basis for providing resources to the Swedish nuclear industry and its regulators. It means that SKC will contribute to a safe, effective and thus reliable nuclear energy production, which is an important part of the Swedish energy supply.

SKC has five top-level goals for reaching its vision:

1. Increase the interest among students to enter nuclear technology education.
2. Make sure that the needs of the SKC financing parties to recruit qualified personnel with a nuclear technology education are met. To meet this goal, the universities will offer relevant basic education, execute research projects and support continued education of engineers already active in the nuclear technology area.
3. Offer attractive education in the nuclear technology area.
4. Maintain strong and internationally acknowledged research groups within areas that are vital for and unique to the nuclear technology area.
5. 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.

Formally, SKC is organized as a center within the School of Sciences at KTH.

For further information see:
www.swedishnuclear.se

# SKC – consolidation for future growth

*A message from the director*

When looking back at 2011, it feels like much more time has passed, simply because the situation has been so volatile during the year.

The large collaboration program with France (11.3 M€) that was agreed upon in 2010 motivated marketing activities that were expected to be reduced in 2011, but the delay of the program in combination with the Fukushima accident necessitated some extra activities. Fortunately, we had already booked the release of our new information web site www.svenskkarnkraft.se and the magazine Atomen two days before Fukushima. That's timing!

I have spent quite some efforts on information meetings at universities, and it seems as the Fukushima event has not caused lasting damage. We saw indeed a drop in student turn-up in the autumn, but not very large. Moreover, part of it is likely due to other reasons.

Frankly, I am positively surprised that the public debate after Fukushima was far more balanced than I would have imagined beforehand. I think the SKC universities and SSM have made commendable efforts in this societal debate, and we owe them our gratitude for having met a demand from society at large in a very balanced way.

The staffing situation at the universities has improved during 2011. Some long-term vacancies have been filled at KTH, including the professorship in nuclear safety. All universities have recruited new staff, in particular on lecturer level. This will lead to a very welcome reduction in workload. All our universities have expanded in recent years, but due to the tedious recruitment processes, the funding and related work load arrives a year or two before new staff can take office. As a consequence, an expansion can be demanding for the staff.

The division for applied nuclear physics at Uppsala University has been top-ranked in the evaluation of the entire university, and nuclear power is now one of the profile areas of UU. The Chalmers president has initiated a new internal cross-disciplinary nuclear technology centre. Part of the reason is long-term collaboration problems, to a large extent connected to one professor. The new organization provides a better platform for the younger generation to work across disciplinary boundaries.

During the year, Lennart Billfalk (SKC board chairman) and myself has met representatives from the government to discuss possible expansions of nuclear power education and research. It seems as we are entering a situation with a clear separation between present-day reactor technology (i.e. LWRs) and future systems (GenIV). This is due to the agreement within the ruling coalition to allow nuclear new-build but accepting no subsidies to industry. Therefore, the government can finance GenIV research, because its industrial implementation is deemed so far into the future that it is not of direct interest to industry today. Moreover, this also has the consequence that industry is reluctant to finance GenIV research. It is generally seen as good for the industry because it raises the awareness of nuclear energy as a sustaining technology, and it makes students interested in nuclear power. If industry would support GenIV with large funding, however, it might be perceived as a business interest in GenIV, leading to demands that the government-funding of GenIV be classified as subsidies to industry. Therefore, we can see signs that the research landscape is being divided into present-day technology, with operating industry and SSM as important contributors, and future technology, where tax funding will be the major contributor.

Nevertheless, SKC can provide expertise and guidance in the process to establish GenIV research in Sweden. There is a political interest in a project that can put Sweden on the map. A small-scale lead-cooled fast reactor has been deemed to be the most interesting option.

Per Brunzell, former CEO of ABB Atom, has made a pre-study with a "devil's advocate" perspective, i.e., to identify potential show-stoppers. He concluded that technology was not the most likely stumble block, but legislation, licensing, finding a site, etc. This motivated a second investigation, coordinated by Margaretha Engström, Vattenfall R&D. The findings can be summarized as:

- Building such a reactor would be positive for competence build-up, but building a commercial reactor would be far more positive.
- There are severe difficulties due to legislation, non-proliferation aspects as well as lack of suitable sites that will take several years to solve before a research reactor can be built.
- For the proposed technology (fast-neutron lead-cooled reactor), the main obstacles are non-nuclear. Corrosion and pump technology are today the limiting factors.
- A non-nuclear mock-up, i.e., an electrically heated system without nuclear fuel, would be possible to build on relatively short notice, does not impose severe licensing obstacles and addresses the major problems involved.

To summarize, the recommendation was to go for a non-nuclear mock-up as a first stage, with the option to go nuclear in a later phase. This was reported to the department of education, which in turn launched an official investigation early 2012.

January 1, 2011, a 30 year moratorium on nuclear technology was terminated with the new law allowing new nuclear reactors to be built to replace the existing ones. During the year, many important steps have been taken towards realizing new-build, although most of these activities have not been reported in media. This concerns legislation, costs for applying, licensing procedures, etc. Early 2012, the CEOs of the two largest owners of nuclear power in Sweden, Öystein Löseth for Vattenfall and Ingemar Engkvist of E.On, both described in public the preparations of their respective companies for new-build, and the chairman of the Vattenfall board, Lars G Nordström, discussed the possibility to invite retirement funds as co-owners of future reactors.

Thus, nuclear new-build has gone from utopia to a generally considered option in just a few years. This means that SKC needs to stay alert for new opportunities due to new-build. In fact, SKC needs to be a few years ahead of the development in society, because we operate early in the competence chain. We need to inspire high-school students *now* for new-build projects starting at the end of the present decade. What is quite troublesome is the demography; the number of first-year students at universities will drop significantly during the coming five-year period, simply because rather few children were born in the 1990s. Activities to inspire a larger fraction of the young generation to pursue a career in science and technology are therefore a joint challenge for the coming years.

With 2011 in the mirror, I would like to conclude that nuclear power is today in a far better shape than could have been the case. It seems as Fukushima will not have consequences beyond repair in Sweden. In spite of this event, the discussion about a future for nuclear energy is vital. Three years ago I would have deemed the idea that Sweden should host a GenIV research facility to be moonshine; today I see it as a possibility. In parallel, the prospects of nuclear new-build in the Swedish industry are in progress. Expect some interesting years ahead!

Jan Blomgren

SKC director

# Organization and funding

*SKC financing organizations provide 17 million Swedish kronor annually to the universities.*

Svenskt Kärntekniskt Centrum – SKC – started a new organizational model January 1, 2008, which has been in operation since.

The funding organizations are:

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

Until 2007, SKC was to a large extent supporting individual PhD projects. Each project was approved or rejected by the board. This model was abandoned, and SKC has since 2008 distributed funding to the universities as a contribution to the total activity. The universities declare all their activities, irrespective of funding source, and the support from SKC is no longer targeting various individuals.

During 2009, various new steering routines were implemented, motivated by this change of organizational model. The board does no longer decide upon individual PhD projects, and therefore scientific representation is no longer required. Accordingly, the representation from the universities is now on a top-managerial level. A new activity council has been formed to advise the board in scientific matters, with an independent chairman, Per Brunzell, private consultant.

The contract states that the funding organizations shall contribute 17 million SEK annually to senior positions at the universities and to research activities. About half the support is provided as a guaranteed base funding, and the rest is possible to re-distribute between the universities.

An advisory council has been formed in which discussions on strategy and funding take place. The members have been selected to cover the most important areas of nuclear technology, and a relatively even representation of the funding organizations has been strived for. The delegates do, however, not represent their organizations in the council. The council provides advice to the board, but takes no decisions.

The advisory council has consisted of:

- Per Brunzell, chairman
- Farid Alavyoon, Forsmarks Kraftgrupp AB
- Henrik Dubik, OKG AB
- Björn Forssgren, Ringhals AB
- Ninos Garis, SSM
- Ingemar Jansson, Westinghouse
- Karl-Henrik Weddig, Ringhals AB

In addition, Jan Blomgren has attended the meetings as secretary.

The SKC Board has consisted of:

- Lennart Billfalk, Chairman, Vattenfall
- Lars Berglund, Forsmarks Kraftgrupp AB
- Magnus Antonsson, OKG AB
- Lennart Eckegren, Ringhals AB
- Gustaf Löwenhielm, SSM
- Stig Andersson, Westinghouse
- Gustav Amberg, KTH
- Irene Kolare, Uppsala University
- Per Jacobsson, Chalmers

In addition, Jan Blomgren has attended the board meetings but has no vote.

# SKC financials in 2011

The following table summarises the SKC financials for 2011

| | | |
|---|---|---|
| Received from financing parties | | 17 000 000 SEK |
| Saved from previous years | | -2 133 361 SEK |
| French laboratory support + other income | | 2 306 338 SEK |
| KTH | 6 700 000 SEK | |
| Chalmers | 5 300 000 SEK | |
| Uppsala University | 3 000 000 SEK | |
| SKC centrally | 3 447 246 SEK | |
| Balance at year's end | | -2 588 269 SEK |

The contributions from the financing organizations are split as follows:

| | |
|---|---|
| SKI/SSM | 33% |
| Westinghouse | 20% |
| Ringhals | 19% |
| Forsmark | 14% |
| OKG | 14% |

Comment: The negative balance at the end of the fiscal year is due to a large marketing campaign motivated by the upcoming collaboration with France. It will be paid off during the remaining SKC contract period, to balance at the end of 2013.

# Winners of the Sigvard Eklund Price in 2011

Chi Thanh Tran, KTH, was awarded the prize for the best PhD thesis, which has the title "The Effective Convectivity Model for Simulation and Analysis of Melt Pool Heat Transfer in a Light Water Reactor Pressure Vessel Lower Head". His work is characterized by the review committee:

"This highly relevant dissertation is the result of an in-depth study into the heat transfer mechanism of a melt pool in the lower head of a BWR. The nuclear accident in Fukushima has shown how important and relevant the topic is.

The application of the various methods (analytical, CFD-ILES, ECM and PECM) to real scenarios shows the usability of the methods. Validation shows that these methods reproduce the important physical parameters surprisingly well and that they can be used to accurately predict several important outcomes, like the thermal load to the reactor vessel.

The author shows a good understanding of the complex phenomena occurring in accident scenarios, and is able to make judgments about the importance of the various processes in a melt pool. The candidate has reported his work and results in various papers, which together make a very nice piece of work."

*Chi Thanh Tran.*

Martin Lundgren, Chalmers Institute of Technology, was awarded the prize for the best Masters' thesis, which has the title "Analysis of predictive models for correlation of irradiation effects on pressure vessel steels". His work is characterized by the review committee:

"Martin Lundgren has studied the embrittlement of reactor pressure vessels due to neutron irradiation. The material embrittlement, given by the change in ductile to brittle transition temperature, is evaluated with data and different predictive models for Analysis of predictive models for correlation of irradiation effects on pressure vessel steels

Martin Lundgren has studied the embrittlement of reactor pressure vessels due to neutron irradiation. The material embrittlement, given by the change in ductile to brittle transition temperature, is evaluated with data and different predictive models for the PWRs at the Ringhals nuclear power plant. The thesis is well written and the topic is important in the context lifetime for nuclear power plants, and thus of significant interest to industry and society.the PWRs at the Ringhals nuclear power plant. The thesis is well written and the topic is important in the context lifetime for nuclear power plants, and thus of significant interest to industry and society".

*Martin Lundgren.*

*Katja Göller.*

Katja Göller, Uppsala university, was awarded the prize for the best Bachelors' thesis, which has the title "Spectroscopic ellipsometry study on the oxide films formed on nickel-base alloys in simulated boiling water reactor environments. Determination of oxide film thickness." Her work is characterized by the review committee:

"The diploma work describes a new method, spectroscopic ellipsometry, used to determine the thickness of oxide films formed on nickel-based alloys in simulated BWR environments. The work is based on a scientific ground and the academic quality is high with respect to results, analysis and interpretations with error estimations and suggestions on further work to improve the method".

# Chalmers University of Technology

*Overview of Activities in 2011*

Research and education in nuclear engineering is mainly pursued at the Departments of Nuclear Engineering (Applied Physics) and Nuclear Chemistry (Chemical and Biological Engineering) in Chalmers. The nuclear education is given jointly by the two groups.

A main activity of the last few years is the international master's course in Nuclear Engineering, which is based on a contract between E.ON and Chalmers, and financially supported by SKC.

## Nuclear Engineering

### Research in:

- reactor physics, dynamics and noise diagnostics; deterministic and stochastic transport; nuclear safeguards; random aspects of advanced reactors;
- coupled core physics – thermal-hydraulics: method development, application to safety analysis of power uprates; full static and dynamic modeling of all Swedish reactor units; competence centre for SSM; BWR instability research;
- nuclear measurement methods for material science, positron annihilation techniques;
- thorium fuel cycle; Gen-IV reactors, in particular molten salt reactors;
- fusion plasma physics, with a special focus on fast particles and impurity transport in magnetically confined plasmas.

### Facilities, tools and other data:

- Access to all major system codes for neutronic and thermal-hydraulic calculations.
- A pulsed beam for variable energy slow positrons.
- A portable 14 MeV pulsed neutron generator.
- 8 PhD students (4 with SKC support, 1 jointly with Nucl. Chemistry). 2 PhD exam and 2 licentiate exams during 2011.

### Highlights of the year:

Two new promotions to professors: Prof. Christhophe Demazière and Adj. Prof. Henrik Nylén (Ringhals AB).
Dr. Richard Sanchez was selected by Chalmers as one of three visiting Anniversary Professors in 2012.
Tünde Fülöp was elected to be one of 22 founding members of a new academy for young researchers, established by the Royal Swedish Academy.
Prof em. Nils-Göran Sjöstrand received the Eugene P. Wigner Reactor Physicist award from the American Nuclear Society.
Martin Lundgren received the Sigvard Eklund Prize for best master thesis.

## Nuclear Chemistry

### Research in:

- actinide science; nuclear waste repository investigations
- nuclear reactor chemistry including accidents
- separation and transmutation; nuclear fuel fabrication and investigations

### Facilities and other data:

Laboratories for α, β, γ experiments and activity measurements; hot cell laboratory for γ activity.
In 2010-2011 a special laboratory for research on advanced nuclear fuels (collaboration with KTH) has been built 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.
13 PhD students (2 with SKC support, 1 jointly with Nuclear Engineering). 1 PhD defence and 1 licentiate during 2011.

### Highlights of the year:

Dr. Henrik Ramebäck from FOI was appointed adjunct professor.
The ASGARD project of 9.6 MEuro was approved and coordinated by Christian Ekberg.
Christian Ekberg was appointed member of the international committee of ISEC.
Participation in the SEARCH project began.

## Education

Chalmers has started a masters program in Nuclear Engineering in 2009, following an initiative from and agreement with E.ON. The masters program in nuclear engineering is now two years old.

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

A few highlights:

• 26 students are now registered on the masters program, and on the introductory course in physics 63 students have registered. This means an all-time-high in student volume for the masters program as well as the individual courses. Thus, in spite of the Fukushima incident and fees for non-European students the number of students on the program has dramatically increased.

• As part of a French-Swedish agreement regarding exchange of nuclear services, the students for the master program have been to a research reactor in Saclay, France. The exercise was in form of a two-and-a-half day laboratory exercise on a small open pool reactor. This was much appreciated by the students and will be repeated in 2012.

• A new course in nuclear materials is being developed and is planned to be launched during spring 2013. The course is aimed at materials in nuclear reactors and the rather special environment with high temperature and high neutron radiation levels.

• The first master students have been examinated from the program. Many of them (approx. half of them) have been employed before the master thesis work was finished.

## New Nuclear Centre

A new centre, called the Sustainable Nuclear Energy Centre (SNEC), has been established in January 2012 at Chalmers. This centre allows coordinating and structuring research, education, and communication about nuclear energy in a comprehensive, responsible, and critical manner. The coordination of the centre is performed by:

• The Division of Advanced Non-destructive Testing (Department of Materials and Manufacturing Technology).

• The Division of Microscopy and Microanalysis (Department of Applied Physics).

• The Division of Nuclear Chemistry (Department of Chemical and Biological Engineering).

• The Division of Nuclear Engineering (Department of Applied Physics).

This centre acts as an entity to:

• Coordinate research and education within Chalmers, and between Chalmers and external partners (both nationally and internationally).

• Provide a forum of exchange and discussions between researchers, students, and industry members, thus leading to a creative research environment and to a direct networking between the different actors involved.

• Provide information about nuclear energy to the society at large in a timely and reliable manner.

• Seek external funding from the industry and research councils.

• Allow attracting foreign researchers and students.

• Provide to the industry one single entity to deal with in nuclear energy-related matters.

With SNEC, Chalmers is one of the very few technical universities, both nationally and internationally, being an independent actor dealing with all aspects of nuclear energy systems for today and tomorrow, with all nuclear-energy based systems being considered (Gen-II/III/III+/IV, fusion, and hybrid fission/fusion systems). Such aspects are tackled along three pillars: safety, security, and sustainability. Chalmers research and education shall be recognised as having a high value for the society with special emphasis on safety culture, responsibility and integrity/professionalism.

# KTH – Royal Institute of Technology

*Overview of Activities in 2011*

At KTH, research and education within the field of nuclear energy engineering is currently carried out at 11 different divisions:

- Reactor physics
- Reactor technology
- Nuclear power safety
- Nuclear chemistry (part of the division of Applied Physical Chemistry since 2011-07-01)
- Nuclear physics
- Surface and corrosion science
- Applied materials science
- Materials processing science
- Computational thermodynamics
- Solid mechanics
- Philosophy

The core activities within the nuclear engineering field are covered by the first four groups. The six latter groups have started their activities during 2010, thanks to grants from the science council (GENIUS) and support from Vattenfall. Their activities have been continued throughout year 2011.

### Staff

Year 2011 was very successful in further strengthening the staffing of the nuclear engineering divisions at KTH. Sevostian Bechta was appointed as the chair professor at the Nuclear Power Safety division. Waclaw Gudowski returned to the Reactor Physics division from the leave of absence. Jan Dufek joined the Nuclear Reactor Technology division as an assistant professor.

At the outcome of the year, the staffing of the divisions consisted of:

6 professors
7 associate professors
1 assistant professor
31 PhD students
15 researchers
2 emeritus professors
1 affiliated professor
1 technician

Tomasz Kozlowski got a position as assistant professor at the University of Illinois at Urbana-Champaign and left the Nuclear Power Safety division in October 2011. Several PhD students left after graduation and new students were appointed.

### Highlights and major research outcome

Year 2011 was very intensive for the KTH's divisions. In March a major disaster occurred in the Fukushima-Daiichi nuclear power plant. Several of KTH's staff were interviewed and served as experts in the Swedish television and the press. The year was also rich in international conferences and workshops, promoting intensive research and dissemination work. Below is a short summary of highlights of KTH's activities.

The handbook "Nuclear Safety in Light Water Reactors: Severe Accident Phenomenology" published by Elsevier; Bal Raj Sehgal was the editor and Weimin Ma contributed to Chapter 2.6, December 2011.
Shengjie Gong received his PhD degree, December 2011.
Sevostian Bechta was appointed as the chair professor of the Division of Nuclear Power Safety (NPS) in October 2011.

Tomasz Kozlowski received Docent in Nuclear Power Safety, October 2011.

The Deterministic/probabilistic Safety Analysis (DPSA) workshop was organized in Helsinki with 60 participants from EU, US and Russia, October 2011.

Prof. Bal Raj Sehgal gave a keynote speech at the 14th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-14), Toronto, Canada, September 25-29, 2011.

Chi-Thanh Tran received the Sigvard Eklund Prize for best PhD thesis, September 2011.

The review meeting of the EU project THINS was organized by KTH-NPS in September 2011.

The KTH-NPS gave the short course "Nuclear Reactor Simulation – Hands-on Training" in collaboration with Pisa University in July 2011.

The review meeting of the EU project SARNET2 was organized by KTH-NPS in June 2011.

KTH-University of Illinois symposium at KTH, initiating cooperation between KTH and University of Illinois in area of Nuclear Energy Engineering (among others), May 2011.
The kickoff meeting of the OECD Benchmark for Oskarshamn-2 BWR Stability was organized by KTH-NPS in April 2011.
Creation of the new PhD program in Physics, which all nuclear students will be part of, January 2011.
The EU-financed project SILER on seismic safety of Generation-IV reactor systems has been approved.
Prof. Bal Raj Sehgal gave several public lectures and seminars on the Fukushima accident.
KTH-NPS was nominated as coordinator in preparation of EU project proposal on Integrated Deterministic – Probabilistic Safety Analysis.
The DEFOR and POMECO-HT tests were selected by EU-SARNET community as a benchmark for severe accident fuel-coolant interaction analysis codes.
The test facility POMECO-HT was commissioned for coolability study of particulate beds.
The test facility PDS was designed and commissioned for study of particulate debris spreading.
The test facility PULIMS was designed and commissioned for high temperature melt spreading under water with up to 80 kg of melt.
Jan Dufek was appointed as assistant professor at Nuclear Reactor Technology division.
Henryk Anglart was invited to deliver a keynote lecture at "Mathematical Modeling and Applications to Industrial Problems", NIT, Calicut, India.
High-Pressure Water Test (HWAT) loop was successfully used for post-dryout measurements in five different test sections which provided about 22000 heat transfer data points.
HWAT loop was adopted to perform thermal mixing experiments at prototypical reactor conditions.

Nuclear Reactor Technology division joined two consortia within European Union to perform education in Gen IV reactors (EURECA!) and to perform research on Monte-Carlo methods (HPMC).
Nuclear Reactor Technology division organized "NRT Open Day" meeting in which the division research was presented to industrial partners.
Ionut Anghel received his Technology Licentiate degree.
Henryk Anglart published three handbooks: "Thermal Hydraulics in Nuclear Systems", KTH Royal Institute of Technology, urn:nbn:se:kth:diva-86358, 2011.
"Applied Reactor Technology", KTH Royal Institute of Technology, urn:nbn:se:kth:diva-86312, 2011.
"Nuclear Reactor Dynamics and Stability", KTH Royal Institute of Technology, urn:nbn:se:kth:diva-86324, 2011.
Henryk Anglart was interviewed by the Swedish national television and newspapers (Expressen and Ny Teknik) in connection to the Fukushima accident and new technology development on modular small reactors.
Henryk Anglart was invited as a member of the editorial board in "Journal of Power Technologies" and in "Energetyka".
27th Miller Conference on Radiation Chemistry was organized by Mats Jonsson and co-workers in Tällberg (20-25 May).
Susanna Wold received her Docent title in Nuclear Chemistry in 2011.
Daqing Cui (Studsvik Nuclear AB) received his Docent title in Nuclear Chemistry in 2011.
In the nuclear fuel laboratory, UN and (U,Zr)N fuel powders were manufactured from metallic source materials. Applying spark plasma sintering pellets with 98% density were obtained, which is a world record.
Nitridation of UZr metallic alloys also permitted to manufacture solid solution (U,Zr)N powders without heat treatment.
The design concept and safety analysis of ELECTRA, was accepted for publication in Nuclear Technology.
The ELECTRA concept was presented to the minister of research during a dedicated two hour seminar in August 2011.
Janne Wallenius' text book on "Transmutation of Nuclear Waste" was published. The text book is intended for use in nuclear engineering masters programs and is a unique treatise of MOX recycling in LWRs, minor actinide recycling in fast neutron Generation IV reactors and Accelerator Driven Systems.
The 19th workshop on multi-scale modelling of Fe-Cr alloys was arranged by the division in Sala Silvermine in October 2011.

Janne Wallenius was interviewed in national television (Aktuellt, Nyheterna & Vetenskapens värld) and the Swedish television of Finland on the Fukushima events. In addition the division provided of the order of 50 interviews to radio channels and newspapers.
The science television program ”Vetenskapens värld” dedicated 1/3rd of it's post-Fukushima program to Generation-IV reactors and the ELECTRA concept, including an interview with Janne Wallenius.
The Reactor Physics division obtained grants for participation in the FP7 projects ”FREYA”, ”ASGARD” and PELGRIMM, totalling 700 k€.
Janne Wallenius was invited speaker at the Korean Nuclear Society meeting in Gyeongju, October 2011.
The Reactor Physics division organised the international FAIRFUELS workshop at KTH in February 2011, with speakers from Japan, Russia and EU.

### PhD education

The following PhD and Licentiate Theses were completed during year 2011:

**Shengije Gong**: "An experimental study on micro-hydrodynamics of evaporating/boiling liquid film", PhD Thesis, Nuclear Power Safety, ISBN:978-91-7501-165-3, December 2011.

**Ionut Anghel**, "Experimental study of post-dryout heat transfer in annuli with flow obstacles", Nuclear Reactor Technology, ISBN:978-91-7501-020-5, Maj 2011.

**Michael Holmboe**, The Bentonite Barrier: Microstructural properties and the influence of γ-radiation, Nuclear Chemistry, ISBN: 978-91-7501-001-4, June 2011.

**Martin Trummer,** The effect of solid state inclusions on the reactivity of UO2: A kinetic and mechanistic study, Nuclear Chemistry, ISBN: 978-91-7415-960-8, May 2011.

**Helena Bergenudd**, Understanding the mechanisms behind atom transfer radical polymerization: exploring the limit of control, Nuclear Chemistry, ISBN: 978-91-7415-933-2, April 2011.

The following PhD projects have been carried out:

Roman Thiele: "Thermal-hydraulics in lead-bismuth cooled nuclear fuel assemblies", supported by the GENIUS project.

Maria Jaromin: "Heat transfer to non-unity Prandtl number fluids", supported by the THINS project and SSM.

Diana Caraghiaur: "Two-fluid annular flow model", supported by the NURISP project and SSM.

Ionut Anghel: "Post-dryout heat transfer in channels with flow obstacles", supported by SKC.

Carsten 't Mannetje, "Influence of axial power distributions on dryout", supported by SKC.

Viet-Anh Phung, "Development of a method for the treatment of two-phase flow patterns in nuclear reactor thermal hydraulic system code", supported by SKC.

Joanna Peltonen, "Development of effective algorithm for coupled thermal-hydraulics – neutron-kinetics analysis of reactivity transients", supported by SSM.

Hua Li, "Condensation and mixing phenomena in a BWR suppression pool", supported by NORTHNET-RM3 and NKS.

Ivan Gajev, "Sensitivity and uncertainty analysis of BWR stability", supported by the NURISP project and SSM.

Kaspar Kööp, "Passive safety systems in advanced nuclear power plants: design, performance analysis and integrated assessment", supported by SKC and SSM.

Sachin Thakre, "Simulation of fuel coolant interactions and corium coolability during a severe accident of LWRs", supported by the APRI-7 and SARNET2 projects.

Marti Jeltsov, "Coupling of system code with cfd for nuclear reactor thermal hydraulic and safety analysis", supported by the THINS project.

Karin Norrfors: "Colloid facilitated transport of radionuclides" supported by SKB.

Åsa Björkbacka: "Radiation induced corrosion of copper" supported by SKB.

Claudio Lousada: “Interfacial radiation chemistry” supported by SKC.

Veronica Diesen: “Photocatalytic purification of water” supported by Wallenius Water AB.

Miao Yang: “Interfacial radiation chemistry” supported by CSC.

Sara Nilsson: “Radiation induced dissolution of spent nuclear fuel” supported by SKB.

Kristina Nilsson: “Effects of solid phase alterations on the redox reactivity of UO2-based spent nuclear fuel” supported by SKB.

Youpeng Zhang, Transmutation of americium in sodium fast reactors and accelerator driven systems, funded by SKB. PhD thesis presented in Februrary 2012.

Odd Runevall, Multi-scale modelling of gas migration in inert matrices, funded by the EU project FAIRFUELS. PhD thesis to be presented on April 4th 2012.

Milan Tesinsky, Transmutation of americium in lead colled fast reactors, funded by SKB. PhD thesis to be presented in May 2012.

Jitka Zakova, Transmutation of americium in boiling water reactors. Funded by SKB. PhD thesis to be presented in June 2012.

Merja Pukari, modelling and characterisation of nitride fuels. Funded by GENIUS. PhD thesis to be presented in 2013.

Pertti Malkki, High performance nitride fuels for LWRs. Funded by SKC. Licentiate thesis to be presented in 2012.

Erdenechimeg Suvdantsetes, Design and safety studies of ELECTRA. Funded by SKB. Licentiate thesis to be presented in 2012.

Zhongwen Chang, Multi-scale modelling of swelling in austenitic steels. Funded by GENIUS. Licentiate thesis to be presented in 2012.

Luca Messina, Modelling of nickel precipitation in pressure vessel steels. Funded by Vattenfall. Licentiate thesis to be presented in 2013.

### Undergraduate education

KTH divisions have been successfully running the Master Program in Nuclear Energy Engineering since 2007. During that time the program has gained high international reputation and the courses taught within the program have attracted many international and domestic students. The following major courses were given in 2011:

“Nuclear reactor technology”, H. Anglart, 8 ECTS, 30 students.

“Thermal-hydraulics in nuclear systems”, H. Anglart, 6 ECTS, 15 students.

“Nuclear reactor dynamics and stability”, H. Anglart, 6 ECTS, 16 students.

“Nuclear power safety”, P. Kudinov, 6 ECTS, 15 students.

“The nuclear fuel cycle”, M. Jonsson, 9 ECTS, 15 students.

“Photo, Radiation and Radical Chemistry”, M. Jonsson, 7.5 ECTS, 10 students.

“Miljöfysik” - J. Wallenius & P. Olsson (100 students)

”Reactor physics” - W. Gudowski (25 students)

“Research methodology” - N. Sandberg (40 students)

“Management in nuclear industry” - O. Runevall (15 students)

“The nuclear fuel cycle” - M. Pukari (15 students)

“Generation IV reactors” - J. Wallenius (12 students)

“Radiation damage in materials” - N. Sandberg (15 students)

“Numerical methods in nuclear engineering” - V. Arzhanov (10 students)

“Non-proliferation of nuclear materials” - J. Wallenius (10 students)

“Transmutation of nuclear waste” - J. Wallenius (5 students)

“Chemistry and physics of nuclear fuels” - M. Jolkkonen (5 students)

“Neutron transport theory” - V. Arzhanov (5 students)

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

The following Master and Bachelor Theses have been completed during 2011:

**Edouard Michta**, “Modelling of subcooled nucleate boiling with OpenFOAM”, Master Thesis of KTH, February 2011.

**Fredrik Nimander**, “Investigatin of spent nuclear fuel pool coolability”, Master Thesis of KTH, August 2011.

**Stefano Racca**: “TRACE code validation for BWR spray cooling injection based on GÖTA facility experiments”, Master Thesis of KTH, March 2011.

**Fabio Veronese**: “TRACE code validation for DVI line break LOCA in the ATLAS facility”, Master Thesis of KTH, March 2011.

**Daniel Jara Heredia**: “DNB and Void Fraction TRACE Model Validation with PSBT Experiments”, Master Thesis of KTH, April 2011.

**Aziz Bora Pekicten**: “Assembly homogenization of light water reactors by a Monte Carlo reactor physics method and verification by a deterministic method”, Master Thesis of KTH, May 2011.

**Huaqiang Zhong**: “A study on the coolability of ex-vessel corium by late top water flooding”, Master Thesis of KTH, June 2011.

**Marti Jeltsov**: “Application of CFD to safety and thermal-hydraulic analysis of lead-cooled systems”, Master Thesis of KTH, June 2011.

**Yiqiong Shao**: “TRACE analysis for transient thermal-hydraulics of a heavy liquid metal cooled system”, Master Thesis of KTH, June 2011.

**Elias Amselem**: “Analysis of boiling water reactor design and operating conditions effect on stability behaviour”, Master Thesis of KTH, August 2011.

**Marta Magdalena Lasik**: “Analysis of reflood phase of a PWR LOCA”, Master Thesis of KTH, September 2011.

**Joan Bertran**: “TRACE code validation for natural circulation during small break LOCA in EPR-type reactor”, Master Thesis of KTH, September 2011.

**Guillem Beltran Arroyos**: “Investigation of conditions for activation of rupture disk in BWR containment filtering system”, Master Thesis of KTH, September 2011.

**Paulus Alexander Breijder**: “Analysis of advanced fuel behaviour during loss of coolant accident in Swedish boiling water reactor”, Master Thesis of KTH, October 2011.

**Simone Basso**: “Experimental and analytical investigation of particulate debris spreading”, Master Thesis of KTH, October 2011.

**Eric Beaussant, Victor Björkegren, Ellen Bruce, Beatrice Johansson**, “Effekter av joniserande strålning på jonvätskors lösningsmedelsegenskaper”, Bachelor Thesis of KTH, May 2011.

**Miquel Torres,** Production of mixed U-Zr nitride nuclear fuel powders from metallic U-Zr alloys, KTH 2011.

**Sebastian Raub**, Transient behaviour in a BWR with Hafnium Cladding, KTH 2011.

**Sideeg Salah**, Spatial dependence of reactivity coefficient, KTH 2011.

**Tobias Hollmer**, Manufacturing methods for (U-Zr)N-fuels, KTH 2011.

## National and international projects

The KTH divisions have been very active in promoting national and international cooperation. These activities manifest themselves with participation and leadership in numerous projects, as shortly described below.

Nuclear Reactor Technology has been involved in the following European projects: NURISP – on development of simulation tools for nuclear engineering applications; THINS – on development of thermal-hydraulics methods for new innovative nuclear systems; EURECA! – on education within Gen IV supercritical water cooled reactors; HPMC – on development of high performance Monte-Carlo methods. In addition, the division is leading the following national projects: NORTHNET RM1 – on development of thermal-hydraulic models for nuclear fuel assemblies; THEMFE – on experimental investigation of thermal mixing phenomena using the HWAT loop; THEMFA – on analytical investigation of thermal mixing phenomena using CFD models with URANS and LES closures for turbulence.

Nuclear Power Safety has been involved in the following European projects: SARNET2 for research on severe accident phenomena;

NURISP for development of simulation tools for nuclear engineering applications; THINS for experiment and analysis of thermal-hydraulics new innovative nuclear systems. Nuclear Power Safety is also performing the international projects: ENSI-MSWI and MHI-SAM for study on corium coolability and steam explosion risk. Nuclear Power Safety has the national projects: APRI-7 for research on corium coolability and steam explosion in BWRs; DSA for transient and severe accident safety analysis for Swedish nuclear power plants; NORTHNET-RM3 for simulation of condensation and mixing phenomena in a BWR suppression pool.

Nuclear Chemistry has the following projects: Radiation induced dissolution of spent nuclear fuel (SKB), Effects on solid phase alterations on the redox reactivity of spent nuclear fuel (SKB), Radiation induced corrosion of copper (SKB), Colloid facilitated transport of radionuclides (SKB), Interfacial radiation chemistry (SKC), ReCosy (Euratom), Photocatalytic purification of water (Wallenius Water AB).

Reactor Physics division has been involved in the following projects:

GENIUS, national Gen-IV project. Coordinated by the division. VR funded.

LEADER, Lead fast reactor R&D project, Work package leadership, FP7.

GETMAT, Generation IV and transmutation materials, Work package leadership, FP7.

FAIRFUELS, Fabrication and irradiation of fuels for transmutation, FP7.

FREYA, Fast reactor experiments in Guinevere, work package leadership, FP7.

ASGARD, Dissolution and reprocessing of advanced fuels, domain leadership FP7.

PELGRIMM, Pellets and granulates for minor actinde transmutation, FP7.

## Conferences and publications

The divisions actively participated in major international conferences within nuclear engineering field and also published in several reputed journals. The most important publications within 2011 are as follows:

W.M. Ma, A. Karbojian, T. Hollands, M.K. Koch, Experimental and numerical study on lead-bismuth heat transfer in a fuel rod simulator, *Journal of Nuclear Materials*, 4**15**: 415-424, 2011.

L.X. Li and W.M. Ma, Experimental study on the effective particle diameter of a packed bed with non-spherical particles, *Transport in Porous Media*, **89**: 35-48, 2011.

L.X. Li, W.M. Ma, Experimental characterization of effective particle diameter of a packed bed with multi-diameter spheres, *Nuclear Engineering and Design*, **241**(5): 1736-1745, 2011.

T. Kozlowski, J. Peltonen, Qualification of the RELAP5/PARCS code for BWR stability events prediction, *Nuclear Technology*, **174**(1): 51-63, 2011.

J. Peltonen, T. Kozlowski, Development of effective algorithm for coupled thermal-hydraulic-neutron-kinetics analysis of reactivity transient, *Nuclear Technology*, **176**(2): 195-210, 2011.

V.I. Almjashev, M. Barrachin, S.V. Bechta, et al., Ternary eutectics in the systems $FeO-UO_2-ZrO_2$ and $Fe_2O_3-U_3O_8-ZrO_2$, *Radiochemistry*, **53** (1): 13-18, 2011.

V.B. Khabensky, V.S. Granovsky, S.V. Bechta, et al., Operation of thermal protection shields used in the corium catcher at a nuclear power station equipped with VVER reactors, *Thermal Engineering*, 58(4): 310-316, 2011.

S.V. Bechta, S.A. Vitol, V.S. Granovskii, et al., Formation of a nuclear reactor's molten pool in a crucible type corium catcher for a nuclear power station equipped with VVER reactors, *Thermal Engineering*, **58**(5): 424-428, 2011.

D. Grishchenko, P. Piluso, Recent progress in the gas-film levitation as a method for thermophysical properties measurements: application to $ZrO_2-Al_2O_3$ system. *High Temperatures-High Pressures*, **40**(2): 127-149, 2011.

W.M. Ma, Prediction of dryout heat flux of volumetrically heated particulate beds packed with multi-size particles, Proc. of NURETH-14, Toronto, Canada, Sept. 25-29, 2011.

L.X. Li, S. Thakre, W.M. Ma, An experimental study on two-phase flow and coolability of particulate beds packed with multi-size particles, Proc. of NURETH-14, Toronto, Canada, Sept. 25-29, 2011.

R. Thiele, W.M. Ma, H. Anglart, Investigation of the influence of turbulent models on the prediction of heat transfer to low Prandtl number fluids, Proc. of NURETH-14, Toronto, Canada, Sept. 25-29, 2011.

S.G. Gong, W.M. Ma and T.N. Dinh, Measurement of film dynamics in a boiling liquid film, Proc. of NURETH-14, Toronto, Canada, Sept. 25-29, 2011.

W. Villanueva, C.T. Tran, P. Kudinov, A computational study on instrumentation guide tube failure during a severe accident in boiling water reactors, Proc. of NURETH-14, Toronto, Canada, Sept. 25-29, 2011.

W. Villanueva, C.T. Tran, P. Kudinov, Assessment with coupled thermo-mechanical creep analysis of combined CRGT and external vessel cooling efficiency for a BWR, Proc. of NURETH-14, Toronto, Canada, Sept. 25-29, 2011.

C.T. Tran, P. Kudinov, Local heat transfer from the corium melt pool to the BWR vessel wall, Proc. of NURETH-14, Toronto, Canada, Sept. 25-29, 2011.

S. Yakush, P. Kudinov, N.T. Lubchenko, Sensitivity and uncertainty analysis of debris bed coolability, Proc. of NURETH-14, Toronto, Canada, Sept. 25-29, 2011.

P. Kudinov, M. Davydov, Prediction of mass fraction of agglomerated debris in a LWR severe accident, Proc. of NURETH-14, Toronto, Canada, Sept. 25-29, 2011.

M. Jeltsov M., F. Cadinu, W. Villanueva, A. Karbojian, K. Kööp, P. Kudinov, An approach to validation of coupled CFD and system thermal-hydraulics codes, Proc. of NURETH-14 , Toronto, Canada, Sept. 25-29, 2011.

M. Jeltsov, P. Kudinov, Simulation of a steam bubble transport in the primary system of the pool type lead cooled fast reactors, Proc. of NURETH-14, Toronto, Canada, Sept. 25-29, 2011.

O. Zerkak, I. Gajev, A. Manera, T. Kozlowski, et al., Revisiting temporal accuracy in neutronics/TH code coupling using the NURESIM LWR simulation platform, Proc. of NURETH-14 , Toronto, Canada, Sept. 25-29, 2011.

L.X. Li and W.M. Ma, Experimental investigations on friction laws and dryout heat flux of particulate beds packed with multi-size spheres and irregular particles, Proc. of ICONE19, Chiba, Japan, May 16-19, 2011.

I. Gajev, T. Kozlowski, Y.L. Xu, T. Downar, Ranking of input parameters importance for BWR stability based on Ringhals-1, M&C Conference 2011, Rio De Janeiro, Brazil, May 8-12, 2011.

S.J. Gong, L.X. Li and W.M. Ma, An experimental study on bubble and film dynamics in boiling of a horizontal liquid layer, Proc. of ICAPP 2011, Nice, France, May 2-5, 2011.

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Anghel, I., Anglart, H. and Hedberg, S. “Experimental Investigation of Post-Dryout Heat Transfer in Annuli with Flow Obstacles,” *Nuclear Engineering and Design*, doi:10.1016/j.nucengdes.2011.08.026.

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J. Vegelius, I. Soroka, P. T. Korelis, B. Hjörvarsson, S. M. Butorin, Atomic and electronic structure of amorphous Al-Zr alloy films, Journal of Physics: Condensed Matter, 23: 2011.

P. A. Korzhavyi, I. Soroka, M. Boman, B. Johansson, Thermodynamics of stable and metastable Cu-O-H compounds, Solid State Phenomena, 172-174: 973-978, 2011.

W. Yu, B. Azhdar, D. Andersson, T. Reitberger, J. Hassinen, T. Hjertberg, U. Gedde, Deterioration of polyethylene pipes exposed to water containing chlorine dioxide, Polymer degradation and stability, 96: 790-797, 2011.

M. Jonsson, Radiation Induced Dissolution of Spent Nuclear Fuel, International Workshop on Radiation Effects in Nuclear Technology, Tokyo, Japan, 9-10 March, 2011 (invited).

M. Jonsson, Radiation Induced Dissolution of Spent Nuclear Fuel, 14th International Congress of Radiation Research, Warsaw, Poland, 28 August- 1 September, 2011 (invited).

M. Jonsson, S. Nilsson, Å. Björkbacka, M. Holmboe, K. Norrfors, S. Wold, M. Trummer, C. Lousada, Effects of ionizing radiation on the dissolution of UO2 based fuel and on the integrity of the engineered barriers in the KBS-3 concept, Geological Disposal of Radioactive Waste: Underpinning Science and Technology, Loughborough University, UK, 18-20 October, 2011.

S. Hansson, P. Antoni, H. Bergenudd, E. Malmström, "Selective cleavage of polymer grafts from solid surfaces: assessment of initiator content and polymer characteristics", POLYM CHEM, 2: 556-558, 2011

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# Uppsala University

*Division of Applied Nuclear Physics*

Another exciting year for the division has passed. The overall trend for our activities is that the three pillars of activity: Research, education and outreach all have increased in volume. With a limited capacity we have therefore been forced to a) focus our educational efforts on our main field i.e. nuclear technology and related subjects and, b) start a process to employ more personnel.

The fact that the research programme, Ion Physics, now is a part of Applied Nuclear Physics has facilitated cross-disciplinary activities. For example, the material research within Genius will benefit by the possibility to implant for example Xe in new fuel materials in order to investigate their properties. Structural materials research will also use the accelerators here for various irradiation studies.

The research programme Material Theory at UU is more and more involved with material issues related to nuclear power technology. For example, a large FP 7, RADINTERFACES, project with main focus on Gen IV materials has started where Professor Mattias Klintenberg from the Division of Materials Theory coordinates one work package. There are also discussions about collaboration with Pål Efsing at KTH regarding research on materials for today's reactor application as well as for Gen IV. It is foreseen that the concentration of material related work around our division in Uppsala will form an important support for nuclear materials research in Sweden at large.

During the INMM conference in July 2010 it became clear that the Los Alamos National Laboratory (LANL) was eager to initiate collaboration with our division. In a first step in this direction, Sophie Grape was assigned as a member of a review committee on 14 NDA techniques for determining the plutonium and fissile content of spent fuel, in a network led by LANL. The objective was to find a few technologies that can form a basis for research and development within this field at LANL. The review committee has issued a document, "Next Generation Safeguards Initiative Spent Fuel Effort External Committee: Final Report" (July 14, 2011). In a second step of this collaboration, we have now employed a Master student, Niklas Lundqvist, who will conduct his Diploma work partly in Uppsala and partly at LANL. It is anticipated that this project will evolve to a Ph.D. project later on, and further collaborative projects are also foreseen.

Other collaborations of interest under establishment are with SCK-CEN in Belgium and with the IFE/OECD Halden Reactor Project in Norway (besides the on-going one with Scott Holcombe as Ph.D. student). Worth to mention is also Sophie Grape's engagement in the development of the DCVD instrument. Although recently approved by the IAEA for partial verification, it is believed that the DCVD:s performance may be enhanced even further by applying sophisticated analysis techniques. We plan to investigate this somewhat further with the goal of advising improvements in the current methodology.

Altogether, we feel that our efforts during 2011 have been successful and that there are more to come. There is, however, a bottleneck as we may not be able to expand the staff in accordance to the increasing volume. How to cope with this situation is probably something we need to focus on during 2012.
Below is an account on education, outreach and research conducted during 2011.

## Education

Education within the fields of energy systems and nuclear engineering is conducted through a number of courses within the various Master of Science in Engineering programmes (civilingenjörsprogram) and the Bachelor's Programme in Nuclear Engineering. (högskoleingenjörsprogram i kärnkraftteknik ), which is on its second year since the start in autumn 2010. Also, since 2003 UU provides higher education for the nuclear power industry within the framework of an agreement with Kärnkraftsäkerhet och Utbildning AB (KSU AB). The objective of this activity is to secure competence building of existing and newly recruited personnel, primarily within reactor operation and radiation protection.

In addition to managing the Bachelor's programme in nuclear engineering, in 2011 the Division of applied nuclear physics was given the responsibility to manage the *Master of Science in engineering programme for energy systems*. This program is the 2nd largest Master of Science in engineering programme at Uppsala University

## Bachelor's program in nuclear engineering

*Figure 1. The Bachelor's of nuclear engineering class graduating in June 2011*

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 / 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 reason for establishing the programme is that it is expected to 1) increase the volume of employable people to the nuclear industry and 2) decrease the industry's total training cost. The latter is due to the fact that almost a year of training, that otherwise would charge each power plant individually, would be centrally funded without the need to provide salaries etcetera to course participants.

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 most courses experts from industry and authority are involved as guest teachers, collaborating with the UU teachers. This concept has proved very successful and will be developed further. During 2011 two of the industry-expert teachers attended a 2 week UU teacher training course in order to gain knowledge about university pedagogics and didactics.

In addition to study visits to the Swedish NPPs students have also made study visits to the SKB facilities in Oskarshamn, the Westinghouse nuclear fuel fabrication plant in Västerås, Siemens Turbomachinery in Finspång (steam turbines) and ABB in Ludvika (generators and transformers). 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. A reactor laboration is included in the reactor physics course. During the first study year (2010/2011) the laboration was performed at VTT's TRIGA reactor in Helsingfors. For the study year 2011/2012 and years to come, the reactor laboration has been moved to the ISIS training reactor at Saclay outside of Paris. This change allows the reactor laboration to be increased in scope as well as in time from 1 day to 3.5 days, in order for the students to gain a better understanding of reactor physics.

The professional network Women in Nuclear (WiN) provides a mentoring programme that runs in parallel with the programme courses. Each student is assigned a personal mentor working in the nuclear industry and over the course of the study year, WiN organizes six meetings for all students and mentors with seminars on various topics, e.g. career planning, radiation safety and protection and the nuclear fuel disposal. In between these meetings students and mentors meet on an individual basis.

Considerable effort is devoted to student recruitment activities. The need for this has increased considerably during 2011. There are several reasons for this, most obviously the Fukushima accident and the German decision to shut down all nuclear power plants by 2022 that has caused Swedish students some anxiety as to the future of Swedish nuclear power. Recruitment activities include advertising in various media, mailings, lunch lectures at several engineering colleges around Sweden and participation in several student careers fairs at Swedish universities, e.g., UTNARM, CHARM, LARM etc. These activities are often done in collaboration with SKC that also participate in these events.

The nuclear engineering programme with its very close collaboration with the Swedish nuclear industry has attracted international attention and has been presented at the 2011 NESTet conference and by invitation at IAEA's 2011 INSEN meeting.

### The study year 2010/11 in brief

For the first year of the programme 80 students applied, 48 were found to fulfil the prerequisites and in the end 32 students were admitted. Of the students admitted, 24 commenced the education and at the end of the study year 19 students had completed approximately 90 % the courses. At the time of writing (feb 2012) 14 students have completed their diploma work. One of the students, Katja Göller, was awarded the 2011 Sigvard Eklund prize for the best B.Eng. diploma thesis.

The large majority of students graduating from the programme have been employed by the NPPs. Two has been employed by consulting companies and one by VPC.

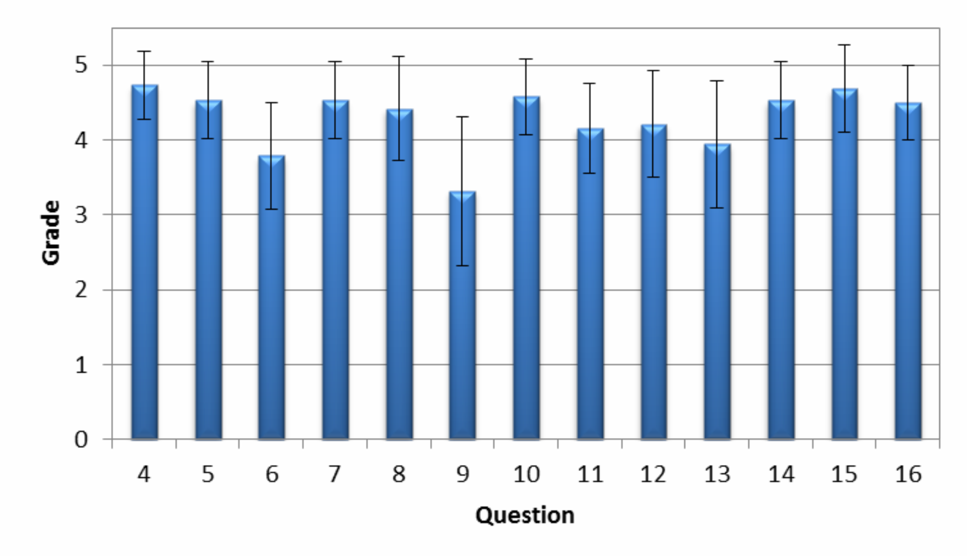


*Diagram 1. Summary of the result of a programme evaluation survey for the Bachelor's program in nuclear engineering for the study year 2010/11. In the diagram the average and standard deviation of student's response to questions in the survey are shown, 5 being the highest grade.*

### The study year 2010/11 in brief

For the study year 2011/12 the programme attracted 61 applicants, 32 were found to fulfil the prerequisites and admitted to the programme. At the beginning of autumn semester 12 students commenced the education. The large discrepancy between the number of students admitted and the number of students actually commencing the education is remarkable. To the best of our knowledge much of the discrepancy can be attributed to effects of the Fuskushima accident including the German decision to shut down its NPPs and the student's uncertainty about how this may affect Swedish nuclear power operation in the long run. At the time of writing (February 2012) all 12 students are still active within the programme.

### Master of Science in engineering programs

Within the Master of Science in Engineering programmes, the division gives courses dedicated to nuclear power. Also, the educational strategy of the Division of Applied Nuclear Physics includes offering courses which integrate nuclear power into a wider context of energy-related questions. The objective with these courses is (a) to attract students who otherwise might not be interested in nuclear power and (b) to give a wider perspective where nuclear power appears as one important part of the energy system.

During 2011, the following courses were given:

- ”Nuclear Power – Technology and Systems”: A course on nuclear power with focus on today's techniques, given within the Master of Science in Engineering programme for Energy Systems. About 30 students per year.
- ”Energy System Physics”: A general course on energy-related issues with some chapter on nuclear power. Given within the Master of Science in Engineering programme for Sociotechnical Systems Engineering. About 45 students per year.
- ”Complex Systems – Technology”: A course on risk assessment with one focus on nuclear energy (PSA). Given within the Master of Science in Engineering programme for Sociotechnical Systems Engineering. About 45 students per year.
- ”Energy Physics I”: A course similar to ”Energy System Physics”. Given within the Master of Science in Engineering programme in Engineering Physics and the Bachelor Programme in Physics. About 40 students per year.

- ”Energy Physics II with nuclear power”: Advanced course with focus on nuclear energy. Given within the Master of Science in Engineering programme in Engineering Physics. About 25 students per year.
- ”Project in Applied Physics”: Within this course, the division offers projects on energy-related questions, including nuclear energy, in collaboration with Vattenfall. About 15 students per year.

### Contract education for the industry

Following the high pace of recruitment within the Swedish nuclear industry up to 2010, during the last years the nuclear industry have entered a period of lower recruitment rates and cost cutting measures. This is reflected in the demand for courses given within UU’s contract education agreement with KSU, exhibiting a decrease from 26 weeks in 2010 to 20 weeks in 2011.

During 2011, courses have been conducted on 12 occasions:

- Kärnkraftteknik, H1 (12 hp), 2 occasions
- Fördjupad strålskyddsutbildning FS1, 2 occasions
- Fördjupad strålskyddsutbildning FS2, 1 occasions
- Aktivitetsmätning med Ge-detektor, 1 occasion
- Material och konstruktion, 1 occasion
- Värme- och strömningslära (KGP), 2 occasions (OKG)
- Reaktorfysik fördjupad (KGP), 1 occasion (OKG)
- Härdkylning BWR, 2 occasions (OKG)

For two of the courses, Kärnkraftteknik H1 and Fördjupad strålskyddsutbildning FS1, the attendees can be registered as students at Uppsala University and get academic credits after passing the examinations.

### ESARDA

Our engagement in ESARDA has increased during 2011. For example, Sophie Grape is a regular member of the “Working Group of Training and Knowledge Management”.

Another example is that during 12-16 September, we arranged, in collaboration with the SSM, the “8$^{th}$ ESARDA Course on Nuclear Safeguards and Non-proliferation” in Uppsala. This course was the first of its kind held in Sweden and attracted 45 participants from authorities, organisations and universities from all over the world. The course got a very good reception from the participants and we believe therefore that it may form a regular item of the ESARDA course portfolio.

### NANSS

During 2011, we intensified the work to create the “Nordic Academy for Nuclear Safety and Security”, NANSS. NANSS is an educational network consisting of participants from the Nordic countries. The basic idea with NANSS is to deliver education within non-technical aspects of nuclear safety and security to the surrounding world. NANSS is planned to be self-financed and is planned to direct its education towards embarking countries as well as to the managements of existing facilities around the world. We have a valuable discussion with the IAEA regarding this initiative and we have reasons to believe that IAEA will help to promote NANSS in the world.

During 2011 it became clear that SSM, IFE in Norway and KSU are interested to join NANSS and from this platform we will also approach other universities and authorities across the Nordic countries to participate. The plan is to offer the first courses in autumn 2012.

## Outreach

Continuing the strategy to increase our outreach activities aiming at obtaining an increased public interest for nuclear power and new collaborations has resulted in a number of interesting prospects. Below a short account on the most prominent features is made.

Due to the catastrophic event in Japan, the division staff became engaged in various supporting actions directed towards the public. To that end, the personnel were subject to interviews and participation in several Radio and TV shows. In addition, the division personnel were interviewed both regarding nuclear power in general and Gen IV in particular.

During the Nomage 4 meeting in Halden autumn 2011 it was once again concluded that Norway has interest to conduct Gen IV work together with us in Sweden. The dialogue with Norway will continue during 2012.

In November we were visited by Professor Jasmina Vujic from UC Berkeley. During this meeting we discussed collaborations and other things of common interest. It was decided to continue the discussions with all relevant research leaders at UC Berkeley, Lawrence Livermore, Lawrence Berkeley and Los Alamos National Laboratories in a meeting in January 2012 (which also took place. From these discussions it is evident that our US colleagues are most interested to collaborate and we will certainly have some interesting new projects to report next year).

In July, Ane Håkansson visited Almedalsveckan where he and Christian Ekberg from Chalmers addressed Gen IV issues to the public. This seminar, arranged by Uppsala University for the second time, included a panel consisting of Peter Honeth (Ministry of Education and Research), Gert Nilson (Jernkontoret) in addition to Håkansson and Ekberg. The whole event was moderated by Linda Nyberg, known for her research coverage in radio and TV.
The vice chancellor decided to provide strategic funding in order to affiliate the former IAEA director of safeguards, Kaluba Chitumbo, to our division. Obviously Dr. Chitumbo's knowledge, experience and comprehensive network around the world will be an asset for us in several aspects e.g. supervision of undergraduate and graduate students, teaching and research within the field of non-proliferation.

## Research

### Nuclear fuel diagnostics and safeguards group

#### Senior personnel

January 1, 2011, Peter Jansson was employed as a researcher. Although connected to a project with the SKB, his main field is Gen IV research. In addition, Sophie Grape accepted a non-tenured researcher appointment after finishing a 2-year postdoc appointment in November 2011.

#### PhD student progress

**Studies of Void using Neutron Tomography: Peter Andersson** started his Ph.D. studies in May 2008 on the topic of void monitoring in thermal-hydraulic test loops using neutron transmission tomography. Peter presented his licentiate thesis in May 2011, entitled "Optimization of Equipment for Tomographic Measurements of Void Distributions using Fast Neutrons". A device for transmission tomography using portable neutron sources is under construction and measurements on models imitating two-phase flows will be carried out at the Swedish Defence Research Agency (FOI) starting 2012. A reference group meeting was held at the SKC symposium in Västerås in October, gaining large interest from industry representatives and resulting in valuable feedback to the project. As a result from that meeting, Peter has developed a technique for dynamic bias correction, i.e. correcting for a non-linear response to temporal changes in void content during a measurement, which will be published during 2012.

**A Pilot Gamma Tomography System for Nuclear Fuel Monitoring: Scott Holcombe** started his Ph.D. studies in October 2009 in collaboration with Westinghouse Electric Sweden AB. Scott is now situated in Halden, continuing his Ph.D. project on “Advanced diagnostics of nuclear fuel based on tomographic techniques and high-resolution gamma-ray spectroscopy”. A tomographic instrument for measurements on irradiated fuel at the OECD Halden reactor is under development. The instrument will allow measurements to be performed on test fuel with short cooling times (1-2 days) for experimental determination of various fuel parameters. Recent work has been focused on the measurement of short-lived fission gasses and their assessment using tomographic techniques, and two conference contributions have been presented during 2011. Two reference group meetings have been held during 2011, with representatives from Uppsala University and Westinghouse Electric Sweden AB. Scott will present his licentiate thesis during 2012.

**Core Monitoring in Metal-Cooled Fast Reactors: Peter Wolniewicz** was the first Uppsala student to take on the Genius project, with core monitoring in metal-cooled fast reactors as his subject. Peter has shown that the introduction of coolant void, which is a safety concern in metal-cooled fast reactors for reasons of both reactivity and loss of coolant, affects the neutron spectrum in the vicinity of the voided region. The idea is primarily to use neutron detectors with different sensitivity to slow and fast neutrons in order to detect such void formation. Peter presented his results at the IAEA technical meeting on Fast Reactor Physics and Technology in India in November 2011, gaining a large interest from the Gen IV community. In his future work, Peter will also study the inclusion of gamma-ray detectors in the monitoring system in order to further improve the void detection capabilities. Furthermore, this technique is also expected to be useful for detecting geometric anomalies in the core, such as assembly bow or core flowering, which is also a safety concern. According to plan, Peter will present his licentiate thesis during autumn 2012.

**Nuclear Safeguards in a Pilot Facility for Recycling of Nuclear Waste: Matilda Åberg Lindell** started her Ph.D. studies in November 2010 with the goal to develop methodologies for assessing the proliferation resistance in a Gen IV demonstration facility consisting of a reactor, an interim storage for spent fuel, a reprocessing facility and a fuel fabrication plant. A manuscript is under development, where the established TOPS methodology has been applied to this type of facility, which will be submitted in the beginning of 2012.

A reference group has been formed consisting of Kaluba Chitumbo (former IAEA SG director), Klaas van der Meer (SCK CEN), Lars Hildingsson (SSM), Theodora Retegan (Chalmers) and Katarina Wilhelmsen (FOI), and a first meeting was held in Uppsala in December 2011. The work will now be focused on the safeguards system for monitoring the reprocessing step, taking joint-use equipment into account and enabling “safeguards-by-design” for future facilities of this kind. Matilda is expected to present her licentiate thesis late 2012 or early 2013.

## Nuclear reaction research group

### Senior personnel

A postdoc, Junfeng Duan, was hired during spring 2011. With his background as a theoretical nuclear physicist that has worked at the Chinese nuclear data bank in Beijing, Duans task is to study the input parameter range for the Talys code for our Total Monte Carlo project.

Elisabeth Tengborn has left the group to take a job at Vattenfall. She was replaced in October by Andreas Solders who defended his thesis “Precision mass measurements” at Stockholm University during 2011. Andreas works with the IGISOL facility in Jyväskylä, Finland, within the AlFONS project.

Two new PhD students took up their positions during spring; Andrea Mattera, the first of two PhD students within AlFONS, and Erwin Alhassan, aiming at using the Total Monte Carlo method for LWR.

Finally a research assistant, Giovanni Scian, was hired for one year to help us in our preparations for planned measurements at NFS (Neutrons For Science) at GANIL, France.

## PhD student progress

**Massive Computational Methodology for Reactor Operation - MACRO**: The GENIUS sub-project MACRO aims at using the Total Monte Carlo (TMC) method (proposed by Koning and Rochman from NRG Petten, The Netherlands) to determine uncertainties in macroscopic reactor parameters as they arise from uncertainties in the underlying nuclear physics data.

A PhD student, **Gustav Wallin**, was recruited for this project in spring 2010. His first task was to develop a computational chain (and loop) that transports the nuclear physics calculations from the Talys code all the way through the Monte Carlo code MCNP for ELECTRA.

Unfortunately, Wallin is on long term sick leave since the summer of 2010 and could only work during brief periods since then. It has gradually turned out that Wallin will not be able to deliver the promised calculations within the time frame allocated for the Genius project.

Measures have been taken to not only fulfill our task within the Genius project but for the further development of the TMC method as such. In spring 2011, a second PhD student**, Erwin Alhassan**, was hired. His initial study plan aimed at applying TMC to LWR. While Wallin was so far not able to finish the needed computation chain, Alhassan is currently exploring some possible shortcuts, using developments made elsewhere. Rochman and Koning have recently produced 630 randomized Pu-239 libraries. Alhassan is working on using these libraries for simulations of ELECTRA using the Serpent Monte Carlo model developed at KTH. This will allow for studying the influence of nuclear physics uncertainties on ELECTRA safety parameters aimed for in the Genius project.

It is important to point out that our work with TMC is aiming at much higher goals than that. Therefore, Henrik Sjöstrand, lecturer at UU agreed to spend more of his research time on the TMC and Genius project and will take over as the local project leader for the TMC work in 2012. We have also initiated the process to create positions for Koning and Rochman as adjoint professors at UU.

**Vasily Simutkin**, Ph.D. student within the NEXT project, defended his thesis in January. The title of the thesis is “Fragment Mass Distributions in Neutron-Induced Fission of $^{232}$Th and $^{238}$U from 10 to 60 MeV”. One of the results of the thesis is a study of the development of the symmetric fission component as function of incoming neutron energy. For thorium, this is the first such study at energies above 20 MeV. It was found that the increase in symmetric fission was more enhanced for thorium than uranium. Vasily also worked on improving the nuclear reaction model code Talys for fission, a work that he plan to continue since it is linked to the TMC work. Vasily currently holds a postdoc position at CENBG, Bordeaux, France.

**Riccardo Bevilacqua**, the second NEXT Ph.D. student, defended his thesis “Neutron-Induced Light-Ion Production from Iron and Bismuth at 175 MeV” in May. The measured double-differential cross sections are compared with state-of-the-art models and an extension of the so-called Kalbach systematics to higher energies is proposed. One specific outcome of the work is improved knowledge about the amount of tritium production in an ADS system. He is now working as postdoc at IRMM in Geel, Belgium.

**Ali Al-Adili**, working on neutron-induced fission studies of $^{234}$U in the range of 0.2 to 5 MeV at IRMM in Geel, Belgium, defended his licentiate in January. He was during 2011 financed by a stipend from IRMM. His final year at UU in 2012 will be financed with the help of SKC. Ali has already produced several papers on the experimental methods and first results from the fission studies.

**Andrea Mattera**, the first AlFONS Ph.D. student was hired in spring. The aim of the AlFONS project is to use the IGISOL facility in Jyväskylä, Finland, to measure independent fission yields in both thermal and fast neutron spectra. The first important step towards the planned measurements is the development of the neutron production target. The plan is to use either Be or W as target material for the 30 MeV proton beam, followed by water of plastic sheets as moderator. Andrea worked, together with Mattias Lantz and Andreas Solders on the design, addressing questions like cooling and target activation. Tests at TSL are planned for 2012 and should form the basis for Andreas licentiate thesis in spring 2013.

## Materials theory group

Some of the most demanding challenges that present, but also future, nuclear energy technology faces are related to materials and this is true from both educational and scientific perspectives. In a fruitful collaboration with the Division of Materials Theory at Uppsala University (professor Mattias Klintenberg) some of these challenges are addressed. At present time three Ph.D. students are involved in this collaboration.

### Senior personnel

No changes since last year.

### PhD student progress

**Lisa Bläckberg** is involved in a project that concerns detector materials (scintillator materials) that are used in, for example, the detection of radioactive Xe. Lisa's efforts are both experimental (ALD, microscopy, detection) and theoretical (electronic structure, molecular dynamics). This highly successful project is designed as a collaboration between the Division of Applied Nuclear Physics, the Division of Materials Theory and FOI. Lisa is financed by Uppsala University.

**Anna Shepidchenkos** work addresses questions related to local materials defects in semiconductor detector materials, e.g. CdTe and CZT. One of the more exciting findings by Anna is that these local defect levels can be manipulated (i.e. moved around on the energy scale) by applying small strains to the crystal. This could be very important because the local defect levels influence (worsen) the hole- and electron transport properties in the material. The latter is one of the most limiting problems of semiconductor detectors today. If time allow, Anna will also investigate if HPGe can be replaced by an appropriate choice of scintillator material at room temperature. It turns out that the theoretical limit in energy resolution for highly luminous scintillators with nearly perfect intrinsic linearity will often be enough, even for isotope identification. The project is a collaboration between the Division of Applied Nuclear Physics and the Division of Materials Theory.

**Erki Metsanurk** is in the process of becoming a Ph.D. student (he has been working with us since 1 October 2011). Erkis efforts are in the area of multi-scale modeling of materials in extreme environments such as high temperature, demanding chemical- or mechanical environment and/or environments with high neutron flux/fluence. The work is focused on molecular dynamics simulations, a very powerful technique that can address events at several length and time scales. Today's state-of-the-art is able to get up in the micro-scale region! Erki is now investigating interfaces between mismatched metals because of the fact that radiation induced defects can self-heal extremely efficient at these interfaces. The project is a collaboration between the Division of Applied Nuclear Physics and the Division of Materials Theory. Erki is financed by EC (the FP7 project RADINTERFACES).

All the projects briefly described above are extensive in many respects and there is a multitude of questions that remain to be addressed. The methodologies we use can be directly applied to materials challenges for nuclear energy technology. Examples are creep and swelling, interface optimization in ODS steels (including other advanced steels), friction and wear, as well as erosion and corrosion in, for example, demanding Gen IV environments.

## Doctoral theses

**Vasily Simutkin**: “Fragment Mass Distributions in Neutron-Induced Fission of $^{232}$Th and $^{238}$U from 10 to 60 MeV”. The thesis was successfully defended in January 2011 with Dr. Franz-Josef Hambsch from IRMM, Geel, Belgium, as the scrutinizer.

**Riccardo Bevilacqua**: “Neutron-Induced Light-Ion Production from Iron and Bismuth at 175 MeV”. The thesis was successfully defended in May 2011 with Prof. Anthony Cowley from the University of Stellenbosch, South Africa, as the scrutinizer.

## Licentiate theses

**Ali Al-Adili**: “Investigation of $^{234}$U(n,f) with a Frisch-grid ionization chamber”. The thesis was successfully defended in January 2011 with Prof. Richard Brenner from UU as the scrutinizer.

**Peter Andersson**: ”Optimization of Equipment for Tomographic Measurements of Void Distributions using Fast Neutrons”. The thesis was successfully defended in May 2011 with Dr. Rudi van Nieuwenhove, OECD Halden Reactor Project as the scrutinizer.

**Lisa Bläckberg**: ”Surface coatings as xenon diffusion barriers on plastic scintillators – Improving Nuclear-Test-Ban Treaty verification”. The thesis was successfully defended in December 2011 with Stephan Pomp as the scrutinizer.

## Masters theses

**John Johnsson**: ”Detailed $^{10}$B depletion in control rods operating in a Nuclear Boiling Water Reactor” – in collaboration with Westinghouse

**Filip Gottfridsson**: "Simulation of Reactor Transient and Design Criteria of Sodium-cooled Fast Reactors" – in collaboration with Vattenfall.

## Masters diploma work in progress

**Isbel Llerena Herrera**: ”Tool for calculation of residual heat in spent nuclear fuel” (prel. title) – the work is performed in collaboration with SKB and started in 2009.

**Christian Alex**: ”Safety analyses of power excursions in a nuclear reactor core in case of a falling control rod” (prel. title) – the work is performed in collaboration with FKA.

**Kristina Moberg:** “An investigation of fuel cycles and material flows for a lead-cooled fast reactor using Serpent” (prel. title). The work started in the fall of 2011.

## Bachelors theses

**Safdar Kargar**: ”Trendanalys av rapporterade störningar vid de svenska kärnkraftverken” – in collaboration with SSM

**Tony Björkman**: "Bränslestavsmätning med LabVIEW" – in collaboration with Studsvik Nuclear AB.

**Oscar Molin**: "Kalibreringsprogram for SSPS-test" – in collaboration with Ringhals.

**George Chahoud** and **Erik Vestin**: “Virtuell presentation av elmatning” – in collaboration with FKA.

**Patrik Berg** and **Johan Erlandsson**: “Analys av turbulensmodeller för CFD” - in collaboration with FKA.

**Niklas Ekström** and **Johan Grandin**: ” Jämförelsestudie av datoriserat underhållssystem FENIX” - in collaboration with FKA.

**Jakob Thorvaldsson**: “Analys av utbildningsmaterial för haveriinstruktioner för PWR” - in collaboration with KSU and Ringhals.

**Jorge Garrido**: “Elektronik och sensorers påverkan i radiologisk miljö” - in collaboration with KSU and Studsvik Nuclear AB.

**Johan Blomström**: “Tvärfunktion avseende STF” - in collaboration with OKG.

**Katja Göller**: “Spectroscopic ellipsometry for analysis of the surface layers of Ni-base alloys for nuclear applications” - in collaboration with Studsvik Nuclear AB.

**Faty Vanaki**: “Verifiering av indata till program avsedda för härdövervakning” - in collaboration with VNF.

## Bachelors diploma work in progress

**Lennart Strandman**: ”Analys av skillnader mellan internationell och svensk rapportering av inträffade händelser på kärnkraftverk” (prel. title) – in collaboration with SSM

**Mattias Lennkvist**: ”Fissionskammare - Modellering och beräkning” (prel. title)

**Björn Bartholdsson** and **Erik Hultgren**” Sfäriskt fotografi för interaktiv presentation av elmatning” – in collaboration with FKA.

**Johan Hyllengren**: “Analys av sprängbläck i säkerhetssystemen 361 och 362” – in collaboration with Rejlers.

## Publications

P. Andersson, H. Sjöstrand, S. Jacobsson Svärd, “Effects of proton escape on detection efficiency in thin scintillator elements and its consequences for optimization of fast-neutron imaging”, Nuclear Instruments and Methods in Physics Research Section A, 651(1), September 2011.

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K-H. Bejmer and C. Malm, "PWR fuel of high enrichment with erbia and enriched gadolinia", International Conference on Mathematics and Computational Methods Applied to Nuclear Science and Engineering (M&C 2011), Rio de Janeiro, Brazil, May 8-12, 2011.

L. Bläckberg, M. Klintenberg, A. Ringbom, H. Sjöstrand, "Effects of surface coatings on the light collection in plastic scintillators used for radioxenon detection" Nordic conference of Nuclear Physics, Stockholm, Sweden, June 13-17, 2011.

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More information about the Division for Applied Nuclear Physics is available at:

http://www.fysast.uu.se/tk/

# Research projects

Below, SKC relevant research projects are presented grouped by their respective university in alphabetic order, i.e., first Chalmers, followed by KTH and finally Uppsala University.

# Uncertainty and sensitivity analysis applied to the simulation of the Swedish Boiling Water Reactors

*PhD student: Augusto Hernández-Solís, Department of Nuclear Engineering, Chalmers University of Technology*
*Supervisors: Professor Christian Ekberg and Associate Professor Christophe Demazière*

## Background

In earlier days, the modelling of nuclear reactors, both for static and transient calculations, was very often performed using highly conservative tools. Such analyses were rather crude and only worked analytically for a number of simple cases. This conservatism was, among others, the result of limited computer power, which prevented using sophisticated models, especially on the thermal-hydraulic side. With the recent increase of cheap CPU power, advanced modelling methods are now in reach. The actual trend worldwide is to develop and use so-called Best-Estimate (BE) methods for nuclear reactor simulations. These BE methods are based on coupled (or sometimes integrated) neutronic/thermal-hydraulic calculations, where the interplay between the neutron kinetics and the thermal-hydraulics can be properly accounted for. This coupling thus makes it necessary to have detailed modelling tools on both the neutronic and the thermal-hydraulic sides. Although this coupling allows significantly improving the accuracy of the calculations, a full evaluation of the uncertainties associated to these BE methods is highly beneficial, in order to assess the reliability, the robustness and the fidelity of the simulations. The main advantage of uncertainty evaluation is to decrease even further the conservatism of the safety analyses, which can lead to a decrease of the safety margins and thus to a maximisation of the reactor output/utilization.

## Goals of the project

Developing an uncertainty and sensitivity analysis methodology is highly beneficial for many different reasons:

- For licensing and safety purposes: if a BE approach is used in connection with an uncertainty evaluation, a relaxation of the licensing rules is possible, leading to less conservative safety margins, and a maximization of the reactor output/utilization. This is of particular interest for the extensive program of power uprates in Sweden.
- For identifying important parameters: sensitivity analysis is the study of how uncertainty in the output of the model can be apportioned to different sources of uncertainty in the model inputs.

The goal of the present project is thus to develop a tool for uncertainty and sensitivity analysis applied to nuclear reactor simulations. This project exclusively focuses on the case of the Swedish BWRs. The simulation tool is based on the POLCA-T code. In this framework, Chalmers closely collaborates with the POLCA-T code developers (Westinghouse Electric Sweden AB). If successful, the last past of the project will be devoted to a generalization of the methodology to other types of reactors/codes.

## Organization

The work is performed by PhD student Augusto Hernández-Solís under the supervision of Professor Christian Ekberg and Professor Christophe Demazière. Dr. Arvid Ödegaard –Jensen also supports Augusto Hernández-Solís on some aspects of the project. The members of the reference group are: Ninos Garis, SSM, Henrik Nylén, Ringhals, Christer Netterbrant, OKG, Henrik Bergersen, FKAB, and Ulf Bredolt, Westinghouse.

## Methodology

Ringhals 1 (R1) is an ASEA-Atom Boling Water Reactor (BWR). 36 Traversing Incore Probe (TIP) detectors are permanently positioned within the core, and during each cycle a few TIP measurements at different burnup conditions are performed in order to estimate the actual spatial neutron flux throughout the core and thus, the spatial distribution of the power and thermal margins. Therefore, the accuracy of core simulator calculations along the cycle can be assessed by computing the difference between predicted and measured quantities; such a procedure builds confidence in using the simulator for the long term fuel loading plans. During the project work performed in 2011, discrepancies between spatial measured and calculated fluxes in R1 were used to perform an inverse uncertainty analysis on the spatial dependence of the input parameters of the Westinghouse POLCA7 core simulator. Such parameters are the macroscopic cross-sections and diffusion coefficients per control volume or node that are inputs to the discretized two-group diffusion equation. This analysis was carried out using Bayesian statistics, where, for a certain cycle, the frequency distributions of the simulator inputs at every assembly node are updated based on the error distribution of the spatial thermal flux. For example, results of the Bayesian uncertainty analysis of R1 cycle 13 are shown below. The cycle No. 13 database consists of POLCA7 predictions performed at 60 different equivalent full power hours (EFPH) conditions. Measured core properties are available for 11 of these EFPH points. Since there are 648 fuel assemblies (FAs) and each assembly is axially discretized with 27 nodes, the database contains information of the core simulator outputs and inputs (cross-sections and diffusion coefficients) for each and all of the 16200 nodes defining the core. Code outputs include the macroscopic cross-sections and diffusion coefficients values per node. Thus, a frequency distribution consisting of 60 samples for each of the simulator input parameters at each node can be assessed. Bayes theorem states that the frequency of occurrence of random variables can be modified if some evidence that depends on such variable is available. Applying this concept to our particular case, a thermal flux error or evidence distribution that depends both on the measurements and calculations can be computed for each node and defined as $P(e=\text{error}|\theta)$ (where θ represent the input parameters). Such distribution is used to update the simulator input parameters distributions (defined as $P(\theta)$) through the following equation:

$$P(\theta|e) = \frac{P(\theta)P(e|\theta)}{\int P(\theta)P(e|\theta)d\theta} \qquad (1)$$

where $P(\theta|e)$ is the so called updated (or posterior) distribution of the simulator inputs.

In Fig. 1, the uncertainty of the thermal diffusion coefficient (D2) along cycle 13 is shown for the top node of a given fuel assembly. It can be seen that the distribution is skewed and far away from being normal. In Fig. 2, the core radial distribution of the variance of D2 for the top nodes is shown. Thus, a spatial standard deviation of each parameter along the core can be appreciated with this method. Such results have been published in Hernández-Solís et. al. [3].

This technique is a good way of performing a realistic uncertainty analysis, since the probability density functions of the input parameters of a core simulator are assessed without the need of expert opinion. The uncertainty pattern for different burn-up points and during successive reactor cycles will be studied in the future, so that possible trends in the macroscopic cross-section models used in core calculations can be highlighted. This new methodology opens the possibility of validating macroscopic cross-section models used in core simulators, without any need of propagating the uncertainties in the nuclear data libraries via many tedious lattice physics calculations.

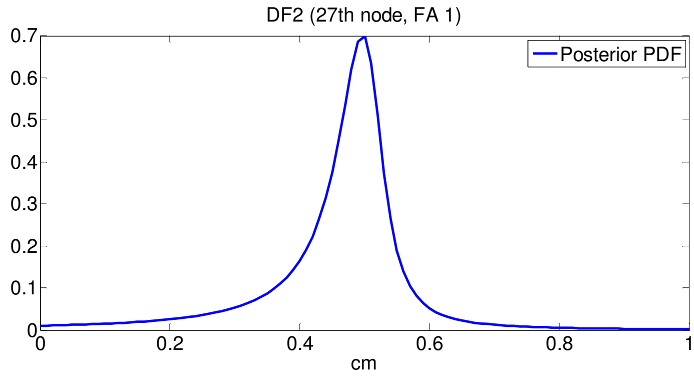
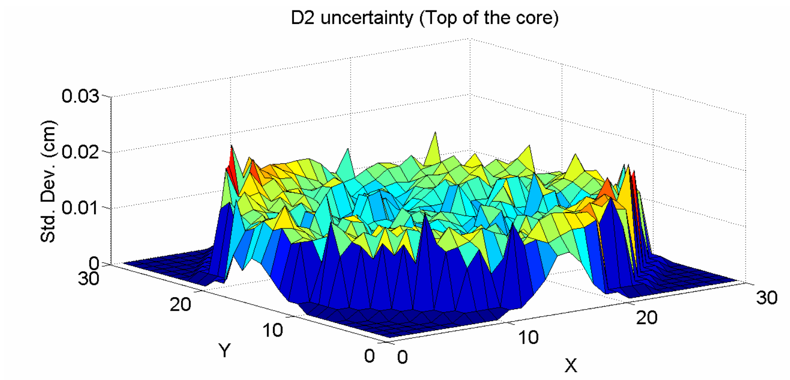



*Figure 1. Macroscopic cross-section uncertainties due to discrepancies in the thermal flux.*

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# Development of an integrated neutronic/thermal-hydraulic tool for noise analysis

*PhD student: Viktor Larsson, Department of Nuclear Engineering, Chalmers University of Technology*
*Supervisor: Professor Christophe Demazière*

## Background

The neutron noise, i.e. the difference between the time-dependent neutron flux and its time-averaged value, assuming that all the processes are stationary and ergodic in time, allows determining many interesting features of a reactor. The neutron noise can be used either for diagnostic purposes, when an abnormal situation is suspected, or for estimating a dynamical core parameter, whereas the reactor is at steady-state conditions. Noise diagnostics has the obvious advantage that it can be used on-line without disturbing reactor operation. Such a monitoring technique received further attention in the past few years due to the extensive program of power uprates worldwide. Some of main issues/concerns related to the operation of the plants at the uprated power level are the reduction of the safety margins, such as the margins to instability for BWRs, and increased vibrations (flow induced vibrations). When analyzing neutron noise measurements, the knowledge of the so-called reactor transfer function is of prime importance. This transfer function gives the space-dependent response of the reactor to perturbations that might be localized or spatially-distributed. As a matter of fact, most of the diagnostic tasks require the prior determination of the reactor transfer function, since the original perturbation has to be estimated from the detector reading (unfolding task).

## Goals of the project

The Department of Nuclear Engineering, Chalmers University of Technology, developed in the past a tool, usually referred to as a “neutron noise simulator” [1], allowing the determination of the reactor transfer function. This simulator is able to calculate the response of a nuclear core to perturbations expressed as fluctuations of the macroscopic nuclear cross-sections or of the possible external neutron source, assuming that the operating conditions of the reactor are stationary. The noise simulator was successfully benchmarked against analytical or semi-analytical solutions and was already used in many diagnostic tasks. This preliminary version of the tool was demonstrated to work properly and to give new physical insights for the interpretation of noise measurements. Nevertheless, the tool had some shortcomings, such as its inability to model closed-loop reactor transfer functions. The goal of the present PhD project was to further develop this tool to bring it to a level of development/sophistication/reliability similar with coupled time-dependent codes. The PhD project was thus aiming at developing a full-core integrated neutronic/thermal-hydraulic tool for noise analysis. This required extensive work both on the neutronic side (use of nodal methods) and on the thermal-hydraulic side (development of thermal-hydraulic models). The main advantage of the new tool is that the neutronics is based on the calculation of the actual Green’s function of the reactor, and that all the time-dependent equations describing the fluctuating quantities are Fourier-transformed. The applications of this tool are numerous for noise analysis. Due to the coupling to any code system, this tool could be easily applied to any PWR.

## Organization

The work was performed by PhD student Viktor Larsson under the supervision of Professor Christophe Demazière. Prof. Imre Pázsit and Dr. József Bánáti were also supporting Viktor Larsson on some aspects of the project. The members of the reference group were: Ninos Garis, SSM, Henrik Nylén, Ringhals, Farid

Alavyoon, Forsmark, Christer Netterbrant, OKG, and Camilla Rotander, Westinghouse. **The PhD work was successfully defended on October 21, 2011 at Chalmers**. The cross-examiner was Assis. Prof. Tomasz Kozlowski (Royal Institute of Technology), and the members of the examination committee were Adj. Prof. Klaes-Håkan Bejmer (Uppsala University), Assis. Prof. Sandra Dulla (Politecnico di Torino), and Dr. Erwin Müller (Westinghouse Electric, Sweden).

## Methodology

In 2011, a macroscopic thermal-hydraulic model was developed for both static calculations and dynamic calculations in the frequency-domain. Such a model was successfully validated against CFD calculations performed in FLUENT [7], and a one-to-one coupling to the neutronic model earlier developed within the project was established. Likewise, the coupled model was successfully validated against coupled simulations performed with RELAP5/PARCS [7].

The coupled model thus allows investigating the effect of perturbations in fully heterogeneous three-dimensional nuclear cores on both the neutron field and on the thermal-hydraulic field. Such perturbations can be artificially introduced in the system via fluctuations in the macroscopic cross-sections. Alternatively, such perturbations can be defined from physical grounds via the inlet conditions of the fluid (velocity and enthalpy/temperature). The developed tool is the only of its kind.

The tool was also used for investigating the possibility of estimating the Moderator Temperature Coefficient (MTC) of reactivity in PWRs using noise analysis [9].

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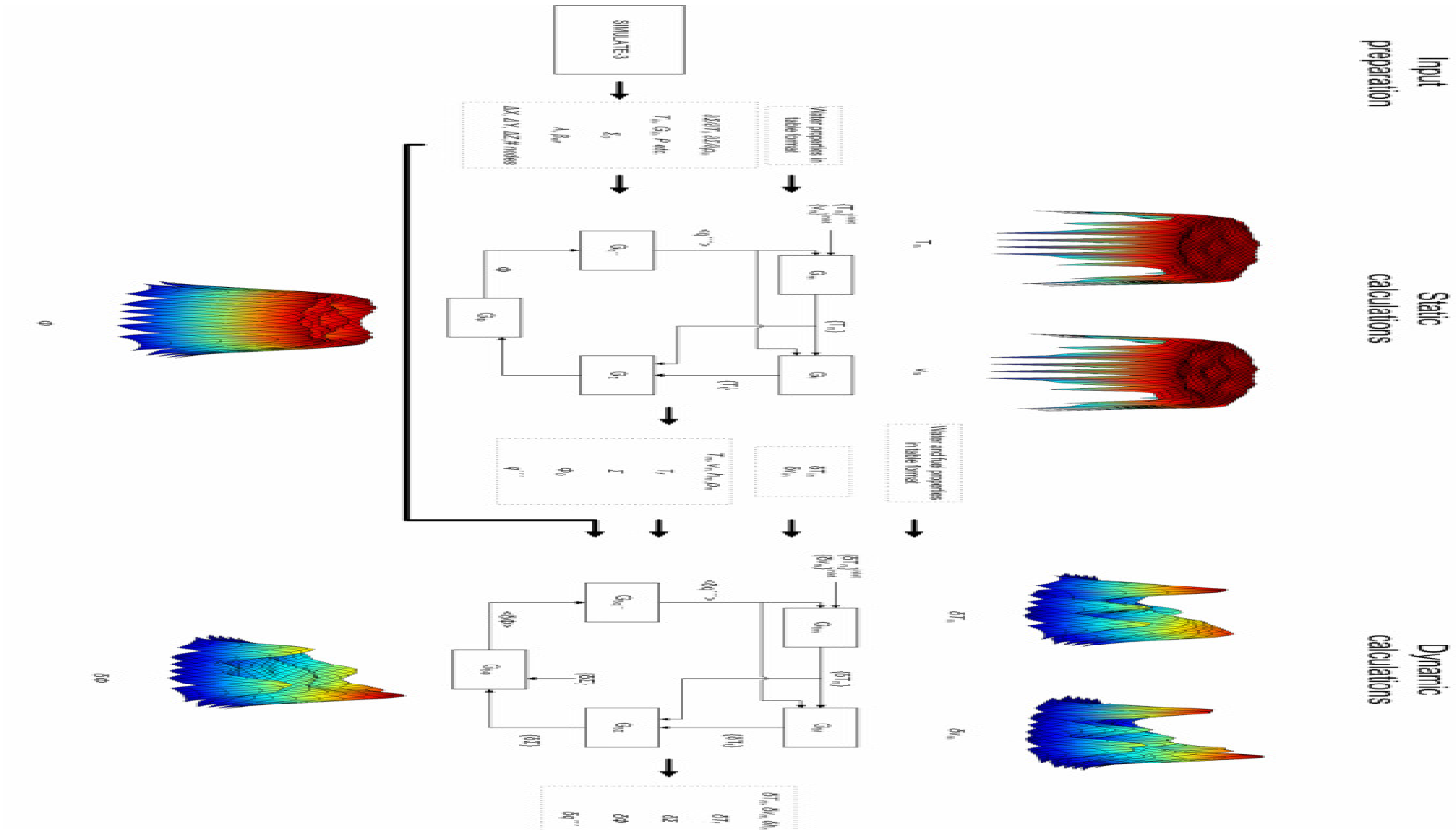


***Figure 1: Overview of the integrated neutronic/thermal-hydraulic tool for static and dycnamic calculations.***

# Reactor diagnostics with advanced signal analysis (READS)

*PhD student: Victor Dykin, Department of Nuclear Engineering, Chalmers University of Technology*
*Supervisor: Professor Imre Pázsit*

## Background

The goal of this project is the development of new and more effective methods for the diagnostics of the reactor core and the primary circuit. The work consists of two ingredients. One is the development of models of the perturbations and the core transfer properties that are more advanced than the ones in use, by physical modelling and a qualitative and quantitative study of the properties of the system response to various perturbations. The second is the elaboration of powerful inversion methods, by which the searched diagnostic parameters can be unfolded from the measured noise, assuming that the relationship between the measured noise and the inducing perturbation has a functional form described by the theory.

It is in this step where the new advanced signal analysis methods come into play. These can take into account that the behaviour of the system is often non-stationary and/or non-linear. The non-linearity has to be taken into account partly at the model construction stage, and partly at the inversion stage. In the latter case the non-linearity, and possible redundance in the measured data, can be handled by the use of artificial neural networks. There are in addition several other promising non-parametric methods emerging in the field which open new possibiities for extending the power of diagnostic methods.

## Goals

The goal of the project is to give contributions for method development both regarding advancement of modelling the system and the various normal and abnormal regimes, and to apply them to solve relevant diagnostic problems in collaboration with the power plants. The emphasis is put on understanding and diagnosing BWR instability, on the diagnostics of two-phase flow regimes, and on determining two-phase flow parameters in BWRs. The test of the methods is performed on both simulated signals as well as measurements taken in Swedish power plants.

## Organisation

The project is led by Prof. Christophe Demaziere, the main advisor, and by Prof. Imre Pázsit, examiner. Since the middle of 2011 Adjunct Prof. Henrik Nylén, as well as some of our foreign collaborating partners, primarily Assoc. Prof. Tatiana Tambouratzis, also support the project.

## Methodology and results

The project started during the summer of 2008 with the analysis of BWR stability in a model system driven by a driving force with a non-white power spectrum. As a continuation, the space-dependent noise, induced by propagating perturbations, i.e. by density and/or temperature fluctuations was investigated in 2009. In 2010 the project activity was mainly focused on the development of the Reduced Order Model for BWR stability analysis. This work resulted in two journal publications [1,2]. The results from the work performed since 2008 led to a licentiate degree in 2010.

In 2011 the research activity was split into two separate lines. The first one was mainly pursued on a continuation and finalizing the activities started in 2010. These activities consisted partly in a work concerning the investigation of the neutron noise induced by propagating perturbations by two-group theory in five different systems [3], and partly the investigation of past instability events, using a nonlinear analysis approach, such as Reduced Order Models (ROMs). During this stage, a fully consistent Reduced Order Model applicable for analyzing both core-wide (global and regional) and local instabilities was developed. The second line was primarily focused on the development of methods for void fraction (steam content) determination in a BWR core from neutron noise detector measurements.

Concerning the first project, the ROM developed in 2010 was significantly modified in such a way that the effect of local instabilities was accounted for in a simplified manner. For this reason, several artificial local sources whose space dependences were calculated via the CORE SIM tool, were introduced into the heat transfer submodel to reproduce the effect of local instabilities. The corresponding neutron kinetic submodel was also modified by introducing an additional feedback effect. The thermal-hydraulic submodel was kept unchanged. To provide a consistent coupled calculational scheme between the static and dynamic parts of the ROM, a special iteration procedure based on updating the cross-section data via CORE SIM was developed. In addition, a non-uniform power profile, representing the separate heat production for the single or two phase regions was incorporated into the ROM to provide the correct axial void profile. The newly developed ROM was applied to the analysis of the Formark-1 channel instability event of 1996/1997. Good qualitative agreement between the ROM simulations and real power plant measurements was observed. The corresponding results were reported in the following publications [1,2,4]. Some of the results of the ROM simulations for the Formark-1 instability event are presented in

Fig. 2.

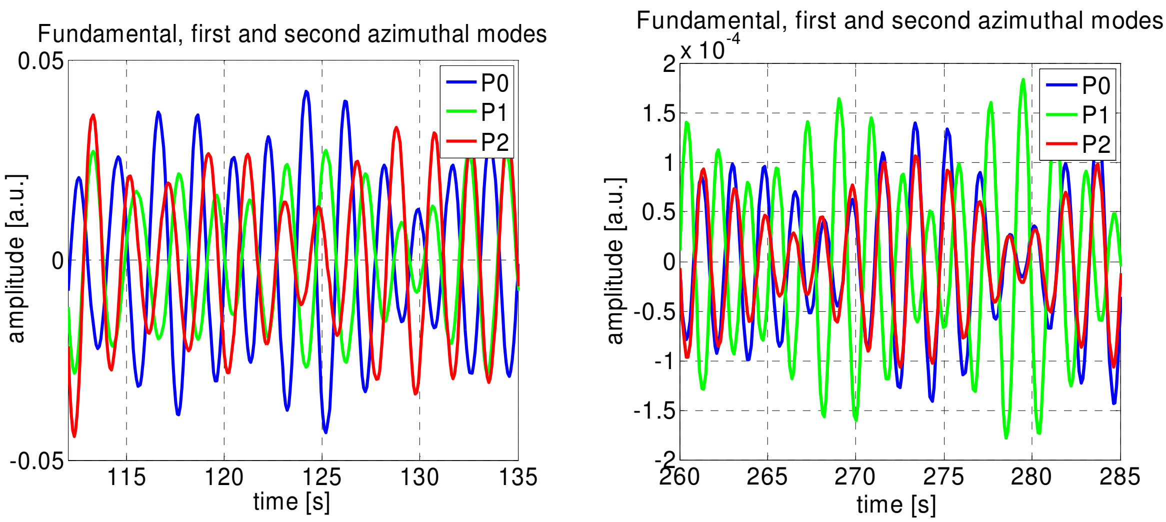


*Fig. 2 Time evolution of the induced neutron noise decomposed into the fundamental, the first, and the second azimuthal modes, as computed from the measurements(left figure) and from the ROM (right figure).*

The second research activity mentioned above, performed under the current year, concerned the reconstruction of the void fraction in BWRs from neutron noise measurements. In order to test different methodologies for steam content reconstruction, a Monte Carlo model of two-phase flow for simulating digital neutron noise detector signals was set up. To provide a realistic simulation of bubbly two phase flow, the bubbles were sampled randomly in such a way that the axial void profile corresponded to a real BWR one. The main advantage of the present model is that in addition to the simulated neutron noise signals, one has excess to the original void and velocity profiles since they are input for the model. Another advantage of the model is its applicability to non-stationary processes. Such a model provides a unique opportunity to test different methods for void fraction reconstruction. Among others, two methods, one based on the break frequency of APSD and another on the transit time approach were investigated. As an illustration of the ability of the model to simulate realistic cases, the APSDs calculated from measureemnts and from the simulations are shown in

Fig. 3.

The results in the above two topics resulted in two separate papers submitted to the coming PHYSOR 2012 conference in Knoxville, Tennessee, USA [5,6]. The thesis defence is planned to be held in September 2012.

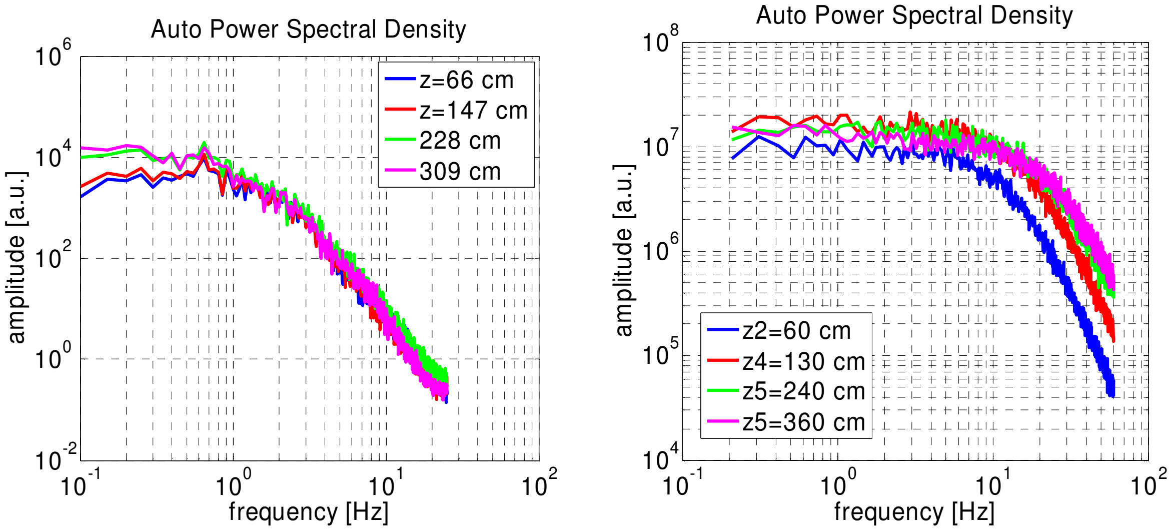


*Fig. 3 Auto Power Spectral Densities calculated form measurements (left figure) and from simulations (right figure.*

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# Neutron fluctuations in zero power systems and power reactors

*PhD student: Anders Jonsson, Department of Nuclear Engineering, Chalmers University of Technology*
*Supervisor: Professor Imre Pázsit*

## Background

Neutron fluctuations in multiplying systems can be divided into two classes which differ from each other what regards their origin, mathematical treatment and domain of dominance. One is the fluctuations in zero power systems with a constant material composition, where the noise is due to the branching (fission) process. The other area is high power systems, where the origin of the fluctuations is due to the temporal changes of reactor material (boiling, vibrations etc).

The subject of the present project is concentrated on the theory of the dynamics and reactor noise a particular reactor type, the so-called Molten Salt Reactor (MSR), which is one of the six selected Gen-IV types.

## Goals

Reactor systems with a moving fuel, such as the MSR, have kinetic and dynamic properties rather different from traditional systems. The goals of the project are to describe, analyze and interpret the dynamical behaviour of, and neutron noise in an MSR by solving the corresponding space-time dependent equations in adequate models.

## Organisation

The research in neutron fluctuations and stochastic theory is led by Prof. Imre Pázsit, who is also the leader of this SKC-project. There is a parallel on-going PhD project (READS) which is partially in the same area, and hence there are some synergy effects between the two projects.

## Methodology

The treatment of power reactor problems is based on setting up a model for the noise source and deriving a Langevin equation with the stochastic noise source as the inhomogeneous part of the equation. This equation is usually solved with the Green's function technique, which gives insight into the dynamics of the system in general. To calculate the noise induced by perturbations, one has to integrate the Green's function with the noise source. Due to the differring physics of the MSR (moving delayed neutron precursors), new solution methods and new kinetic approximations have to be found.

## Activities in 2011

The research in 2011 continued to be focused on the kinetics, dynamics and netron noise in Molten Salt Reactors (MSR). MSR is one of the six selected Generation-IV reactor types, in which the fuel is in a liquid molten salt state and it passes through the core and returns in a closed loop. The main difference between the MSR and a traditional reactor is that the delayed neutron precursors travel with the fuel and hence are not stationary. This changes the structure of the equations, but also the physics and the static and dynamic properties of the core. Some of the precurcors in addition decay outside the core, which leads to a loss of reactivity.

The work this year concerned three subjects: a) a comparison of the neutronic response to propagating perturbations of an MSRs as well as several types of traditional reactors; b) a new derivation of the reactivity (point kinetic) term of the noise, and c) an analytical solution to the MSR equations.

In order to clarfiy some remaining questions from last year's work, a study was performed on the effects of propagating perturbations in five different types of systems with stationary fuel but with different spectral properties, in two-gropu theory. This was a study of its first kind to see the spectral effects on the space dependence of propagation induced noise. The results were summarised in a journal publication [1].

The equation for the reactivity or point kinetic term of the noise in an MSR cannot be derived by using flux factorisation techniques in the space-time dependent diffusion equations. By starting with the Greens function of the full solution, it was seen earlier that it factorises it into space and a frequency dependent term, the latter containing a zero power transfer function. However, this result is only valid asymptotically at low frequencies. In order to be able to study the case of higher frequencies (and other problems which require a fully analytical solution), we have earlier introduced the approximation of infinite fuel velocity. In this approximation we were able to derive a full analytical form of the point kinetic term of the noise. It was found that in the solution, factorized into a space and a frequency dependent term, the latter cannot be given as a product of the reactivity and a zero power transfer function. This is the result of the phsyics of the MSR being more complicated than that of the traditional systems. This work was invited as a talk in a special session of the ANS Annual Meeting [2].

We have also introduced another approximation amenable for analytical solutions, i.e. the case of no recirculation of the fuel into the core (or rather, very long recirculation times, during which all delayed neutron precursors decay before returning into the core). In the course of this work we discovered that the full (non-approximated) one group homogenenous MSR equations have a fully analytic solution. This opens up the possibility of studying a number of cases at finite fuel velocities and returning of the delayed neutron precursors into the core. We have investigated the effect of the various boundar conditions (logarithmic versus vanishing of the flux at the extrapolated boundary) with and without delayed neutron precursor recirculation. The results were written up for a journal publication [3].

Some results, illustrating the last two items above, are shown in the figures below.

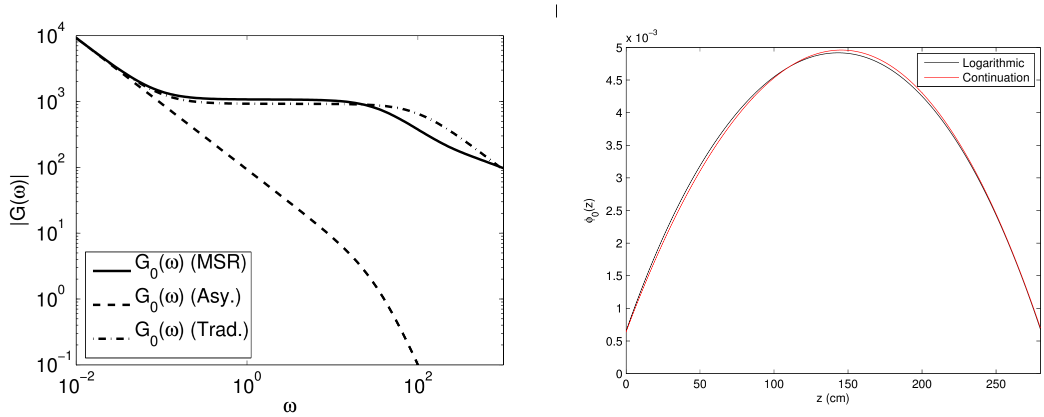


*Fig. 1. Left figure: Comparison between the exact point kinetic term for an MSR with infinite fuel velocity (full line), the asymptotic result from factorisation, valid for low frequencies only (broken line), and a traditional reactor with similar parameters (dotted line). Right figure:difference in flux between logarithmic boundary conditions and extending its natural curvatur (vanishing at the extrapolated boundary).*

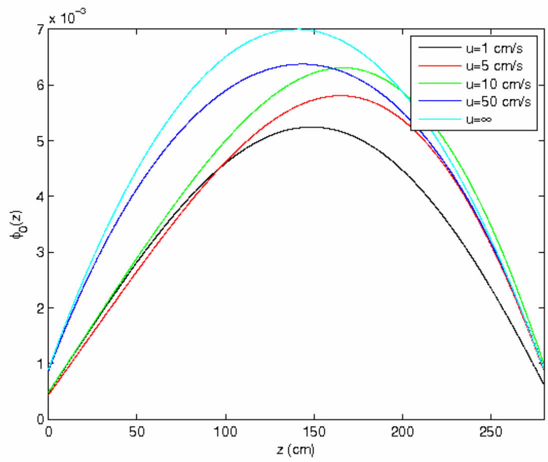


*Fig. 2. Neutron flux in an MSR with no recirculation, for different fuel velocities.*

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# Analysis of the statics and dynamics of thorium-based nuclear reactors

*PhD student: Cheuk Wah Lau*
*Supervisor: Professor Christophe Demazière, adjunct professor Henrik Nylén.*

## Background

There has been a renewed interest in the use of thorium as nuclear fuel in the recent years. Th-232 is the main isotope of thorium, which is 4 times more abundant compared with uranium. Th-232 is not fissile, but fertile and could be converted to U-233 by neutron capture and decay. U-233 is a fissile isotope, i.e. can undergo fission by thermal neutrons, and as such has a big potential in thermal reactors. It is estimated that the resources in thorium would be sufficient to last between 17000 and 35500 years when used in a thermal spectrum [1]. In addition to its abundance in nature, the use of thorium 233 does not lead to significant production of transuranic elements, as this would be the case in a traditional light water reactor loaded with 3-4% of uranium 235 (and thus 96-97% of uranium 238, which is the isotope leading to the production of transuranics). Despite such interesting features, the use of thorium in commercial reactors has been very limited compared with uranium, because of economical drawbacks in thorium-based reactors [2].

## Goals of the project

The PhD project aims at investigating the use of thorium in LWRs. Emphasis will be put on utilization of thorium to improve the safety margins in nuclear reactors. The first part of the project focuses on PWRs, whereas the second part of the project will most likely focus on BWRs. During the first part, an innovative use of thorium in PWR fuel assemblies was investigated. Namely, thorium was used for controlling the excess of reactivity at beginning of life, and flattening the intra-assembly power distribution, rather than converting fertile Th-232 into fissile U-233. The more even power distribution is of particular importance from an operational and safety viewpoint, since the margin to departure from nucleate boiling becomes larger.

## Organization

The work is performed by PhD student Cheuk Wah Lau under the supervision of Prof. Christophe Demazière, adjunct professor Henrik Nylén and Prof. Imre Pázsit. The members of the reference group are: Ninos Garis and Elisabeth Rudbäck, SSM, Urban Sandberg, Ringhals, Tommy Einarsson, Forsmark, Christer Netterbrant, OKG, and Per Seltborg, Westinghouse.

The Department of Nuclear Engineering is also supervising Klara Insulander Björk's PhD thesis on "Development of thorium based nuclear fuel for light water reactors", project that is carried out at Thor Energy, Oslo, Norway. Mutual interaction between these two projects is thus favoured.

## Methodology

Since the start of the project, emphasis has been put on thermal systems and on the investigation of the use of thorium as a “burnable fertile” species in PWRs. Today’s light water reactors use gadolinium as a burnable absorber in order to decrease the power in fresh fuel assemblies, as well as to allow a lower boron concentration [thus preventing possible positive values of the isothermal temperature coefficient of reactivity (ITC) and moderator temperature coefficient of reactivity (MTC)].

Since Th-232 has a higher absorption cross section than U-238, thorium could be inserted to replace some of the gadolinium. The use of thorium as a burnable fertile species in commercial PWRs is investigated in a collaborative project with Ringhals AB. More specifically, the design studies of the use of thorium as a burnable fertile species are conducting on the Ringhals-3 PWR core.

The project was divided into 3 phases. The first phase was to design a fuel assembly using CASMO-4E. The fuel has the same structural design as the traditional uranium-based fuel assemblies. The changes are only made in the composition of the fuel pellets, where some of the fuel pellets contain a mixture between uranium and thorium oxides. The uranium-thorium-based fuel assemblies were designed so that they achieve the same discharge burnup as the uranium-based fuel assemblies [3, 4].

The second phase of the project was to simulate the use of the uranium-thorium-based- and uranium-based-fuel assemblies in the core of Ringhals 3 in the first transition cycle, before reaching equilibrium. The core loaded with uranium-based fuel assemblies and uranium-thorium-based fuel assemblies are referred to as the Reference core and the Thorium core, respectively. The core safety and performance were assessed by the reload safety evaluation method, which is used by the Swedish Radiation Safety Authority to ensure that the reactor will operate safely during the whole cycle. The main benefit in the Thorium core compared with the Reference core is the reduction of the pin peak power in the core, as shown in figure 1 [5].

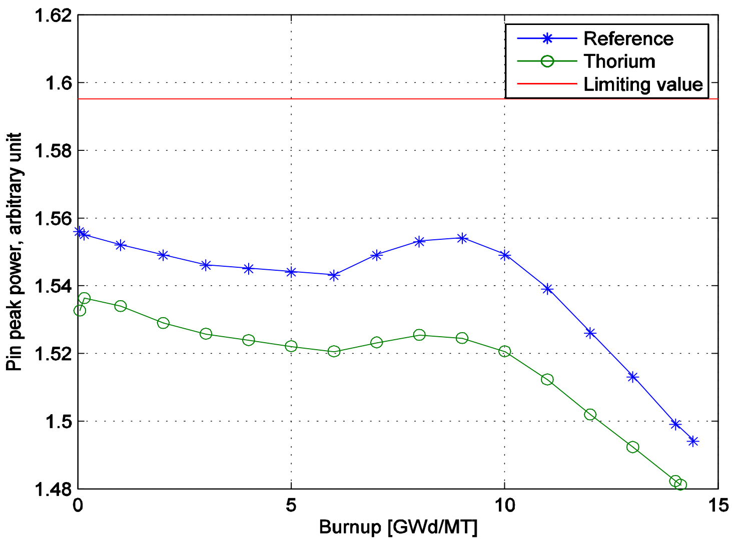


*Figure 1. Variation of the pin peak power for the Reference- and the Thorium-core (about one sixth of the core is using the uranium-thorium-based fuel assembly) as function of burnup. The reduction of the pin peak power in the Thorium core compared with the Reference core will decrease the possibility of fuel damage.*

The third phase of the project is to analyze the safety/performance parameters of the core with the uranium-thorium-based fuel assemblies reaching equilibrium cycles. This core will be compared with a core using traditional uranium based fuel assemblies at equilibrium. This third phase is currently underway.

Cheuk Wah Lau presented a conference paper in ICAPP 2011 in Nice and participated to the Young Generation Sweden during 2011.

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# Complexation of iodine species with organic molecules under severe accident conditions in LWRs

*PhD student: Sabrina Tietze[1]*
*Supervisors: Prof. Christian Ekberg[1]; Dr. Mark Foreman[1]; Dr. Henrik Glenneskog[2]*
*[1] Nuclear Chemistry, Chalmers University of Technology, Göteborg*
*[2] Vattenfall Power Consultant, Göteborg*

## Background

During a severe nuclear reactor accident in LWR`s such as Fukushima a large amount of short lived radioactive iodine isotopes will be released into the environment from the damaged $UO_2$ fuel. Dissolved and gaseous iodine species can react with organic molecules formed by the pyrolysis and radiolysis of e.g. paints and electrical cable plastics to form volatile organic iodine compounds such as methyl- and ethyl iodide. These cannot be retained with the same efficiency as elemental iodine with the present used safety installations in Swedish nuclear power plants. In Swedish nuclear power plants containment gases can be vented through a Venturi scrubber in case of a pressure increase in the containment building. The containment air is scrubbed with a sodium thiosulfate solution of alkaline pH before being released into the environment. This scrubbing is very efficient to trap elemental iodine ($I_2$) but it is known that the decontamination factor (DF) of the scrubber solution for methyl iodide (DF = 5) is about 20 times lower than for elemental iodine. Thus those species have a high potential to cause biological harm to humans when getting released to the environment. Since iodine is essential for the human body, it gets concentrated in the thyroid gland and thus increases the risk of cancer. Of high relevance are $^{131}I$ containing species. Those have a half-life of circa 8 days which is long enough for harmful bioaccumulation.

Concrete walls and floors in the containment of present operating Swedish nuclear power plants are painted with epoxy paints. These coatings have an influence on the iodine chemistry during a severe nuclear accident. From a safety point of view the paint is of interest since its components (resin, solvents) can react with iodine species. Thus the paint could act as a relevant “iodine depot” during a severe nuclear accident and reduce the amount of iodine released into the scrubber building.

## Goals

The two main projects within this research field are:

- Modification of the present used scrubber medium to increase the removal efficiency for organic iodides like methyl iodide

- Studies on the interactions of inorganic and organic iodine species (e.g. $I_2$; $CH_3I$; $C_2H_5I$) with epoxy paint films under light water reactor containment conditions

## Organisation

The work is performed by the Ph.D. student Sabrina Tietze under the supervision of Prof. Christian Ekberg, Dr. Mark Foreman and Dr. Henrik Glänneskog. The experimental work is performed at the Nuclear Chemistry department, Chalmers University of Technology.

## Methodology

- Modification of the present used scrubber medium

The research is based on the principle that a non-polar nucleophilic organic or highly lipophilic inorganic additive in the scrubber medium is more likely to absorb methyl iodide or to break the C-I bond than thiosulfate ions of the current scrubber solution do. Different potential reagents are tested in respect to their trapping ability for iodine and methyl iodide in shaking experiments and experiments performed in the FOMICAG (**F**acility set-up for **O**n-line **M**easurements of the **I**odine **C**oncentration in an **A**queous and **G**as phase) facility, which is a model of the Swedish BWR Oskarshamn 3 (schematic see Figure 1).

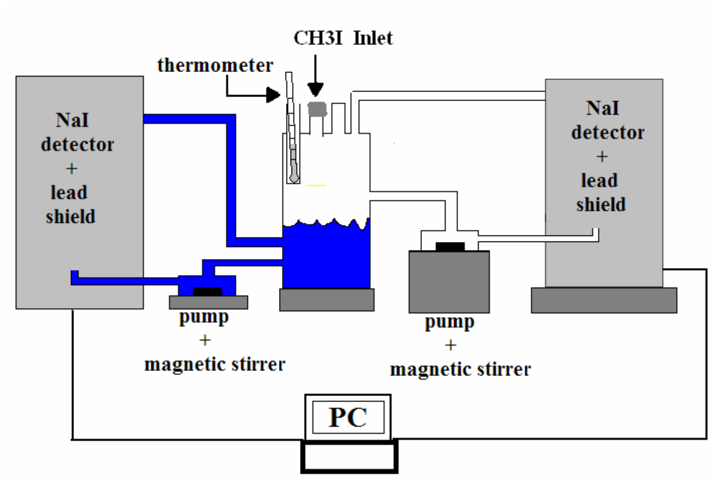



*Figure 1: Schematic of the FOMICAG set-up*

-Studies on the interactions of different iodine species with epoxy paint films in LWR containments

Paints are a mixture of pigments, organic polymers and solvents. Under the influence of radiation and heat degradation of the polymers can occur which can lead to the formation of short chained high volatile hydrocarbons. Those could form with elemental iodine gaseous organic iodides like methyl iodide.

At the same time the components of the paint can react with iodine species present in the containment air and bind them. Thus the iodine species become non-volatile. The uptake of different iodine species in dependence of temperature, γ-irradiation pre-irradiation of the paint and chlorine gas presence is tested since significant amounts of chlorine will be released from molten cable plastics used in the containment. Within the studies it is analysed with e.g. temperature-programmed pyrolysis experiments, gas chromatographic mass spectroscopic measurement methods if volatile species are formed from pure paint and if iodinated organic compounds are re-released from with different iodine species exposed paints under severe accident conditions (high radiation field, hot steam, high temperature) into gaseous phase. In aqueous leaching experiments on with iodine species exposed paint films the (re)release behaviour of ad/absorbed iodine species or new formed iodinated molecules from epoxy paint films into different aqueous phases (pH, temperature, chlorine impurities, γ- irradiation) is tested.

Within the research new paint samples and aged paint samples of the present at Ringhals used epoxy paint and paint samples from other nuclear installations are compared with for 20 years under real reactor conditions aged paint samples from the by now shut-down Swedish nuclear power plant Barsebäck.

## Results

- Modification of the present used scrubber solution

A series of organic and inorganic nucleophilic molecules like amines have been tested by adding them to the present used thiosulfate scrubber solution or to similar aquatic systems. No significant improved trapping efficiency compared to the thiosulfate solution could be reached. Methyl iodide is too hydrophobic and unable to react within the short residence time with the tested nitrogen and sulphur containing nucleophiles in the scrubber medium. Alternative scrubber media with an increased fraction of a hydrophobic organic dissolving medium containing the nucleophilic reagent have been tested and showed an improved trapping ability compared to the aquatic systems. A to thiosulfate similar fast and to other organic nucleophiles improved trapping effect could be obtained with phosphorus containing organics both in aqueous and organic based scrubber media.

Tributyl phoshine was found to be a suitable scrubber additive which allows a reduction of the sulphur content in the current scrubber medium and thus contributes to a reduced corrosion risk of the scrubber tank.
Tributyl phosphine is investigated in more detail (kinetics, thermodynamics, corrosion behaviour etc.) and proved for its industrial application.

-Studies on the interactions of different iodine species with epoxy paint films in LWR containments

A comparison of the composition of the epoxy paint used at Ringhals, other in nuclear installations applied paints and Barsebäck paint samples show significant differences in the containing solvents. Thus the reactivity with iodine species will vary significantly in different nuclear power plants and will depend on the last painting of the containment.

Performed experiments with self-synthesised I-131 labelled elemental iodine, iodine oxide aerosols, iodine chloride, methyl iodide, ethyl iodide, butyl iodide, benzyl iodide and allyl iodide have shown that those species can be absorbed by chemisorption in the at Ringhals 2 used epoxy paint coatings. A short aging process of one month at 100 °C led to a significant decreased uptake ability of the epoxy paint for methyl iodide. It could be shown that the presence of chlorine gas influences the uptake of methyl iodide. A paint film with chlorine molecules on its surfaces takes less methyl iodide up. Heating of the exposed paint samples up to 150 °C showed that a re-release of I-131 of absorbed organic iodine occurs mainly in form of organic iodine species and not as elemental iodine. Although it could be shown that in contact with aqueous phases of different composition even without influence of heat significant amounts of $^{131}I$ were re-released. The released iodine species were identified to be e.g. iodinated species of benzyl alcohol (plasticiser) and inorganic iodine ions.

The goal of the work is it to modify the paint composition to increase its retainability for gaseous iodine species. To achieve that goal different paint additives with high affinity to bind elemental iodine and methyl iodide are investigated.

# Study of Post-dryout heat transfer and internal structure of annular and mist two-phase flows in annuli with spacers

*PhD student: Ionut Anghel, Division of Nuclear Reactor Technology, KTH, Stockholm*
*Supervisor: Associate Professor Henryk Anglart*

## Introduction

Accurate prediction of thermal margins during operation of nuclear reactors has important safety and economic implications. On the one hand the power level in a nuclear reactor must be low enough to avoid a sudden deterioration of heat transfer due to the occurrence of the boiling crisis. On the other hand, the power should be high enough to promote a good efficiency of the plant. In nuclear reactors the post-dryout heat transfer should not appear during the normal reactor operation. During certain anticipated transients, however, the local conditions may deteriorate and the onset of dryout may take place. Consequently a proper model to calculate the maximum clad temperature and time history of the temperature distribution is required. To validate such models, appropriate experimental data, such as provided through this project, are needed.

## Objectives and methodology

The objective of this project is to investigate the post-dryout heat transfer and in particular, to study the influence of spacers on the onset of dryout and on the post-dryout heat transfer. The new post-dryout measurements were performed in two-side heated annulus 12.7x24.3.1x3650 mm using pin spacers and various flow obstacles, such as cylinders and unit cells of a commercial BWR grid spacer. The main thermal hydraulic parameters such as mass flux, static pressure, pressure drop over test section, wall temperatures and vapor temperature are measured under different flow conditions. The experimental matrix includes measurements of wall temperature distributions for single and two phase flow for both convective boiling and post-dryout heat transfer. The experimental results include as well pressure drop measurements for single phase flow in the test section in order to obtain the friction coefficient relationship and an expression for local pressure losses for flow obstacles. Investigations include the occurrence of dryout on the inner rod and the occurrence of dryout on the outer tube. Various mass fluxes, inlet sub-cooling values and system pressures have been studied.

## Results in 2011

Several objectives were achieved during year 2011. In the beginning of the year, main effort was devoted to carry out experimental tests in case of simple pipe with pins-spacer. In this regards, a simple tube with five levels of pins-spacer was employed. Over 100 experimental runs were carried-out. Variations in pressure (7 and 9 MPa) and mass flux (500-1200) kg/($m^2$s) were investigated and compare with similar experiment in a bare tube. The experimental part was carried out in parallel with the Licentiate thesis preparations. The Licentiate seminar was held in June 2011,[8].

A thorough analysis of experimental uncertainties has been performed. The validity of the one-dimensional model used in the calculation of the wall temperature on the "fluid" side is demonstrated in Fig.1, where the 1-D model was compared with an exact solution obtained with a finite element computational code. The distribution of resultant uncertainties of the heat transfer coefficient is shown in Fig. 2. As can be seen, the uncertainties vary between 2 % (for high wall superheats) and 16% (for low wall superheats, close to 30 K), confirming the excellent accuracy of the present experiments.

In total over 22000 experimental heat transfer coefficients have been obtained in this project, from which 1792 data points are in the post-dryout heat transfer regime. The measured data have been compared with major existing correlations for post-dryout heat transfer and it has been concluded that all of them significantly over-estimate the heated wall temperature. An example comparison between the present data and the Saha model (one of the best presently available models of post-dryout heat transfer) is shown in Fig. 3. In conclusion, there is a need to develop better models to predict post-dryout heat transfer and this will be the objective of the continued research in this project.

The results of measurements have been presented at such conferences as ICONE-17, IHTC-14, NENE-2010, [1-3], and as an invited lecture at the UK-Japan Seminar on Multiphase Flows, [4]. The results from the project were analysed and published in 2011 in two conference papers (ICONE-19, NURETH-14) and a journal paper (Nuclear Engineering and Design), [7]. Two additional journal articles and the defence of the doctoral thesis are scheduled to be accomplished during year 2012.

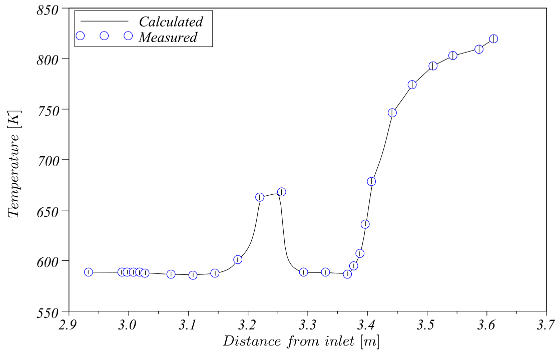



*Fig. 1. Calculated and measured wall temperature.*

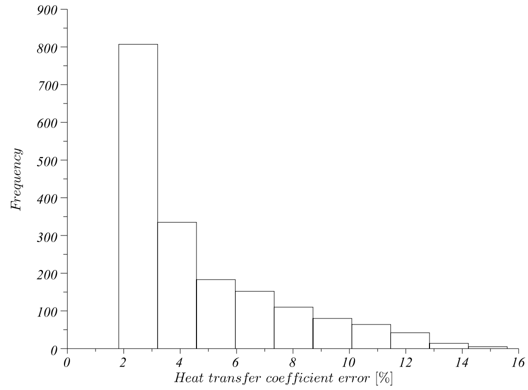
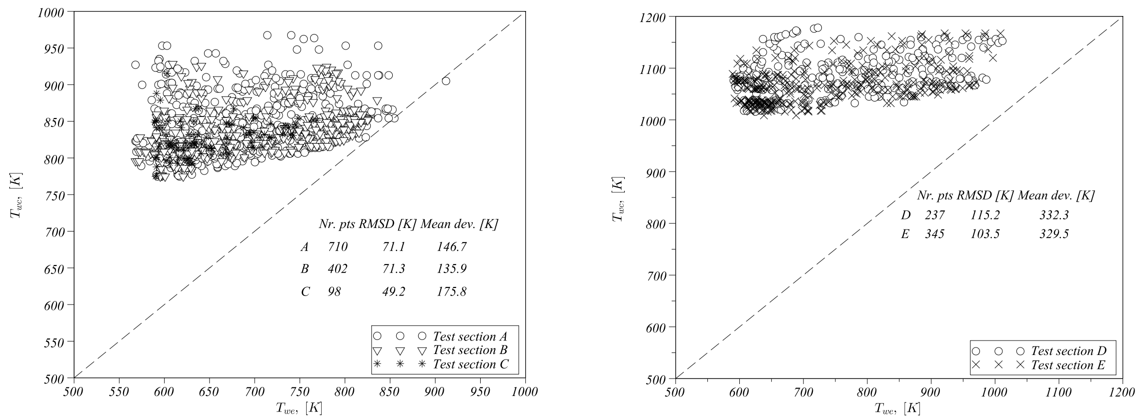



*Fig.2. Distribution of uncertainties.*




(a) (b)

*Fig. 3. Comparison of calculated (Saha model) and measured wall temperature: (a) in annular test section with pins (A), with pins and cylindrical obstacles (B), with pins and grid obstacles (C); (b) in tubular test section (D) and in tubular test section with pins (E).*

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# Influence of power distribution on dryout occurrence in heated channels

*PhD student: C.H.C.M. 't Mannetje (Carsten), Division of Nuclear Reactor Technology, KTH*
*Supervisor: Associate Professor Henryk Anglart*

## Background

Power distribution is one of the parameters that influence the flow and enthalpy distributions in heated channels. In particular (axial and lateral) power distribution in nuclear fuel assemblies is known to have a significant impact on the occurrence of Critical Heat Flux. This is especially important to fuel rod assemblies of Boiling Water Reactors since dryout (a limiting factor in BWR fuel assemblies) occurs in the exit region of the assembly, where the two-phase flow structure is very much influenced by the flow history, including the power distribution. This type of influence has been intensively tested in the past and a large experimental database has been obtained. Measurements have been performed in a variety of channel geometries and under a broad range of operational parameters. The objective of the current work is to increase the predictive capability through simulation of chosen flow conditions.

## Objectives and methodology

The objective of the present project is to develop a simple analytical method to describe the influence of axial power distribution on the thermal-hydraulic performance of nuclear fuel bundles. Such models are particularly needed in correlations for critical power (or dryout) in BWR fuel assemblies. The major difficulty stems from the fact that axial power distributions are always described with functions, whereas correlations are based on single-valued parameters. Experimental derivation of the function which describes the influence of axial power profiles on dryout is very costly, since a large number of such profiles have to be investigated. This motivates efforts to perform analytical studies on this subject.

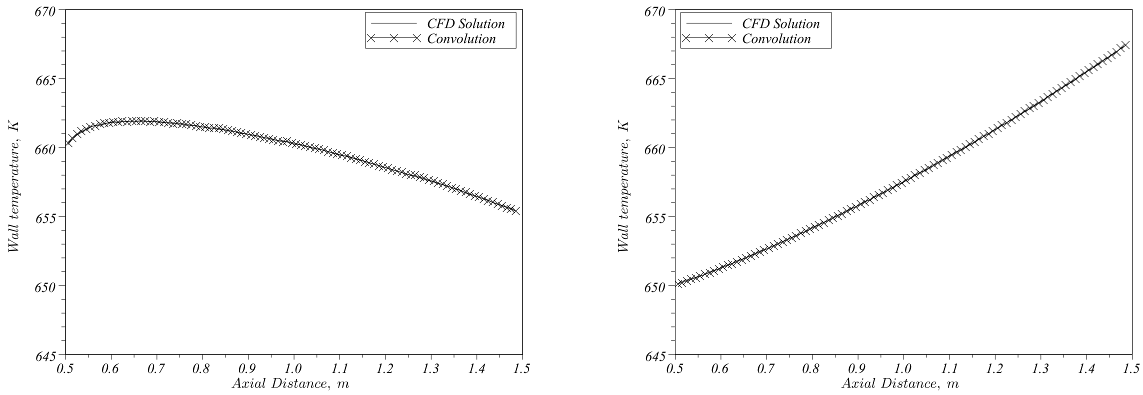
## Results in 2011

During year 2011 a new analytical expression has been derived to account for the influence of axial power distribution on the wall temperature distribution in single-phase flows. The present approach will be further developed for two-phase flows and dryout applications.

The new approach was derived and verified in references [1] and [2], where it was shown that the wall temperature distribution for an arbitrary axial power shape can be obtained from a convolution of the wall temperature distribution for the uniform axial power shape with the axial derivative of the power shape function. Figure 1a show three axial power profiles which were tested to verify the theory. The wall temperature distributions for the three profiles obtained from the CFD calculations are shown in Fig. 1b. Figures 2a and 2b show comparisons of wall temperature distributions obtained from CFD calculations and from the proposed analytical approach based on the convolution theorem. As can be seen, the agreement between the two methods is excellent. In continuation, an extension of the method to two-phase flows will be developed.

(a) (b)

*Fig. 1. Axial power profiles (a) and the corresponding wall temperature distributions obtained from CFD calculations.*




(a) (b)

*Fig. 2. Comparison of wall temperature obtained from CFD calculations and from the proposed method based on the convolution theorem: (a) for the linearly decreasing power, (b) for linearly increasing power.*

## Organisation

The work is performed by PhD student Carsten 't Mannetje under the direction of scientific advisor associate professor Henryk Anglart and scientific co-advisor Dr. Jan Dufek.

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# Development of a Method for the Treatment of Two-Phase Flow Patterns in Nuclear Reactor Thermal Hydraulic System Code

*PhD student: Viet-Anh Phung, Division of Nuclear Power Safety, KTH*
*Supervisor: Assoc. Prof. Pavel Kudinov*

## Background

Reactor thermal-hydraulic system computer code such as RELAP5 and TRAC play an important role in assessing safety analysis for nuclear plants, designing thermal-hydraulic experimental facilities, research reactors and commercial nuclear reactors. Main advantage of these codes is that they provide economical calculation tools in terms of computational time while giving reasonably good results for system steady-state and transients. For closure, the codes, however, employ correlations with empirical coefficients from different scale separate effect experiments. In addition, to simulate two-phase system behavior, a two-fluid model with time- and volume-averaged parameters of flows is used. The neglect of physical effects together with volume averaging result in a concern that the codes will fail in calculating complex system behavior such as strongly oscillating two-phase flows with rapid transitions among flow regimes.

In addition to the system codes, Computational Fluid Dynamics (CFD) codes have been already used in new reactor system design. However, 3-dimensional two-phase flow simulations using CFD for LWR thermal-hydraulics and safety analysis are still rare and facing many challenges. A vital challenge to CFD codes for predicting two-phase flow accurately and reliably is to develop methods to overcome the weakness of averaged model and to introduce information about flow patterns and flow regime history into consideration.

## Goals of the project

Because the correct prediction of multiphase flow is important for designing and especially for safety analysis of BWR plants, a treatment of two-phase flow pattern in nuclear reactor thermal-hydraulic system code is necessary.

First, the work in this project will focus on investigating the capability of the system code to predict two-phase oscillatory flows. A number of experimental facilities with relevant data will be modeled using the system code.

Then, based on understanding of sensitive parameters of the system code and operating region of thermal-hydraulic systems which strongly affect correct simulation result, a method for the treatment of two-phase flow pattern will be derived. The method will be developed and implemented into the system code for a better two-phase system simulation.

CFD codes can be used as another tool in evaluating system codes result, taking the advantage that 3-D CFD codes can calculate more precisely two-phase flows than system codes do.

## Organization

The work is performed by PhD student Viet-Anh Phung under the direction of scientific advisor Associate Professor Pavel Kudinov. The members of the reference group are: Ayalette Walter (SSM), Farid Alavyoon (Forsmark), Claes Halldin (OKG), Henrik Nylén (Ringhals) and Anders Andrén (Westinghouse).

## Results in 2011

The main part of the work in 2011 was further study of RELAP5 and TRACE capability in predicting natural circulation two-phase flow instability. Analysis continues to use single channel experiments at the CIRCUS-IV facility (Delft University of Technology). The experiments provide representative conditions for natural circulation boiling water reactors at low pressure.

Result shows that TRACE and RELAP5 can calculate relatively well natural circulation two-phase flow instability phenomenon at low pressure for some cases. Both codes overestimated amplitude of the oscillations. The codes can not calculate correctly two-phase flow regime during the instability. RELAP5 seems more tolerant to incorrect prediction of important parameters such as instantaneous flow regime.

To examine whether RELAP5 can provide better results with corrections in flow regime prediction, the flow regime transition boundaries in the code were changed so that the calculated instantaneous flow regime became closer to the observed experimental flow pattern. Result shows that all performed modification of the transition boundaries made results significantly worse.

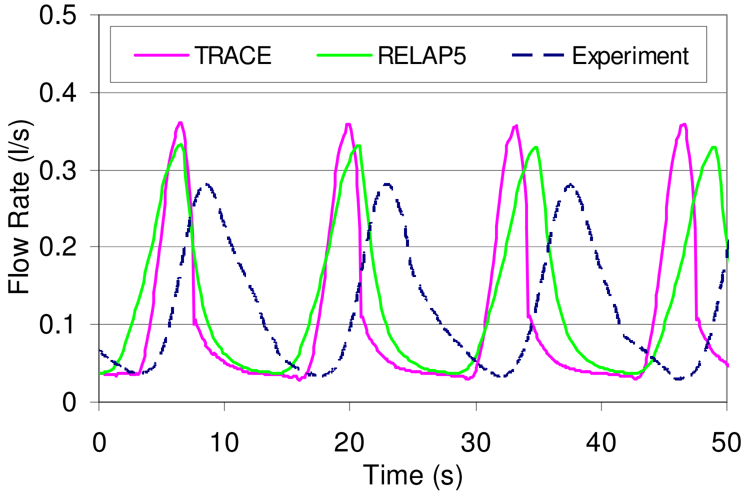


*Figure 1: Inlet flow rate during instability in CIRCUS-IV (Tin = 100 °C, high frequency oscillation)*

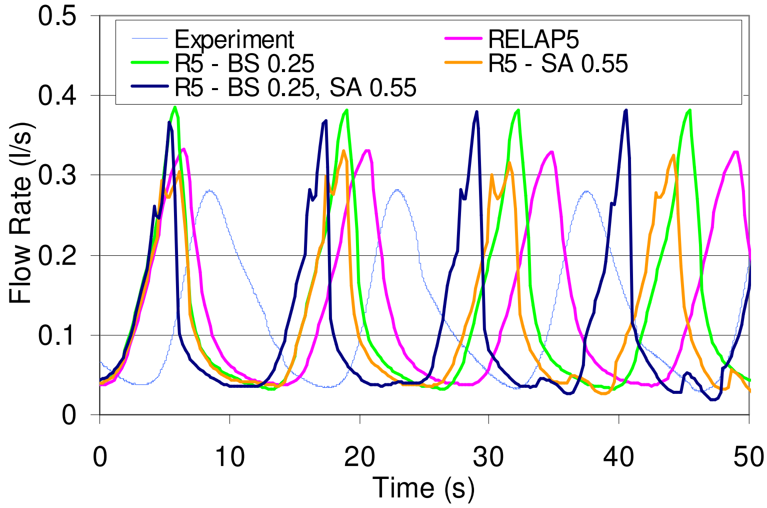


*Figure 2: Inlet flow rates from the experiment, calculations with the original RELAP5 and the code with modified flow regime transition boundaries*

The flow regime transition relaxation time model development is continued with calculation and analysis of the relaxation time in bubbly-to-slug flow regime transition based on experimental data from the literature. The estimated relaxation time will be used later to provide guidelines for the model development (identify area where flow regime transition should be corrected), and to provide data for model validation.

# Passive Safety Systems in Advanced Nuclear Power Plants: Design, Performance Analysis and Integrated Assessment

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*Supervisor: Assoc. prof. Pavel Kudinov*

## Background

Advanced nuclear power plants (Generations III, III+, and IV) are designed to meet increasingly stringent requirements on plant performance reliability, safety and economy. Toward the safety objective, it is paramount to ensure the plant's high resilience against external impacts and internal equipment malfunctions, as well as failures of the plant operator to timely perceive, and act effectively in, abnormal situations. A highly-publicized platform to develop such a resilient plant design (aka "fool-proof") is built on a so-called passive safety principle – a concept pioneered in a Swedish plant design during the 1980s known as PIUS (Process Inherently Ultimate Safe). Since then, passively-safe systems have successfully paved their way into design of several commercial nuclear power plants, such as Westinghouse's AP1000/AP600 and General Electric's ESBWR. The idea of passive safety is also considered in Generation IV designs, e.g. LFR (lead-cooled fast reactor).

In passive plants, both under normal operation and in emergency situations, Laws of Physics (e.g., natural circulation) and Forces of Nature (e.g., gravity) are used to drive reactor operation and ensure safety functions. All sounds great, simple and easy. However, the passive safety technology is only at the dawn of its development and deployment. Neither were all possibilities examined, nor were all implications understood. Although their components were tested part-by-part, the advanced passive plants – as a whole – have so far existed only on paper. The design's true merits and success can only be judged after decades of the plant operation. Yet, it is of both academic interests and practical significance that we understand the inner-workings and implications of the technology. Scrutinizing the designs and all safety

## Project Goals

Taken broadly, the proposed research aims to develop a theoretical basis and to advance computational methodologies for the design analysis and performance characterization of passive safety systems in advanced nuclear power plant designs.

## Research Approach

Both probabilistic and deterministic safety analysis methods will be addressed. The research should help establish a procedure to effectively search for credible scenarios and parameter ranges, when individually-tested passive-safety systems interact nonlinearly and fail to perform their pre-defined functions. Such a failure signifies the deficiency of the decomposition (divide-and-conquer) strategy adopted in system design and testing. Consequently, a vulnerability map for a passive system shall be devised for use in probabilistic treatments, similarly to the equipment failure rate of an active system. Case studies include Generation III plant (AP1000), Generation III+ plant (ESBWR) and Generation IV plant (a passive LFR). The proposed research is expected to lead to recommendations on improving passive safety systems and operating procedures for the advanced plant designs under consideration.

## Organization

The work is performed by Ph.D. student Kaspar Kööp under the direction of Dr. Pavel Kudinov. The contact reference group consists of Wiktor Frid (SSM), Pär Lansåker (Vattenfall) and Tomas Öhlin (Westinghouse).

## Work in 2011

Advanced methodologies for design analysis and performance characterization (mentioned in the project goals) need to be validated against experimental data. A large part of the work in 2011 was performed in the area of support calculations for TALL-3D facility design and optimization, as this facility will play an important role in validating proposed safety analysis methods for passive systems. Performed system code calculations were instrumental in defining the experimental parameters and validation matrix.

Further research in the area of system code input optimization using DPSA tool was also performed. The application prompted several key improvements in the used DPSA tool resulting in modifications to the GA-NPO software allowing the use of separate script safety goal functions. Now instead of evaluating local system parameters as goal functions, any external script can be used. For example, one can optimize the system code control logic variables to fit the known power curve of Oskarshamn-2 1999 event.

Preliminary work on automation of DPSA result grouping and characterization for decision making has also been performed. Key issues in grouping of large amount of scenarios have been identified and preliminary draft of the method presented.

## Publications

M. Jeltsov, F. Cadinu, W. Villanueva, A. Karbojian, K. Kööp and P. Kudinov "AN APPROACH TO VALIDATION OF COUPLED CFD AND SYSTEM THERMAL-HYDRAULICS CODES", The 14th International Topical Meeting on Nuclear Reactor Thermalhydraulics, NURETH-14, Toronto, Ontario, Canada, September 25-30, 2011, NURETH14-446.

# High performance nitride fuels for LWRs

*PhD Student: Pertti Malkki, Reactor physics, KTH*
*Supervisor: Prof. Janne Wallenius*
*Assistant supervisor: Dr. Mikael Jolkkonen*

## Background

Pure or mixed actinide nitrides feature several properties that make them highly suitable as nuclear fuel - high fissile density, excellent thermal conductivity and good thermal stability, to name only a few. However, they are susceptible to degradation by water/steam or atmospheric oxygen. Such degradation of sintered pellets is not noticeable under ambient conditions but accelerates with temperature.

Zirconium nitride is often considered as a solid-solution additive to further improve the thermal stability of e.g. PuN under normal or accident conditions in fast reactors, which is the type that ntride fuels are mainly being developed for. However, there is reason to believe that an addition of ZrN may also improve the stability of UN in water/steam, which might allow the use of ntride fuels in conventional LWRs.

The decomposition of a metal mononitride in water/steam follows the reaction

$2\ MeN + 4\ H_2O \rightarrow 2\ MeO_2 + 2\ NH_3 + H_2$ (1)

The present SKC project aims to find a way to slow down this reaction sufficiently that the fuel will be suitable for LWRs. The most likely method to achieve this is by spontaneous or active passivisation of the material. The formation of a dense $ZrO_2$-rich oxide layer at grain boundary level would serve this purpose, as $ZrO_2$ is known to be very resistant to dissolution not only in water but even in hot nitric acid..

## Previous work

A manufacturing route for high-purity nitrides of uranium and zirconium by hydriding/nitriding of the pure metals has been established. High-density reference pellets of the pure nitrides have been produced by SPS (Spark-Plasma Sintering).

## Some results during 2011

Upgrading of equipment

One electric press has been aquired and installed in a glove box under inert atmosphere. A graphite-heated high-temperature furnace with a capacity to reach 2650°C has been installed in the lab. With this added equipment conventional sintering can be performed as an alternative to SPS. Temperature monitoring during digestion is now performed with internal thermocouples in the pressure capsules, allowing more accurate determination of experimental conditions.

Manufacturing of mixed nitride pellets

SPS proceeds too rapidly (≈ 5 min) for solid solution to form by diffusion between dissimilar grains (mixture of UN and ZrN powders). A nitride powder already in solid-solution, (U,Zr)N, must be used to directly produce solid-solution pellets. Such a powder was produced by preparing (U,Zr) alloy and nitriding the alloy. A cyclic hydriding-dehydriding method was applied to ensure complete reaction of the alloy in the hydriding step (Fig. 1). It was confirmed that both the nitride powder and the sintered pellets were monophasic (U,Zr)N.

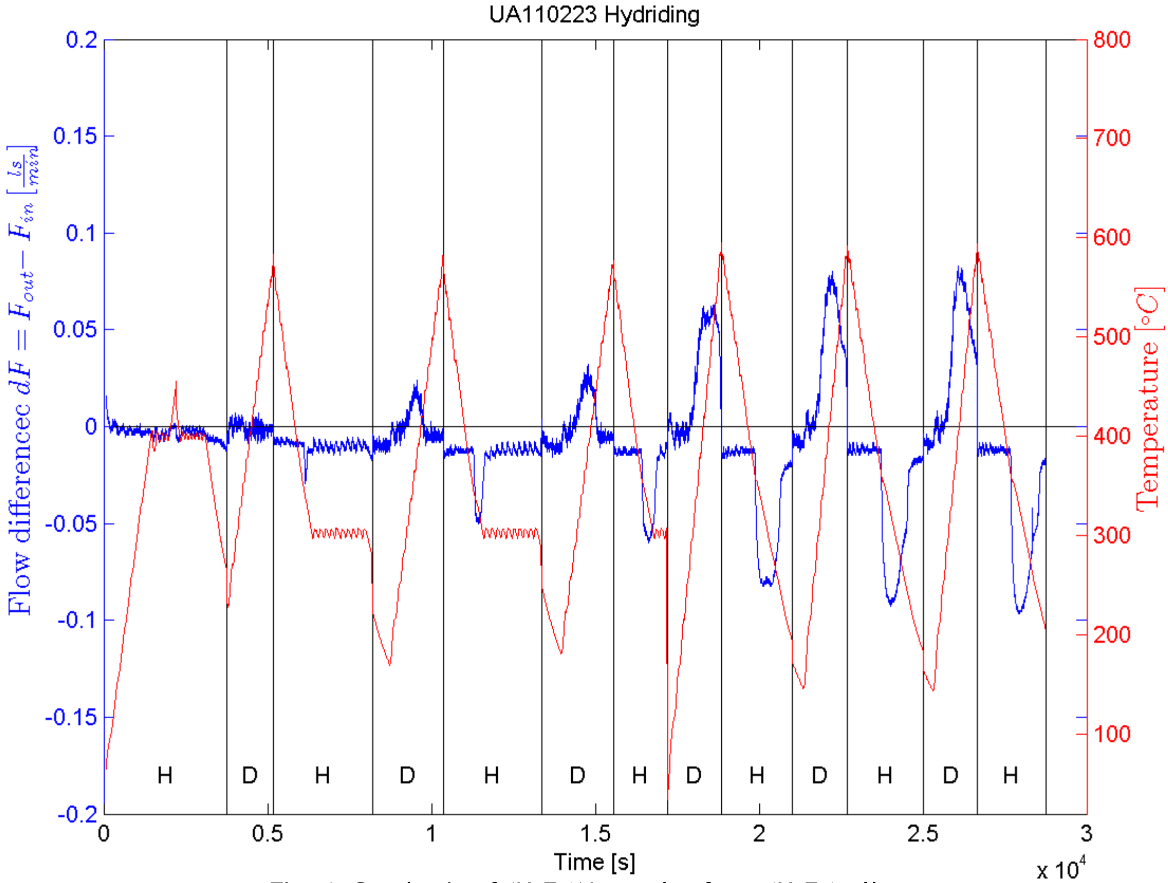


*Fig. 1. Synthesis of (U,Zr)N powder from (U,Zr) alloy*

An alternative method was tried, in which two-phase (UN,ZrN) pellets were produced by SPS sintering of a mixture of the two powders, and the resulting pellets were then annealed under argon at 1400 °C in the conventional sintering furnace. Also this method resulted in good solid-solution (U,Zr)N pellets (Fig. 2). This was confirmed by XRD analysis, showing that the peaks moved almost to the theoretical values predicted by Vegard's law.

Also new sets of reference pellets of pure UN and ZrN have been produced by SPS and conventional sintering.

Along another line of experiment, we have (in collaboration with prof. Gunnar Westin, Ångströmlaboratoriet, Uppsala) artificially coated nitride powders with a layer of $ZrO_2$, and made pellets from this material. The digestion experiments on these pellets are not yet concluded.

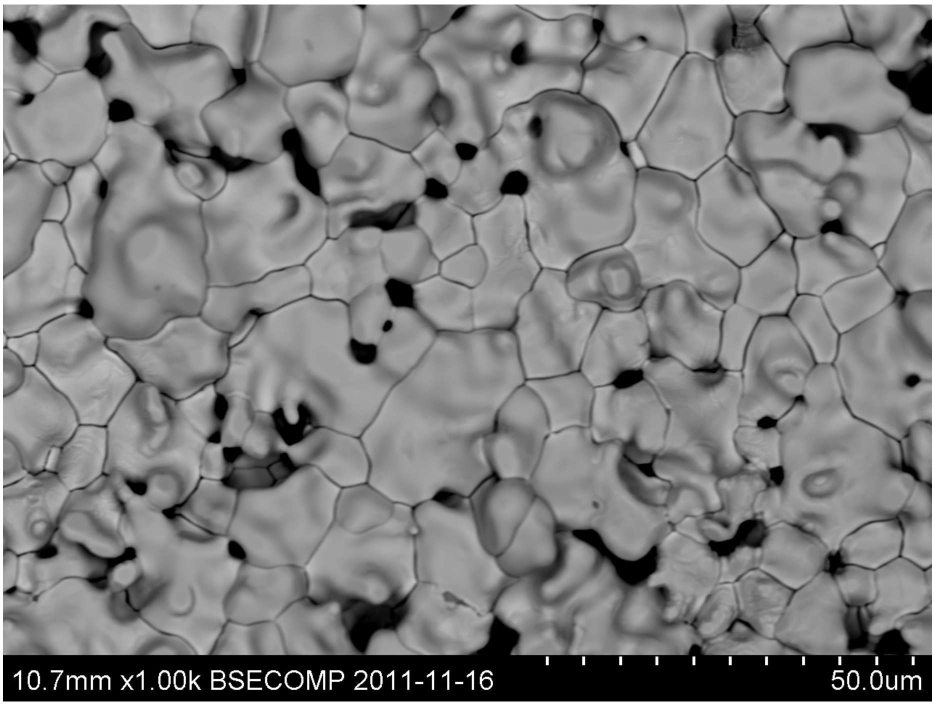


*Fig. 2. SEM of (UN,ZrN) pellet after annealing: Solid solution achieved.*

<u>Digestion studies</u>

High-temperature water/steam tests of nitride pellets have been performed during 2011 (Fig. 3). It was found that a dense UN pellet can withstand several four-hour runs at increasing temperatures, up to a temperature of 250°C. The final test was done at 300°C for four hours and resulted in disintegration of the pellet (Fig. 4). This result is in agreement with earlier studies reported in literature. The thus found limiting conditions for pure UN will be used as a reference test for the upcoming tests with (U,Zr)N pellets and surface-modified pellets.

*Fig. 3. Setup for digestion experiment*

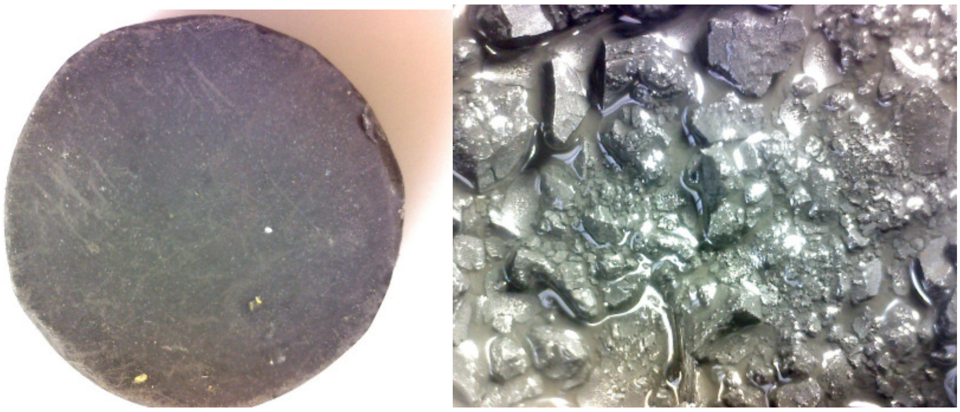

*Fig. 4. UN pellet after digestion at 250°C for 4 hours (left) and after digestion at 300°C for 4 hours (right).*

One complication with the digestion experiments is that once a ZrN-containing pellet reacts to some small extent with the originally pure water, according to reaction (1), the formed ammonia leads to an increase in the pH of the small volume of water in the digestion vessel. There is reason to believe that the high pH converts protective $ZrO_2$ to soluble $HZrO_3^-$ (Fig. 5), thereby accelerating the process in a self-reinforcing fashion, causing rapid and complete dissolution once a certain point is reached. This does not accurately reflect the conditions expected in an LWR where, assuming single pin failure, the large body of cooling water would efficiently dilute the ammonia formed. Thus our testing method may underestimate the times and temperatures that would lead to fuel pellet dissolution.

It is not practically feasible to actively monitor and adjust the pH in real-time during digestion, and adding sufficient amounts of a soluble pH buffer to the water before the start of the experiment would defeat our intention to study dissolution in pure water. We are therefore investigationg whether an initially insoluble substance, such as powdered ZnO, can be efficient as a hydroxide-ion scavenger and thus buffer the pH during digestion.

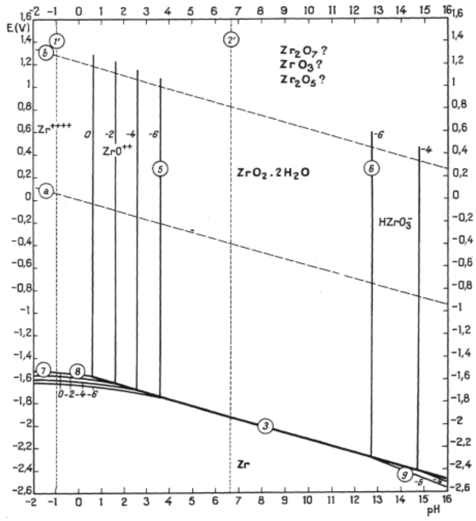


FIG. 1. Potential–pH equilibrium diagram for the system zirconium–water, at 25°C. (Considering $ZrO_2.2H_2O$.)

*Fig. 5. Pourbaix diagram for zirconium. From Pourbaix, M.: Atlas of electrochemical equilibria in aqueous solutions, 2d English ed., 1974. National Association of Corrosion Engineers, Houston, Texas.*

## Future work

• Evaluation of the efficiency of solid buffering compounds.
• If the pH buffering method is found successful, a complete new set of reference data from digestion of the pure nitrides under pH-controlled conditions will be collected.
• Digestion of (U,Zr)N pellets and surface-modified pellets.
• SEM analysis of surface and bulk of digested (but surviving) pellets.

A criterion of partial success (significant improvement over pure UN behaviour) has been established. One criterion of complete success would be if the degradation of suitably tailored nitride fuel pellets can be shown to proceed at a rate comparable to the degradation of $UO_2$ pellets. We will therefore manufacture $UO_2$ pellets of similar size and porosity, and study their behaviour under the same conditions.