# SKC Annual Report 2009

Swedish Centre for Nuclear Technology

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## Summary of 2009

SKC has streamlined its administration to release energy for financial growth through collaborations between the universities. The best result of this is the successful GENIUS Generation-IV project application to the Swedish Research Council that will provide 36 MSEK until 2012.

The nuclear education steadily grows in Sweden. A new masters programme in nuclear energy engineering and nuclear chemistry was started at Chalmers with 17 students attending. Uppsala University has renewed and increased its agreement with KSU (Kärnkraftsäkerhet och Utbildning) on industry training courses. Decision have been taken on a new bachelors´programme in nuclear engineering at Uppsala University, starting autumn 2010. The Swedish nuclear power plants sponsors the program with 30 MSEK over the first six years.

Several new positions for professors, lecturers and researchers are presently being filled. Research programs on materials mechanics and preventive nuclear safety are being started at KTH.

The Sigvard Eklund prize to the best PhD thesis of the year was awarded to Åsa Henning for her work on $^{14}C$ production in reactors. Petty Bernitt Cartemo won the prize for the best masters´ thesis for her work in the area of noise analysis. Thus, for the first time there were two female winners.

SKC has been evaluated in 2009, resulting in a very positive report.

## SKC Sponsors in 2009

SKC has been sponsored by the following organisations during 2009:

- Forsmark Kraftgrupp AB
- OKG AB
- Ringhals AB
- Swedish Radiation Safety Authority
- Westinghouse Electric Sweden AB

The total support from these organisations was 17 million Swedish kronor during 2009.

# 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 – meeting the needs in the nuclear renaissance

*A message from the director*

When looking back at my first year as SKC director, I feel gratitude to have had the chance to be present in the activity in this very hectic year. Less than a year ago, we decided to reduce the administration to free energy for growth-oriented activities. This new strategy has resulted in a series of accomplishments.

First and foremost, the new spirit of collaboration between the universities has lead to the remarkably successful GENIUS project application. The three universities formed a joint project on all aspects of Generation-IV research, a project the Swedish Research Council (Vetenskapsrådet) awarded in total 36 MSEK until 2012. This is by far the largest state support to novel reactors since 1980, and constitutes a raw model for future collaboration. In fact, the project kick-off was reported in prime-time TV (!).

A new Masters education in nuclear engineering with nuclear chemistry started at Chalmers in September 2009. This program was the most popular new education at Chalmers. Assisting the local team to successfully establish the new education program will be one of the most important challenges in 2010 and beyond.

A new Bachelor's program in nuclear technology was established at Uppsala University during 2009. The three Swedish nuclear power plants decided to jointly support the education with the largest industry sponsorship program in Sweden, 30 MSEK over six years. One fifth of this goes to KSU, the jointly operated education and training company, to conduct simulator teaching, training exercises in the Barsebäck training facility, etc. Thus, industry and academy join forces in a much closer collaboration than hitherto attempted in Sweden. It is my hope that this will provide a template for deeper integration of authority and industry into the academic teaching, and for a larger involvement of academic staff into industry and authority competence development.

SKC has been evaluated by Per Brunzell and Lars Högberg, who delivered their final report recently. In short, the evaluation is very positive. SKC started as an emergency activity in 1992, and over time the situation has improved dramatically. A successful generation change has been accomplished and education and research is thriving. The new spirit of cooperation between the universities is highly appreciated by the evaluators, as well as the SKC board. The evaluation results in fifteen recommendations on future development. It is a great source of inspiration to implement these suggestions.

The marketing activities at SKC have been dramatically increased. The SKC secretariat has attended all general student fairs at the three universities, as well as organized topical nuclear power information luncheons, evening meetings, etc. The SKC media coverage has reached all-time high. In addition, a plan for extending these marketing activities to universities without nuclear education of their own has been launched, exemplified by events at the universities in Umeå and Linköping that will take place in 2010.

The first SKC annual symposium was organized at Ringhals in September with 80 (!) participants. This is a new meeting place for industry, authority and academy. The symposium was very positively evaluated by the participants, which found the idea and most of the program very useful. Obviously, a first-time event is not free from improvement possibilities. For instance, next year the announcement will come earlier, and the organization of topical meetings will be firmer. In 2010, the symposium will have an unusual frame, because IAEA will organize its Technical Meeting on Nuclear Education and Training in parallel with the SKC annual meeting in Uppsala. The reason is that IAEA want to learn from the Swedish model on how to rejuvenate nuclear education.

The SKC director has been deeply involved in the creation of the European Nuclear Energy Leadership Academy (ENELA), an initiative by six European companies with support from the EU. ENELA will offer education that can become of large interest to Swedish nuclear power industry, to SSM, and to academic students.

New research activities are being started through adjunct professors. Research on materials mechanics of nuclear safety relevance, as well as preventive nuclear power safety, is expected to start during 2010 at KTH.

Last but not least, the political landscape has been subject to change in the right direction in 2009. The Swedish government announced in February that the phase-out is phased out. It will be allowed to build new reactors replacing the existing fleet. The situation is, however, volatile because the decision is not endorsed by the opposition. Nuclear power could therefore become an issue in the campaign preceding the elections in September 2010.

On the European scene, the situation has changed rapidly in the last two years. Both the commission and the parliament are now strongly pro-nuclear. The EC Strategic Energy Technology (SET) Plan, published in November 2007, pointed out nuclear energy as a key ingredient in the future European energy mix. During 2009, the EC has endorsed the Sustainable Nuclear Energy Technology Platform (SNETP) Strategic research Agenda, in which deployment of fast reactor technology, in particular a sodium-cooled fast reactor to be operational by 2020, is the top priority.

We are living in exciting times. New-build projects are no longer just dreams, they are already reality. In October 2009, Industrikraft AB – representing the large base-load electricity user in Sweden, i.e. paper, wood, metal and chemistry industry – and Vattenfall presented a collaboration agreement. Vattenfall shall suggest a plan to secure the availability of base-load electricity to a competitive price with acceptable environmental impact. Obviously, nuclear power is a prime candidate in the process. At about the same time, E.On presented their intention to study possibilites for a new reactor at the OKG site.

I sometimes get questions on whether Sweden is really capable of nuclear new-build. I am in now way pessimistic. Sweden managed to build twelve reactors in just thirteen years a generation back in time. In those years, there was no prior experience and very little nuclear industry beforehand; all had to be built up simultaneously. The present situation is dramatically more favourable. We foresee a slower replacement scenario, with not just one but a few years in between, the new-build will be by purchase from abroad and not through domestic construction, and we have an industry of more than 5000 people as starting point. SKC is ready to give its contribution to the Swedish nuclear renaissance!

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. Thus, the new model has been in operation during two years. It is, however, fair to say that it was during 2009 that the new organization founds its role and mode of operation.

Until 2007, SKC was primarily supporting 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. During 2008 and 2009, the turnover has been about 2 MSEK higher per year because of a backlog of unused resources from the previous SKC contract period. Starting 2010, the funding is down to the base-line of the contract.

It should be pointed out that about half the support is provided as a fixed based funding, and the rest is possible to re-distribute between the universities. There has, however, been very little freedom for re-distribution. The previous project-oriented system in reality locked a majority of the resources for the first two years, because the previous SKC guaranteed PhD student support beyond the end of the previous contract. In addition, there have been no formal process tools available for a re-distribution. From 2010 and on, there is some freedom in the funding. Accordingly, an evaluation has been conducted in 2009, partly to provide the information required, and an activity council has been formed in which such discussions can take place.

The funding organizations are:

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

During 2009, discussions with presumptive new supporters have been initiated. It is likely that new contributors will join SKC during 2010.

The SKC Board has included:

- Lennart Billfalk, Chairman, Vattenfall
- Lars Berglund, Forsmarks Kraftgrupp AB
- Magnus Antonsson, OKG AB
- Björn Sjöström, Ringhals AB (spring)
- Lennart Eckegren, Ringhals AB (autumn)
- Gustaf Löwenhielm, SSM
- Stig Andersson, Westinghouse
- Gustav Amberg, KTH
- Irene Kolare, Uppsala University
- John Holmberg, Chalmers

In addition, Jan Blomgren, Vattenfall, and director of SKC, has attended the meetings but has no vote.

# Chalmers University of Technology

*Overview of Activities in 2009*


Research and education in nuclear engineering is pursued at the Departments of Nuclear Engineering (Applied Physics) and Nuclear Chemistry (Chemical and Biological Engineering) in Chalmers. The research is pursued separately, but as from the academic year 2007/08, the specialized nuclear engineering course is given jointly by the two groups.

A main event of the year was the start-up of the international master's course in Nuclear Engineering, which 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.

### 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.
- 11 PhD students (6 with SKC support, 1 jointly with Nucl. Chemistry). 1 PhD exam and 1 licentiate exam during 2009.

### Highlights of the year:

Expanding the department with a new group in fusion research, lead by Assoc. Prof. Tünde Fülöp. T. Fülöp has during 2009 received, in a competition with 338 applicants, a special Research Position of the Royal Swedish Academy of Sciences (KVA).

Petty Bernitt Cartemo received the Sigvard Eklund Prize for best MSc thesis.

I. Pázsit and C. Demazière were invited to write a chapter on noise techniques in a coming 4-volume Handbook of Nuclear Engineering by Springer.

## Nuclear Chemistry

### Research in:

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

### Facilities and other data:

Laboratories for low activity α, β, γ experiments and activity measurements; hot cell laboratory for γ activity.

10 PhD students (2 with SKC support, 1 jointly with Nucl. Engineering). 3 PhD exams and 2 licentiate during 2009.

### Highlights of the year:

G. Skarnemark has written one chapter in "Handbook of Nuclear Chemistry".

C. Ekberg is co author of a OECD/NEA book on uncertainties in sorption modelling.

The EU-project CINCH dealing with international teaching in nuclear chemistry was approved.

Our 60-Co source is upgraded to give a dose of 23 kGy/h.

The building of a new nuclear fuel lab has started at Chalmers in collaboration with KTH.

## Education

In autumn 2009 an international master programme in Nuclear Engineering was started at Chalmers. 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 new 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.

The master programme has currently 17 students. There has also been a large interest in taking the introductory courses as elective courses from other master programs. One of the introductory courses has as much as 55 registered students. About 2/3 of the students are Swedish speaking. New study material, focusing more on the engineering approach and the application of nuclear reactors, had to be developed within a very short time. KSU is greatly acknowledged for helping with simulators, pictures and suggestions for study material. The amount of students taking courses in nuclear engineering has greatly increased and this has put high demands on the departments of Nuclear engineering and Nuclear chemistry.

The following study material has been specifically developed for the courses in the new master programme:

- A. Nordlund, “Introduction to nuclear reactors”, Chalmers University of Technology, 2009;
- C. Demazière, “Physics of nuclear reactors”, Chalmers University of Technology, 2009;
- C. Demazière, “Modelling of nuclear reactors”, Chalmers University of Technology, 2010.
- G. Skarnemark, “Solvent extraction”, Chalmers University of Technology, 2009
- G. Skarnemark, “Lanthanide, actinide and super heavy element chemistry”
- G. Skarnemark, “Radiopharmaceutical chemistry”, Chalmers University of Technology, 2010
- G. Skarnemark, “Radioecology and radioanalytical chemistry”, Chalmers University of Technology, 2010

There is a very high interest from the industry and several companies participate in lecturing in topics such as PSA, safety engineering, fluid calculations etc. Presently a large number of elective courses are under development.

The programme consists of 60 hp compulsory courses and 60 hp elective courses plus a 30 hp master thesis.

Nuclear chemistry is also taught in another Master programme where we had additional 19 students for the first course and 8 for the advanced course.

# 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 via very 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 Associate Professor Christophe Demazière. Dr. Paolo Vinai and Dr. Arvid Ödegaard-Jensen also support Augusto Hernández-Solís on some aspects of the project. The members of the reference group are: Oddbjörn Sandervåg (SSM), Henrik Nylén (Ringhals), Christer Netterbrant (OKG), and Ulf Bredolt (Westinghouse).

## Methodology

Since 2008, Chalmers has been part of the OECD/NEA BWR Full-Size Fine-Mesh Bundle Test (BFBT) benchmark, which offered a good opportunity to evaluate many of the POLCA-T code features in predicting steady-state and transient void fractions, pressure drops and critical powers under a wide range of system conditions [1]. In 2009, the validation process of the BFBT cases modelled with POLCA-T was enhanced with a statistical uncertainty analysis, where two different sampling strategies were employed: Latin Hypercube (LHS) and Simple Random Sampling (SRS).

LHS has the property of densely stratifying across the range of each input probability distribution, allowing a much better coverage of the input uncertainties than SRS. As a result, it is well known that if the obtained code outputs tend to form a monotonic function, the uncertainty assessment is much more efficient using LHS than SRS [2]. The aim of comparing both strategies is to show that even if the code outputs are non-monotonic, LHS still performs a more efficient uncertainty analysis than SRS. For instance, uncertainty analyses were performed both on the BWR assembly void axial profile prediction in steady-state, and on the transient void fraction prediction at a certain axial level coming from a simulated re-circulation pump trip scenario. In Fig. 1, the results show that ten replicates of the predicted void fraction mean (either in steady-state or transient conditions) have less variability when using LHS than SRS for the same number of calculations, even if the resulting axial void fraction profiles are non-monotonic. Due to this fact, the uncertainty limits achieved with SRS by running 410 calculations (sample size required to cover 95% of 7 uncertain input parameters with a 95% confidence), result in the same uncertainty limits achieved by LHS with only 100 calculations [3], as shown in Fig. 2. Using LHS is thus clearly advantageous.

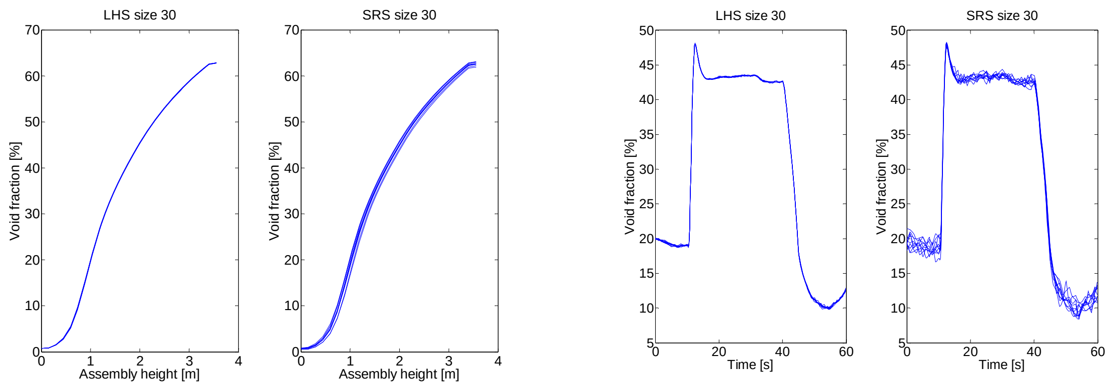


*Figure 1. Ten void fraction mean replicates with different sample sizes (steady-state and pump trip scenario).*

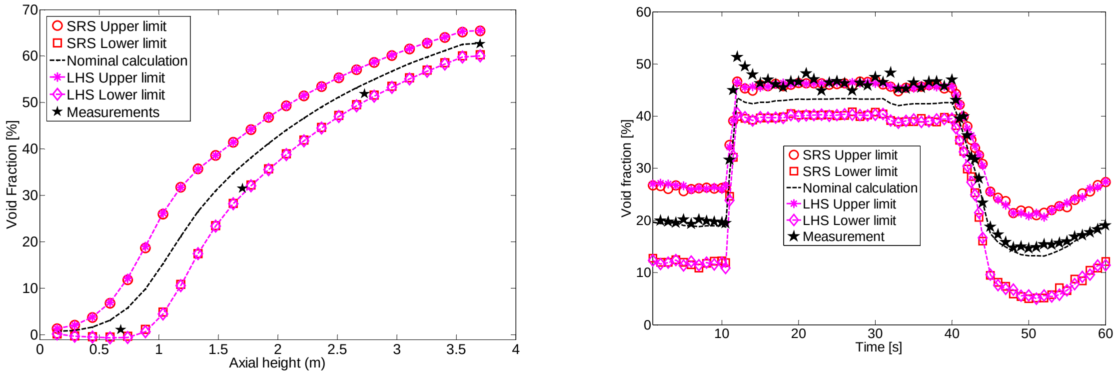


*Figure 2. Void fraction uncertainty analyses (100 LHS vs. 410 SRS steady-state and pump trip scenario).*

## References

1. A. Hernandez-Solis, P. Vinai, U. Bredolt. (2009), “An Assessment Study of the POLCA-T Code Based on NUPEC Data”. ANS Annual Meeting Transactions, 2009. Vol. 100. pp. 750-751.

2. J.C Helton & F.S. Davis. (2003), “Latin Hypercube Sampling and the propagation of uncertainty in analyses of complex systems”. Rel. Eng. & System Safety. Vol. 81, Issue 1.

3. A. Hernandez-Solis et. al. (2010), “Statistical uncertainty analyses of void fraction predictions using two different sampling strategies: Latin Hypercube and Random Sampling”. Submitted to International Conference on Nuclear Engineering (ICONE) 18, May 2010, Xi’an, China.

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

*PhD student: Viktor Larsson, Department of Nuclear Engineering, Chalmers University of Technology*
*Supervisor: Associate 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”, allowing the determination of the reactor transfer function [1]. 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 (see [2] for an overview of some of those). 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 existing tool has some shortcomings, such as its inability to model closed-loop reactor transfer functions.

The goal of the present PhD project is to further develop this tool to bring it to a level of development/sophistication/reliability similar with coupled time-dependent codes. The PhD project is thus aiming at developing a full-core integrated neutronic/thermal-hydraulic tool for noise analysis. This requires 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 would be 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 would be numerous for noise analysis. Due to the coupling to any code system, this tool could be easily applied to any of the Swedish nuclear power plants.

## Organization

The work is performed by PhD student Viktor Larsson under the supervision of Associate Professor Christophe Demazière. Prof. Imre Pázsit and Dr. József Bánáti are also supporting Viktor Larsson on some aspects of the project. The members of the reference group are: Ninos Garis (SSM), Henrik Nylén (Ringhals), Farid Alavyoon (Forsmark), Christer Netterbrant (OKG), and Camilla Rotander (Westinghouse).

## Methodology

In 2009, the work with the semi-analytical one-dimensional models used for determining the spatial dependence of the neutron noise was finished and an article was published ([3]). This study demonstrated that there were only negligible benefits in using higher order theories (such as $P_1$) for performing noise calculations on Swedish power plants.

The next step of the project was to use nodal methods for calculating the neutron noise. The nodal method chosen was the Analytical Nodal Method (ANM) which is a simple but yet powerful method. The programming language used for this was FORTRAN since the need for large matrices requires heavy computations. In addition, most codes related to the nuclear industry use FORTRAN. Furthermore, there are also extensive library sets with mathematical functions available in FORTRAN, for example LAPACK/ARPACK (these libraries are free of charge, have been tested for many years, and are thus reliable).

The implementation is almost complete; there are some numerical considerations yet to be evaluated. For the static problem, which is an eigenvalue problem, the Power Iteration Method is accompanied by the Implicitly Restarted Arnoldi Method. For the noise calculations, some variant of GMRES is under implementation.

The results so far are accepted for presentation at PHYSOR2010, which takes place in Pittsburgh in May, 2010.

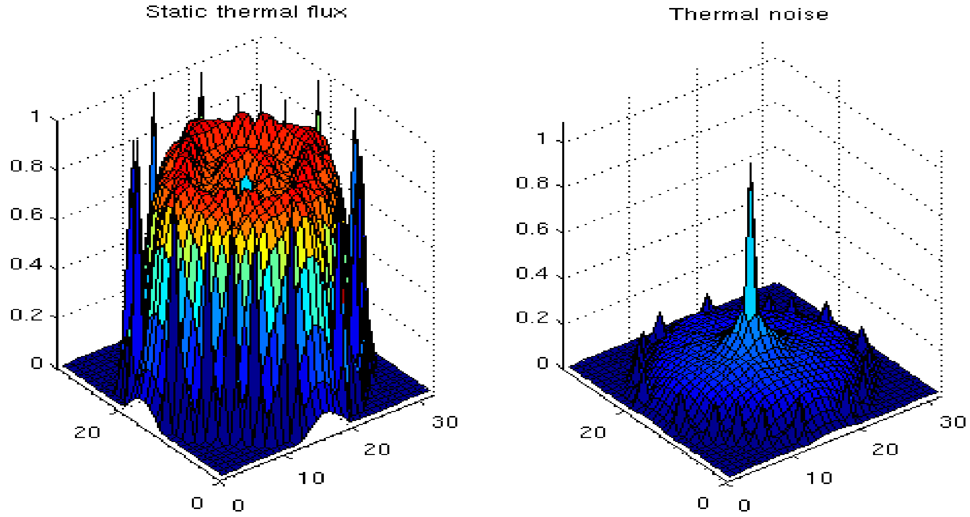


*Figure 1: The static thermal flux and thermal neutron noise calculated with ANM for a two-dimensional system.*

## Publications


1. C. Demazière, "Development of a 2-D 2-group neutron noise simulator," *Annals of Nuclear Energy*, **31**, pp. 647-680 (2004).

2. C. Demazière and I. Pázsit, "Numerical tools applied to power reactor noise analysis," *Progress in Nuclear Energy*, **51**, pp. 67-81 (2008).

3. V. Larsson and C. Demazière, "Comparative study of 2-group P1 and diffusion theories for the calculation of the neutron noise in 1D 2-region systems", *Annals of Nuclear Energy*, **36**, pp. 1574-1587 (2009).

4. V. Larsson and C. Demazière, "Neutron noise calculations using the Analytical Nodal Method," Submitted to *PHYSOR2010 – Advances in reactor physics to power the nuclear renaissance*, Pittsburgh, PA, USA, May 9-14, 2010.

# 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, by replacing the FFT based spectral methods with wavelet analysis, and also invoking fractal and bifurcation analysis in the diagnostic step. 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. Phenomena which need further development of models and methods include BWR instability, vibrations of internals and the core-barrel in PWRs, and diagnostics of two-phase flow regimes and determination of two-phase flow parameters in BWRs. Regarding the new signal analysis methods, we plan to investigate several new methods that were reported to be very suitable for various diagnostic applications. These include fuzzy logics, fuzzy inference systems, principal component analysis etc. whose suitability for diagnostic applications will be explored. The test of the methods will be performed on both simulated signals as well as measurements taken in Swedish power plants.

## Organisation

The reactor diagnostic group is led by Prof. Imre Pázsit, who is also the leader of this SKC-project. Assoc. Prof. Christophe Demaziere, senior lecturer, acts as a deputy adviser. Other PhD students at the department, and 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. In 2009 the activity was pursued on three different lines.

First, the work started in 2008 was completed and published [1]. After that, a second, related problem was tackled, namely the calculation of the space-dependent noise induced by propagating perturbations, i.e. by density and/or temperature fluctuations, travelling with the coolant of a PWR. This problem was investigated extensively several decades ago, but only in the point kinetic approximation, that is by calculating the effect of the reactivity fluctuations only. The recent renewed interest in the problem is partly related to one of the Gen-IV reactor types, the Molten Salt Reactor (MSR) in which such perturbations are expected to play an important role in the induced in-core noise. The MSR problem is being investigated in a parallel PhD project (Anders Jonsson), described also in this Annual Report. The case of the MSR is, however, more complicated, because not only the density perturbations, but also the delayed neutron precursors are moving in the core.

The case of propagating perturbations in a traditional PWR was therefore investigated partly for the inherent interest in the problem, and partly to expedite the interpretation of the results obtained in the MSR project. The problem was treated in a one-dimensional model using one-group diffusion theory, assuming a propagating fluctuation of the absorption cross sections along the spatial coordinate *z* in the form

$$\delta\Sigma_a(z,t) = \delta\Sigma_a(0, t - z/v); \qquad \delta\Sigma_a(z,\omega) = \delta\Sigma_a(0,\omega)e^{-\frac{i\omega}{v}z} \quad (1)$$

where $v$ is the propagation velocity and $\delta\Sigma_a(0,\omega)$ is assumed to be a white noise.

The calculations gave the interesting result that although both the point-kinetic and the pure space-dependent components have a smooth spatial form, their joint existence in the case when none of them is completely, leads to an interesting interference that manifests itself in a spatial oscillation of the noise amplitude. The reason is that the phase delay of the point kinetic component is constant in the core, whereas that of the space dependent component follows the phase of the perturbation, which changes linearly with the position (see Eq.1). The interference effect does not exist at very low frequencies where the point kinetic term dominates, but grows with increasing frequencies. This is illustrated in the Figures below.

The work was written up in a paper and it was submitted to a journal [2]. A paper was also submitted to the PHYSOR 2010 conference which was accepted for oral presentation and inclusion in the conference proceedings [3]. The results were also used for benchmarking the results of the MSR investigations, reported in another account in this Annual Report.

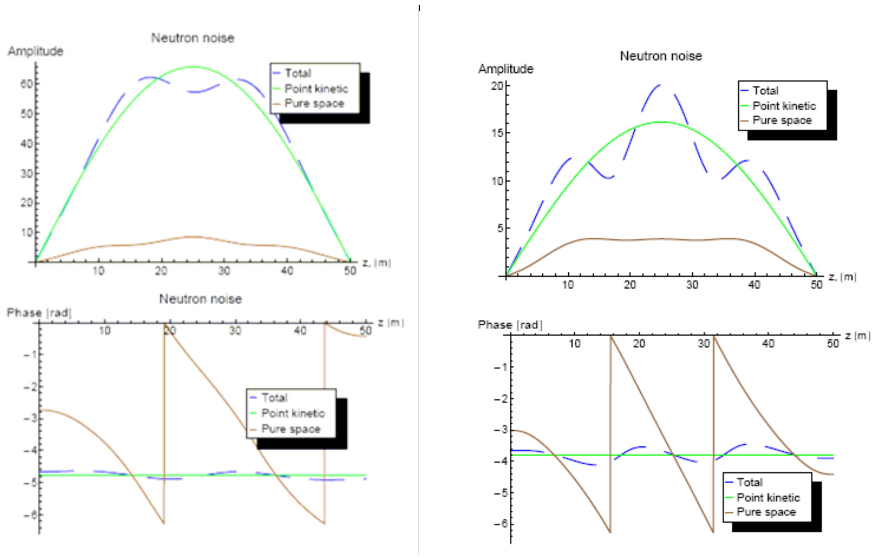


*Figure 1. The space dependence of the amplitude and the phase of the total induced noise together with its two components, the point kinetic and pure space-dependent terms. Left figure: $\omega$ = 7.8 rad/sec (corresponding to a maximum reactivity effect); right figure: $\omega$ = 10 rad/sec. It can be seen how the interference between the point kinetic and space dependent terms leads to a spatially oscillating amplitude of the total induced noise.*

The third and final subject pursued during 2009 concerned methods of determining stability parameters for describing BWR instability. Study of some Reduced Order Models was started, and methods of characterising stable and unstable oscillations by considering the fluctuations in the peak-to-peak interval in oscillating signals, measured in Swedish BWRs, was also started. This work is on-going.

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[2] Pázsit I. and Dykin V. Investigation of the space-dependent noise induced by propagating perturbations. Submitted to *Ann. nucl. Energy* (2010).

[3] Dykin V. and Pázsit I. Investigation of the space-dependent noise induced by propagating density fluctuations. To be presented at the ANS Topical Meeting PHYSOR2010, Pittsburgh, Pennsylvania, 9-14 May 2010.

# 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 recent interest in the theory of zero power noise is related to new applications, such as reactivity measurement in accelerator driven systems (ADS), and applications in nuclear safeguards for material control and accounting. Regarding power reactor noise, several of the planned future systems, such as some of the Gen-IV reactors, raise challenging questions of stochastic nature (random core composition etc). These require advanced stochastic modelling, both for a deeper understanding of the physics of the systems and for studying their noise diagnostics. This is also planned in the project.

## Goals

Research is planned to be conducted in the above described areas. There are many open questions in the applicability of the zero power noise methods, i.e. the master equation technique, for systems with temporally varying composition. Several of these, such as the use of the zero-power reactor methods for reactivity measurement in zero power systems, will be investigated in the project. Stochastic problems, kinetics and dynamics in systems that arise in the development of new reactor concepts, such as those containing a random distribution of fissile material as well as non-stationary fuel, will also be investigated.

## 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 methodology of zero power noise is based on the forward and backward forms of the master equation, also called Chapman-Kolmogorov equation. 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 eqation.

## Activities in 2009

The research in 2009 was concentrated on the kinetics, dynamics and netron noise in so-called 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.

In such a reactor the spatial inhomogeneities of the fuel concentration/burnup, propagating with the fuel in the core, constitute a strong noise source. The goal of the present work was to investigate the neutron noise induced by such perturbations. The problem was solved with the Green's function technique, where the properties of the system transfer properties can be studied separately from the final solution for the neutron noise, in which the noise source also plays a role.

In the work a number of novel and rather interesting features of the MSR were found, namely:

1. The amplitude of the noise in an MSR is larger than in an equivalent traditional reactor with solid (fixed) fuel. The reason is the decrease of the effective delayed neutron fraction through the loss of neutrons from precursors that decay outside the core during recirculation;
2. By calculating the frequency dependence of the noise in a small system where point kinetic behaviour is expected, we showed that the generally used empirical model for the zero power transfer function $G_0(w)$ does not correctly reproduce the ripples in the amplitude at frequencies corresponding to the recirculation time of the fuel;
3. An interference between the point kinetic and pure spaced dependent components of the induced noise was found which leads to noise amplitudes with spatial osciallations in the core. This is an effect similar to that observed in traditional PWR model calculations, in the parallel PhD project READS (see description elsewhere in this Annual Report);
4. An MSR retains a point kinetic behaviour for a higher frequency and larger system size as a traditional equivalent PWR. The reason is the extra spatial coupling (in addition to that represented by the neutron chains) arising from the movement of the precursors, which decay at a certain distance away from the point where they were created. The consequence is that the interference effect mentioned above prevails even in power reactor sizes in an MSR, in contrast to a traditional PWR where at such sizes space dependent effects already dominate;
5. Due to the directed flow of the fuel and hence the movement of the precursors, the MSR equations are not self adjoint even in one-group diffusion theory. We have constructed the adjoint equation and the static adjoint function for an MSR in one-group diffusion theory.

Some results, illustrating items 2 and 3 above, are shown in the figure below.

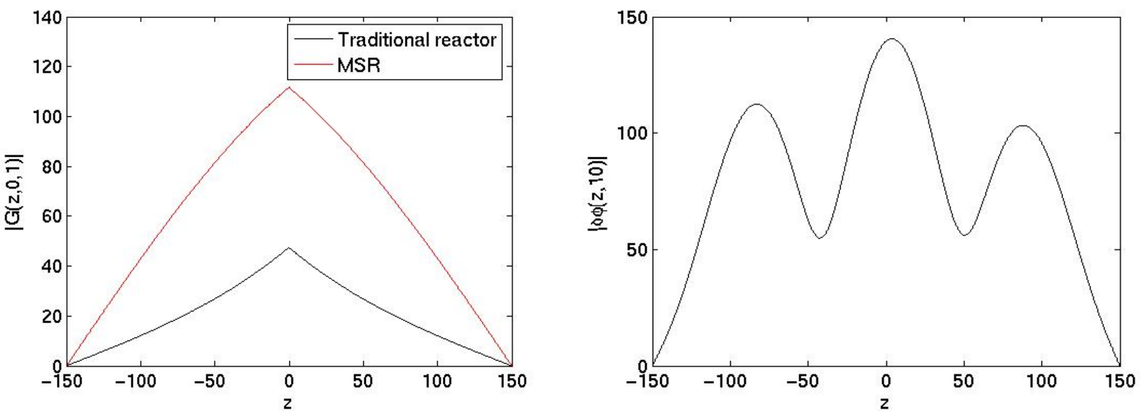


*Figure 1. Left figure: the space dependence of the dynamic transfer function $G(z,z_0,w)$ of an MSR and an equivalent traditional reactor for a central perturbation ($z_0$ = 0) at $w$ = 1 rad/s. The response of the MSR has a much larger amplitude and a more point kinetic shape (more resembling to the static flux which has a cosine form). Right figure: the space dependence of the amplitude of the noise induced by propagating perturbations of the absorption cross section with a core size of 500 cm and $w$ = 1 rad/s. The reason for the oscillations is an interference between the point kinetic term (same phase in the whole core) and the pure space dependent term (phase changing linearly in the core). Such an interference at this frequency exists in a traditional reactor only with a much smaller size.*

The work was written up in an article and submitted for publication [1]. It was also submitted and accepted for presentation at the PHYSOR 2010 meeting in Pittsburgh [2]. Both this paper and the conference paper regarding the parallel PhD project (propagating perturbations in a traditional PWR) will be presented in the same session with the research leader (I.P.) as session co-chairman.

## References

[1] Pázsit I. and Jonsson A. *Reactor kinetics, dynamic response and neutron noise in molten salt reactors*. Submitted to *Nucl. Sci. Engng* (2010)

[2] Pázsit I. and Jonsson A. *Reactor kinetics, dynamic response and neutron noise in molten salt reactors*. To be presented at the ANS Topical Meeting PHYSOR2010, Pittsburgh, Pennsylvania, 9-14 May 2010.

# Measurements with the pulsed positron beam at Chalmers

*Ph.D. Student: Petty Cartemo, Department of Nuclear Engineering, Chalmers University of Technology*
*Supervisor: Assoc. Prof. Anders Nordlund*

## Background

Positron based measurement techniques are used widely in defect physics due to the high sensitivity to micro defects, in particular open volume defects. The lifetime of positrons in a material, or the time positrons exist in a material before annihilating with an electron, is governed by the electron density in the material. In many types of micro defects the atomic density is lower than in the bulk material, resulting in fewer electrons and larger positron lifetime. When entering a material positrons are first slowed down and may migrate for a short time in the material. Since positrons are repelled from atomic nuclei, any region of lower than average atomic density has the effect of attracting positrons and trapping them and this can increase the positron lifetime.

The positron beam technique measures defects relative to a reference sample. The method is particularly well suited for resolving open volume defects, such as vacancies within a few micrometers of the surface.

At the Dept. of Nuclear Engineering, Chalmers University of Technology, a pulsed positron beam has been built and a technique for extracting positron life times has been developed. The beam has variable positron energy, which makes it possible to change the implantation depth of the positrons and thus perform a depth scanning.

Currently the beam is used for measurements of irradiated iron and steel for material application in present and future reactors. Measurements within the EU-project GETMAT have been performed and measurements are also planned within the GENIUS projects, for material modelling for Gen IV reactor applications.

## Goals

At present the main goal is to increase the spatial resolution in depth profiling of radiation induced damage in samples. In order to achieve this a special version of the Monte carlo code PENELOPE is used itogether with a series of experiments on thin (10-50 nm) Au foils on fused silica.

## Organisation

The work with the positron mean is carried out by PhD student Petty Cartemo and supervised by Anders Nordlund. The work within this field will, for 2010 be moved from SKC to GENIUS.

## Methodology

The time distribution of the annihilation gamma is measured using the beam and this time spectrum is a convolution of the beam resolution function and the positron decay in the sample. In order to extract positron lifetimes and intensities, the measured time spectrum has to be deconvoluted with the beam resolution function, containing the positron time distribution, which depends on beam parameters. Since the width of the resolution function is larger than the expected positron lifetimes for metal, it has to be defined well. The beam resolution function is determined by measuring on a well defined, defect-free sample with only one known lifetime component. Using the resolution fuction lifetimes and relative weights can be analyzed for irradiated samples using deconvolution.

The depth deposition profile as function of energy varied for different materials and this profile, depending on both the positron slowing down process and diffusion, has to be modelled carefully in order to interpret experimental data.

## Activities in 2009

In June 2009 we received 4 different FeCr alloys from the CEMHTI site Cyclotron in Orleans which differed significantly in the amount of Cr. So far the samples have not been irradiated and any defects that might occur in the crystal structure are assumed to originate from manufacturing procedures. In a later stage of the project the samples will be irradiated. Thereafter they will be remeasured with the Chalmers Positron Beam in order to analyze additional lifetime components which are due to irradiation induced defects.

The samples and a reference of pure iron were put in the beam line of positrons with kinetic energy of 5 and 15 kV.

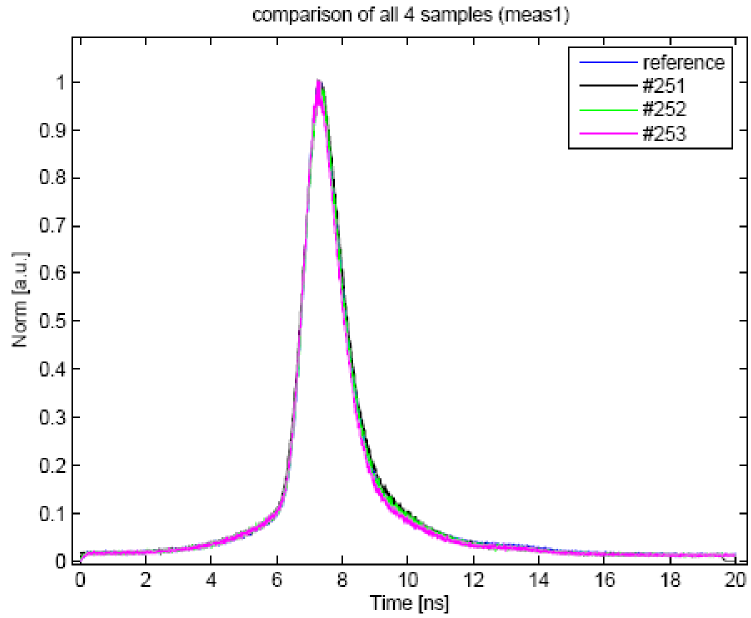


*Figure 1. Positron beam time spectra at 5 kV positron acceleration voltage.*

The over-all shape of such positron lifetime spectrum is given by some important beam parameters as for example chopper and buncher settings. The positron lifetime components of a sample are hidden in the falling slope of the spectrum.

In order to increase the depth resolution a series of the Au on fused silica samples were manufactured. Au has an expected lifetime of around 120 ps and the fused silica tured out to have to lifetime components, one of them well above 1 ns, thus making it easy to detect when positrons penetrated the topmost Au layer.

A special version of the Monte carlo code PENELOPE was also taken into use to simlulate properly positron deposition in the samples.

## Summary of the results

The measurements with the FeCr samples do not show significant differences between the reference used - annealed, pure Fe - and the FeCr samples. This in turn indicates that there is no significant vacancy concentration in the material.

A second set of measurements showed good repeatability and it is concluded that the samples are well suited for the Chalmers Positron Beam. The obtained data are independent of sample position and orientation in the beam. The results indicate that it will be possible to perform the measurements on irradiated samples and this has been reported in the GETMAT collaboration.

# Phenomenological analysis of the statics and dynamics of thorium-based nuclear reactors

*PhD student: Cheuk Wah Lau*
*Supervisor: Associate Professor Christophe Demazière*

## Background

There has been a renewed interest in the use of thorium as a nuclear fuel in the recent years. The main isotope of thorium is thorium 232, which is very abundant in nature. Thorium 232 is not fissile, but fertile. By neutron capture, its leads to thorium 233, which decays into protactinium 233, which itself leads to uranium 233 by decay. Uranium 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 232 compared to uranium 235 in commercial reactors has to be carefully checked in terms of proliferation resistance, radiotoxicity of the waste, and reactor safety.

## Goals of the project

The PhD project aims at investigating the use of thorium in nuclear reactors (both existing and future designs). Emphasis will be put on the best utilization of thorium (breeding, reduction of the radiotoxicity of the existing nuclear wastes from the existing fleet of LWRs, reduction of the weapons-grade plutonium stockpiles, proliferation resistance). The use of thorium will be studied in a phenomenological manner, i.e. the development of simple comprehensible models will be preferred to the use of existing sophisticated computational tools. The advantage of using analytical models is that they favour physical understanding of the system.

## Organization

The work is performed by PhD student Cheuk Wah Lau under the supervision of Associate Professor Christophe Demazière. Prof. Imre Pázsit, Dr. Henrik Nylén, and Dr. Jan Dufek also support Cheuk Wah Lau on some aspects of the project.

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

The student will first collect and review the existing literature on thorium. In addition, the development in India with respect to thorium will be reviewed. In parallel, the student will perform elementary calculations to find out the best spectrum to be used for thorium and the best driver material. A system (i.e. spectrum/driver) will then be selected based on its performances in terms of breeding, proliferation resistance, radiotoxicity of the waste, reactivity coefficients, and kinetic data. Such elementary calculations will be performed using data coming directly from the nuclear data libraries, complemented by deterministic calculations using the ECCO/ERANOS code package for fast systems and/or the CASMO-4/SIMULATE-3 code package for thermal systems, and probabilistic calculations using MCNP5 if needed. The transition from the existing fuel cycles to the chosen system will also be looked at.

Thereafter, a static calculational route will be set up for the chosen system, and some elementary fuel/core design optimization will be carried out. It has to be emphasized that the main goal of the PhD project is to study in a conceptual/phenomenological manner the chosen system. Therefore, a fine optimization of the system that is retained in terms of fuel loading pattern, etc. is out of the scope of this project. An equilibrium core will be developed, and the characteristics of this equilibrium core with respect to fuel utilization, breeding, reactivity coefficients, kinetic parameters, proliferation resistance, radiotoxicity of the waste will be assessed.

Finally, the dynamics of the chosen system will be studied. Analytical models will be derived using realistic data provided by the static calculations of the equilibrium core, since it is most likely that there is no transient code package available for the chosen system. Nevertheless, if a thermal system is retained, SIMULATE-3K might be used.

Cheuk Wah Lau started his employment on June 1st, 2009. Since then, Cheuk Wah Lau mostly attended courses in Nuclear Engineering, started looking at the literature published in the field of thorium, and made some preliminary calculations based on first-principles in order to find out the main characteristics of thorium from a reactor physics viewpoint. He also participated to a training course on ERANOS organized at CEA, Cadarache, France between October 13 and 16, 2009.

## References

1. R. Price and J. R. Blaise, ”Nuclear fuel resources: Enough to last?”, *NEA Updates NEA News*, 20 (2), 2002.

# Iodine chemistry in the reactor containment during a severe accident

*Ph.D. Student: Joachim Holm, Department of Nuclear Engineering, Chalmers University of Technology*
*Supervisors: Prof. Christian Ekberg and Dr. Henrik Glänneskog (Ringhals)*

## Background

Iodine is a volatile fission product, which is formed during normal operations in the nuclear core. During a severe accident iodine is transported from the melted fuel mainly as CsI to the containment. Iodine is distributed in the containment pool as non-volatile iodide ions. However, several processes will produce volatile iodine species, like elemental iodine ($I_2$) and methyl iodide. Thermal and radiolytic oxidation of iodide is the main processes for production of airborne iodine in the containment during a severe accident. Radiolysis products like ·OH, formed due to the expected extensive gamma radiation field, will react with iodide ions and produce $I_2$. The radiolysis product may also produce organic radicals, because of organic impurities. These organic radicals may react with iodide ions and produce organic iodine like methyl iodide, which is even more volatile than $I_2$. The volatile iodine species can be released to the environment from the containment via e.g. leakage and pressure relief.

Recently different experiments have shown that airborne inorganic iodine may be depleted from the gas phase in the containment [1]. The experiments shown that the radiolysis product ozone, which is formed by radiolysis of air, may deplete the gas phase of iodine.

## Goals

Experiments performed year 2008, the reaction between inorganic iodine ($I_2$) and ozone was investigated. The aim of this project, year 2009, was to investigate reaction between methyl iodide and ozone and the behaviour of methyl iodide in a radiation field of UVC-light. Several different parameters and conditions were investigated, like temperature, humidity, ozone concentration and radiation intensity. The most interesting was the eventual depletion of methyl iodide from the gas phase when ozone and/or UVC radiation were present in the system. The speciation of the eventual formed particles was also prioritized.

## Organisation

The work is performed by Ph.D. student Joachim Holm under the supervision of Prof. Christian Ekberg and Dr. Henrik Glänneskog. A considerable amount of the work was performed at VTT, Helsinki, Finland, together with Teemu Kärkelä and Ari Auvinen.

## Methodology

The experiments are performed in the experimental set-up seen in figure 1. The set-up consists of several parts. In the beginning of the stream there is a unit for a continuous production of gaseous methyl iodide to the remainder of the facility. Methyl iodide is transported by a stream of mixture of nitrogen and oxygen to the UV-furnace. In the furnace is the gas mixture inside a glass tube exposed to UVC radiation from four lamps place outside the glass tube. In the experiment with ozone present in the system, ozone was produced from a separate generator.

The gas mixture was transported from the UV furnace to the sampling furnace. In this furnace the stream was divided into several streams for analysis of the gas mixture and analysis of eventual formed iodine particles. The gas mixture was analysed with a FTIR device (Fourier Transform Infra Red). The formed particles were analyzed with CPC (Condensation Particle Counter), SMPS (Scanning Mobility Particle Sizer), ELPI (Electrical Low Pressure Impactor) and TEOM (Tapered Element Oscillating Microbalance). All these measurements were done on-line. Particles were trapped on special grids, of either carbon or copper, for analysis with SEM-EDX (Scanning Electron Microscopy – Energy Dispersive X-ray). The ratio between gaseous and solid iodine was determined by trapping particles and methyl iodide at paper filter and in gas washing bottles, respectively. This was happening in a third stream from the sampling furnace. The stream was divided in three tubes, which can be open for throughout separately. The advantage with this set-up is that three different conditions can be used in one experiment. The iodine content on the filters and in the gas washing bottles was analyzed with ICP-MS (Inductively Coupled Plasma Mass Spectroscopy).

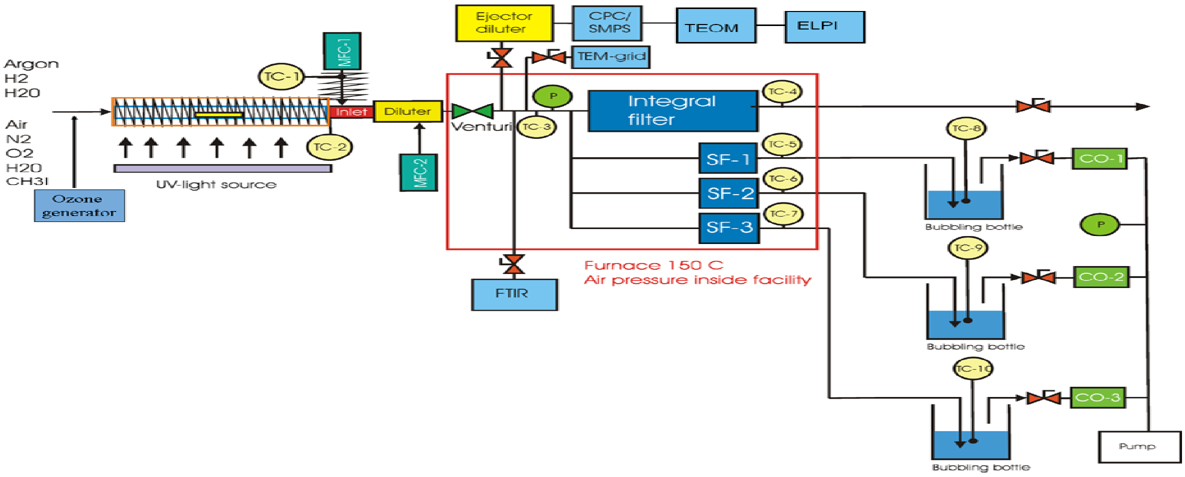


*Figure 1: The experimental set-up, the EXSI facility.*

## Results

In totally ten experiments were performed and several parameters were investigated, like temperature effect (50 °C, 90 °C and 120 °C), ozone concentration and humidity.

When methyl iodide was introduced into the facility with a present UVC radiation field a significant amount of particles were immediately formed. The particle mass, measured by TEOM, was increased with increased radiation intensity. At elevated temperature, 120 °C, the particle mass was larger than at lower temperatures. The temperature seems to affect more then the UV radiation. Similar results were received when ozone was introduced into the system, the difference was the even larger particle mass compared to the case with UV radiation (Fig. 2 and Fig. 3).

The experiments with humid system, ~ 100 % relatively humidity, the particle production was even higher. The particle mass was a factor five higher in the humid system compared to similar conditions in the dry system. Some of the tubes were totally clogged and prevent further measurement.

The size of the formed particles ranged from primary particle diameter ~5-10 nm to the diameter of agglomerates as large as ~180 nm. The particles size did not varied in size dependent on the particle production way.

The SEM-EDX analyses shown that the particles contained both iodine and oxygen. But the precise speciation of the particles was impossible to determine, because the particles melted and were fused together.

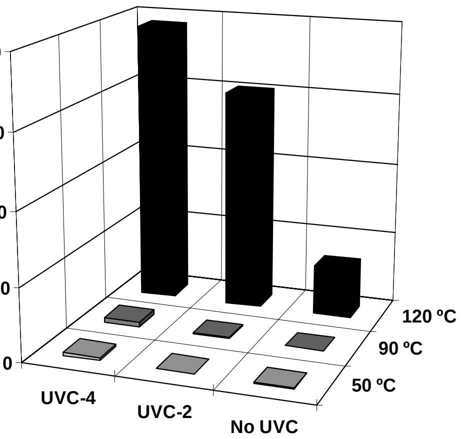


*Figure 2. The particle mass at three different temperatures and three different radiation levels.*

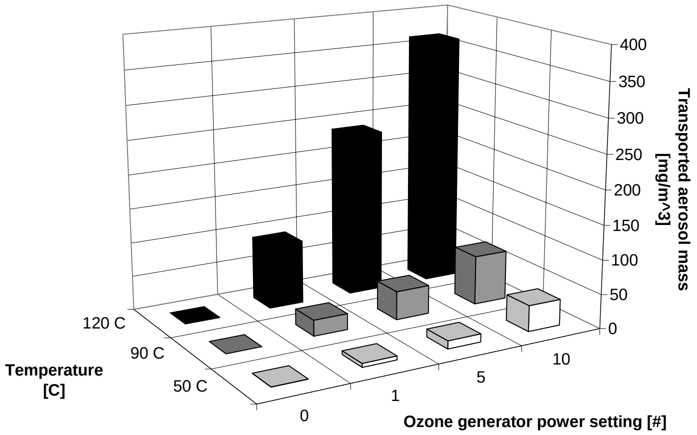


*Figure 3. The particle mass at three different temperatures and three different ozone levels.*

## Reference

[1] T. Kärkelä, J. Holm, A. Auvinen, C. Ekberg, H. Glänneskog, U. Tapper, R. Zilliacus, Gas Phase oxidation of Elemental Iodine in Containment Conditions, Proceedings of the 17th International Conference on Nuclear Engineering, ICONE17, Belgium, 12-16 July, 2009.

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J. Holm, C. Ekberg and H. Glänneskog, Deposition of $RuO_4$ on various surfaces in a nuclear reactor containment, J. Nucl. Mater. 392 (2009) 55-62.

# KTH – Royal Institute of Technology

*Overview of Activities in 2009*

At KTH, research and education within the field of nuclear energy engineering is performed at the following divisions:

Reactor physics (dept. of physics)

Reactor technology (dept. of physics)

Nuclear power safety (dept. of physics)

Nuclear chemistry (dept. of chemistry)

These four divisions are jointly members of CEKERT (Centre for nuclear energy technology) at KTH, together with representatives of SSM, Westinghouse Electric and Forsmark Kraftgrupp AB. Within CEKERT, the internal distribution of funds obtained from SKC is agreed. Further, CEKERT functions as a think-tank and centre of coordination for joint actions, such as the KTH masters programme in nuclear energy engineering.

Roughly 2/3 of the research effort at KTH is focused on R&D related to the existing Swedish light water reactor park, the remainder being related to repository performance, transmutation in ADS and Generation IV reactors.

Three PhD theses were defended and six licentiate theses were presented during 2009:

- Carl Adamsson: “Dryout and Power Distribution Effects in Boiling Water Reactors”PhD thesis in reactor technology

- Jan Dufek: “Development of new Monte Carlo methods in reactor physics”, PhD thesis in reactor physics.

- Chi Thanh Tran: “The effective convectivity model for simulation and analysis of melt pool heat transfer in a light water reactor pressure vessel lower head”, PhD thesis in nuclear power safety.

- Diana Caraghiaur Garrido: “Experimental Study and Modelling of Spacer Grid Influence on Flow in Nuclear Fuel Assemblies”, Lic. Eng. thesis in reactor technology

- Odd Runevall: “Helium in CERMET fuel – binding energies and diffusion”, Lic. Eng. thesis in reactor physics.

- Song Han: “Computational methods for multi-dimensional neutron diffusion problems”, Lic. Eng. thesis in reactor physics.

- Joanna Peltonen: “Development of effective algorithm for coupled thermal-hydraulics – neutron-kinetics analysis of reactivity transient”, Lic. Eng. thesis in nuclear power safety.

- Michael Holmboe: The Bentonite Barrier: Microstructural Aspects on Colloid Filtration and Radiation Effects on Bentonite Colloid Stability, Lic. Eng. thesis in nuclear chemistry.

- Haidong Liao: Sol-gel Synthesis and Photocatalytic Characterization of Immobilized $TiO_2$ Films, Lic. Eng. thesis in nuclear chemistry.

The international masters programme in nuclear energy engineering enrolled ten students in the class of 2009. Among the 14 students from the first class of the masters programme (enrolled in 2007), eleven have graduated during 2009. Out of these, three are employed by Swedish industry and five are pursuing PhD studies.

In January 2009, the uranium fuel fabrication laboratory at KTH was inaugurated. In this laboratory, the reactor physics division fabricates UN and (U,Zr)N fuels for an SKC funded PhD project, as well as for the GENIUS project.

The High-pressure WAter Test (HWAT) loop of the reactor technology division was refurbished and put into operation in June 2009. The loop was upgraded with new remote control system and fittings allowing for sophisticated pre-described transient operations such as testing of transient dryout and post-dryout, thermal mixing, thermal stratification and fatigue, and power/flow instability events.

Pavel Kudinov gave his docent lecture in October 2009.

The CEKERT divisions participated in the following EU-projects during 2009: HPLWR2, NURISP, EUROTRANS, ELSY, VELLA, PUMA, MICADO, GETMAT and FAIRFUELS. In addition, the proposals for the THINS and the LEADER projects were approved.

KTH coordinated the proposal for Generation IV research in Swedish Universities (GENIUS), where KTH, Chalmers and Uppsala University together were awarded a research grant of 36 MSEK from the Science Council for the period 2009-2012.

Six SKC funded PhD projects have been in progress during 2008. A summary description of these projects is provided in the following pages.

# 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

For safe and economic operation of nuclear reactors it is important that the mechanisms which govern heat transfer and fluid flow in fuel assemblies are well understood. 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. The current safety standards stipulate that a nuclear reactor under normal operation conditions should have safety margins high enough to avoid the onset of dryout or Departure from Nucleate Boiling (DNB). This is mainly due to the fact that heat transfer conditions beyond the onset of dryout or DNB are not well understood and predictions of clad and fuel temperatures are quite uncertain. Whereas post-DNB heat transfer is very poor and typically lead to an immediate damage of the heater, post-dryout heat transfer can be quite efficient, and a damage of the heater can be avoided. This opens a new perspective towards the definition of the safety margin as a margin to the clad damage rather than a margin to the occurrence of dryout. However, more research is needed to firstly provide an extensive experimental database with post-dryout heat transfer measurements and secondly, to develop and validate adequate computational models to predict post-dryout heat transfer in a wide range of operational conditions.

## 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. Recent experimental study of post-dryout heat transfer in an annulus has shown a considerable influence of the spacers on the heat transfer intensity, [1]. The measurements revealed that dryout patches could be effectively quenched just downstream of spacers and that the measured wall temperature was much lower than that predicted from currently available correlations and/or models, [1-6]. In order to have a detailed view of the spacer influence on post-dryout heat transfer, the following issues are addressed: (a) the influence of spacer geometry details on heat transfer, (b) the level and the influence of vapor superheat on heat transfer, (c) exact position of quenching/rewetting fronts, and (d) the influence of spacers on drop dynamics. The new post-dryout measurements are performed in two-side heated annulus 12.7x24.3.1x3650 mm using various types of spacers. 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. In addition of classical procedure [1], the following experimental procedures are foreseen: the *constant-quality-line* method and the *constant-local-quality* method [7]. The experimental matrix includes measurements of wall temperature distributions for single and two phase flow for both convective boiling and post-dryout heat transfer under various mass fluxes, inlet sub-cooling values and system pressures.

## Results in 2009

In 2009 the main effort was devoted to design and build the test section, to perform preliminary tests, as well as to calibrate and to carry out experimental tests. During preliminary runs over 150 experiments were performed. Variations in mass flux (500-1750) kg/(m$^2$s), inlet subcooling (10-40) K and system pressure 5-7 MPa were investigated, with the focus on typical operating conditions in BWRs. Two different situations were investigated: occurrence of dryout on the inner rod and occurrence of dryout on the outer tube in case of an annulus with pins spacers. Figures 1 and 2 show the temperature distributions during post-dryout experiments.

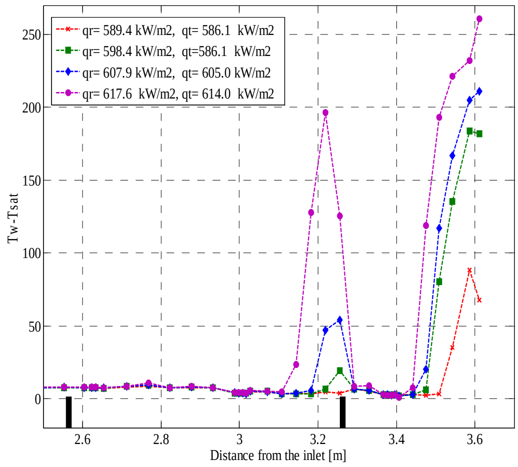


*Fig.1. Measured superheat of rod wall surface for various heat fluxes. Mass flux G=750 kg/m$^2$s, inlet subcooling ΔT=10 K, pressure p= 7 MPa.*

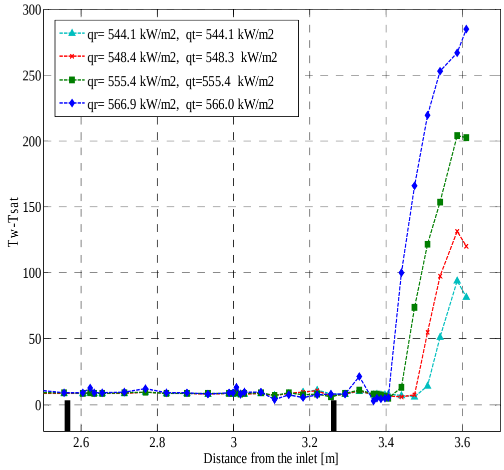


*Fig.2. Measured superheat of rod wall surface for various heat fluxes. Mass flux G=500 kg/m$^2$s, inlet subcooling ΔT=40 K, pressure p= 7 MPa.*

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[7] Anghel, I., Anglart, H, Hedberg, S., Rydström, S., 2009. Experimental Investigation of the Influence of Flow Obstacles on Post-Dryout Heat Transfer in an Annulus, Proceedings of the 17th International Conference on Nuclear Engineering Brussels, Belgium.

# 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 our predictive capability through simulation of chosen flow conditions.

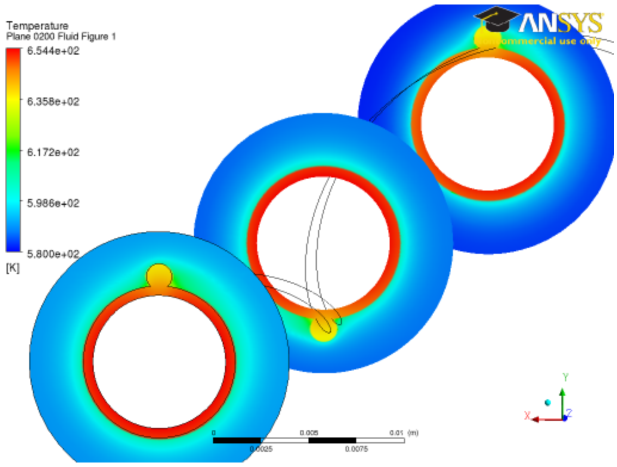
## Objectives and methodology

To establish limitations and possibilities of the simulation software used (CFX, initially v11.0) and to examine the planned quantifying of results in a simpler environment, research in 2009 has been focussed primarily on single phase flow in an annulus with wire wrap spacer. Implementation of inhomogeneous boundary conditions (in particular, power distribution) and two phase flow are expected to follow when post processing of simulation results is satisfactory in terms of both simplicity (automation) and coverage.

## Results in 2009

Initial simulations did not include heat transfer within solids (wire and cladding) which resulted in unphysical outcomes. With a change to conjugate heat transfer, this effect has disappeared. Results appear to be in good agreement with other methods that were tried concurrently elsewhere. Post processing is at a sufficient level for the current comparisons, but extensions need to be made to accommodate for additional values of interest when inhomogeneous boundary conditions and two-phase flow are implemented.

*Figure 2: Example of simulated temperature distribution in twisted wire geometry*



# Development of a Method for the Treatment of Two-Phase Flow Patterns in Nuclear Reactor Thermal Hydraulic CFD-Based Analysis

*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 ill-posed character of the model. Thus, there is a concern that the codes will fail in calculating complex system behavior such as strongly oscillating two-phase flows with rapid transitions between bubbly, slug and annular regimes.

In addition to the system codes, Computational Fluid Dynamics (CFD) codes have been already used in new reactor system design. Their application is expected to be significant in future reactor system safety analysis as computing power is being improved rapidly. 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.

Second, those oscillatory flows will be simulated and analyzed using three-dimensional Computational Fluid Dynamics (CFD) codes. Taking the advantage that CFD codes can calculate more precisely two-phase flows than system code does, result from CFD calculation will be used as another “experiment” in evaluating the system code.

Finally, 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.

## Organization

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

## Methodology

A procedure for code validation was developed based on sensitivity analysis and uncertainty assessment. Main purposes of the procedure are to identify and reduce the influence of experimental uncertainty in the code input model, and to estimate uncertainty in simulation results. Analysis of simulation results performed for CIRCUS-I experimental facility (a test loop for modeling of natural circulation Boiling Water Reactor systems at low pressure) suggested that there was significant source of uncertainty in the experimental procedure. Proposed changes in the experimental procedures were accepted and new set of experiments on two-phase flow instability was performed in 2009 at CIRCUS-IV facility in Delft University of Technology, the Netherlands.

New experimental data was utilized for reduction of uncertainty in the code input model and validation of the RELAP5 code. New simulation results demonstrate that the RELAP5 can predict well low frequency two-phase flow oscillations. Calculation errors are larger for higher frequency oscillatory flow. Influence of possible uncertainties in the input model has been taken into account.

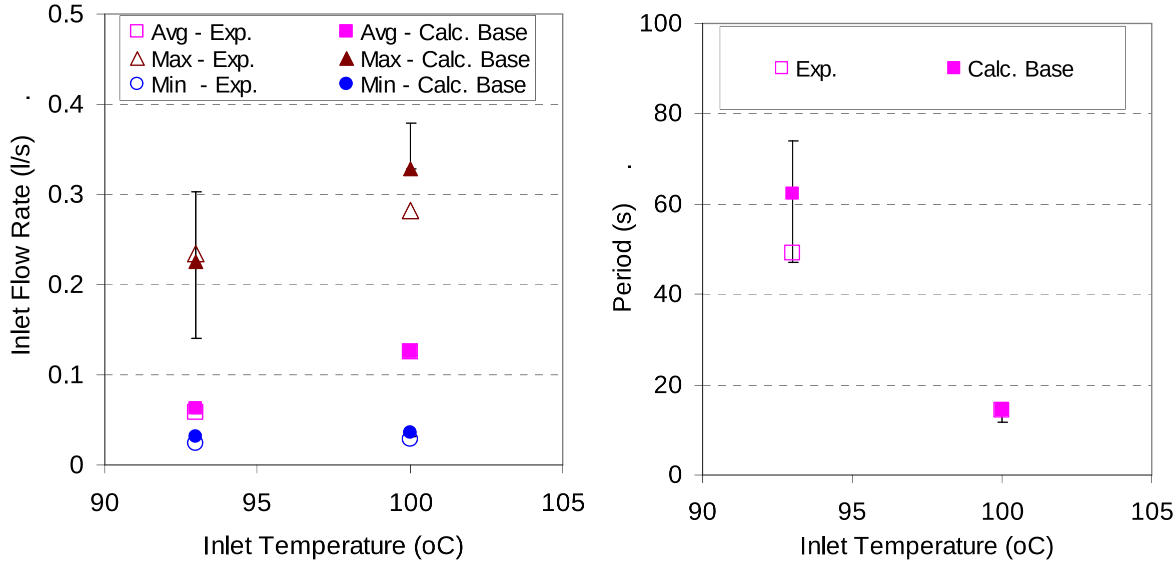



*Figure 1: Calculated inlet flow rate (a) and oscillation period (b) with calculated uncertainty in comparison with measurements (CIRCUS-IV)*

Data from integral effect test facilities is very useful for validation of the ultimate code validation, but usually it is not possible to clearly identify particular models which are responsible for simulation errors. Therefore a separate effect problem was chosen for investigation of the effect of flow regime transition in two-phase flows.

Two-phase flow in a tube with sudden expansion is used as a separate effect test case. In standard flow regime treatment approach transition from one regime to another happens instantaneously after the sudden expansion. In reality the transition requires finite relaxation time related to micro-scale changes of the flow pattern. Sensitivity of flow characteristics to relaxation time of flow regime transition is studied by varying the position of flow regime transition in the tube after the sudden expansion. Analytical results show that for the investigated cases, the relaxation time has considerable effect on system behavior only at some combinations of flow parameters (such as gas/liquid flow rates etc.). In the further study it is proposed to implement relaxation time concept into the system codes for two-phase flow calculations.

## Publications

Phung V.A., Kozlowski T., Kudinov P., Rohde M., *Simulation of Two-Phase Flow Instability in CIRCUS Facility Using RELAP5*, ANS Transactions, 2008, paper 197733.

Phung V.A., Kudinov P., Rohde M., *Validation of RELAP5 with Sensitivity Analysis for Uncertainty Assessment for Natural Circulation Two-Phase Flow Instability,* Proceedings of the 13th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-13), Kanazawa, Japan, 2009, paper 13P1248.

Phung V.A., Kudinov P., *Relaxation Time Concept for Flow Regime Transition in Two-Phase Flow Simulations,* ANS Transactions, 2009, paper 210649.

# Development of a Multi-Scale Simulation Methodology for Nuclear Reactor Thermal Hydraulic and Safety Analysis

*PhD student: Francesco Cadinu, Division of Nuclear Power Safety, KTH*
*Supervisor: Assoc. prof. Pavel Kudinov*

## Background

The thermal-hydraulics analysis of nuclear power plants has been traditionally carried out using so-called system thermal-hydraulic (STH) code such as RELAP5, TRACE, CATHARE and ATHLET.

STH codes are based on a multi-fluid model of two-phase flow, whose closure is provided by flow regime maps and constitutive relations for fluid-fluid and fluid-wall mass/momentum/energy exchange.

From the geometrical point of view, they employ a one-dimensional description of the plant, simplified as a series of control volumes. Even though this approach may seem overly simplified, system codes have enabled analysts to successfully perform simulations of complex transients of safety relevance. However, they cannot capture correctly the features of those transients where the multi-dimensionality of the flow plays a key role.

It was soon recognized, in the nuclear engineering community, that Computational Fluid Dynamics (CFD) could complement system codes in the toolbox of the safety analyst. Based on the solution of the Navier-Stokes equations, CFD has the capability to analyze multi-dimensional flows and, beyond the nuclear industry, it is considered a well-developed and reliable tool, especially for single-phase applications.

The most natural way to couple CFD and system codes is what we refer to as a “domain decomposition” approach. Namely, the computational domain is divided into a “CFD subdomain” and a “STH subdomain” where the corresponding solvers are used. Matching conditions on the primitive variables or the fluxes, are imposed at the interface between different subdomains. While this is very intuitive, there are fundamental issues such as possible coupling instabilities between codes marching at different time steps and the difficulty of obtaining boundary conditions for the CFD subdomain from the 1D data provided by the system code; generally speaking, this is possible only if more information on the physics at the interface between different subdomains is available (for example if such interface is located in a region of fully developed flow) or if the solution of Navier-Stokes equations in the CFD subdomain is not sensitive to the details of the boundary conditions.

However, the calculation of multidimensional temperature and velocity profiles, which requires a “domain decomposition” approach, is not the only instance where coupling between CFD and STH codes is needed.

## Goals of the project

The goal of this work is the development of efficient simulation techniques which can shed light on complex multiscale phenomena in reactor thermal hydraulics and safety analysis.

Viewing the STH/CFD coupling as a multi-scale problem, our goal is also to explore the possibility of introducing, in the analysis of nuclear power plants, the latest advances in the theory of multi-scale techniques for heterogeneous systems (such as E and Engquist’s Heterogeneous Multiscale Method and Kevrekidis’ Equation Free Method). At the same time we aim to create practical recommendations which can guide the coupling process for various classes of multiscale problems of safety relevance.

## Organization

The work is performed by Ph.D. Student Francesco Cadinu under the direction of assoc. prof. Pavel Kudinov. The contact reference group consists of Wiktor Frid and Oddbjörn Sandervåg (SKI), Lilly Burel-Nilsson and Thomas Probert (OKG), Farid Alavyoon (Forsmark), Anders Andren (Westinghouse), and Henrik Nylén (Ringhals).

## Methodology

The first part of the work has been devoted to a literature review on multi-scale methods with the goal of assessing their suitability for application to the CFD/STH coupling problem.

Most multi-scale methods found in the literature are problem specific, so they cannot be easily extended. However, it was found that two popular frameworks used to study multi-scale systems, namely the Equation Free Method (EFM) and the Heterogeneous Multiscale Method (HMM) are general enough to be considered for application to the CFD/STH coupling problem. In particular, it can be shown that it is possible to devise a coupling strategy between a system code and a CFD code which can be cast in a form very similar to the Equation Free Method. Such a strategy prescribes the use of a CFD code to calculate the coefficients (closures) needed by the system code. This strategy will be applied to those phenomena that cannot be properly simulated by a STH code because of the lack of appropriate closures. This procedure is thought to be more robust than the domain decomposition approach with respect to the fact that accurate initial and boundary conditions for the CFD solver cannot be determined from the 1D data provided by the system code. It must be remarked, however, that the coupling-by-closure strategy is not an appropriate simulation tool for those transient where the goal is the calculation of 3D flow and temperature patterns.

As an example of coupling-by-closure procedure, the flow in an axisymmetrical sudden expansion subject to time-dependent inlet and outlet pressure boundary conditions is considered.

Despite its simplicity, this is an example of a phenomenon which cannot be adequately simulated by a STH code. The missing closure is, in this case, the loss coefficient across the expansion, which exhibits a strong dependence on time, as it can be shown by a full transient CFD simulation. However, CFD simulations also show that unsteady correlations for the loss coefficient can be developed for a certain class of transients. Therefore, a combined CFD/STH analysis enables the STH code to predict correctly the system behavior at a much lower computational cost than the one required by a CFD simulation of the entire transient.

Another application considered in this study is a simulation of the cooling of a melt pool located in the lower plenum of a BWR vessel performed via the Control Rod Guide Tube (CRGT) flow. The heat transfer from the debris pool to the vessel and the CRGT wall is calculated with the Effective Conductivity Model and Phase-Change Effective Conductivity Model (ECM/PECM) (Tran, Dinh, 2007) implemented as a set of user defined functions in the CFD code Fluent. Realistic boundary conditions for the ECM/PECM are obtained by coupling Fluent, on-the-fly, with the STH code RELAP5. The coupled simulation allows predicting the maximum temperature reached in the CRGT walls and assessing their integrity.

## Publications

Francesco Cadinu, Tomasz Kozlowski, Truc-Nam Dinh, *Relating System-to-CFD Coupled Code Analyses to Theoretical Framework of a Multiscale Method*, International Congress on Advances in Nuclear Power Plants (ICAPP 2007), Nice, France, May 2007.

Francesco Cadinu, Tomasz Kozlowski, Pavel Kudinov, *Study of Algorithmic Requirements for a System-to-CFD Couling Strategy*, XCFD4NRS, Grenoble, 10-12 September, 2008.

Francesco Cadinu, Tomasz Kozlowski, Pavel Kudinov, *A Closure-On-Demand" Approach to the Coupling of CFD and System Thermal-Hydraulic Codes*, NUTHOS-7, Seoul, October 5-9, 2008.

Francesco Cadinu, Tomasz Kozlowski, Pavel Kudinov, *A "Closure-On-Demand" Approach to the Coupling of CFD and System Thermal-Hydraulic Codes*, NUTHOS-7, Seoul, October 5-9, 2008.

Francesco Cadinu, Pavel Kudinov, *Development of a "Coupling-by-Closure" Approach between CFD and System Thermal-Hydraulics Codes*, NURETH-13, Kanazawa, September 27 – October 2, 2009.

Francesco Cadinu, Chi Thanh Tran, and Pavel Kudinov, "*Analysis of In-Vessel Coolability and Retention with Control Rod Guide Tube Cooling in Boiling Water Reactors*", Joint OECD/NEA – EC/SARNET2 Workshop, In-Vessel Coolability, NEA Headquarters, Issy-les-Moulineaux, France, October 12 - 14, 2009.

# Radiation-induced processes at liquid-solid surfaces

*PhD Student: Claudio Lousada, Nuclear Chemistry, KTH*
*Supervisor: prof. Mats Jonsson*

Due to the importance of the system $ZrO_2$ and $H_2O_2$ in nuclear and spent nuclear fuel applications, we have performed a kinetic, energetic and mechanistic study to better understand this system. In the literature there is still a lack of information about these properties of the system mentioned above. The study focused on a better understanding of the dynamics of the reaction between $ZrO_2$ and $H_2O_2$ in aqueous phase. For that, suspensions of $ZrO_2$ particles were left to react with solutions of $H_2O_2$ and the consumption of the latter was tracked spectrophotometrically by using the triiodide Ghormley method. This gave us knowledge about the reaction time and how the reaction rate depends on factors like concentration of $H_2O_2$, mass of $ZrO_2$ and pH. The same study was performed at different temperatures (between 20 and 85 ºC, with a temperature step of 5 ºC) with the goal to obtain the activation energy for the reaction figure 1.

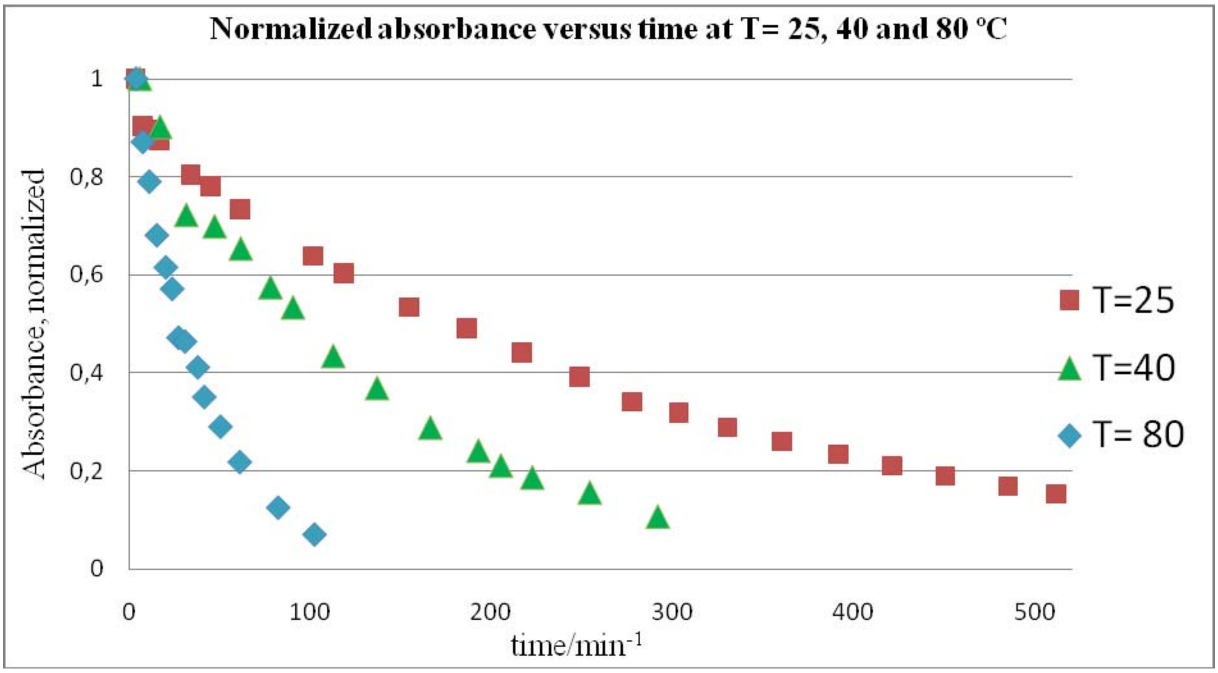



*Figure 1. Plot of the normalized absorbance vs reaction time at different temperature values. This procedure was repeated for temperatures between 25 and 80 ºC with steps of 5ºC.*

For each temperature, three experiments were performed. The resulting rate constants were then averaged and allowed us to determine the activation energy for the reaction in the temperature range mentioned above. The obtained value for the activation energy of the reaction was 32 ± 1 $kJ.mol^{-1}$. This is in accordance with other values found in the literature for the same reaction but with other oxides. Also, the precision of the obtained value can be considered good since the associated error is around 3%. Characterization of the solid particles and of the solution where also performed, before and after reaction in order to track possible chemical or physical changes in the solid and in the solution (by means of release of zirconium into the solution). The data obtained by XRD, B.E.T. and inductively coupled plasma spectroscopy, indicates that the $ZrO_2$ only acts as a catalyst in this reaction and no structural or chemical changes occur in $ZrO_2$. Also was verified that no release of $ZrO_2$ into the solution occurs during the reaction. This gives us an idea of the mechanism of the reaction. A search in the literature revealed that there was little knowledge about the mechanism of this reaction and this fact lead us to develop a method to better understand it. Was developed a method to track the presence of intermediate species in the course of the reaction. The intermediate species in this case are the hydroxyl radical and possibly superoxide. The method has proven to be useful, simple and cheap when compared with the most expensive, time consuming and chemiluminescence for example. It was possible to obtain the dynamics of formation of the hydroxyl radical in the course of the reaction and thereby to prove the mechanism.

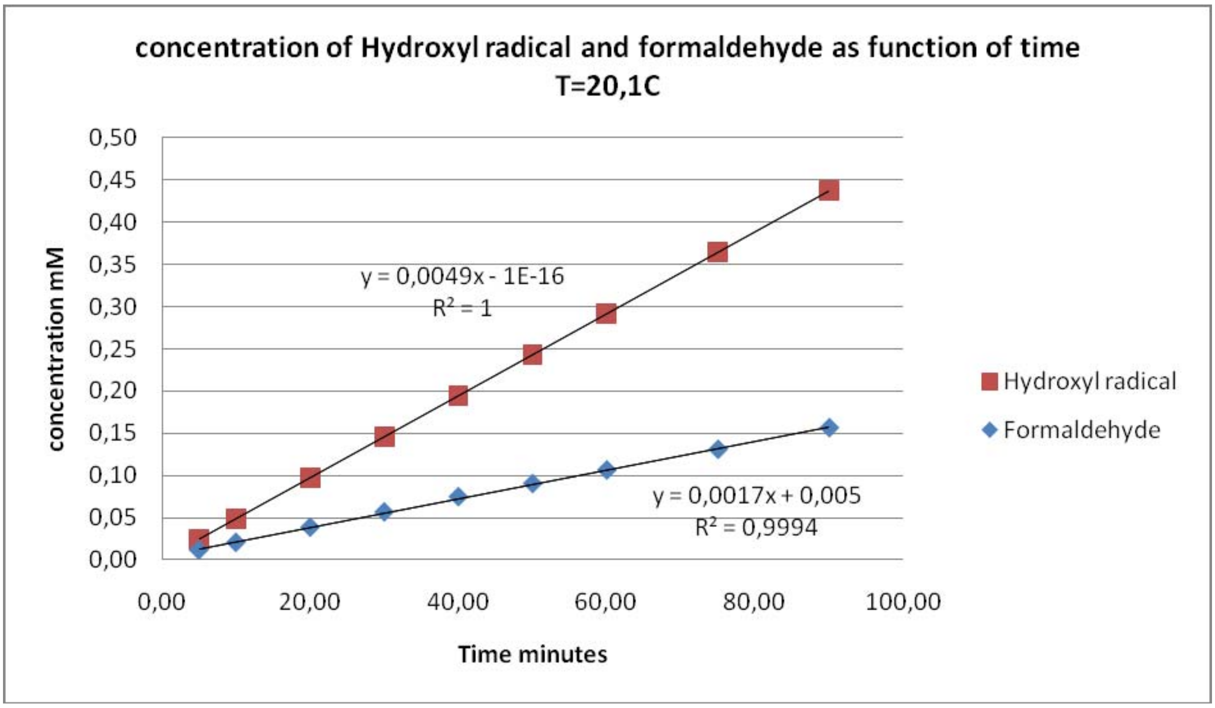



*Figure 2. Formaldehyde and hydroxyl radical concentrations evolution with time during reaction of $ZrO_2$ with $H_2O_2$.*

The method allowed us to plot the consumption of Hydrogen peroxide and the production of hydroxyl (figure3).

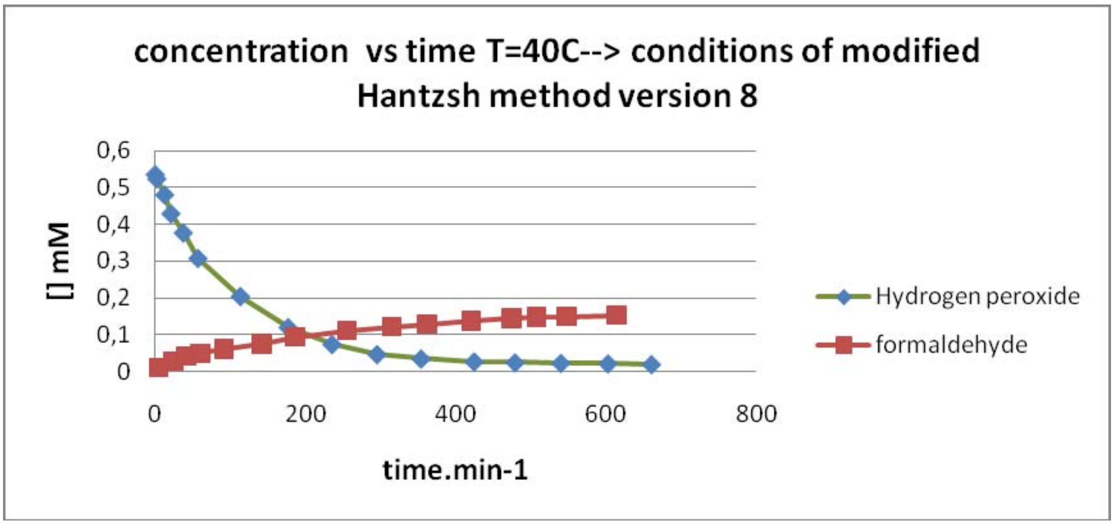



*Figure 3. Formaldehyde and hydrogen peroxide concentrations evolution with time during reaction of $ZrO_2$ with $H_2O_2$.*

The rate of formation of formaldehyde is directly proportional to the rate of formation of hydroxyl radicals and inversely proportional to the rate of consumption of hydrogen peroxide. This fact in combination with studies involving calibration of the system under the influence of radiation allowed us to prove the existence of intermediate radicals in the reaction and consequently to confirm the initially proposed mechanism. Was also verified that the zirconium dioxide only acts as a catalyst for the reaction by lowering the energy barrier of the later.

A future study that will allow us to better understand the effects of radiation in the catalytic properties of some solids, including zirconium dioxide will be performed.

The method develop in this study will allow us to apply it to a diversity of systems with great interest in the nuclear industry such as $UO_2/H_2O_2$ system. A similar study will be performed in the system mentioned above with the goal to better understand the kinetics, mechanism and energetics of the reaction.

The corrosion processes of steels will be studied by means of developing a method to perform in-situ electrochemical impedance spectroscopy.

# Uppsala University

*Division of Applied Nuclear Physics*

2009 was a year rich of inspiring events for the division. In addition to education and research activities presented below, the personnel were involved in extensive contacts with the mass media regarding nuclear technology.

The division was involved in a project arranged by the Swedish Chambers of Commerce aiming at presenting Swedish universities to the UN system. In June, Ane Håkansson, Jan Blomgren (SKC) and Karin Persson (Uppsala University Education) visited IAEA in Vienna where the division's education programmes were presented. A follow-up meeting in November established an understanding implying that Uppsala University is indeed an interesting possible partner for IAEA's internal educational needs.

As a consequence of the contacts with IAEA the mentioned people above were invited to the G8 meeting in Bologna for presenting the "Swedish model" that includes the trinity of academy, authority and industry. The ideas presented received a great deal of interest from the meeting.

A result of the G8 meeting was the start of a close discussion with representatives from the United Arab Emirates who plan to embark a civil nuclear programme and therefore needs help to educate their specialists. This discussion will continue during the IAEA conference on global competence supply for future nuclear expansion in Abu Dhabi March 2010. In addition, at this conference, Ane Håkansson is invited to a panel discussion regarding educational strategies.

From 1 January 2010, the department of physics and astronomy will be merged with the department of physics and material sciences into a new department called the department of physics and astronomy.

## Education

Education in the field of energy systems and technology is conducted through a number of courses within the various master engineering programs and bachelors engineering programmes. Since 2003 the division develops and conducts higher education for the nuclear power industry within an agreement with the Nuclear Safety and Training Centre (KSU). This activity aims to secure competence building of existing and newly recruited personnel, primarily within reactor operation and radiation protection.

From 1 July, a new agreement was settled between KSU and Uppsala University regarding: ”Högre utbildning inom kärnkraftindustrin”. The agreement runs during three years with a possibility to prolong it for additional three years and implies an increase of the educational volume of 25 % as compared to previous agreement.

Preparations for the new bachelors engineering programme in nuclear power technology have been one of the focus areas during 2009. The idea behind this new, unique, programme is to allow students from various engineering programmes, e.g. mechanical engineering and electrical engineering, all over Sweden to apply for this education.

The program is planned to cover all non-site specific issues and it is believed that such an education would 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.

In June, the vice chancellor decided that this programme should start in autumn 2010. In December an agreement between KSU and Uppsala University was settled implying that the Swedish nuclear power industry, in a long-term perspective, supports the new education both financially and practically.

*Signing of the contract for industry sponsoring of the new bachelors engineering programme in nuclear power technology.*

The high pace of recruitment within the industry has implied a continuous high educational volume. Especially for the course H1, a very high fraction of attendees are newly recruited personnel. During 2009, courses have been conducted during 14 occasions corresponding to 29 teaching weeks according to:

Kärnkraftteknik, H1 (12 hp), 4 occasions, one at OKG

Tillämpad reaktorfysik (7,5 hp), 1 occasion

Fördjupad strålskyddsutbildning FS1, 1 occasion

Värme- och strömningslära (KGP), 3 occasions

Reaktorfysik fördjupad (KGP), 4 occasions

Reaktorfysik fördjupad (Halden, Norge), 1 occasion

For two of the courses, *Kärnkraftteknik H1* and *Tillämpad reaktorfysik*, the attendees can get academic credits (”högskolepoäng”) when they pass the examinations and are registered as students at Uppsala University.

On initiative from the division, an educational day was arranged 11 November together with SKB. The theme was the planned geological repository in Sweden and the aim was to involve researcher and students from several faculties. Ten seminars were held during the day and these included subjects ranging from ethics to nuclear technology. The day was ended by a panel discussion moderated by Linda Nyberg. About 200 students attended this arrangement.

### Undergraduate level

In the table below, courses given by the division personnel is shown.

| Course | Prog. | Points (HP) | Stud. |
|---|---|---|---|
| Projektarbete i energi | STS | 15 | 12 |
| Energisystemfysik | STS | 7.5 | 30 |
| Komplexa system i teknik och samhälle | STS | 7.5 | 51 |
| Kärnkraft - teknik och system | ES | 7.5 | 13 |
| Energifysik 1 | F | 6 | 16 |
| Energifysik 2 | F | 6 | 13 |
| Energifysik projektkurs | F | 7.5 | 9 |
| Joniserande strålning och detektorer | F | 7.5 | 12 |
| Introduktionskurs | STS | 10 | 60 |
| Energisystemfysik | STS | 10 | 43 |
| Projektarbete i energi | STS | 15 | 7 |

STS = Systems in Technology and Society, ES = Energy Systems, F = Engineering Physics

During 2009, the following teachers have been involved in the division's nuclear technology education:

Cecilia Gustavsson, UU
Ane Håkansson, UU
Staffan Jacobsson Svärd, UU
John Loberg, UU
Stephan Pomp, UU
Henrik Sjöstrand, UU
Matthias Weiszflog, UU
Michael Österlund, UU
Bo Stenerlöw, UU/BMS
Klaes-Håkan Bejmer, UU/Vattenfall Bränsle
Christian Ekberg, CTH, kärnkemi
Åsa Enarsson, CTH, kärnkemi
Joachim Holm, CTH, kärnkemi
Klaes Lundgren , CTH, kärnkemi
Christer Hjalmarsson, Elajo
Bernt Ögren, FKA
Hans Edvall, KSU
Tim Lundström, KSU
Dan Aronsson, RAB
Henrik Glänneskog, RAB
Carl Lowisin, Relcon Scandpower
Birgitta Ekström, SSM
Peter Hofvander, SSM
Lars Björnkvist, Vattenfall Bränsle
Andreas Lidén, Vattenfall Bränsle
Christian Malm, Vattenfall Bränsle
David Schrire, Vattenfall Bränsle
Tom Serén, VTT

*Attendees of the H1 course in Uppsala winter 2009/2010.*

## Research

Research has being performed in the following areas:

The technical aspects of international safeguards. The work is more and more focusing on safeguards within Gen IV systems.

Development of advanced measuring techniques based on detection of ionising radiation. These methods are intended for validation of core simulators and determination of fuel parameters of relevance for encapsulation and final storage of spent nuclear fuel.

Research and development of advanced measuring and analysis tools for measurements of nuclear cross sections and fission yields with relevance for applications within transmutation of nuclear waste and dosimetry. One aim of this research is the development of new equipment and methods for fission reactor diagnostics as well as technologies for future reactor concepts.

Theoretical studies and simulations of the transport of the uncertainties and covariances of basic nuclear physics parameters into macroscopic reactor parameters. This work uses state-of-the-art nuclear model codes and connects their results with reactor simulation codes.

Theoretical studies of the neutronics in lead cooled fast reactors. The aim is to develop supporting systems for e.g. core monitoring.

## Personnel

**Jan Blomgren** left the division in the end of January for a new position at Vattenfall AB. In this context, Michael Österlund was assigned as the new person in charge for the KSU education, and Ane Håkansson was assigned responsible professor.

**Henrik Sjöstrand** has taken up a position as researcher/teacher at the division on January 1, 2009.

**Cecilia Gustavsson** has taken up a position as researcher/teacher from March 1, 2009. In addition to a research background, she has several years experience from work at the core physics group at FKA.

**Elisabeth Tengborn** has been employed (from 1 September 2009) as a project leader for management of the new bachelors engineering programme in nuclear power technology. She has previously been SKC-supported PhD student.

**Sophie Grape** was in December 2009 appointed to a post-doctoral position based on grants from the Swedish Radiation Safety Authority, SSM.

Preparations were carried out for six new lectorates at the division. It is anticipated that at least two of them will be absorbed by the current staff. The new employees are expected to be operative early summer 2010.

## Diploma works started during 2009

**Viktor Sivertsson**: ”Hydrogen production using high temperature nuclear reactors” (prel. title) – in collaboration with Vattenfall R&D

**Richard Fridström**: ”Simulations of the response in the gamma-ray TIP detectors of a nuclear power plant” (prel. title) – in collaboration with Westinghouse.

**Cecilia Larsson**: “Upgrade and Validation of PHX2MCNP for Critical Analysis Calculations for Spent Fuel Storage Pools” – in collaboration with Westinghouse.

**Jonas Isaksson**: "Påverkan på torrkoknings-gränsvärden vid avvikelse från planerad drift", - in collaboration with FKA.

**Axel Rudling**: "Mechanistic modeling of dryout in fuel assemblies with complex spatial power distribution". – in collaboration with Westinghouse.

## New PhD projects

Together with KTH and Chalmers, Uppsala University took part in the large application on research for Gen IV reactors to the Swedish Research Council, VR, rendering in four PhD projects to Uppsala University:

**Core Diagnostics in Gen-IV reactors**
PhD student Peter Wolniewicz started working within this project in autumn 2009.

**Safeguards in Advanced Fuel Cycles and New Reactor Technologies**
A pre-study has been initiated and diploma student Matilda Åberg-Lindell starts working with this project in January 2010.

**New high-energy resolution detector materials for nuclear technology applications**
An advertisement for a PhD student will be issued in March 2010.

**Massive computation methodology for reactor operation**
Gustav Wallin has been identified as a suitable PhD student within this project.

**Other new PhD projects:**

Together with FOI and theoretical material physics at UU, a project aiming at developing the so-called SAUNA instrument has started. The Swedish construction SAUNA is used worldwide as a means to discover tests of nuclear devices.

The ongoing PhD projects all run according to plan.

## Publications and conferences

T. Lundqvist, S. Jacobsson Svärd, A. Håkansson, “Recent progress in the design of a tomographic device for measurements of the power distribution in irradiated nuclear fuel assemblies”, scheduled for publication in *Nuclear Science and Engineering* in June 2010.

S. Jacobsson Svärd, S. Grape, A. Hjalmarsson, "Modelling of the Cherenkov light emission from nuclear fuel assemblies with partial defects”. Full paper reviewed and accepted for the International Conference on the Physics of Reactors (PHYSOR), Pittsburgh, USA, May 9-14, 2010

P. Andersson, S. Jacobsson Svärd, H. Sjöstrand, "Neutron tomography for void distribution measurements". Accepted for a poster presentation at the European Nuclear Conference (ENC) in Barcelona, Spain, May 30 – June 2, 2010

## Theses presented

**Vasily Simutkin**: "Fragment mass distributions in neutron-induced fission of Th-232 and U-238 from 10 to 175 MeV" (Lic.)

**Pernilla Andersson**: "An upgrade of the SCANDAL facility for neutron scattering measurements at 175 MeV" (Lic.)

**Kenny Granath**: ”Feasibility study of a light-weight, transportable equipment for gamma-scanning measurements on nuclear fuel” (February 2009) - in collaboration with Westinghouse. M.Sc.

**Gustav Wallin**: ”Gamma Scanning Software for ORTEC DSPEC Pro” (April 2009) – in collaboration with Westinghouse. M.Sc.

**Cheuk Wah Lau**: ”Prerequisites for a future implementation of a closed nuclear fuel cycle in Sweden” (May 2009) – in collaboration with Vattenfall R&D. M.Sc.

**Mattias Håkansson:** "Monte Carlo simulations of proton background in the Medley experiment" (June 2009). M.Sc.

**Carolina Brynjell Rakkola**: “Validation of VIPRE-01 for application to BWR subchannel core thermal hydraulics”. – in collaboration with Westinghouse. M.Sc.

**Anna-Maria Carstensen**: “A method for energy analysis using electricity as basis of evaluation applied to a Swedish nuclear power plant”. M.Sc.

**Joel Edström**: “Utvärdering av Flowmaster som verktyg för flödestekniska beräkningar”. – in collaboration with Westinghouse. M.Sc.

**Henrik Larsson**: “Evaluation of POLCA7’s void prediction performance during start-up conditions”. – in collaboration with Westinghouse. M.Sc.

**Anna Sand**: “Modelling of the Reactor Containment Cooling in OL1 and OL2”. – in collaboration with Westinghouse. M.Sc.

More information is available at:

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

# Novel diagnostics and analysis of neutron fluxes in boiling water reactors

*PhD student: John Loberg, Division of applied nuclear physics, Uppsala University*
*Supervisors: Dr. Michael Österlund, Adj. Prof. Klaes-Håkan Bejmer (Vattenfall)*

The present PhD project is composed of two distinct and separate parts, where the first concerned neutron-detection based void monitoring in boiling water reactors. This first part was described in the SKC 2008 annual report. The results have been published in international journals, and have constituted a licentiate thesis. The second part of the PhD project is devoted to the studies described below.

## 1) Simulations of neutron fluxes in boiling water reactors for depletion of withdrawn control rods

### Background

In the nuclear reactor field, large emphasis is nowadays put on calculating control-rod depletion inside the core in order to determine when the control-rod lifetime is reached, but control-rod depletion is seldom taken into account, or is poorly modeled, when the control rod is withdrawn from the core.

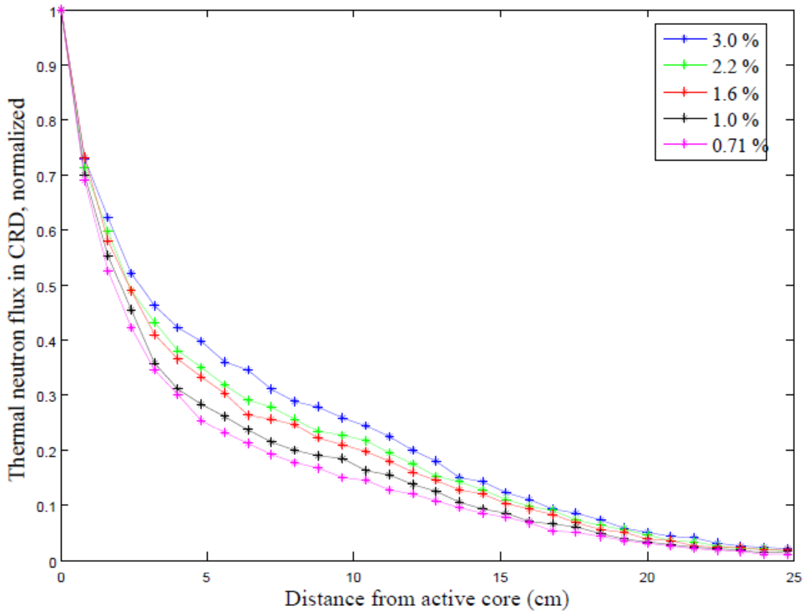
In Swedish BWRs, only a few control rods are used during operation to regulate the power of the core while the rest of the control rods spend most of their time withdrawn from the core where no consideration of the neutron flux is made. Even though the bottom reflector is a low-power region, the top of the active part of a withdrawn control rod still experiences a neutron flux that will contribute to the depletion of the active control-rod top and thereby decreasing the control-rod lifetime.

### Methodology

This project involves neutron-flux calculations of a typical reflector region of a BWR with the Monte Carlo code MCNP5. The reflector region is a very heterogeneous region in 3D and it is therefore suitable to use a Monte Carlo code for this kind of study. Many nodal codes use albedos or simplified 2D constants from lattice codes to get adequate boundary conditions for the reflector regions of the core; none calculate the actual neutron flux in the reflector and thus control-rod depletion in the reflector is not determined. The ambition of this project is to create models of the control-rod neutron flux that can be implemented in conventional nodal codes.

The thermal, fast (epithermal) and MeV neutron flux, defined as $\leq$0.625 eV, 0.625 eV to 1 MeV, and $\geq$ 1 MeV, respectively, is calculated. The thermal and fast neutron fluxes are used for the depletion calculations of absorbing materials in the control rod whereas the MeV-flux is calculated for mechanical aspects of long-time radiation effects of construction materials in the control-rod skeleton.

G-factors are calculated for the purpose of coupling the neutron-flux models to conventional nodal codes, where the nodal neutron flux at the beginning of the active core is used. The sensitivity of these G-factors to different reflector models and different control rod types are investigated. The G-factors are found to be fairly insensitive to reflector and control rod geometries and blanket enrichments, but very sensitive to the absorbent material in the control rod ($B_4C$ and Hf in this project).




*The thermal neutron flux in the control rod at different enrichments in the fuel blanket zone. The flux is normalized to the first absorbing pin.*

### Status

The calculations have been finalized during 2009 and the paper "SIMULATIONS OF NEUTRON FLUXES IN BWRs FOR DEPLETION OF WITHDRAWN CONTROL RODS" has been submitted to Nuclear Science and Engineering.

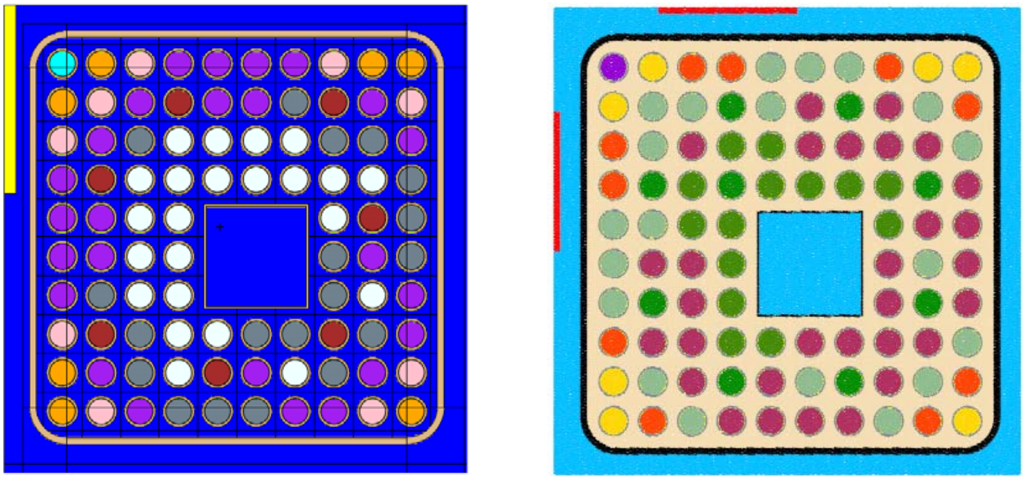
## 2) Investigation of axial power gradients near an unsymmetrical control blade tip

### Background

The fuel assemblies adjacent to a CRB (control blade) in BWRs (Boiling Water Reactor) experience the largest axial power gradients in the core during operation. Partly inserted CRBs will strongly suppress the power in the adjacent fuel assemblies but above the CRB tip the power will increase rather fast with the distance form the CRB. The gradient of this power increase limits the speed at which CRBs can be withdrawn in order to avoid fuel damages. Accordingly, it is important to calculate this gradient with good accuracy.

### Methodology

The axial power gradient will reach its maximum at the CRB handle, not far from the active part of the CRB. In order to calculate this power gradient, 2D homogenised cross sections are used in 3D nodal codes. The problem subject for investigation in this project is that the CRB handle part in Swedish BWRs is asymmetric, i.e., the CRB handle only exist in the north-south direction while the 2D cross section program CASMO assumes all parts of a CRB to be symmetric, i.e., that also the handle is present in both north-south and east-west, as the CRB wings. Accordingly, the 2D cross sections of the CRB handle part are calculated with the handle divided in two equal parts with half the original thickness. This introduces an error in the 3D calculation of the power gradient that will be investigated in this project with the Monte Carlo code MCNP5 and the deterministic 2D/3D codes CASMO5/SIMULATE5.



*The CRB handle geometry in 2D. To the left is the MCNP geometry with the handle only present in north south and to the right is the CASMO handle geometry with the handle divided in two parts.*

The power gradient is calculated as the power difference between two consecutive nodes divided by the node length. A typical node length is traditionally around 15 cm, i.e., the core is axially divided in 25 nodes, but is this refined enough to reflect the power increase around an axially heterogeneous area such as the CRB handle? In order to investigate this, nodes of varying size is used to calculate the pin power gradients.

## Status

Final calculations and analysis are ongoing and planned to be finished spring 2010.

# Studies of void distributions using neutron tomography

*PhD student: Peter Andersson, Department of Physics and Astronomy, Uppsala University.*
*Supervisor: Dr. Staffan Jacobsson Svärd*

## Background

Proper knowledge of the distribution of void and water in BWR fuel during reactor operation is important for fuel design and for optimization of the reactor operation. Accordingly, extensive research on two-phase flow and heat transfer is carried out at various experimental facilities, such as the HWAT loop at KTH in Stockholm and the FRIGG loop at Westinghouse in Västerås. In particular, at the latter facility, an electrically-heated, full-scale fuel model is used for establishing correlations between the power distribution and the void content.

Previously, gamma-ray tomography has been used for experimental determination of the void distribution at FRIGG. Some interesting results have been obtained using this technique [1], but some drawbacks have also been identified; (i) the need for a strong radioactive source and (ii) a relatively poor sensitivity to the water/void content as compared to the construction material.

Neutron tomography is a promising alternative technique for this type of measurements, without the drawbacks stated above. Firstly, an accelerator-based neutron source may be used, which can be turned off when not used, and secondly, neutrons are more sensitive to the content of water/void in the object.

## Objectives and methodology

The objectives of the current project are to assess how to design a measurement device for neutron tomography for future implementation at HWAT and FRIGG and to demonstrate the applicability of the technique in laboratory measurements.

In particular, the investigations shall lead to the identification of practical solutions for the hardware; the neutron source, the neutron detectors and the data-acquisition system, but also for which tomographic reconstruction techniques to use and how to analyze the results. Optimisation of the experimental setup will be pursued based on simulations. In the largest extent possible, the suggested solutions shall be verified experimentally in a laboratory environment.

## Results in 2009

The project was started in May 2008. During 2009, various measurement setups have been modelled using the MCNP simulation code [2]. An illustration of a model is illustrated in figure 1. Various properties of importance for the practical implementation have been studied, such as the level of scattered neutrons in the detectors and their energy distribution. Also the background of neutron-induced gamma radiation has been addressed.

The feasibility of two accelerator-driven neutron sources has been investigated, namely DD (deuterium-deuterium), giving neutrons at 2.5 MeV, and DT (deuterium-tritium), giving neutrons at 14 MeV. The investigations show no large difference in feasibility of the two sources for the present application. Since the neutron energy and the detector's response function both strongly affect the measurement quality, via e.g. the signal-to-background ratio, the choice of source will be closely connected to the choice of detectors.

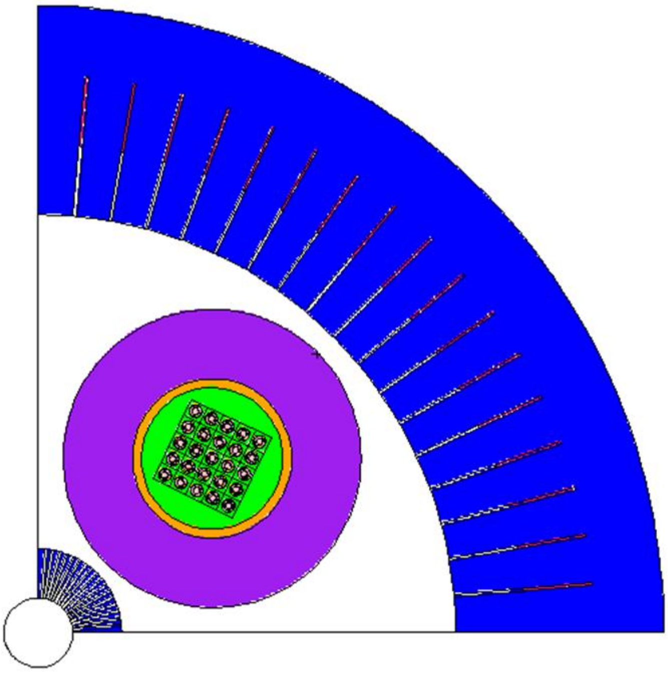


*Figure 1. One measurement setup modelled in the simulation code MCNP. By means of simulations, various properties of importance for the practical implementation can be assessed, such as the signal-to-background ratio and the energy distribution of scattered neutrons and neutron-induced gamma radiation reaching the detectors.*

In addition to the investigations above, two PhD courses have been completed during 2009, implying that courses of totally 22 hp have been completed in the first 20 months of the project. In addition, courses of yet another 12.5 hp have been started during 2009. Furthermore, the work has comprised teaching at the undergraduate level to an extent of about 20%.

## Personnel and collaborations

The scientist is Peter Andersson and the main supervisor is Staffan Jacobsson Svärd. Contacts have been taken with KTH and Westinghouse and study visits have been carried out at the HWAT facility and at the FRIGG facility. Prof. Henryk Anglart, KTH, has been invited to join the reference group. FOI has offered to host the experiments at their experimental facilities in Stockholm, comprising a DT neutron source.

## Reference group

The reference group consists of the following persons:

Uffe Bergmann (Westinghouse), Jesper Ericson (Forsmark), Elisabeth Rudbäck (SSM), Jonas Lanthén (OKG) and Fredrik Winge (Ringhals/Barsebäck). In addition, Henryk Anglart (KTH) has accepted to join the group. A reference group meeting was held in Uppsala 9-10 June 2009.

## References

1) G. Windecker and H. Anglart, “Phase distribution in BWR fuel assembly and evaluation of multidimensional multi-field model”, proceedings from the NURETH 9 conference in San Fransisco, October 1999.

2) L. S. Waters, “MCNPX User’s Manual, Version 2.3.0” Report LA-UR-02-2607, Los Alamos, USA, April 2002.

# SKC financials in 2009

The following table summarises the SKC financials for 2009

| | | |
|---|---|---|
| Received from financing parties | | 17 000 000 SEK |
| Saved from previous years | | 1 996 406 SEK |
| KTH | 7 729 000 SEK | |
| Chalmers | 6 053 000 SEK | |
| Uppsala University | 3 445 000 SEK | |
| SKC centrally | 1 910 333 SEK | |
| Balance at 2009 end | | -140 927 SEK |

The contributions from the financing organizations are split as follows:

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

# Winners of the Sigvard Eklund Price in 2009

*Left to right: Petty Bernitt Cartemo, Jan Blomgren and Åsa Henning at the price ceremony at Varberg Castle during the SKC Ringhals symposium.*

Åsa Henning (b. Magnusson), Lund University, was awarded the price for the best PhD thesis, which has the title " $^{14}C$ Produced by Nuclear Power Reactors – Generation and Characterization of Gaseous, Liquid and Solid Waste". Her work is characterized by the review committee:

"The work is well motivated and of high relevance for present and future nuclear technology. It is clearly written and the author analyzes the problem from many perspectives. The experimental work is impressive and the analysis of the data, including new data, is very adequate. The author shows the relevance of distinction between carbon-14 in organic and inorganic compounds and she developed a new analysis method to separately quantify the carbon-14 in the waste and release streams. This method has already been successfully applied in Korea. Åsa Magnusson shows the weaknesses in the present methods of waste assessment and gives the way for improvement. She also gives valuable suggestions for the handling of this type of waste which has an important impact on final storage."

Petty Bernitt Cartemo was awarded the price for the best master thesis, which has the title "In-Core Neutron Noise Analysis for Diagnosis of Fuel Assembly Vibrations". Her work is characterized by the review committee:

"Use of accurate diagnostic methods to detect and characterize anomalous behaviour in the reactor core is important for safe and economical reactor operation. In the present study a methodology based on analysis of neutron noise has been applied to determine and classify flow-induced vibration characteristics of fuel and internals of the Ringhals 4 reactor. The analysis was based on radial and axial in-core measurements which also could be correlated with simultaneous ex-core measurements. The thesis is very well written and the discussion focussed on identification of probable vibration modes."