SKC Annual Report 2012

Swedish Centre for Nuclear Technology

March 2013
SKC 13-01

SKC, KTH/AlbaNova, Roslagstullsbacken 21, SE-106 91 STOCKHOLM
www.swedishnuclear.se janbl@kth.se +46 (0)76 7878 336

Summary of 2012

July 31, 2012, Vattenfall submitted a formal application on new-build of one or two reactors. Although this in reality represents only a modest first step in a lengthy process, the signal to society at large is clear. SSM needs to increase its capacity immediately to handle this application and to develop criteria for assessment, and if the process continues, several hundred extra recruitments will be required in industry in a few years as well as at the authority, beyond the several hundred per year required for operation of the existing fleet.

The contract on 11.3 MEUR on cooperation with France signed a few years ago has resulted in practical work during 2012. This framework comprises work packages on access to training reactors in Saclay for Swedish students, transfer of nuclear physics experimental research equipment to the GANIL laboratory in Caen, as well as access for Swedish PhD students to the research centres in Cadarache and Marcoule. Three major research projects have started in 2012 with the admission of a number of PhD students. Moreover, laboratory tutorials in France for students are now routine operation.

The nuclear education has grown steadily in Sweden during previous years. 2012 has to some degree been a year of consolidation. The educational programs that have been initiated during the recent years have now found their forms and come into steady operation. During 2012 more efforts have been made on increasing the enrolment to existing programs rather than initiating new ones.

The Fukushima event in March 2011 hampered the student recruitment, but now it seems the situation has essentially returned back to pre-Fukushima conditions.

The Sigvard Eklund price to the best PhD thesis of the year was awarded to Anders Puranen for his work on repository chemistry issues. Antoine Claisse won the price for the best masters´ thesis for his work on irradiation effects on materials. Finally, Azur Bajramovic was awarded the price in the bachelors' thesis class for work on overload protection of control equipment.

Contents

SKC-Partners, Tasks and Goals

By Jan Blomgren,
Director of SKC

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

The partners are:

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

and the three universities:

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

SKC is active within three research programs:

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

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

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

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

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

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

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

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

For further information see:
www.swedishnuclear.se

SKC – preparing for the future

A message from the director

When looking back at 2012, it feels like much more time has passed, simply because the situation has been so volatile during the year.

January 1, 2011, a 30 year moratorium on nuclear technology was terminated with the new law allowing new nuclear reactors to be built to replace the existing ones. July 31, 2012, Vattenfall submitted an application on construction of 1-2 new reactors. It was clearly stated in the application that no investment decision had yet been made, but that the application was made to investigate the option. With the funding provided by the application fee of 100 MSEK, SSM has intitated the work on outlining the requirements for a full-scale application. At present writing, such requirements are planned to be available during 2015. Construction of new reactors requires new competence, and first out is SSM.

If Vattenfall chooses to go ahead with a full application ambition when the requirements have been presented, next phase would require recruitments of the order of 500 full-time staff at Vattenfall, as well as a smaller but significant number also at SSM. Given that the entire nuclear power industry hires about 500 persons per year, this would make a significant increase in staffing needs. If E.On decides to go for new-build as well, the numbers would obviously be even higher. E.On has previously described in public their preparations for new-build, but a formal application has not been made.

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

Vattenfall is one of the co-founders of Tekniksprånget, an initiative coordinated by IVA, to promote interest in a technical career among youngsters. Students leaving high school can apply for a four-month internship at a workplace, in our case Ringhals and Forsmark. The Vattenfall candidates also get an additional one-month employment to be “ambassadors”, i.e., visit high schools and tell about their experience, thereby inspiring others to strive for a technical career. Vattenfall is the only company providing this ambassadorship, and this has resulted in quite some positive media coverage. SKC is not part in Tekniksprånget, but collaborates with it because Tekniksprånget addresses one of the missions of SKC; to increase the interest among students to enter nuclear technology education.

The large collaboration program with France (11.3 M€) that was agreed upon in 2010 finally materialized in recruitment of PhD students and postdocs. Three major research projects have started in 2012 with the admission of a number of PhD students. Moreover, laboratory tutorials in France for students are now routine operation. A large part of the full project comprises research of fast reactors, as well as the GENIUS project that started in 2009 on GenIV issues. This has paved way for increased ambitions in the Swedish nuclear research community on future nuclear technologies.

During 2011-12, a discussion on the possibility to construct a lead-cooled fast reactor for research in Sweden has been a major theme. So far, these discussions have not materialized in governmental support. There seems not to be unanimous agreement in the ruling coalition that GenIV research should be given priority, and the future of this research area presently seems uncertain.

The annual SKC symposium was held at Chalmers, jointly with the inauguration of the Chalmers Sustainable Nuclear Energy Centre. This centre has been initiated by the Chalmers president to promote cross-disciplinary nuclear technology education and research. We wish SNEC the best and hope that nuclear energy will flourish at Chalmers, and that SNEC can strengthen collaboration with the other SKC-supported universities.

Last but not least, the present SKC runs closer to its termination. The contract regulating the activities expires by the end of 2013, and discussions are in progress about a future thereafter. At present writing, there is consensus on continuation by the same parties at about the same total funding level. It seems likely though that SSM will leave this collaboration and establish a separate funding scheme, whereas the four industrial parties are negotiating how to continue jointly. This amicable divorce is the consequence of the new-build process, which motivates a clear separation between industry and regulator in the coming years. Therefore, one of our challenges in 2013 and on is to find routines for fruitful collaboration in a new situation where we are no longer formally together.

With the challenges outlined above, I am convinced SKC will play a vital role also in the years to come.

Jan Blomgren

SKC director

Organization and funding

SKC financing organizations provide 17 million Swedish kronor annually to the universities.In addition, SKC administrates a grant on 3 million SEK for education.

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

The funding organizations are:

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

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

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

The advisory council has consisted of:

- Per Brunzell, chairman
- Farid Alavyoon, Forsmarks Kraftgrupp AB
- Henrik Dubik, OKG AB
- Björn Forssgren, Ringhals AB
- Ninos Garis, SSM
- Ingemar Jansson, Westinghouse
- Karl-Henrik Weddig, Ringhals AB, replaced by Elisabeth Tengborn, SSM from 2012-05-28.

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

The SKC Board has consisted of:

- Lennart Billfalk, replaced by Karl Bergman from 2012-12-05, Chairmen, both from Vattenfall
- Lars Berglund, Forsmarks Kraftgrupp AB
- Johan Dasht, OKG AB
- Lennart Eckegren, Ringhals AB
- Eva Simic, SSM
- Anders Andrén, Westinghouse
- Gustav Amberg, KTH
- Irene Kolare, Uppsala University
- Mats Viberg, Chalmers

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

SKC financials in 2012

The following table summarises the SKC financials for 2011

Received from financing parties		17 000 000 SEK
Balance from previous years		-2 589 002 SEK
French laboratory support + other income		4 164 463 SEK
KTH	6 300 000 SEK	
Chalmers	5 100 000 SEK	
Uppsala University	3 300 000 SEK	
SKC centrally	2 343 290 SEK	
French laboratory costs	2 712 834 SEK	
Balance at year’s end		-1 180 664 SEK

The contributions from the financing organizations are split as follows:

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

Comment: The negative balance at the end of the fiscal year is due to a large marketing campaign motivated by the upcoming collaboration with France. It will be paid off during the remaining SKC contract period, to balance at the end of 2013. It can be noted that the deficit was reduced by 1 408 339 SEK in 2012, whereas the remaining deficit is 1 180 664 SEK.

Winners of the Sigvard Eklund Price in 2012

Left to right: Azur Bajramovic, Anders Puranen and Antoine Claisse, with the SKC director Jan Blomgren below, at the price ceremony at Universeum during the SKC symposium at Chalmers.

Anders Puranen, KTH, was awarded the prize for the best PhD thesis, which has the title “Near field immobilization of selenium oxyanions”. His work is characterized by the review committee:

Since the revision of the half-life of 79Se to a much higher value than previously considered, the potential impact of this isotope on geological disposals has substantially increased. However not much is known about the possible reductions of selenate and selenite in the near field, which if they can be demonstrated would increase the safety margin of existing geological disposal concepts. The objective of this thesis is to provide such data and the understanding on the speciation processes that could occur in the near field region.

Due to the very low concentrations, the experimental studies need to be carefully performed with several techniques. Anders Puranen used a variety of analytical techniques (spectrophotometry, Raman microscopy, irradiation in a Microtron) including the µ-XAS at the SLS facility of the Paul Scherrer Institute in Switzerland. From his work result many quantitative data and images with an in depth analysis and conclusions, which contribute to fill a gap in the knowledge of the waste disposal community.

The thesis is clearly written and illustrated. In addition, the candidate has reported his work and results in several papers, which together make a very nice piece of work.

Antoine Claisse, KTH, was awarded the prize for the best Masters’ thesis, which has the title “Ab Initio based Multi-Scale Simulations of Oxide Dispersion Strengthened Steels”. His work is characterized by the review committee:

Antoine Claisse is awarded the prize for furthering the understanding of application of advanced materials in nuclear reactors and an excellent communication of the results.

Antoine Classe’s master thesis is written easily comprehensible in spite of quantum mechanics which is the theory for nanoclusters that are studied. The thesis is an enhancement of earlier studies in the area of point defect simulations, and is an ambitious project. The extensive result is a good example of a concise presentation illustrated with 3-D pictures in addition to prevalent diagrams and pictures.

The thesis covers an important area for today’s reactors as well as tomorrow’s gen IV and fusion reactors. Material properties is of importance for operation availability and hence for nuclear operation economy. Antoine Claisse’s brilliant master thesis goes out over the ordinary one can expect of a master thesis, and is a piece in an important development of further understanding of advanced materials for nuclear reactor applications.

Azur Bajramovic, Uppsala University, was awarded the prize for the best Bachelors’ thesis, which has the title “Selection ov over-load protection for electric valve control equipment at the Forsmark nuclear power plant”. His work is characterized by the review committee:

Azur Bajramovic has presented a thorough diploma work with an in-depth analysis of the functionality of valves and the factors that affect the parameter settings of over-load protection systems. The report contains many advanced assessments and interesting conclusions and discussions.

Chalmers University of Technology

Overview of Activities in 2012

Establishment of the Sustainable Nuclear Energy Centre

A new centre, called the Sustainable Nuclear Energy Centre (SNEC), was created on January 31, 2012 at Chalmers, and was formally inaugurated on October 8, 2012 with the participation of more than 120 registered attendees. This centre allows coordinating and structuring research, education, and communication about all aspects of nuclear energy and uses of radioactive elements in a comprehensive, responsible, and critical manner. This centre creates a Forum where researchers, students, and industry members are in direct contact. More specifically, this centre acts as an entity to:

- Coordinate research and education within Chalmers, and between Chalmers and external partners (both nationally and internationally).
- Provide a forum of exchange and discussions between researchers, students, and industry members, thus leading to a creative research environment and to a direct networking between the different actors involved.
- Provide information about nuclear energy and radioactivity to the society at large in a timely and reliable manner.
- Seek and coordinate external funding from different stake holders.
- Increase Chalmers attractiveness for foreign researchers and students.
- Provide to the industry one single entity to deal with in nuclear energy-related matters.

Some pictures taken during the inauguration of SNEC on October 8, 2012

Mats Viberg (Chalmers First Vice President), inaugurating SNEC

Thomas Smed (Studsvik Scandpower CEO), one of the guests speakers for the SNEC inauguration, giving a talk on nuclear simulation

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

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

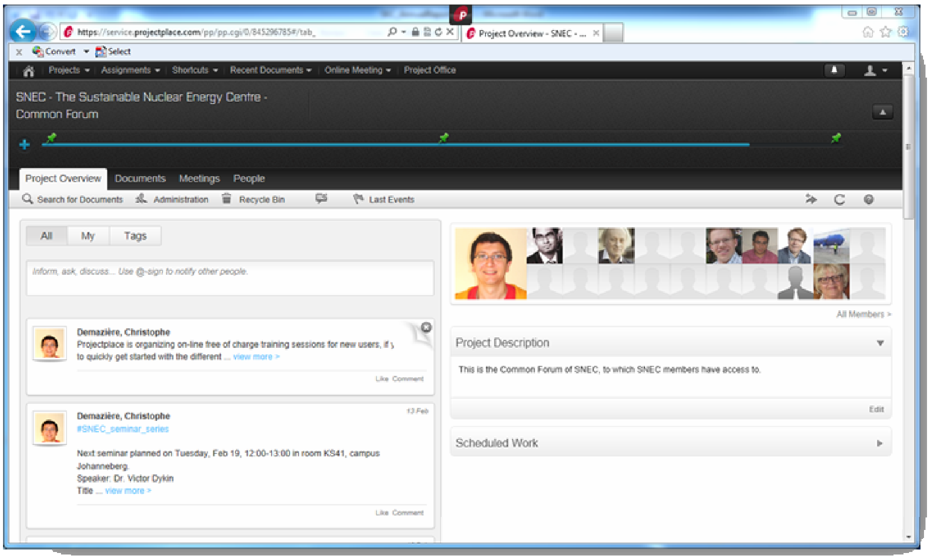
The main outcomes of such a Forum are manifold:

- By creating a network of contacts between the industry and the academia, the industry is aware of the available competences at Chalmers, which could be of use for solving problems of direct industrial relevance. The direct link between the researchers and the industry makes the Forum unique. This is in clear contrast with other networks/efforts that the industry is financing, where only a few industry representatives are aware of the available competences, and are in relation with the academia. Likewise, by a closer contact with the industry, the academia is able to propose innovative solutions to problem of industrial relevance. The mutual awareness the centre creates is a unique feature that presently does not exist in the Swedish nuclear arena.
- In addition, the Forum actively includes both MSc students and PhD students enrolled in nuclear-related education/projects. By involving the students in the Forum, attracting them to either an industrial or academic career is made much easier.
- Finally, the Forum also allows the different Divisions dealing at Chalmers with nuclear energy-related research and education to be in direct contact, to exchange information and knowledge, and to collaborate in a structured and coordinated manner.

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

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

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



Overview of the web-based platform used by SNEC

The following Chalmers Divisions/Departments are participating to the coordination of SNEC and to the Forum:

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

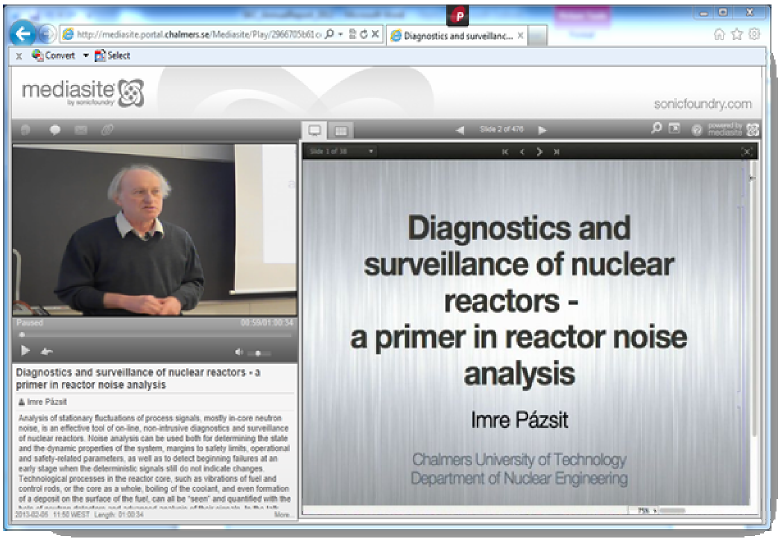
The following Chalmers Divisions/Departments are participating to some extent to the Forum only:

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

The current industry members in SNEC include:

- E.ON.
- Studsvik Scandpower.

SNEC is also organizing a seminar series at a pace of one seminar every two weeks. These seminars are both live streamed on the internet and available On-Demand for later viewing, so that the dissemination of information/knowledge, both within and outside Chalmers, is maximal.



Snapshot of one of the SNEC seminars that was live broadcasted and is also available On-Demand

Use of the SKC funding

The SKC funding is currently supporting three Divisions at Chalmers:

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

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

- A pulsed beam for variable energy slow positrons.
- A portable 14 MeV pulsed neutron generator.
- Access to all major system codes for neutronic and thermal-hydraulic calculations.
- Laboratories for α, β, γ experiments and activity measurements.
- A hot cell laboratory for γ activity.
- A special laboratory for research on advanced nuclear fuels (collaboration with KTH), including both a SEM and XRD facility.
- Several irradiation sources including a 18 kGy/h ^{60}Co and ^{137}Cs facilities ranging from 50 Gy/h and down to 1 Gy/h.
- An Atom Probe Tomography Instrument.*
- Three Transmission Electron Microscopes.*
- Two Scanning Electron Microscopes.*
- Two Focused Ion Beam Workstations.*

*Managed by the infrastructure unit at the Dpt. of Applied Physics

The following PhD projects were supported, either fully or partially, by SKC during 2012:

- Neutron fluctuations in zero power systems and power reactors (PhD student: Anders Jonsson; main supervisor: Professor Imre Pázsit).

- Nitric acid formation, ruthenium chemistry (PhD student: Ivan Kajan; supervisor: Professor Christian Ekberg).

- Development of an integrated neutronic/thermal-hydraulic model using a CFD solver (PhD student: Klas Jareteg; supervisor: Professor Christophe Demazière).

- Complexation of iodine species with organic molecules under severe accident conditions in LWRs (PhD student: Sabrina Tietze; supervisor: Professor Christian Ekberg).

- Reactor diagnostics with advanced signal analysis (READS) (PhD student: Victor Dykin; supervisors: Professor Christophe Demazière and Professor Imre Pázsit).
- Investigation of the use of thorium in LWRs for improving reactor core performance (PhD student: Cheuk Wah Lau; supervisor: Adjunct Professor Henrik Nylén).
- Uncertainty and sensitivity analysis applied to the simulation of the Swedish Boiling Water Reactors (PhD student: Augusto Hernández-Solís; supervisors: Professor Christian Ekberg and Professor Christophe Demazière).

Highlights of the year

Prof. Kåre Axell (SSM) was promoted Adjunct Professor at the Div. of Nuclear Engineering, Dpt. of Applied Physics.

Dr. Richard Sanchez, from CEA Saclay, visited Chalmers as one of three visiting Anniversary Professors in 2012. Dr. Sanchez has been leading the development of the APOLLO code, which is the lattice code used in France.

Professors Imre Pázsit and Christophe Demazière received funding of a total of 34 MSEK from the Swedish Research Council (VR) for nuclear engineering research in a Swedish-French collaboration agreement, which includes KTH and Uppsala University (with Profs. Pázsit and Demazière being the main applicants of two respective multi-project grants). The grants cover a period of five years and contain a total of seven PhD positions. Four of those are at Chalmers. The grants are related to research on the ASTRID fast reactor and on the Jules Horowitz Reactor, the latter being built at CEA Cadarache, France.

Professor Christophe Demazière received an additional framework grant for strategic energy research of 8 MSEK from VR. This grant corresponds to a cross-disciplinary project with researchers from the Div. of Nuclear Engineering, Fluid Dynamics, and Dpt. of Mathematical Sciences at Chalmers, as well as the Fraunhofer Chalmers Centre. The research to be performed is targeted at developing next generation computational methods for nuclear reactor simulations.

The DREAM task force (with DREAM standing for Deterministic Reactor Modelling) was created at Chalmers and is led by Prof. Christophe Demazière. This task force represents a cross-disciplinary research team (with researchers from Applied Physics, Applied Mechanics, Mathematical Sciences at Chalmers, and Fraunhofer Chalmers Centre) and is currently made of 13 researchers. The team gathers expertise in neutron transport, fluid dynamics, heat transfer, and numerical analysis. The team is financially supported by VR, SKC, SSM, and NORTHNET.

The number of academic degrees in nuclear chemistry/Industrial Materials recycling reached an all-time high with 3 graduated PhD students and 5 licentiates. In addition the new nuclear fuel laboratory at nuclear chemistry was commissioned and is now fully operational.

The large scale EU project ASGARD was launched in January. It has a total budget of 9.6 MEuro and involves participants from 16 counties. It is coordinated by Prof. Christian Ekberg and other Swedish participants are KTH (Prof. Janne Wallenius) and Westinghouse.

In SKC-related subjects, the following Licentiate theses were successfully presented during 2012:

- “Atom Probe Tomography of Hydrogen and of Grain Boundaries in Corroded Zircaloy-2,” by Gustav Sundell.
- “Investigation of the use of thorium in LWRs for improving reactor core performance,” by Cheuk Wah Lau.
- “Oxidation and Corrosion of Ni-based Superalloys in Power Plants,” by Haiping Lai.

- “Formation, partitioning and interactions of organic iodides under severe nuclear accident conditions in LWR containments,” by Sabrina Tietze.
- “Diluent and Solvent effects in Liquid-Liquid Extraction Systems based on bis-triazine-bipyridine (BTBP)-class ligands,” by Elin Löfström Engdahl.

In SKC-related subjects, the following PhD theses were successfully presented during 2012:

- “Noise applications in Light Water Reactors with traveling perturbations,” by Victor Dykin.
- “Neutronics in reactors with propagating perturbations,” by Anders Jonsson.
- “Helium measuring system for on-line fuel and control rod integrity surveillance in BWRs,” by Irina Larsson.
- “Uncertainty and sensitivity analysis applied to LWR neutronic and thermal-hydraulic calculations,” by Augusto Hernández-Solís.
- “Development of a Solvent Extraction Process for Group Actinide Recovery from Used Nuclear Fuel,” by Emma Aneheim.
- "Microstructure investigation of the oxidation process in Zircaloy-2 - The effect of intermetallic particle size," by Pia Tejland.

Master education

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

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

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

A few highlights for 2012:

- 12 students are registered in the master program for the academic year 2012-2014, and 26 students are registered in the master program for the academic year 2011-2013. On the introductory course in physics in 2012, 50 students were registered. Students enrollments are much lower this year compared with earlier years. This could be associated with the Fukushima accident, as well as the corresponding political decisions in Germany and Switzerland.

- Within the French-Swedish agreement regarding exchange of nuclear services as part of the European Spallation Source, the students for the master program have been sent to a research reactor in Saclay, France. The tutorials were in form of two-and-a-half day long laboratory exercises on a small open pool reactor. 24 students visited Saclay in 2012.

- A new course in nuclear materials has been developed and is now being launced. The course is aimed at materials in nuclear reactors and the rather special environment with high temperature and high neutron radiation levels.

- A new nuclear track in the högskoleingenjörs education is beeing discussed and evaluated.

PhD education

The Doctoral School in Nuclear Engineering has on the average about 10 enrolled PhD students. The Doctoral School was designed in such a way that students with various backgrounds could be accepted to the Doctoral School. This corresponds to the fact that nuclear engineering is by essence a cross-disciplinary area, and consequently might attract students with various backgrounds (physics, chemistry, mechanical engineering, electrical engineering). Such a mix of students within one single Doctoral School creates a very rich and stimulating environment for the students during their PhD studies. Correspondingly, the list of compulsory courses is kept at a strict minimum so that the students can best choose the courses depending on their background and their research project.

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

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

Publication statistics

Some data taken from the Chalmers Publication Library (CPL) about the 2012 publications from the Divisions getting some SKC financial supports are given below. No data from the Div. of Materials Microstructure could be gathered, since this Division was established in 2012.

	Div. of Nuclear Chemistry	Div. of Nuclear Engineering	Total
Number of peer-reviewed journal articles	19	29	48
Number of peer-reviewed conference articles	4	20	24
Number of PhD theses	3	3	6
Number of Lic. theses	5	1	6
Number of MSc theses	2	6	8
Number of reports	5	3	8
			100

KTH – Royal Institute of Technology

Overview of Activities in 2012

During 2012, divisions within nuclear energy engineering field at KTH experienced a significant growth both in research and education. CEKERT - a Centre for Nuclear Energy Engineering at KTH was re-activated to coordinate common actions. All professor positions have been filled within CEKERT and the Centre has now in total 14 faculty members. Research and education within the field of nuclear energy engineering is currently carried out at 11 different divisions:

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

Staff

Year 2012 was very successful in further strengthening the staffing of the nuclear engineering divisions at KTH. Weimin Ma was appointed as Associate Professor at the Nuclear Power Safety division.

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

5 professors
1 adjunct professor
7 associate professors
1 assistant professor
28 PhD students
15 researchers
2 emeritus professors
1 affiliated professor
2 technicians

Several post-docs and PhD students left after completion of their research and graduation, and new post-docs and PhD students were appointed.

Highlights and major research outcome

The major highlights and research outcome during year 2012 can be summarized with the following numbers:

- 70 scientific publications
- 9 PhD theses
- 1 Licentiate theses
- 12 Master and Bachelor theses
- ~1462 student*ETCS of undergraduate education in nuclear engineering

In particular, year 2012 was rich in international conferences and workshops, promoting intensive research and dissemination work.
Collaboration agreements in nuclear power safety have been signed with KIT, Germany, KAERI, Korea and POSTECH, Korea.
KTH, in collaboration with Scandpower and VTT, organized international Workshop on Integrated Deterministic-Probabilistic Safety Analysis.
In collaboration with CEA, France, KTH started new safety research project for ASTRID sodium-cooled fast reactor.
KTH further developed cooperation with Japan assisting MHI in safety analysis and justification of severe accident management concept of APWR reactor designed for Europe.
Several new test facilities have been designed and are under construction and commissioning:

- TALL-3D liquid metal loop for validation of coupled STH and CFD codes in application to thermal hydraulic and safety analysis of heavy liquid metal cooled systems.
- SES facility for investigation of stratified steam explosion.
- PDS-C and PDS-P for study of particulate corium debris spreading.

PULiMS facility was successfully used for the tests with well controlled conditions of stratified steam explosion.
The EU-financed project MAXSIMA on methodology, analysis and experiments for

support of the safety assessments of MYRRHA lead-bismuth cooled reactor has been started.
KTH continued several projects for safety improvement of Nordic BWR reactors and provided technical support to SSM in coupled neutronic/thermohydraulic analysis of different NPP units and in MELCOR simulation of severe accidents. KTH participated in OECD benchmark on Oskarshamn-2 BWR 1999 Stability Event.
Nuclear Reactor Technology division organized "NRT Open Day" meeting in which the division research was presented to industrial partners.
Maria Jaromin defended her thesis on "Theoretical and Computational Study on the Onset of Heat Transfer Deterioration in Supercritical Water" and received a Technology Licentiate degree.
Diana Caraghiaur defended her thesis "On Drops and Turbulence in Nuclear Fuel Assemblies of Boiling Water Reactors" and received a PhD degree.
Henryk Anglart was invited by the President of Pakistan Institute of Engineering and Applied Sciences and delivered a 5-day course in thermal-hydraulics of nuclear systems in PIEAS, Islamabad, Pakistan.
Henryk Anglart was invited by IAEA to an expert mission at the Nuclear Power Institute of China (NPIC) and delivered 5-day lectures on progress in thermal-hydraulics using two-phase CFD technology.
Henryk Anglart was offered by the Warsaw University of Technology a visiting professor position.

PhD education

The following PhD and Licentiate Theses were completed during year 2012:

Ivan Gajev, "Sensitivity and uncertainty analysis of boiling water reactor stability simulations", PhD Thesis, Nuclear Power Safety, ISBN:978-91-7501-565-1, December 2012.

Maria Jaromin, "Theoretical and Computational Study on the Onset of Heat Transfer Deterioration in Supercritical Water", Nuclear Reactor Technology, December 2012.

Diana Caraghiaur, "On Drops and Turbulence in Nuclear Fuel Assemblies of Boiling Water Reactors", Nuclear Reactor Technology, December 2012.

Sara Sundin, "Radiation induced dissolution of model compounds for spent nuclear fuel: mechanistic understanding of oxidative dissolution and its inhibition". Nuclear Chemistry, ISSN 1654-1081, June 2012.

The following PhD projects were carried out during the year:

Roman Thiele: "Thermal-hydraulics in lead-bismuth cooled nuclear fuel assemblies", supported by the GENIUS project. Licentiate thesis to be presented in 2013.

Ionut Anghel: "Post-dryout heat transfer in channels with flow obstacles", supported by SKC. Doctoral thesis to be presented in 2013.

Reijo Pegonen: "Development of new procedures for thermal-hydraulic analyses of the Jules Horowitz Reactor", supported by VR.

Viet-Anh Phung, "Development of a method for the treatment of two-phase flow patterns in nuclear reactor thermal hydraulic system code", supported by SKC and APRI-8 projects.

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

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

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

Sachin Thakre, "Simulation of fuel coolant interactions and corium coolability during a severe accident of LWRs", supported by the APRI-8 and SARNET2 projects.

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

Simone Basso, "Particulate Debris Spreading and Debris Bed Coolability in Light Water Reactor Severe Accident", supported by APRI-8 and MHI-HQ projects.

Sebastian Raub, "Safety analysis of ASTRID core catcher", supported by ASTRID project.

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

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

Claudio Lousada: “Interfacial radiation chemistry” supported by SKC. Doctoral thesis to be presented in 2013.

Veronica Diesen: “Photocatalytic purification of water” supported by Wallenius Water AB. Doctoral thesis to be presented in 2013.

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

Alexandre Barriero Fidalgo: “Radiation induced dissolution of spent nuclear fuel” supported by SKB.

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

Björn Dahlgren: “Theoretical studies of interfacial radiation chemistry” supported by CHE, KTH.

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

Pertti Malkki, High performance nitride fuels for LWRs. Funded by SKC.

Erdenechimeg Suvdantsetes, Design and safety studies of ELECTRA. Funded by SKB.

Zhongwen Chang, Multi-scale modelling of swelling in austenitic steels. Funded by GENIUS.

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

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

Rickard Shen, Solid Mechanics Department.

Martin Bjurman, Solid Mechanics Department.

Per Ljustell, Solid Mechanics Department.

Undergraduate education

KTH divisions have been successfully running the Master Program in Nuclear Energy Engineering since 2007. During that time the program has gained high international reputation and the courses taught within the program have attracted many international and domestic students. The following major courses were given in 2012:

“Nuclear reactor technology”, H. Anglart, 8 ECTS, 25 students.

“Thermal-hydraulics in nuclear systems”, H. Anglart, 6 ECTS, 18 students.

“Nuclear reactor dynamics and stability”, J. Dufek, 6 ECTS, 16 students.

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

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

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

”Reactor physics” - W. Gudowski (9 ECTS, 40 students)

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

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

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

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

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

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

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

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

“Monte Carlo methods and simulations in nuclear technology”, J. Dufek (6 ECTS, 15 students).

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

At the Department of Solid Mechanics, no specific nuclear science related course has been given during 2012, but the Department is hosting approximately 20 under graduate students on a yearly basis. Courses in Solid Mechanics, Fracture Mechanics, Mechanical testing, Materials Mechanics, Finite Element modelling, Paper Mechanics and Continuum Mechanics at undergraduate/advanced level are given on a regular basis, whereas courses in more specialized areas such as Fatigue and Deformations Mechanisms are given when suitable.

Adj Professor Pål Efsing has given an overview lecture on Nuclear Power in the general Energy System course given at CTH during the fall 2012. A course on "Materials for nuclear reactor systems" is in the planning stages to be included in the Master's program on Nuclear Technology.

The following Master and Bachelor Theses have been completed during 2012:

Maxime Villemin, "Alarm handling in the control room of a Nuclear Power Plant", Master Thesis of KTH, March 2012.

Andrew Caldwell "Addressing Off-site Consequence Criteria Using Level 3 Probabilistic Safety Assessment A Review of Methods, Criteria, and Practices", Master Thesis of KTH, May 2012.

Xiao Hu: "TRACE analysis of LOCA transients performed on FIX-II facility experiments", Master Thesis of KTH, June 2012.

Mian Xing: "Validation of TRACE code against ROSA/LSTF test for SBLOCA of pressure vessel upper-head small break", Master Thesis of KTH, June 2012.

Reijo Pegonen: "Investigation of thermal mixing using OpenFOAM", Master Thesis of KTH, Nuclear Reactor Technology, June 2012.

Igor Trisic: "Simulation of transient dryout heat transfer in the HWAT loop using the TRACE code", Master Thesis of KTH, Nuclear Reactor Technology, June 2012.

Alberto Ghione: "Development and validation of a two-phase CFD model using OpenFOAM", Master Thesis of KTH, Nuclear Reactor Technology, December 2012.

Jacob Bergenstråle: "POLCA-T – evaluation of a parallel steam separator model", Master Thesis of KTH, Nuclear Reactor Technology, October 2012.

Maria Kajstad, Technology assessment of spent nuclear fuel reprocessing, Master Thesis of KTH, March 2012.

Camilla Gustafsson, Correlations and pattern analysis of dopamine D1 – and D2 receptor binding in the human brain, Master Thesis of KTH, June 2012.

Ante Hultgren and **Ola Roos**, "TRACE simulations of HWAT-loop", Bachelor Thesis of KTH, April 2012.

National and international projects

KTH is participating in numerous national, European and international cooperation projects. In 2012 several new project were initiated.

Nuclear Reactor Technology was involved in the following European projects: NURISP – on development of simulation tools for nuclear engineering applications; THINS – on development of thermal-hydraulics methods for new innovative nuclear systems; EURECA! – on education within Gen IV supercritical water cooled reactors; HPMC – on development of high performance Monte-Carlo methods. In 2012 three new projects were started: ALDESA – a PhD project in cooperation with CEA, France - dealing with acoustic leak detection in sodium systems; DEPTHS-JHR – a PhD project in cooperation with CEA, France – dealing with a development of new procedures for thermal-hydraulic analyses of the Jules Horowitz Reactor; NURESAFE – European Framework project concerned with a development of a nuclear reactor simulation platform. In addition, the division is leading the following national projects: NORTHNET RM1 – on development of thermal-hydraulic models for nuclear fuel assemblies; THEMFE – on experimental investigation of thermal mixing phenomena using the HWAT loop; THEMFA - on analytical investigation of thermal mixing phenomena using CFD models with URANS and LES closures for turbulence.

Nuclear Power Safety has been involved in the following European projects: SILER – on seismic issues of heavy liquid metal cooled reactors; THINS for experiment and analysis of thermal-hydraulics new innovative nuclear systems; SARNET2 for research on severe accident phenomena; NURISP for development of simulation tools for nuclear engineering applications. Nuclear Power Safety is also performing the international projects: MHI-APWR-HQ, MHI-SES-TRDC and ENSI-MSWI for study on corium coolability and steam explosion risk. Nuclear Power Safety has the national projects: APRI-8 for research on corium coolability and steam explosion in BWRs; DSA for transient and severe accident safety analysis for Swedish nuclear power plants; NORTHNET-RM1 for experimental study on micro-hydrodynamics of flow boiling and CHF mechanisms; NORTHNET-RM3 for simulation of condensation and mixing phenomena in a BWR suppression pool.

The Department of Solid Mechanics has four on-going projects relating to the nuclear industry and to the sponsors of SKC at the department. These are:

- Modelling of stress corrosion cracking, with emphasis on initiation and short crack growth;
- -Stress corrosion cracking in Alloy 690;
- -Thermal ageing and decomposition of cast and welded austenitic materials and;
- -Fatigue under variable loading conditions.

Of these, the program on modelling of Stress corrosion cracking has financial support, 50%, from SKC. The project on stress corrosion cracking in Alloy 690 is fully financed by the owners of the Swedish Nuclear Power Plants, Vattenfall, E.On and Fortum as part of the agreement on the placement of Efsing at the department. The fatigue project, which is near the end since the student, Per Ljustell, will defend his thesis in February 2013 has been financed by the Swedish nuclear regulatory agency SSM and finally the project on Thermal ageing is financed by SSM and the Swedish nuclear power plants materials utility group. With the exception of Ljustell's project, the current programs are in the beginning of their cycle.

Rickard Shen presented results from the first step of his project, i.e. metallographical analysis of welded Alloy 690 components to determine the relative residual strains in Alloy 690 base materials at the NRC-MRP Alloy 690 research collaboration meeting in Tampa, Florida, US.

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

Reactor Physics division has been involved in the following projects:

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

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

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

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

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

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

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

Conferences and publications

The divisions actively participated in major international conferences within nuclear engineering field and also published in several reputed journals. The most important publications within 2012 are as follows:

Villanueva W., Tran C.-T., Kudinov P., "Coupled thermo-mechanical creep analysis for boiling water reactor pressure vessel lower head," Nuclear Engineering and Design, 249, 2012, 146-153.

L.X. Li, W:M. Ma, S. Thakre, An experimental study on pressure drop and dryout heat flux of two-phase flow in packed beds of multi-sized and irregular particles, *Nuclear Engineering and Design*, **242**: 369-378, 2012.

S.J. Gong, W.M. Ma, T.N. Dinh, Simulation and validation of the dynamics of liquid films evaporating on horizontal heater surfaces, *Applied Thermal Engineering*, **48**: 486-494, 2012.

L.X. Li, S.J. Gong, W.M. Ma, An experimental study on two-phase flow regime and pressure drop in a particulate bed packed with multi-diameter particles, *Nuclear Technology*, **177**: 107-118, 2012.

K. Wang, B.F. Bai, J.H. Cui, W.M. Ma, A physical model for huge wave movement in gas-liquid churn flow, *Chemical Engineering Science*, **79**: 19-28, 2012.

Bottomley, D., Stuckert, J., Hofmann, P., Tocheny, L., Hugon, M., Journeau, C., Clément, B., Weber, S., Guentay, S., Hozer, Z., Herranz, L., Schumm, A., Oriolo, F., Altstadt, E., Krause, M., Fischer, M., Khabensky, V.B., Bechta, S.V., Veshchunov, M.S., Palagin, A.V., Kiselev, A.E., Nalivaev, V.I., Goryachev, A.V., Zhdanov, V. & Baklanov, V. "Severe accident research in the core degradation area: An example of effective international cooperation between the European Union (EU) and the Commonwealth of Independent States (CIS) by the International Science and Technology Center", Nuclear Engineering and Design, vol. 252, 2012, pp. 226-241.

Jeltsov M., Kööp K., Kudinov P., Villanueva W., "Development of domain overlapping STH/CFD coupling approach for analysis of heavy liquid metal thermal hydraulics in TALL-3D experiment," CFD4NRS-4, OECD/NEA and IAEA Workshop, Daejeon, Korea, September 10-12, 2012.

Phung V.-A. and Kudinov P., "Identification of Two-Phase Flow Regimes in Unstable Natural Circulation Using TRACE and RELAP5," Proceedings of The 9th International Topical Meeting on Nuclear Thermal-Hydraulics, Operation and Safety (NUTHOS-9), Kaohsiung, Taiwan, September 9-13, , N9P0062, 2012.

Villanueva W., Tran C.-T., and Kudinov P., "Analysis of Instrumentation Guide Tube Failure in a BWR Lower Head," Proceedings of The 9th International Topical Meeting on Nuclear Thermal-Hydraulics, Operation and Safety (NUTHOS-9), Kaohsiung, Taiwan, September 9-13, , N9P0268, 2012.

Tran C.-T., Villanueva W., and Kudinov P., "A Study on the Integral Effect of Corium Material Properties on Melt Pool Heat Transfer in a Boiling Water Reactor," Proceedings of The 9th International Topical Meeting on Nuclear Thermal-Hydraulics, Operation and Safety (NUTHOS-9), Kaohsiung, Taiwan, September 9-13, , N9P0289, 2012.

Jeltsov M., Kööp K., Grishchenko D., Karbojian A., Villanueva W., and Kudinov P., "Development of TALL-3D Facility Design for Validation of Coupled STH and CFD Codes," Proceedings of The 9th International Topical Meeting on Nuclear Thermal-Hydraulics, Operation and Safety (NUTHOS-9), Kaohsiung, Taiwan, September 9-13, , N9P0299, 2012.

Jeltsov M., Kööp K., Grishchenko D., Karbojian A., Villanueva W., and Kudinov P., "Development of multi-scale simulation methodology for analysis of heavy liquid metal thermal hydraulics with coupled STH and CFD codes," Proceedings of The 9th International Topical Meeting on Nuclear Thermal-Hydraulics, Operation and Safety (NUTHOS-9), Kaohsiung, Taiwan, September 9-13, , N9P0298, 2012.

Konovalenko A., Basso S., Karbojian A., and Kudinov P., "Experimental and Analytical Study of the Particulate Debris Bed Self-leveling," Proceedings of The 9th International Topical Meeting on Nuclear Thermal-Hydraulics, Operation and Safety (NUTHOS-9), Kaohsiung, Taiwan, September 9-13, , N9P0305, 2012.

Konovalenko A. and Kudinov P., "Development of Scaling Approach for Prediction of Terminal Spread Thickness of Melt Poured into a Pool of Water," Proceedings of The 9th International Topical Meeting on Nuclear Thermal-Hydraulics, Operation and Safety (NUTHOS-9), Kaohsiung, Taiwan, September 9-13, , N9P0302, 2012. (**Best paper award**)

Konovalenko A. , Karbojian A., and Kudinov P., "Experimental Results on Pouring and Underwater Liquid Melt Spreading and Energetic Melt-coolant Interaction," Proceedings of The 9th International Topical Meeting on Nuclear Thermal-Hydraulics, Operation and Safety (NUTHOS-9), Kaohsiung, Taiwan, September 9-13, , N9P0303, 2012.

Yakush S., Lubchenko N., and Kudinov P., "Risk-Informed Approach to Debris Bed Coolability Issue," Proceedings of the 20th International Conference on Nuclear Engineering (ICONE-20), Anaheim, CA, USA, July 30 - August 3, Paper 55186, 2012.

Villanueva W., Tran C.-T., and Kudinov P., "Effect of CRGT Cooling on Modes of Global Vessel Failure of a BWR Lower Head," Proceedings of the 20th International Conference on Nuclear Engineering (ICONE-20), Anaheim, CA, USA, July 30 - August 3, Paper 54955, 2012.

Vorobyev Y., Kudinov P., "Development of Methodology for Identification of Failure Domains with GA-DPSA," 11th International Probabilistic Safety Assessment and Management Conference (PSAM) and The Annual European Safety and Reliability (ERSEL) Conference, Scandic Marina Congress Center, Helsinki, Finland, 25-29 June 2012.

Kudinov P., Davydov M., Pohlner G., Bürger M., Buck M., Meignen R., "Validation of the FCI codes against DEFOR-A data on the mass fraction of agglomerated debris," 5th European Review Meeting on Severe Accident Research (ERMSAR-2012) Cologne (Germany), March 21-23, 2012.

Y.D. Chen, W.M. Ma, J.Y. Shi, G.H. Chai, MELCOR simulation of SBO scenario of Fukushima Daiichi-3 BWR, Proc. NUTHOS-9, Kaohsiung, Taiwan, September 9-13, 2012.

Y.Q. Shao, W.M. Ma, TRACE analysis for transient thermal-hydraulics of a LBE-cooled system, Proc. of NUTHOS-9, Kaohsiung, Taiwan, September 9-13, 2012.

L.X. Li, S. Thakre, W.M. Ma, Experimental study on coolability of debris beds with cuboidal and triangular shapes, Proc. of NUTHOS-9, Kaohsiung, Taiwan, September 9-13, 2012.

I. Gajev, W.M. Ma, T. Kozlowski, Space-time convergence analysis of BWR stability based on a model for Oskarshamn-2 99 event, Proc. of NUTHOS-9, Kaohsiung, Taiwan, September 9-13, 2012.

S. Raub, S. Roshan, W.M. Ma, 1 and 3D TRACE analysis of ROSA/LSTF test 6-1 for SBLOCA, Proc. of NUTHOS-9, Kaohsiung, Taiwan, September 9-13, 2012.

S.J. Gong, W.M. Ma, Investigation on boiling phenomena in a liquid film under high heat flux, ECI 8th International Conference on Boiling and Condensation Heat Transfer, Lausanne, Switzerland, June 3-7, 2012.

A. Miassoedov, T.W. Tromm, J. Birchley, F. Fichot, W.M. Ma, G. Pohlner, P. Matejovic, Corium and debris coolability studies performed in the severe accident research network of excellence (SARNET2), Proc. ICONE20, Anaheim, California, USA, July 30 - August 3, 2012.

W.M. Ma, W. Villanueva, P. Kudinov, A. Miassoedov, X. Gaus-Liu, M. Hoffmann, B. Jaeckel, J. Birchley, P. Matejovic, M. Barnak, Progress in melt pool behavior and coolability in the lower head of a light water reactor, Proc. of ERMSAR-2012, Cologne, Germany, March 21-23, 2012.

A. Palagin, A. Miassoedov, X. Gaus-Liu, H. Muscher, M. Buck , W.M. Ma, P. Kudinov, L. Carenini, C. Koellein, W. Luther, V. Chudanov, Analysis and Interpretation of the LIVE-L6 Experiment, Proc. of ERMSAR-2012, Cologne, Germany, March 21-23, 2012.

G. Repetto, T. Garcin, M. Rashid, R. Kulenovic, W.M. Ma, L.X. Li, Investigation of Multidimensional Effects during Debris Cooling, Proc. of ERMSAR-2012, Cologne, Germany, March 21-23, 2012.

Granovsky, V.S., Sulatsky, A.A., Khabensky, V.B., Sulatskaya, M.B., Gusarov, V.V., Almyashev, V.I., Komlev, A.A., Bechta, S., Kim, Y.S., Park, R.J., Kim, H.Y. & Song, J.H. 2012, "Modeling of melt retention in EU-APR1400 ex-vessel core catcher", International Congress on Advances in Nuclear Power Plants 2012, ICAPP 2012, pp. 1412.

I.G. Anghel and H: Anglart, "Post-dryout heat transfer to high-pressure water flowing upward in vertical channels with various flow obstacles", Int. J. Heat and Mass Transfer, 55 (2012)8020-8031.

R. Thiele and H. Anglart, "Numerical modelling of forced-convection heat transfer to lead-bismuth eutectic flowing in vertical annuli", accepted to Nuclear Engineering and Design, 2012.

J. Dufek, D. Kotlyar, E. Shwageraus and J. Leppänen, "Numerical stability of the predictor-corrector method in Monte Carlo burnup calculations of critical reactors", accepted to Annals of Nuclear Energy, 2012

M. Jaromin and H. Anglart, "A numerical study of heat transfer to supercritical water flowing upward in vertical tubes under normal and deteriorated conditions", accepted to Nuclear Engineering and Design, 2012.

H. Anglart and D. Caraghiaur, "CFD modeling of boiling annular-mist flow for dryout investigations", Multiphase Science and Technology, 23 (2-4): 223-251 (2011), published 2012.

K. Fu and H. Anglart, "Implementation and validation of two-phase boiling flow models in OpenFOAM", CFD4NRS-4 Workshop, Daejeon, Korea, 10-12 September 2012.

H. Anglart, "Application of the convolution theorem to predict heated wall temperature subject to various axial power distributions", proc. 20th Int. Conf. Nuclear Engineering, ICONE20, Anaheim, CA, USA, July 30 – August 3, 2012.

H. Anglart, "Analysis of the onset of dryout conditions in diabatic annular two-phase flows", proc. 20th Int. Conf. Nuclear Engineering, ICONE20, Anaheim, CA, USA, July 30 – August 3, 2012.

H. Anglart, “Recent advances in thermal-hydraulics of nuclear reactors”, Kärnteknik 2012 – Scandic Infra City, 4-5 December 2012.

H. Anglart and I. Anghel, “Experimental investigation of trans-dryout heat transfer”, 6th Japanese – European Two-Phase Flow Group Meeting, Kumamoto City, Japan, 23-27 September 2012.

H. Anglart, “On the onset of stable dryout condition in annular two-phase flows in heated channels”, 50th European Two-Phase Flow Group Meeting, Udine, Italy, 16-18 May, 2012.

P. Ljustell, “Fatigue crack growth experiments on specimens subjected to monotonic large scale yielding”

P. Ljustell and B. Alfredsson, “Variable amplitude fatigue crack growth at monotonic large scale yielding experiments on stainless steel 316L”

P. Efsing, J. Rouden and M. Lundgren, “Long term irradiation effects on the mechanical properties of reactor pressure vessel steels from two commercial PWR plants”, ASTM-JAI 104004

P. Efsing, E-L Green and J. Rouden, “Ringhals Units 3 and 4 –Fluence determination in a historic and future perspective”, Journal of ASTM International, Volume 9, Issue 4, April 2012

M. K. Miller, R. Nanstad and P. Efsing, “Atom probe tomography of low-copper high-nickel RPV welds at high fluence”, Presented at NuMat 2012, Nuclear Materials, Osaka, 22-25 October 2012.

R. Shen and P. Efsing “Microstructural studies of Alloy 690 mock-up components”, Presented at the MRP Alloy 690/152/52 international collaboration meeting, Tampa, November 27-29, 2012.

Michael Holmboe, Mats Jonsson and Susanna Wold, Influence of γ-radiation on the reactivity of Montmorillonite towards H2O2, Radiation Physics and Chemistry, Vol. 81, No. 2, pp. 190-194, 2012.

Mauro Claudino, Inge van der Meulen, Stacy Trey, Mats Jonsson, Andreas Heise and Mats K. G. Johansson, Photoinduced thiol-ene cross-linking of globalide/ε-caprolactone copolymers - curing performance and resulting thermoset properties, Journal of Polymer Science Part A, Vol. 50, No. 1, pp. 16-24, 2012.

Michael Holmboe, Susanna Wold and Mats Jonsson, Porosity investigation of compacted bentonite using XRD profile modeling, Journal of Contaminant Hydrology,Vol. 128, No. 1-4, pp. 19-32, 2012.

Åsa Björkbacka, Saman Hosseinpour, Christofer Leygraf and Mats Jonsson, Radiation Induced Corrosion of Copper in Anoxic Aqueous Solution, Electrochemical and solid-state letters, Vol. 15, No. 5, pp. C5-C7, 2012.

Claudio M. Lousada, Adam Johannes Johansson, Tore Brinck and Mats Jonsson, Mechanism of H2O2 Decomposition on Transition Metal Oxide Surfaces, The Journal of Physical Chemistry C, Vol. 116, No. 17, pp. 9533-9543, 2012.

Marcus Amme, Reijo Pehrman, Rudolf Deutsch, Olivia Roth and Mats Jonsson, Combined effects of Fe(II) and oxidizing radiolysis products on UO2 and PuO2 dissolution in a system containing solid UO2 and PuO2, Journal of Nuclear Materials, Vol. 430, No. 1-3, pp. 1-5, 2012.

Veronica Diesen and Mats Jonsson, Tris(hydroxymethyl)aminomethane as a probe in heterogeneous TiO 2 photocatalysis, Journal of AOTS. Advanced Oxidation Technologies, Vol. 15, No. 2, pp. 392-398, 2012.

Trygve E. Eriksen, David W. Shoesmith and Mats Jonsson, Radiation induced dissolution of UO2 based nuclear fuel - A critical review of predictive modelling approaches, Journal of Nuclear Materials, Vol. 420, No. 1-3, pp. 409-423, 2012.

Reijo Pehrman, Martin Trummer, Claudio Miguel Lousada and Mats Jonsson, On the redox reactivity of doped UO2 pellets - Influence of dopants on the H2O2 decomposition mechanism, Journal of Nuclear Materials, Vol. 430, No. 1-3, pp. 6-11, 2012.

Åsa Zazzi, Anna-Maria Jakobsson and Susanna Wold, Ni(II) sorption on natural chlorite, Applied Geochemistry, Vol. 27, No. 6, pp. 1189-1193, 2012.

Jonas Hedberg, Maria Lundin, Troy Lowe, Eva Blomberg, Susanna Wold and Inger Odnevall Wallinder, Interactions between surfactants and silver nanoparticles of varying charge, Journal of Colloid and Interface Science, Vol. 369, No. 1, pp. 193-201, 2012.

Pavel A. Korzhavyi, Inna L. Soroka, Eyvaz I. Isaev, Christina Lilja and Börje Johansson, Exploring monovalent copper compounds with oxygen and hydrogen, Proceedings of the National Academy of Sciences of the United States of America, Vol. 109, No. 3, pp. 686-689, 2012.

J. R. Vegelius, K. O. Kvashnina, M. Klintenberg, Inna L. Soroka and S. M. Butorin, Cu K beta(2,5) X-ray emission spectroscopy as a tool for characterization of monovalent copper compounds, Journal of Analytical Atomic Spectrometry, Vol. 27, No. 11, pp. 1882-1888, 2012.

J. R. Vegelius, K. O. Kvashnina, H. Hollmark, M. Klintenberg, Y. O. Kvashnin, Inna L. Soroka, L. Werme and S. M. Butorin, X-ray Spectroscopic Study of Cu2S, CuS, and Copper Films Exposed to Na2S Solutions, The Journal of Physical Chemistry C, Vol. 116, No. 42, pp. 22293-22300, 2012.

Q Zhang, N. Akram, P. Skog, Inna Soroka, C. Trautmann and R. Schuch, Tailoring of keV-ion beams by image charge when transmitting through rhombic and rectangular shaped nanocapillaries, Physical Review Letters, Vol. 108, No. 19, 2012

Mats Jonsson, Radiation Effects on Materials Used in Geological Repositories for Spent Nuclear Fuel, ISRN Materials Science, Volume 2012, Article ID 639520, 13 pages, doi: 10:5402/2012/639520, Review Article, 2012

S. Nilsson, H2O2 and radiation induced dissolution of UO2 and SIMFUEL, Oral presentation, Spent Fuel Workshop, Avignon, France, 18-19 April, 2012

M. Jonsson, Reactivity of H2O2 towards metal oxides, Oral presentation, Spent Fuel Workshop, Avignon, France, 18-19 April, 2012

M. Jonsson, Radiation Induced Processes in Geological Repositories for Spent Nuclear Fuel, Invited speaker, The 4th Asia-Pacific Symposium on Radiation Chemistry, Huangshan, China, October 30-November 3, 2012

Uppsala University

Overview of Activities in 2012

With its 50 employees (researchers/teachers and Ph.D. students), the Division of Applied Nuclear Physics (ANP) has grown to be one of the largest division of the nine divisions constituting the Department of Physics and Astronomy at Uppsala University.

The steep increase from about 20 personnel a few years ago to today's size is governed by an increased amount of research and educational undertakings that span over a wide range of research areas, competences and disciplines. Some examples of areas under development are elements of interdisciplinary actions within the Nordic Academy for Nuclear Safety and Security (NANSS), the development of a reactor physics group and the increased activity within materials research, which are all parts of a comprehensive strategy to create a stable and a high-quality enterprise that could serve and support the surrounding society - a part of our mission.

As stated in last year's Annual Report, the increased volume of activities needs to be addressed by employing more personnel and, therefore, the staff has been increased by 5 new employees during 2012. Although ANP today can be stated to be a comparably large research node, we nevertheless need to limit ourselves and focus the available resources adequately. To that end we foresee that the following areas will be highlighted in the coming years:

- Structural materials (stress corrosion cracking and aging).
- Nuclear safeguards (more efficient and less intrusive technologies).
- Nuclear fuel diagnostics and core monitoring (gen II, III, III+, IV).
- Nuclear data and Total Monte Carlo approach (experimental uncertainties and their propagation in core simulators and other relevant tools).
- Offering of nuclear expertize internationally (considering the fact that many developing countries now contemplate of initiating nuclear power programmes).
- Reactor physics in support of the above activities.

It should be stressed that our enhanced focus on reactor physics is *not* to compete with similar activities elsewhere but to *support* the internal needs of ANP.

A determining factor for us to focus on these areas is the considerable international interest for our research and education we have gained. Regarding structural material we have initiated collaboration with UC Berkeley and Los Alamos National Lab (LANL) in the US. As mentioned in the Annual Report for 2011, our discussions with LANL have now resulted in a full-fledged collaboration within the Next Generation Safeguards Initiative, which is financed by the Department of Energy. During 2012 we have planned for Dr. Steve Tobin at LANL to visit us as a guest researcher during a two years period of time starting July 2013. Dr. Tobin will besides assisting the supervision of Ph.D. students also conduct research in the safeguards field.

With LANL and UC Berkeley we also collaborate in designing and constructing a materials testing irradiation facility at Ångström Laboratory (ICE3) for investigating irradiation induced corrosion and aging of structural materials. This work is coordinated by Prof. Mattias Klintenberg who was working at LANL during 2012 to initiate this collaboration.

The collaboration with NRG, Petten in the Netherlands enhances our field in nuclear data and Total Monte Carlo calculations. This collaboration has gained by the fact that Dr. Arjan Koning now is an adjoint professor at UU.

Considering education, highly interesting collaborations are being developed with the IAEA and discussions are on-going directly with specific states on the African and Asian continents.

We believe that focussed efforts on the above areas also create feasible platforms for collaboration with relevant groups at Chalmers and KTH in order to achieve a more efficient use of the available national funding.

Another collaboration that experiences interesting development is with the Institutt for Energiteknikk in Halden (IFE), Norway. Besides the on-going Ph.D. project we conduct together with IFE, there are also discussions on the offer for UU to be a formal member of the OECD Reactor project.

ANP has a long-time engagement with the European Safeguards Research and Development Association (ESARDA). This has been under the SSM umbrella but spurred by SSM, we have applied for a formal membership to ESARDA during 2012. This application has been taken positively and we anticipate a membership during spring 2013. With such a membership we may act more flexible as regards participation in the various working groups of ESARDA.

The activities within NANSS have continued during 2012. The number of interested parties increases steadily and at present the universities of Stockholm, Gothenburg and Trondheim want to participate. Also the group with Carl Rollenhagen at KTH are interested to contribute to NANSS as is SIPRI. The IAEA is also on track and during 2012 we have agreed that a seminar on Knowledge Management will be held during the first half of 2013 in Uppsala. This event will be conducted as a joint venture between NANSS and the IAEA and will be directed to the managements of the Swedish nuclear industry. The core group of NANSS, i.e. SSM, KSU and IFE, work with course packages that are planned to be issued during autumn 2013. However, the reorganisation of KSU may imply a somewhat smaller initial participation from their side than originally planned for.

With these introductory remarks we conclude that our activities during 2012 were quite successful and we look with confidence towards the future.

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

Education

As a result of the long-term strategy within ANP to increase the number as well as the scope of courses offered to engineering students at Uppsala University within the fields of energy physics and nuclear engineering, teaching has become an activity of considerable importance. The division is responsible for managing two engineering programs, the Bachelor of science in engineering programme with a specialisation in nuclear engineering, i.e., H*ögskoleingenjörsprogrammet i kärnkraftteknik* (KKI), which is on its third year since the start in autumn 2010 and the Master of science in engineering programme with a specialisation in energy systems engineering, i.e., *Civilingenjörsprogrammet i energisystem* (ES), which is the 2nd largest master of science in engineering programme at Uppsala University. In addition to courses within these programmes, division staff also provides courses in nuclear technology, energy physics and technical thermo-hydraulics within the framework of other UU engineering programmes.

Also, since 2003 UU provides higher education for the nuclear power industry under an agreement with *Kärnkraftsäkerhet och Utbildning AB* (KSU). The objective of this contract education is to secure competence building of existing and newly recruited personnel, primarily within reactor operation and radiation protection.

All ANP staff involved in teaching has taken teacher training courses as part of the UU continuing education program. During 2012/2013 four of the ANP staff are participating in a didactics course on the advanced level (Avancerad ämnesdidaktisk metodologikurs) with the objective of performing a didactic study about student learning within the KKI programme.

During 2012 UU has, in addition to being a member of the European Nuclear Education Network (ENEN), also become a member of the IAEA International Nuclear Security Education Network (INSEN) in order to further facilitate the development of NANSS.

Bachelor of science in engineering with a specialisation in nuclear engineering

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

- The programme, which comprises 60 hp, contains the following courses:
- Introduction to nuclear engineering (5 hp)
- Reactor physics (5 hp)
- Nuclear thermal hydraulics and steam turbine technology (5 hp)
- Light water reactor technology (5 hp)
- Chemistry, materials and fuels for reactor applications (5 hp)
- Nuclear power safety (5 hp)
- Power Engineering (5 hp)
- Nuclear power operation (5 hp)
- Future nuclear energy systems (5 hp)
- Degree project in nuclear power technology (15 hp)

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

An important aspect of the learning process is for the student to gain knowledge about the nuclear process and the different actors within the nuclear industry. With that in mind a number of study visits are included in the programme. During 2012 students have made study visits to FKA, OKG and RAB, the SKB facilities in Oskarshamn, the Westinghouse nuclear fuel fabrication plant in Västerås, Siemens Turbomachinery in Finspång (steam turbines) and ABB in Ludvika (generators and transformers). There has been no study visit to SSM, but SSM staff is actively involved as teachers in the course Nuclear power operation.

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

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

Recruitment

Considerable effort is devoted to student recruitment activities. In particular the German "Energiewende" and its possible influence on Swedish energy policy as well as the mostly media driven discussion about the future of Swedish nuclear power are causes for concern amongst students and seems to have a rather strong influence on their decision on whether or not to choose a nuclear engineering education . Recruitment activities are focused on arranging lunch seminars at several engineering colleges around Sweden and participation in student careers fairs at Swedish universities, e.g., UTNARM, CHARM LARM. These activities are often performed in collaboration industry and SKC. Additionally, the programme is marketed through advertisements in various media such as educational supplements, included in newspapers, e.g., SKC's Atomen, and also through mailings to students.

As shown in Table 1 below, compared to the 1st year of the programme the number of applicants for the 2nd and 3rd year (post-Fukushima) has decreased. The numbers of applicants for the 2nd and 3rd year are similar. From our contact with students it is clear that students' choice of educational programs is clearly influenced by public opinion and debate. With that in mind it is important that the nuclear industry conveys a positive message to prospective students about the possibility of a career within the field. In order to help the general public and prospective students in particular to form a realistic opinion about the future role of nuclear power in the Swedish energy system, ANP has been very active during 2012 in providing relevant information about nuclear energy trough participation in public radio, writing newspaper debate articles and giving lectures at schools etc.

Compared to other engineering programmes at UU, housing, family, work etc. a larger than average fraction of students admitted to the program does not commence the education at the start of the autumn semester. It is however positive that the drop-out rate during the programme is very low.

Table 1. Recruitment statistics for the period 2010-2012 (source: Verket för högskolestudier)

Study year	Applicants	1st-hand applicants	Applicants admitted to the program	Students registered at start of first semester	Students active at end of semester 2
2010/2011	80	47	34	21	19
2011/2012	57	26	36	12	11
2012/2013	60	29	36	14	12 (feb 2013)

Students' achievements

At the time of writing (february 2013) 21 students have successfully completed their Bachelors theses. A summary of the theses produced during 2012 is found at the end of this chapter. In 2012 Azur Bajramovic from Uppsala program received the Sigvard Eklund award for best diploma work on the Bachelor's level. The year before Katja Göller, also from the nuclear engineering program received the award. The students' achievement for the academic years 2010/2011 and 2011/2012 are shown in Figure 1 below, whereas the students' achievements for the academic year 2012/2013 are shown in Figure 2.

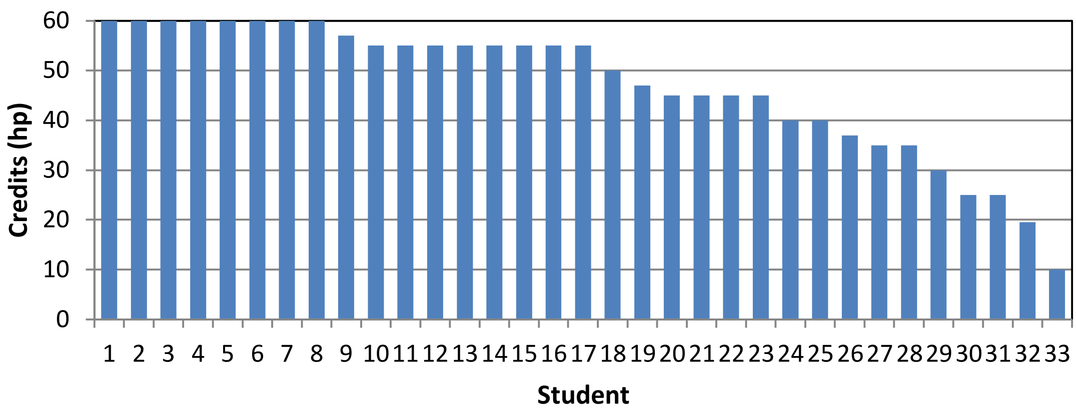


Figure 1: Student achievements for the academic years 2010/2011 and 2011/2012 for all students enrolled in the program. Data were extracted in December 2012 and following re-exams during the spring semester 2013 further improvement in student's achievements are expected.

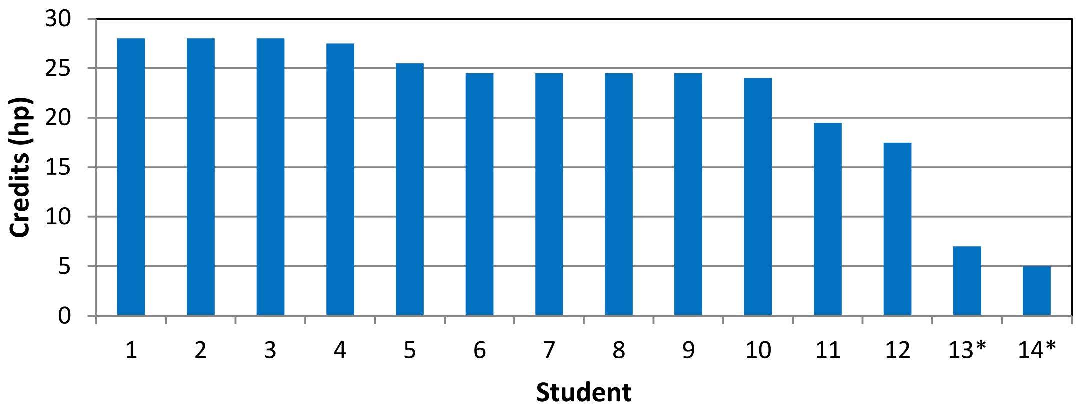


Figure 2: Student achievements for the autumn term of the academic year 2012/2013 for all students enrolled in the program. Two students (* in the figure)), have postponed their studies for personal reasons (studieuppehåll).

Employment

Almost without exception the students graduating from the first two years of the program have been employed within the nuclear industry. Of those students a large majority has taken up positions with the NPPs and we are happy to note that the interest among those students to pursue a career within NPP operation is high. Increasing the supply of candidates for this staff category was one of the original objectives of the programme. Within industry there is on-going work to adapt the on-the job training of turbine and reactor operators in order to take advantage of the higher education level of the new recruits compared to what has previously been required.

Master of Science in engineering programs

Within the Master of Science in Engineering programmes, the division gives courses dedicated to nuclear power. Also, the educational strategy of the ANP includes offering courses which integrate nuclear power into a wider context of energy-related questions. The objective with these courses is (a) to attract students who otherwise might not be exposed to nuclear power, (b) to give a wider perspective where nuclear power appears as one important part of the energy system, (c) forming a basis for recruitment of diploma workers.

During 2012, the following courses were given:

”Nuclear Power – Technology and Systems”: A course on nuclear power with focus on today's techniques, given within the Master of Science in Engineering programme for Energy Systems. 22 students.

”Energy System Physics”: A general course on energy-related issues with some chapter on nuclear power. Given within the Master of Science in Engineering programme for Sociotechnical Systems Engineering. 29 students.

”Energy Physics I”: A course similar to ”Energy System Physics”. Given within the Master of Science in Engineering programme in Engineering Physics and the Bachelor Programme in Physics. 32 students.

”Energy Physics II with nuclear power”: Advanced course with focus on nuclear energy. Given within the Master of Science in Engineering programme in Engineering Physics. 11 students.

”Project in Applied Physics”: Within this course, the division offers projects on energy-related questions, including nuclear energy, in collaboration with Vattenfall. 15 students.

Future nuclear energy systems: In this course, fusion and Generation IV systems are addressed. 11 students.

Technical thermo-hydraulics (F programme): 96 students.

Technical thermo-hydraulics (ES + Electro programmes): 80 students.

Contract education for the industry

The fact that the Swedish nuclear industry have entered a period of lower recruitment rates and cost cutting measures after a number of years with very high recruitment rates is reflected in the demand for contract education courses provide by ANP to industry through a long-term agreement with KSU. During 2012 ANP provided 12 weeks of courses, Kärnkraftteknik (12hp) and Fördjupad strålskyddsutbildning, FS1 (6 hp), which were given on two occasions each. For 2013, 16 weeks of courses have been requested by KSU. For both courses participants can be registered as students at Uppsala University and be awarded academic credits after passing the examinations.

During 2012 considerable effort has been put into revising the FS1 course. In collaboration with the FORS-group, with representatives from KSU, the NPPs and subcontractors, the course curriculum and learning objectives have been thoroughly revised. Changes have also been made to the course schedule in order to further enhance the learning experience and learning outcome. As a consequence of this revision the course, which previously comprised 2 weeks of full-time studies plus prerequisite homework, have now been extended to 3 weeks. The FS1 course in its new form will be given for the first time during the spring semester 2013.

Students' theses

PhD theses completed during 2012

Ali Al-Adili: ”Measurement of the 234U(n,f) Reaction with a Frisch-Grid Ionization Chamber up to En=5 MeV”. The thesis finished in December 2012 and successfully defended on January 18 2013 with Patrick Talou from Los Alamos National Laboratory as faculty opponent.

Licentiate theses completed during 2012

Scott Holcombe: ”Nondestructive Fission Gas Measurements by Means of Gamma Spectroscopy and Gamma Tomography”. The thesis was successfully defended in November 2012 with Guido Ledergerber, KKL, Switzerland, as the scrutinizer.

Peter Wolniewicz: ”A feasibility study of coolant void detection in a lead-cooled fast reactor using fission chambers”. The thesis was successfully defended in December 2012 with Dr. Nils Sandberg, SSM, as the scrutinizer.

Masters theses completed during 2012

Kristina Moberg: ” An investigation of fuel cycles and material flows for a lead-cooled fast reactor using the Monte Carlo code Serpent”

Niklas Lundkvist: ”Investigation of possible non-destructive assay (NDA) techniques for the future Swedish encapsulation facility” – in collaboration with SKB

Per Alfheim: ”Definition and evaluation of a dynamic source term module for use within RASTEP: A feasibility study” – in collaboration with Scandpower

Tariq Zuwac: ” Calculation method based on CASMO/SIMULATE for isotopic concentrations of fuel samples irradiated in Ringhals PWR” – in collaboration with Vattenfall Nuclear Fuel

Isbel Llerena Herrera: ”An automated software for analysis of experimental data on decay heat from spent nuclear fuel” – in collaboration with SKB

Mikael Lundberg: "Environmental analysis of zirconium alloy production".

Masters diploma works in progress

Mattias Bolander: “Nuclear Fuel Pellet Cladding Interaction Failure Modeling”

Moa Eriksson: “Förutsättningar för ett parallellt generation IV system vid svensk nybyggnation av kärnkraft”

Gustav Robertsson: "Simuleringar med MCNP kring styrstavsspets - starka gradienters inverkan på neutronflödet"- in collaboration with Vattenfall Nuclear Fuel.

Christian Alex:" Optimization of RIA-calculations - Simulating Falling Control Rods at Forsmark Nuclear Power Plant" (thesis presented in February 2013) – in collaboration with FKA

Erik Dalborg: "MCNP-modell för beräkning av neutrondos och DPA på reaktortanken vid Ringhals 2 och beräkning av strålningsskador hos reaktorns interndelar" (preliminary title) – in collaboration with Vattenfall Nuclear Fuel

Tom Bjelkenstedt: "Dimensionering av detektorelement inom transmissionstomografi med snabba neutroner"

Bachelors theses completed during 2012 (KKI)

David Angerbjörn: "Visualiseringsverktyg för SY-kedjor i kretsar"

Azur Bajramovic: "Val av överlastskydd för elektriska ventilmanöverdon på kärnkraftverket i Forsmark" (Sigvard Eklunds pris 2012)

Ahmed Abuzohri: "Skapa öppenhet i erfarenhetsregistrering vid Forsmarks Kraftgrupp AB"

Zlatko Dizdarevic: "Skapa öppenhet i erfarenhetsregistrering vid Forsmarks Kraftgrupp AB"

Lennart Strandman: "Analys av skillnader mellan internationell och svensk rapportering av inträffade händelser på kärnkraftverk" – in collaboration with SSM

Ulrik Norrå och **David Angerbjörn**: "Visualiseringsverktyg för Sykedjor" – in collaboration with FKA

Adam Persson: "Aspirantutbildningsprogram" – in collaboration with KSU.

Bachelors diploma works in progress (KKI):

Joel Sundmark: "Analys av nivåproblematik i dränagetank på Ringhals 1"

Lars Spansk: "Analys av nivåproblematik i dränagetank på Ringhals 1"

Research

New senior personnel

In April, **Carl Hellesen**, researcher started working 50% on fission energy related issues besides his previous tasks within fusion energy. Carl devotes the dominant part of his fission research towards Gen IV, and one of his main duties is the supervision of the new Ph.D. student, Vasudha Verma (see below).

Peter Jansson has accepted a non-tenured researcher appointment after finishing a 2-year appointment in December 2012. Peter's main responsibilities currently lie within waste management and safeguards.

Arjan Koning from NRG, Petten, The Netherlands, has during 2012 been approved as adjoint professor at UU (20%). His official starting date is February 1, 2013. Koning is a world-leading expert in nuclear model codes and the main author of the TALYS code which is central for our Total Monte Carlo work. The appointment deepens the long standing scientific collaboration between UU and NRG and will also increase Koning's involvement in student supervision and teaching.

Vasily Simutkin has been recruited as researcher with an initial one-year contract starting April 2012. He defended his PhD thesis at UU in 2011 and has since spent one year as postdoc at CENBG, Bordeaux, France. He is working on neutron-induced fission of 232Th and 238U. It is planned to prolong his contract and involve him in development of the TALYS code for fission.

Diego Tarrio has been recruited as postdoc for 2 years. He took up his position in October 2012 and is involved in the NFS project at GANIL. Besides assisting in PhD student supervision, his key tasks are detector and data-acquisition development for fission measurements. He is also a link to the nuclear data activities at CERN n_TOF where he did his PhD thesis on neutron induced-fission.

New Ph.D. students

During 2012 the following Ph.D. students were recruited:

Vasudha Verma arrived in November to perform research within the Swedish-French collaboration on the ASTRID project, being the first Gen IV prototype reactor, cooled by liquid sodium.

Tomáš Martinik arrived in December to carry out his Ph.D. project within the Next Generation Safeguards Initiative, covering new measurement techniques for assessing the fissile content in spent nuclear fuel. The project is performed in collaboration with Los Alamos National Laboratory (LANL).

Kaj Jansson started in April and is the first PhD student in the NFS project at GANIL. He will perform high-quality measurements of fission standards cross sections. Kajs main supervisor is Cecilia Gustavsson.

Vasileios Rakopoulos started his position in May. Together with his fellow PhD student Andrea Mattera, he will use the IGISOL facility for measurements of independent fission yields in thermal and fast neutron spectra. Vasileios supervisor is Mattias Lantz.

Ph.D. student projects

Peter Andersson started his Ph.D. studies in May 2008 on the topic of void monitoring in thermal-hydraulic test loops using neutron transmission tomography. The goal of the project to develop the technique for application at test loops such as HWAT in Stockholm and FRIGG in Västerås, provided that the technique proves successful in terms of accuracy, time consumption and economy. After some periods of parental leave, Peter's dissertation is now scheduled for early 2014.

During 2012, Peter has published a paper on a technique for dynamic bias correction, i.e. correcting for a non-linear response to temporal changes in void content during a measurement, a source of bias that was of concern for several experts at the SKC symposium 2011. In Peter's research, he has finalised a laboratory measurement device for transmission tomography using a portable neutron source. The device will be demonstrated in measurements at the The Svedberg Laboratory in Uppsala in January-March 2013, using a neutron generator borrowed from Chalmers (Anders Nordlund). Object models have been constructed, imitating the type of two-phase flows that are the main target for this new measurement technique.

A reference group meeting was held at the 2012 SKC symposium at Chalmers in October, also this year resulting in valuable feedback to the project. Special attention was paid to the time required for a tomographic measurement, which primarily depends on the strength of the neutron source and on the detector setup. Shorter measurement times are strongly correlated with higher investments, and as a result of that meeting, Peter will include time and cost estimations for a larger FRIGG-type object during the remaining year of his project.

Scott Holcombe started his PhD studies in October 2009 in collaboration with Westinghouse Electric Sweden AB. Scott performs his PhD project on "Advanced diagnostics of nuclear fuel based on tomographic techniques and high-resolution gamma-ray spectroscopy" as a part of the OECD Halden Reactor Project. Scott presented his licentiate thesis in November 2012, entitled "Nondestructive Fission Gas Measurements by Means of Gamma Spectroscopy and Gamma Tomography". The dissertation is planned for 2014.

During 2012, the manufacturing of a tomographic instrument for measurements on irradiated fuel at the Halden reactor has been started. The instrument will allow measurements to be performed on test fuel with short cooling times (1-2 days) for experimental determination of various fuel parameters. A large part of Scott's work has been focused on the measurement of short-lived fission gasses and their assessment using tomographic techniques. Two papers have been submitted during 2012, of which one has been accepted for publication. Two reference group meetings have been held, with representatives from Uppsala University and Westinghouse Electric Sweden AB.

Tomáš Martinik arrived in Uppsala in December 2012 to start his PhD studies on "Verification of nuclear fuel for safeguards purposes using non-destructive assay techniques for the future Swedish encapsulation facility". He is a joint student between Uppsala University and Los Alamos National Laboratory in the US and he will work within the Next Generation Safeguards Initiative (NGSI). The project concerns simulations, analysis and experimental assessment of measurement techniques for non-destructive assay of spent nuclear fuel. The purpose of Tomáš' project is to contribute to the NGSI techniques being developed to quantify the content of various fissile isotopes in the fuel and to bring a Swedish back-end perspective into their evaluation.

Ali Al-Adili has presented his thesis on fission of ^{234}U in December (and defended on Jan 18, 2013). The ^{234}U isotope is present in nuclear fuel and the ^{234}U(n,f) reaction is also relevant for fission of 235U in LWR at higher neutron energies and fast reactors.

Ali has developed experimental techniques, run experiments, analyzed the data and presented the results in several journal publications and conferences. A very relevant result is the identified need to measure the emission of neutrons from the fission fragments as function of both the fragment mass and the incoming neutron energy. In Alis work surprisingly large changes in the fission yields resulting from various assumed post-fission neutron emission models have been found. This has an impact on our knowledge of the fuel inventory in reactors, especially those with a fast spectrum. Measurements that could clarify some of these issues might, e.g., be performed at IGISOL in Jyväskylä.

Erwin Alhassan started his PhD studies in 2011. He is using the Total Monte Carlo method (TMC) to study the impact of nuclear data uncertainties on reactor parameters. Using TMC, uncertainty propagation was carried to study the impact of nuclear data uncertainties of ^{208}Pb and ^{239}Pu on ELECTRA. The uncertainties on main safety parameters such as k_{eff} and the Doppler constant has been determined and presented at Swedish Nuclear Physical Society meeting and the SKC meeting. The results have been accepted to be presented at the ND 2013 conference in New York. Erwin's work hitherto and during 2013 is planned to result in a licentiate thesis late 2013.

Kaj Jansson started during spring 2012 as the first PhD student on the NFS project. He has mainly been working on detector simulations for the upgrade of the Medley setup with PPAC detectors. Medley was previously installed at TSL but has during autumn 2012 been moved to a new detector development laboratory at Ångströmlaboratoriet. In 2014 the setup will move to the NFS facility at GANIL, France and will be used for precision measurement of fission cross sections used as reference standards. Since cross sections for neutron-induced reactions are almost exclusively measured relative to accepted standard cross sections, improving the knowledge of these cross sections has a potentially large impact.

Medley will also be used for measuring light-ion production (hydrogen and helium isotopes) from various elements induced by neutrons in the 5 to 30 MeV range. Such measurements can provide input for calculation of damage in materials due to neutron irradiation.

During 2013 manufacturing and testing of a PPAC prototype for use inside the Medley chamber is planned.

Andrea Mattera started in spring 2011 as the first Ph.D. student within the AlFONS project. AlFONS, co-financed by SSM and SKB, aims at measuring independent fission yields in thermal and fast neutron spectra at the IGISOL facility in Jyväskylä, Finland. That facility offers the possibility for precision measurements of the yields for products with lifetimes as short as a few hundred milliseconds. The results will be used as guidance for nuclear reaction modelling and will decrease uncertainties in fuel inventory calculations.

The IGISOL facility uses an intense proton beam to produce neutrons in a Be target which is located close to the fission target. This leads to a high neutron flux on the target and ensures that measurements with good counting statistics can be performed. During 2012 the neutron production target has been tested at TSL and the neutron energy spectrum was measured. First measurements of fission yields from ^{238}U in a fast reactor-like spectrum are expected to be performed in autumn 2013. Andrea is expected to present his licentiate thesis late 2013.

Vasileios Rakopoulos joined the division in spring 2012 to work on the AlFONS project together with Andrea Mattera. He has been involved in the TSL measurements mentioned above. Vasileios will work in parallel with Andrea but with different actinide targets and with the goal to perform precision measurements of fission yields in fast and thermalized neutron spectra. While there are many experimental data sets on fission yields from thermal neutrons on ^{235}U and ^{239}Pu only few measurements have been performed for fast neutrons.

There are plans to conduct measurements for, e.g., Pu and Am isotopes for which no measurements exist at all. Such data will proof to be important use for inventory calculations especially at high burnup. Besides getting access to suitable targets, one of the challenges will be to characterize the neutron spectrum to which the actinide target is exposed. While the neutron energy spectra resemble spectra in thermal and fast reactor designs, there will still be differences that need to be corrected. Hence good knowledge of both the neutron spectrum and nuclear models for the energy dependence of fission yields are needed. The project is therefore closely linked to the efforts in nuclear modelling with TALYS and the TMC project.

In addition, the following Ph.D. students are active within the research on Gen IV technology:

Peter Wolniewicz is one of the Ph.D. students within the Genius program, with core monitoring in metal-cooled fast reactors as his subject. Previously, Peter has shown that the introduction of coolant void, which is a safety concern in metal-cooled fast reactors for reasons of both reactivity and loss of coolant, affects the neutron spectrum in the vicinity of the voided region. During 2012, Peter has proposed a detection system for monitoring such changes in the neutron spectrum, based on a set of fission chambers with a content of ^{235}U and ^{242}Pu, respectively. His evaluation of such a monitoring system for a small demonstration reactor, ELECTRA, is presented in a paper that has been submitted to Annals of Nuclear Energy.

Peter presented his licentiate thesis in the beginning of December.

In his future work, Peter will evaluate the monitoring capabilities of larger lead-cooled reactors (ALFRED and ELSY) using this type of detection systems. There are also plans to evaluate if the inclusion of gamma-ray detectors in the system can further improve the void detection capabilities. Furthermore, this technique is also expected to be useful for detecting geometric anomalies in the core, such as assembly bow or core flowering, which is also a safety concern.

Gustav Wallin started in 2010 as Ph.D. student within the Genius project and was supposed to work with the TMC method. However he has been on sick leave almost continuously from the start and it is not yet known when he can take up his studies again.

Matilda Åberg Lindell started her Ph.D. studies in November 2010, also within the Genius program, with the goal to develop methodologies for assessing the proliferation resistance in a Gen IV demonstration facility consisting of a lead-cooled fast reactor, an interim storage for spent fuel, a reprocessing facility and a fuel fabrication plant. The first assessment methodology that was applied to the Gen IV system was the TOPS methodology. Based on selected fuel recycling techniques, material and proliferation barriers, the result of the study is the identification of the weakest proliferation links in the system. A paper of this study, "Assessment of proliferation resistances of aqueous reprocessing techniques using the TOPS methodology, has been written and submitted to Annals of Nuclear Energy in the end of 2012.

Matilda's current efforts are focussed on the application of alternative proliferation assessment methodologies, as well as on the actual design of the fuel recycling facility with the identification of Key Measurement Points (KPM) and possible measurement techniques.

A reference group has been formed consisting of Kaluba Chitumbo (former IAEA SG director), Klas van der Meer (SCK CEN), Lars Hildingsson (SSM), Theodora Retegan (Chalmers) and Katarina Wilhelmsen (FOI) and a second reference group meeting was held in Uppsala in December 2012. Matilda will present her licentiate thesis during 2013.

Vasudha Verma arrived in Uppsala in November to start her Ph.D. studies on the Swedish-French collaboration project "Core Diagnostics in the ASTRID Sodium Fast Reactor (CODIAS)", which is part of the larger project "Core physics, diagnostics and instrumentation for enhanced safety of the sodium cooled fast reactor ASTRID" that is coordinated by prof. Imre Pazsit at Chalmers. In this project, Vasudha has supervisors both at Uppsala University as well as at CEA in Cadarache, and she will spend about half time of her PhD studies at each of these institutions.

There are two more Ph.D. students that are in part supervised by personnel at ANP:

Anna Shepidchenko is supervised by Prof. Mattias Klintenberg at the division of materials theory and works on novel materials for detection of ionising radiation.

Lisa Bläckberg is also supervised by Prof. Klintenberg in a project for improving the Swedish detector system SAUNA used by the CTBTO for detection of illicit nuclear weapons test. This system was used recently for analysing the North Korea test.

Publications and conferences

Work published/accepted in scientific journals

The following scientific papers were published during 2012:

A. Al-Adili, F.-J. Hambsch, S. Pomp, and S. Oberstedt, “Impact of prompt-neutron corrections on final fission fragment distributions”, Physical Review C, 86, 054601 (2012).

A. Al-Adili, F.-J. Hambsch, R. Bencardino, S. Oberstedt, and S.Pomp, “Ambiguities in the grid-inefficiency correction for Frisch-Grid ionization chambers”, Nuclear Instruments and Methods A, 673, 116 (2012).

A. Al-Adili, F.-J. Hambsch, R. Bencardino, S. Pomp, S. Oberstedt, and Sh.Zeynalov, “On the Frisch-Grid signal in ionization chambers”, Nuclear Instruments and Methods A, 671, 103 (2012).

P. Andersson, E. Andersson Sundén, S. Jacobsson Svärd, and H. Sjöstrand, “Correction for dynamic bias error in transmission measurements of void fraction”, Review of Scientific Instruments, 83(12), December 2012.

S. Grape, S. Jacobsson Svärd and B. Lindberg, “Verifying nuclear fuel assemblies in wet storages on a partial defect level: A software simulation tool for evaluating the capabilities of the Digital Cherenkov Viewing Device”, Nuclear Instruments and Methods in Physics Research Section A, vol. 698, January 2013.

S. Holcombe, S. Jacobsson Svärd, K. Eitrheim, L. Hallstadius and C. Willman, ”A Method for Analyzing Fission Gas Release Based on Gamma-ray Measurements of Fuel Rods with Short Decay Time”, accepted for publication in Nuclear Technology.

Conference contributions

The following refereed conference contributions were published or accepted for publication during 2012:

F.-J. Hambsch, A. Al-Adili, S. Oberstedt, and S. Pomp, “Neutron induced fission of 234-U”, EPJ Web of Conferences 21, 08001 (2012).

C. Gustavsson et al., “Inelastic neutron scattering from carbon, iron, yttrium and lead”, EPJ Web of Conferences 21, 03004 (2012).

M. Lantz et al., “Design of a neutron converter for fission studies at the IGISOL facility”, Physica Scripta, T150, 014020 (2012).

C. Gustavsson et al., “Nuclear data measurements at the new NFS facility at GANIL”, Physica Scripta, T150, 014017 (2012).

A. Mattera et al., “A ROOT-based analysis tool for measurements of neutron-induced fission products at the IGISOL facility”, Physica Scripta, T150, 014025 (2012).

S. Pomp, “The Medley facilities past and future: Fast neutron nuclear data measurements for science and industry”, Indian Journal of Pure and Applied Physics, 50, 446 (2012).

A. Al-Adili, F.-J. Hambsch, S. Pomp, and S. Oberstedt, “Indication of anisotropic TKE and mass emission in 234U(n,f)”, Physics Procedia 31, 158 (2012).

Y. Watanabe, et al. “Light-ion production in 175 MeV quasi-monoenergetic neutron-induced reactions on carbon, oxygen and silicon”, accepted for publication in Progress in Nuclear Science and Technology.

S. Pomp, et al., “Light-ion production in 175 MeV quasi-monoenergetic neutron-induced reactions on iron and bismuth and comparison with INCL4 calculations”, accepted for publication in Progress in Nuclear Science and Technology.

S. Holcombe, K.Eitrheim, S. Jacobsson Svärd, L. Hallstadius and C.Willman, “Advanced fuel assembly characterization capabilities based on gamma tomography at the halden boiling water reactor”, International Conference on the Physics of Reactors, PHYSOR 2012, Knoxville, TN, USA, April 2012.

N. Lundkvist, S. Grape, P. Jansson and S. Tobin, “Investigation of Possible Non-Destructive Assay (NDA) Techniques for the Future Swedish Encapsulation Facility”, The 53rd INMM Annual Meeting, Orlando, Florida, USA, July 2012.

S. Tobin et. al. (S. Grape, A. Håkansson, S. Jacobsson and P. Jansson included), “Update on the Next Generation Safeguards Initiative Project to Determine Pu Mass in Spent Fuel Assemblies using Nondestructive Assay”, The 53rd INMM Annual Meeting, Orlando, Florida, USA, July 2012.

D.A. Parcey, E. Sundkvist, J. Dahlberg, K. Axell, R. Kosierb, B. Lindberg, S. Grape, “Determining the effect of adjacent spent fuel on Cerenkov light measurements”, The 53rd INMM Annual Meeting, Orlando, Florida, USA, July 2012.

L. Bläckberg, T. Fritioff, L. Mårtensson, A. Ringbom, H. Sjöstrand, M. Klintenberg, "Investigations of xenon diffusion in plastic scintillators and saturation as a solution to the memory effect problem in radio xenon detection systems", MARCIX (Methods and Applications of radio analytical chemistry) March 2012, Kona, HI, USA.

L. Bläckberg, A. Ringbom, H. Sjöstrand, M. Klintenberg, "Al2O3 coating as a gas diffusion barrier on a cylindrical plastic scintillator used to detect radioxenon for test-ban treaty verification", SORMA West 2012 (Symposium on radiation measurements and applications) May 2012, Oakland, CA, USA.

A. Shepidchenko, S. Mirbt , M. Klintenberg, ”Te-antisite in a deformed CdTe lattice”. IIIE Symposium on Radiation Measurements and Applications SORMA 2012. Oakland, California, USA.

Other conferences and reports

C. Hellesen, “Non-proliferation aspects of Gen-IV systems”, presented at the Nordic Gen4 meeting, Risö, Denmark, October 2012.

A. J. Koning, et al., “TENDL-2012: TALYS-based evaluated nuclear data library”, ftp://ftp.nrg.eu/pub/www/talys/tendl2012/tendl2012.html.

A. Prokofiev, et al., "High-energy nuclear data measurements at TSL", JEF/DOC-1487.

S. J. Tobin and P. Jansson, “Nondestructive Assay Options for Spent Fuel Encapsulation”, review report written in collaboration with Los Alamos National Laboratory (LANL) for SKB.

N. Lundkvist finalised a report on the Differential Die-Away Technique for LANL, being part of the Nest Generation Safeguards Initiative.

A. Shepidchenko, “Detector Materials for Nuclear Safeguards”. KTH Seminar GENIUS , Stockholm.

A. Shepidchenko, M. Klintenberg, “Developing Semiconductor Detector Materials for Nuclear Safeguards”. IFA seminar Uppsala.

Outreach

The engineering Masters students have started a nuclear technology association at the Ångström Laboratory. This association arranges and hosts seminars that address various aspects of the present and future nuclear power technology. The association arranged a special “nuclear power day” September 27 where industry and academy met and discussed various nuclear power related issues with the students. The arrangement was a success with over 200 participants and the venue was finished with an appreciated dinner in the evening.

In addition, below is a list of our outreach activities in brief during 2012:

Professor installation seminar S. Pomp: “Samhällstjänst för snabba neutroner: Kan använt kärnbränsle bli morgondagens energikälla?”; Zttp://media.medfarm.uu.se/play/kanal/97/video/3044.

DN Debatt Nov 27, 2012: ”Kärnkraft nödvändig för att bromsa temperaturökningen”.

DN Debatt Dec 3, 2012: ”Greenpeace spelar högt med klimatet som insats”.

Presentation of energy, electricity and nuclear power for 5th graders.

Almedalsveckan: “Dagens kärnavfall kan bli framtidens resurs”.

Answers by an expert in Forskning och Framsteg

Seminar day for Swedish gymnasium teachers: ”Framtidens Generation IV teknik”.

SKB seminar in Östhammar: ”Framtidens Generation IV kärnkraftsystem”.

Uppsala tekniska fysiker seminar: ”Framtidens Generation IV teknik”.

Lecture for 5:th graders on energy and nuclear power.

Letter to the Minister of Research and Education, Jan Björklund (attached).

Visions and Plans

The mission for ANP is to work for achieving safe, secure and sustainable nuclear energy systems. On the global level this seems as imperative in order to solve the monumental issues mankind faces. To obtain this we believe that new Generation III and III+ power reactors together with adequate waste disposal systems is the first step in this direction. Such a development is mainly an undertaking for the industrial part of the world and in order to address the needs of the developing countries, it seems reasonable that the industrial countries take measures to enter a step two, i.e. developing Generation IV systems. Small autonomous systems could then be located in regions of the world that are not considered feasible for today's technology.

To realize our mission it is important to enhance our ability to use nuclear physics knowledge/know-how to assist in reactor design, monitoring, safety issues, fuel cycle etc. To succeed here we plan to expand our competence in reactor physics and also use the high-quality activities in materials theory (Prof. Mattias Klintenberg) that is hosted at Ångström Laboratory. Specifically, we think that the latter, together with collaborators such as Pål Efsing at KTH, may prove important in order to efficiently develop new tailored materials for the nuclear industry's need.

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

Education

Strengthening the nuclear energy track in the Energy Systems program (civilingenjörsprogrammet ES).

Adding courses to the NANSS portfolio aiming to offer education nationally and internationally in subjects related to nuclear safety and security

Enhancing the training capabilities for engineering students and professionals in collaboration with KSU.

Research

Strengthening our collaboration with OECD Halden Reactor Project (OECD-HRP):

Applying for separate membership for Uppsala University in OECD-HRP,

Setting up a research program within core and fuel diagnostics with experiments to be carried out at the HBWR,

Setting up a research program within materials and aging with experiments to be carried out at the HBWR.

Continuing our efforts to contribute to Gen IV research within our fields of expertise, a field of research that is attractive to students and young scientists.

European collaborations (ASTRID, MYRRHA, ELSY …)

National collaborations to form a continuous Swedish Gen IV program

Researching on autonomous Gen IV systems with a high degree of passive safety

More specifically, create new infrastructure such as:

Detector lab.

Neutron lab; The planned DT source will open new possibilities for detector testing, conducting laboratory work within student courses, and performance of original nuclear physics experiments.

The ICE3 facility for studies of SCC and aging.

Nuclear data measurements (for strategic targets; energies, observables): the projects started at IGISOL and NFS imply a long commitment and work within the new formed collaborations at these facilities will be continued over the next couple of years.

Nuclear model development: important steps will be taken in 2013 by further development of the TALYS codes capabilities for fission yield calculations. The work is supported by an EU project and conducted in close collaboration with NRG and the NEA nuclear data bank in Paris.

Uncertainty propagation of nuclear data knowledge and sensitivity analysis to identify data needs for various systems (LWR, FR, fuel cycle). The Total Monte Carlo method will be further developed and applied and tested on a range of systems. The TMC method opens up a whole new research program at the applied nuclear physics division.

Collaborations

Augmenting the collaboration with OECD-HRP (as above).

Enhancing our collaboration with UC Berkeley, e.g. by inviting their students to the planned summer school on measurements and fuel diagnostics to be held 2014 in collaboration with SKB.

Inviting guest researchers from UC Berkeley, Lawrence Livermore Nat. Lab. and LANL.

Additional information

Commitments

During 2012, Peter Jansson and Sophie Grape participated in the GASMAT project (Gamma Spectrometric Discrimination of Special Nuclear Materials) run by NKS (Nordic Nuclear Safety Research), with respect to the detection of illicit trafficking of nuclear materials. A report is available on the NKS website (www.nks.org).

Sophie Grape has been part of a review committee on 14 NDA techniques for determining the plutonium and fissile content of spent fuel, in the Next Generation Safeguards Initiative network, led by LANL.

Sophie Grape is a member of the ESARDA working group of training and knowledge management.

Mattias Lantz has been appointed chairperson of KSUs “Analysgruppen”. While continue to be employed by UU, he will with starting January 1 2013 spending 50% of his duty on this task.

Networking and collaborations

Sweden: KTH and Chalmers

New research activities on e.g. radiation effects on structural materials with the Ion Physics group at ANP.

National Gen IV efforts (GENIUS and ASTRID)

LANL, UCB, LBNL, LLNL in the U.S.

CEA and GANIL in France

SCK-CEN and JRC-IRMM in Belgium

OECD Halden Reactor Project and IFE in Norway.

NANSS (discussions with Swedish operators, IAEA, Kenya, Vietnam, UAE)

Netherland: NRG

Finland: Univ. of Jyväskylä

Japan: Kyushu University

Thailand: Chiang Mai University

Switzerland: CERN.

Prizes

Lisa Bläckberg was awarded Uppsala Materials academy’s innovation scholarship 2012.

(http://www.uu.se/press/pressmeddelanden/pressmeddelande-visning/?id=1669&area=3&typ=pm&na=&lang=sv).

Overview of Ph.D. projects at UU 2012

Peter Andersson: “Void monitoring in thermal-hydraulic test loops using neutron transmission tomography”.

Main supervisor: Univ. lekt. Staffan Jacobsson Svärd.

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

Scott Holcombe: “Advanced diagnostics of nuclear fuel based on tomographic techniques and high-resolution gamma-ray spectroscopy”.

Main supervisor: Univ. lekt. Staffan Jacobsson Svärd.

Assistant supervisor: Prof. Ane Håkansson

Tomáš Martinik: “Verification of nuclear fuel for safeguards purposes using non-destructive assay techniques for the future Swedish encapsulation facility”.

Main supervisor: Ph.D. Sophie Grape.

Assistant supervisor: Dr. Peter Jansson.

Lisa Bläckberg: Optimisation and modelling of detector materials for ionising radiation.

Main supervisor: Prof. Mattias Klintenberg

Assistant supervisor: Bitr. univ. lekt. Henrik Sjöstrand, Dr. Anders Ringbom (FOI).

Ali Al-Adili: “Measurements of the ^{234}U(n,f) reaction with a Frisch-Grid Ionization Chamber up to E_n=5 MeV”

Main supervisor: Prof. Stephan Pomp

Assistant supervisor: Dr. Franz-Joseph Hambsch, Univ. lekt. Michael Österlund

Kaj Jansson: “Neutron-induced nuclear reactions at intermediate energies”

Main supervisor: Dr. Cecilia Gustavsson

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

Andrea Mattera: “Measurements of independent fission yields from a fast neutron spectrum”

Main supervisor: Prof. Stephan Pomp

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

Vasileios Rakopoulos: “Studies of independent fission yields from fast neutrons”

Main supervisor: Dr. Mattias Lantz

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

Gustav Wallin: “Massive computation methodology applied to nuclear technology”

Main supervisor: Pro. Stephan Pomp

Assistant supervisor: Dr. Henrik Sjöstrand, Dr. Cecilia Gustavsson, Univ. lekt. Michael Österlund

Vasudha Verma: “Core Diagnostics in the ASTRID Sodium Fast Reactor (CODIAS)”

Main supervisor: Dr. Carl Hellesen.

Assistant supervisor: Univ. lekt. Staffan Jacobsson Svärd, Prof. Ane Håkansson, Dr. Peter Jansson, Univ. Lekt. Michael Österlund.

Anna Shepidchenko: “Novel Detector Materials for Monitoring and Safeguards”.

Main supervisor: Prof. Mattias Klintenberg.

Assistant supervisor: Univ. lekt. Susanne Mirbt.

Matilda Åberg Lindell: “Instrumentation and safeguards evaluations of a Generation IV reprocessing facility”.

Main supervisor: Dr. Sophie Grape.

Assistant supervisors: Prof. Ane Håkansson, Univ. lekt. Staffan Jacobsson Svärd.

Erwin Alhassan: “MAssive Computational methodology for Reactor Operation – MACRO”.

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

Assistant supervisors: Univ. lekt. Michael Österlund, prof. Stephan Pomp, Dr. Junfeng Duan, Dr. Dimitri Rochman.

Peter Wolniewicz: “Core Monitoring in Gen IV Reactors”.

Main supervisor: Prof. Ane Håkansson.

Assistant supervisors: Dr. Carl Hellesen, Dr. Peter Jansson, Univ. lekt. Staffan Jacobsson Svärd, Univ. lekt. Michael Österlund.

2013-01-17

UPPSALA UNIVERSITET

Statsrådet Jan Björklund
Utbildningsdepartementet

Institutionen för fysik och astronomi
Avdelningen för tillämpad kärnfysik

Besöksadress:
Ångströmlaboratoriet

Postadress:
Box 525
751 20 Uppsala

Telefon:
018 471 32 51
070 167 90 95

Telefax:
018 471 38 53

E-post:
ane.hakansson@physics.uu.se

Hemsida:
www.physics.uu.se

Department of Physics and Astronomy
Division of Applied Nuclear Physics

Visiting address:
Ångströmlaboratoriet

Postal address:
Box 525
SE-751 20 Uppsala
Sweden

Telephone:
+46 18 471 32 51
+46 70 167 90 95

Telefax:
+46 18 471 38 53

E-mail:
ane.hakansson@physics.uu.se

Finansiering av svensk kärnteknisk forskning och utbildning

Bakgrund

Svenskt kärntekniskt centrum (SKC) är ett samarbete mellan kärnkraftsindustrin, Strålskyddsmyndigheten (SSM) samt Chalmers, KTH och Uppsala universitet. SKC har i sin nuvarande form haft en avgörande betydelse för lärosätenas möjlighet att återuppbygga kärnteknisk forsknings- och utbildningskapacitet. Detta efter att åttiotalets politiska beslut inneburit att forskningsmedel och studenter, rycktes undan helt. SKC var det incitament som behövdes för att lärosätena återigen skulle stödja kärnteknisk forskning internt. Den lilla verksamhet som fortfarande fanns kvar kunde därmed börja utbilda unga forskare som sedan kunde anställas som lärare och bygga upp forskning och utbildning inom området. Processen illustrerar väl kopplingen mellan starka forskningsmiljöer och förmåga att skapa utbildningskapacitet.

Utvecklingen på KTH och Chalmers har liksom i Uppsala varit mycket positiv men eftersom jag har bäst överblick över vad som sker i Uppsala följer en kort beskrivning av läget här. Typiskt följer ca 100 civilingenjörsstudenter varje år våra kurser i kärnkraftteknik. Detta resulterar årligen i ett tiotal examensarbeten, ofta i samarbete med kärnkraftsindustrin. Vårt högskoleingenjörsprogram i kärnkraftteknik resulterar i ingenjörer som raskt kan gå in som stationstekniker med goda förutsättningar för vidareutbildning till reaktoroperatörer etc. Ständigt pågår ett tiotal doktorandprojekt med direkt koppling till kärnkraft. Kapaciteten är i dag tillräcklig för att kunna bedriva fortbildning av kärnkraftspersonal.Vi är också engagerade i den s.k. tredje uppgiften genom ett aktivt deltagande i den offentliga debatten och kontakter med den politiska sfären i frågor med direkt relevans för kärnkraften i landet.

Jag vill påstå att inget av ovanstående hade varit möjligt att genomföra utan samarbetet inom SKC. SKC säkrar dock inte de kärntekniska verksamheterna vid landets lärosäten. Industrin avser inte att stödja *ad infinitum* utan utgår från att statsmakten i stora delar avser att överta finansieringsrollen av den återuppbyggda kapaciteten.

Nuläget

Den positiva utveckling som sittande regering har skapat inom svensk kärnteknisk forskning har spätt på intresset hos landets ungdomar att studera kärnteknik. I sammanhanget är det värt att notera att i synnerhet kvinnliga studenter söker sig till vår verksamhet och här vill

Organisationsnr:
202100-2932

UPPSALA UNIVERSITET

jag peka på forskningen inom fjärde generationens kärnkraftsystem som ett fokus för detta intresse. Det är därför som jag med oro tar del av relevanta propositioner där satsningar på kärnteknisk forskning och utbildning lyser med sin frånvaro. I särskilt minister Hatts proposition kompliceras bilden av att kärnkraft nämns i positiva ordalag på inte mindre än åtta olika ställen och det framgår att förutsättningar skall skapas ”för kontrollerade generationsskiften i den svenska kärnkraften”. Hur detta generationsskifte ska kunna genomföras på ett betryggande sätt framgår dock inte. Helt klart är att nybyggnationer av reaktorer kommer att kräva nya kadrer av välutbildad personal (utöver de som krävs för befintlig kärnkraftindustri och myndigheter) och därmed måste utbildningskapaciteten på landets lärosäten inte bara säkras utan sannolikt också utökas.

Liksom under sextiotalet, när unga hungriga forskare och ingenjörer fylkades runt det svenska kärnkraftkonceptet, behövs i dag något nytt för att locka spetskompetens till lärosätena för forskning och undervisning. Min mening är att fjärde generationens kärnkraftsystem väl fyller en sådan funktion. Här blir finansieringsproblemen än mer uttalade eftersom det i dagsläget saknas ett kommersiellt intresse från industrins sida att engagera sig. Å andra sidan, om Sverige som nation tog ett steg framåt med denna teknik finns stor potential att utnyttja:

- De materialfrågor som måste besvaras kan skapa strategiska produkter för landets stålindustri.
- Sverige är idag världsledande på hantering av utbränt kärnbränsle och denna position skulle förstärkas i och med att tekniker för återvinning av detta material utvecklas.
- Tekniken kan, i princip, utformas så att den relativt lätt kan implementeras i de delar av världen som inte anses lämpliga för dagens kärnkraftteknologi. Sverige skulle här kunna exportera teknik som långsiktigt löser världens energiproblem med ett minimum av miljöpåverkan.

Med dessa ord önskar undertecknad initiera en diskussion om framtiden för kärnteknisk forskning och utbildning vid landets lärosäten.

Med bästa hälsningar

Ane Håkansson
Professor i tillämpad kärnfysik vid Uppsala universitet

Research projects

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

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

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

Background

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

Goals of the project

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

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

The goal of the present project is thus to develop a tool for uncertainty and sensitivity analysis applied to nuclear reactor simulations. The simulation tool is based on different commercial and research oriented neutronic and thermal-hydraulic codes such as DRAGON, POLCA7, CORE SIM and POLCA-T. In this framework, Chalmers closely collaborates with the POLCA7 and POLCA-T code developers (Westinghouse Electric Sweden AB).

Organization

The work was performed by PhD student Augusto Hernández-Solís under the supervision of Professor Christian Ekberg and Professor Christophe Demazière. Dr. Arvid Ödegaard –Jensen also supported Augusto Hernández-Solís on some aspects of the project. The members of the reference group were: Ninos Garis, SSM, Henrik Nylén, Ringhals, Christer Netterbrant, OKG, Henrik Bergersen, FKAB, and Ulf Bredolt, Westinghouse. **The PhD work was successfully defended on September 28th, 2012 at Chalmers**. The cross-examiner was Prof. Rafael Macian-Juan (Technical University of Munich), and the members of the examination committee were Prof. Kostadin Ivanov (Penn State University), Prof. John Helton (University of Arizona), and Dr. Erwin Müller (Westinghouse Electric, Sweden).

Methodology

From 2007 to 2012, uncertainty and sensitivity analyses were completed for the lattice, core and thermal-hydraulic modeling stages of light water reactors [1-8]. In previous annual SKC reports, results of such analyses have been presented only for the core and thermal-hydraulic stages. Therefore, the purpose of this last summary is to show uncertainty analysis performed on a 15x15 PWR lattice fuel segment by means of the DRAGON (Version 4.05) code. This test case corresponds to the Three Mile Island-1 (TMI-1) Exercise I-2 that is included in the neutronics phase (Phase I) of the "Benchmark for Uncertainty Analysis in Modeling (UAM) for design, operation, and safety analysis of LWRs," organized and led by the OECD/NEA UAM scientific board.

In this framework, the isotopic multi-group microscopic cross-sections (which are the input parameters of the lattice code) are considered to be uncertain and to follow a normal distribution. In the major nuclear data libraries (NDLs) created around the world (e.g. JENDL, JEFF, ENDF/B), the evaluation of microscopic cross-section uncertainty is included as data covariance matrices. The covariance data files provide the estimated variance for the individual data as well as any correlation that may exist. The covariance is given with respect to point-wise cross-section data and/or with respect to resonance parameters. Thus, if such uncertainties are intended to be propagated through deterministic lattice calculations, a processing method/code must be used to convert the energy-dependent covariance information into a multi-group format. In this PhD project, the ERRORJ module of the NJOY code was used for this purpose, and isotopic covariance matrices for 172 groups based on JENDL-4 and ENDF/B-VII.1 data can be found in reference [7].

The next step is to propagate such input uncertainty into the lattice code by means of a statistical methodology, in order to assess the associated uncertainties in output parameters such as k_∞ and the energy collapsed and homogenized macroscopic cross-sections. The preferred sampling strategy for the current study corresponds to the quasi-random Latin Hypercube Sampling (LHS). This technique allows a much better coverage of the input uncertainties than simple random sampling (SRS) because it densely stratifies across the range of each input probability distribution. In this project, a methodology was derived for the proper uncertainty assessment of all the terms in the multi-group transport equation, due to the fact that uncertainties are not given by the NDLs for the energy and angular distributions of the differential scattering terms. Also, a methodology was derived to re-normalize the fission spectra once it is being sampled. Such methods can be found in reference [6].

After sampling the different isotopic reactions and running the code 450 times, the final sample of 450 elements is significant to cover 95% of the output space formed by the different homogenized macroscopic cross-sections and k_∞ with a 95% of confidence. For instance, the impact that the microscopic cross-section uncertainties have on k_∞ based on covariance data from both JENDL-4 and ENDF/B-VII.1 is presented in table 1.

Table 1. Uncertainty analysis of k_∞

	Max. value	*Min. value*	*Mean*	σ_{STD}	$\frac{\%\Delta k}{k}$
JENDL-4	1.47408	1.36896	1.40101	0.01532	1.094
ENDF/B-VII.1	1.41076	1.38967	1.40236	0.00250	0.178

By comparing the obtained k_∞ relative uncertainty coming from the two different NDLs, a huge difference could be observed. Such large discrepancies are due to the fact that the multi-group covariances of the $^{235}U(n, fission)$ reaction based on JENDL-4 data, are much larger at thermal and resonant energies than the ones based on ENDF/B-VII.1 data.

The results obtained in this work are important because they demonstrate that it is feasible to statistically perturb and propagate basic uncertainty data through lattice calculations with the current computational technology. This is also the first step to develop an integral statistical uncertainty methodology for nuclear reactor predictions using advanced models, since the lattice code outputs are to be used as inputs to the core simulators.

As a final remark, the aim of the PhD project was to emphasize the importance of performing uncertainty analysis at all stages in the modeling of LWRs, including the nodal macroscopic cross-section models. Since they functionalize the cross-sections based on nodal state-variables such as moderator density, burnup, fuel temperature, etc., they are the link between the neutronic and thermal-hydraulic models in a best estimate coupled calculation. Statistical uncertainty analysis of such models can be found in reference [8].

Publications

1. Hernandez-Solis A., Vinai P., Bredolt U. "An Assessment Study of the POLCA-T Code Based on NUPEC Data". ANS Annual Meeting Transactions, 2009. Vol. 100, pp. 750-751.
2. Hernández-Solís A., Ekberg C., Demaziere C., Ödegaard-Jensen A. "Statistical uncertainty analyses of void fraction predictions using two different sampling strategies: Latin Hypercube and Random Sampling". On the proceedings of the International Conference on Nuclear Engineering (ICONE) 18-30096, Xi'An, China, May 2010.
3. Hernández-Solís A., Ekberg C., Demaziere C., Ödegaard-Jensen A., Bredolt U."Uncertainty and sensitivity analyses as a validation tool for BWR bundle thermal-hydraulic predictions". Nuclear Engineering and Design, Vol. 241, Issue 9, 2011.
4. Hernández-Solís A., Demaziere C., Ekberg C. "Bayesian Uncertainty Analysis of BWR Core Parameters Based on Flux Measurements". ANS Winter Meeting Transactions, 2011. Vol. 105, pp. 803-804.
5. Hernández-Solís A., Demaziere C., Ekberg C., Ödegaard-Jensen A. "Statistical uncertainty analysis applied to the DRAGONv4 code lattice calculations and based on JENDL-4 covariance data". In the proceedings of PHYSOR 2012-Advances in Reactor Physics, Knoxville TN, 2012.
6. Hernández-Solís A., Demaziere C., Ekberg C. "Uncertainty and sensitivity analyses applied to the DRAGONv4.05 lattice calculations and based on JENDL-4 data". Accepted and in press of Annals of Nuclear Energy, 2013.
7. Hernández-Solís A., Demaziere C., Ekberg C. "Uncertainty analyses applied to the UAM/TMI-1 lattice calculations using the DRAGON (Version 4.05) code and based on JENDL-4 and ENDF/B-VII.1 covariance data", Science and Technology of Nuclear Installations, Vol. 2013, 21 pages.
8. Hernández-Solís A., Ekberg C., Demaziere C. "Uncertainty analysis of a nodal cross-section regression model based on Ringhals 1 data by means of a non-parametric bootstrap method", Submitted to Annals of Nuclear Energy.

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

PhD student: Klas Jareteg, Division of Nuclear Engineering, Chalmers University of Technology
Supervisor: Professor Christophe Demazière

Background

The multi-physics environment of a nuclear reactor poses a challenging task from a modelling perspective. To simulate and predict the behaviour of the core, a wide range of fields of physics have to be combined. Due to the interdependence between the thermal-hydraulics (fluid flow and heat transfer) and the neutronics, a coupled approach is needed in order to simulate such systems. In many present day software and modelling tools, simplified or no coupling schemes are assumed. Other methodologies utilize a “divide and conquer” approach, solving different fields of physics in different tools, with posterior coupling.

The use of simplified or scattered methodologies comes with a price; a consistent treatment of the inherent multi-physics coupling cannot be guaranteed. This is true not only for transient calculations, but also for steady-state simulations. To develop better methodologies and to understand the implications of the assumptions in the existing tools, more closely coupled approaches are needed. Such could include the direct coupling between neutronics and thermal-hydraulics on fine scales. This would ensure a higher-resolution of the physical fields and lead to the understanding of coupled phenomena from a fine scale perspective.

In commercial simulation software, rather coarse volumes are used, in which the system properties are spatially averaged. A fine mesh coupled tool could be used to assess the effect of such coarse mesh approximations. The importance of high-resolution calculations increases with the increased complexity of the fuel designs being used today, for which rather significant gradients have been observed.

Goals of the project

The present project is aimed at developing and implementing high-resolution coupled calculations for the modelling of nuclear reactors at the fuel assembly level. The fine-mesh thermal-hydraulics calculations are based on a Computational Fluid Dynamics (CFD) approach. The novelty of the work lies with the fact that the neutronics is directly implemented and combined with the CFD-tool to allow a coupling at the finest simulated level.

The goal of this PhD work is to use such an approach to better capture physical phenomena occurring in modern fuel assembly designs. The primary target is on light water reactors, i.e. Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs), with BWRs representing the most interesting situation because of the strong heterogeneities present in such systems. The first step of the project focuses on steady-state conditions, but at a later point transient cases might be considered. In addition, and in order to reduce the complexity of the modelling task, systems of finite axial size but infinite radial size are considered.

The development of such a tool requires knowledge not only in thermal-hydraulics and neutronics but also insight in the coupling between these two areas while using efficient and fast algorithms.

Organization

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

Methodology

In the first stage of the project a coupled tool has been implemented using the open source C++ CFD-library OpenFOAM [1]. The coupled tool extends the available structures so that the neutron multi-group diffusion equation can also be solved on fine unstructured meshes. Each region of the fuel assembly (fuel, gap, cladding and moderator) is resolved. The thermal-hydraulics at this stage of the project only considers single phase flow conditions, including the solution of a two equation turbulence model. Conjugate heat transfer is used to model the transport of heat released from fission in the fuel to the moderator. The neutronics and thermal-hydraulics are resolved on the same fine, unstructured mesh. As both fields are implemented in the same C++ code, a high-performance parallelized tool is achieved, thus benefiting from the simultaneous high-resolution of the neutronics and thermal-hydraulics within the same software, with no external coupling.

The developed coupled tool has been used to predict the effect of heterogeneity at the pin scale level for a system of 5x5 fuel pins representative of PWR conditions (see Figure 1). The tool is used to determine the axial and radial neutron flux distributions, the density, velocity and temperature of the moderator and the temperature of the solid regions. Even for a PWR case where gradients are rather moderate, a fine-resolution coupling scheme can be shown to be of interest. Using a traditional temperature averaging in the fuel and in the moderator shows that both the criticality factor and the power distribution in the fuel pins are considerably changed using a high-resolution approach. This work also resulted in the submission of a paper to the International Conference on Mathematics and Computational Methods Applied to Nuclear Science & Engineering (M&C 2013) [2].

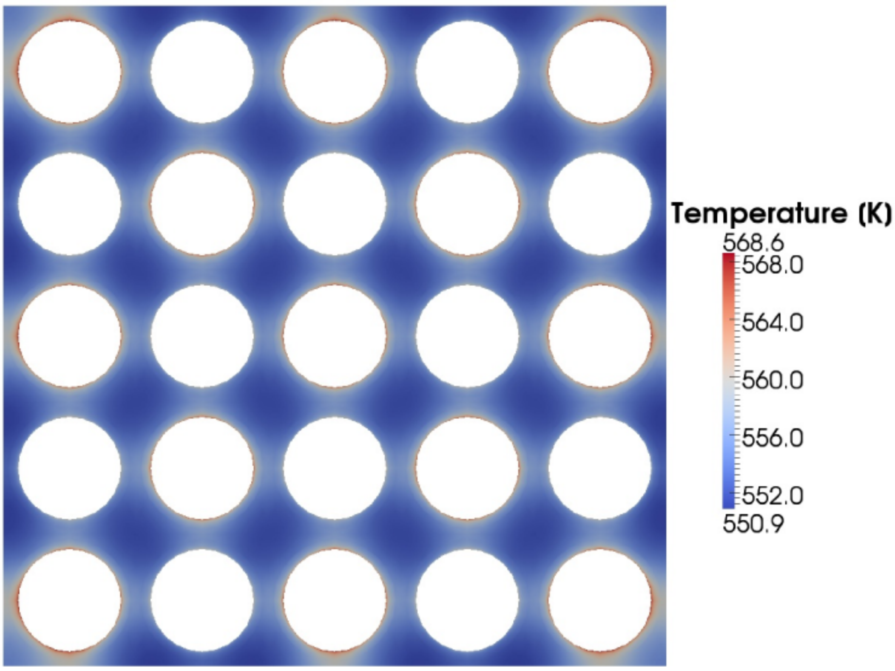


Figure 1: Temperature distribution in the moderator at mid-elevation of a PWR like 5x5 fuel assembly.

In the second stage of the development, the neutronics has been extended to include a module for calculating the angular neutron flux using a discrete ordinates method (S_N) and a fine unstructured mesh. The use of an angle dependent method to resolve the neutronics allows for a better resolution of the heterogeneity at the pin level. The use of the S_N method increases the computational burden as each neutron energy group requires a set of equation for each discrete angle, all to be solved over the full domain. Consequently, fast solver algorithms are of increasing importance.

The near-term plans will focus on the development of a two-phase flow solver, aimed at performing fine-mesh coupled calculations for BWR cases. In this stage major focus will be put on developing and implementing models with a correct reproduction of the radial and axial heterogeneities in the moderator properties. Such heterogeneities will in turn lead to more heterogeneous distributions of the macroscopic cross-sections in the moderator and thus the effect of the coupling to the neutronics will be amplified.

References

1. OpenFOAM, User Guide, Version 2.0.0, OpenFOAM Foundation, 2011.

2. K. Jareteg, P. Vinai, and C. Demazière, "Investigation of the possibility to use a fine-mesh solver for resolving coupled neutronics and thermal-hydraulics," submitted to International Conference on Mathematics and Computational Methods Applied to Nuclear Science & Engineering (M&C 2013), Sun Valley, Idaho, USA, May 5-9, 2013.

Reactor diagnostics with advanced signal analysis (READS)

PhD student: Victor Dykin, Department of Nuclear Engineering, Chalmers University of Technology
Supervisors: Professors Christophe Demazière and 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.

In this project, new advanced signal analysis methods come into play. These can take into account that the behaviour of the system is often non-stationary and/or non-linear. The non-linearity has to be taken into account partly at the model construction stage, and partly at the inversion stage. In the latter case the non-linearity, and possible redundance in the measured data, can be handled by the use of artificial neural networks. There are in addition several other promising non-parametric methods emerging in the field which open new possibilities 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 utilities. The emphasis is put on understanding and diagnosing BWR instability, on the diagnostics of two-phase flow regimes, and on determining two-phase flow parameters in BWRs. The test of the methods is performed on both simulated signals as well as measurements taken in Swedish power plants.

Organisation

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

Methodology and results

The project started during the summer of 2008 with the analysis of BWR stability in a model system driven by a driving force with a non-white power spectrum. As a continuation, the space-dependent noise, induced by propagating perturbations, i.e. by density and/or temperature fluctuations was investigated in 2009. In 2010 the project activity was mainly focused on the development of a Reduced Order Model (ROM) for BWR stability analysis. This work resulted in two journal publications [1,2]. The results from the work performed since 2008 led to a licentiate degree in 2010. In 2011 the research activity included two separate lines. The first one was related to the investigation of past instability events, using nonlinear analysis based on the ROM. During this stage, an earlier developed ROM was modified in such a way that it became applicable for analyzing both core-wide (global and regional) and local instabilities [3]. Another line was primarily focused on elaborating the methods for void fraction (steam content) reconstruction from BWR in-core neutron noise measurements.

In 2012 the research activity mainly pursued the continuation and finalizing the activities started in 2011 as well as preparing for the PhD exam. These activities consisted in an investigation of what stability indicators other than the decay ratio (DR) can be used to characterize the stability of the system. The second part was mainly oriented on testing different techniques for void fraction/void velocity determination in a BWR core from neutron noise detector measurements.

Concerning the first project, the ROM developed in 2010 and significantly modified in 2011, was used to investigate the possibility of utilizing the so-called reactivity feedback coefficients (C_{mn}) as a new stability indicator to characterize BWR stability properties. For this purpose, the dependence between the C_{mn}-coefficients and the DR was qualitatively analyzed. The corresponding dependence of the DR on the C_{mn}-coefficients obtained from ROM analysis, is shown in Fig 1a. As one can see from this figure, the dependence between the DR and the C_{mn} is not monotonic, i.e., the DR first increases with increasing amplitude of the C_{mn}-coefficients, following the traditional behaviour of DR for such a study, and then at approximately $C_{mn} = -0.036$ a.u., the DR suddenly starts to decrease.

In order to get a better understanding of the sudden drop in the DR all physical quantities which were available from the ROM were analysed by using a curve fitting procedure applied to the amplitude of the oscillations of some process signals. Some results of this fitting, performed for void fraction α, surface fuel temperature T_{fs}, power P and inlet pressure drop δP_{inlet} are shown in Fig. 1b. As Fig. 1b shows, for C_{mn}-values between 0 a.u. and -0.0341 a.u. the amplitude change in the void/power oscillations is dominating over the amplitude change in the inlet pressure drop/surface fuel temperature oscillations. The latter means that most of the produced fuel heat is transferred into a change of the void fraction. However, for C_{mn} values between -0.034 a.u. and -0.0907 a.u., the situation is reversed, namely the amplitude change in the inlet pressure drop/surface fuel temperature oscillations becomes the dominant one. In this case most of the heat from the fuel is converted into an increase of the amplitudes of the inlet pressure drop (surface fuel temperature) oscillations (with almost unchanged void fraction) which apparently stabilizes the system and, thus, contributes to the decrease in the DR. Such an unexpected transition between different quantities can be explained by the inertia of the heat transferred between the fuel and the coolant, leading to some time delay between the change in the power and the corresponding change in the feedback. To conclude, the C_{mn} coefficients can be used to asses the stability properties of the system only in a limited range of values (i.e. for small C_{mn}), whereas for the C_{mn} higher than -0.0361 the implementation of C_{mn} is still questionable. It was noticed that in practical cases, the C_{mn} values are significantly negative. This thus opens up the possibility to use the C_{mn} coefficients as a means to characterize the stability of a given core.

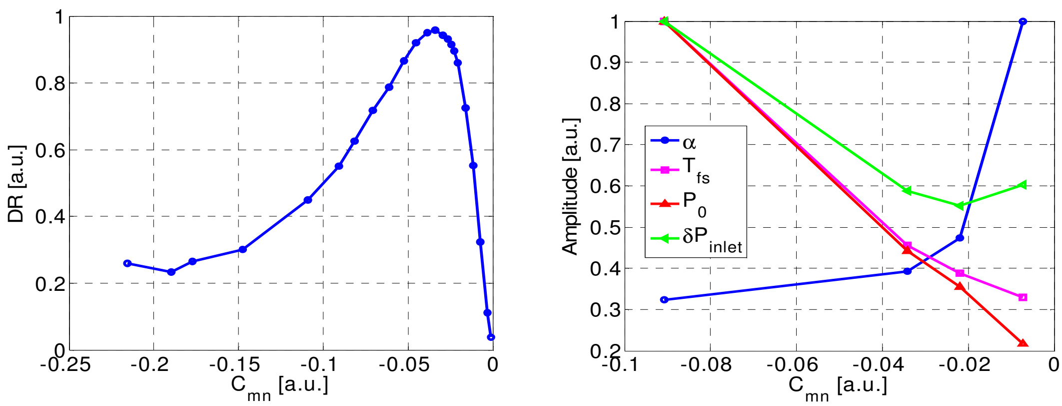


Fig. 1. Left panel: Dependence of the Decay Ratio on the reactivity coefficients C_{mn}; Right panel: dependence of the amplitudes of the void fraction α, averaged surface fuel temperature T_{fs}, power P and inlet pressure drop δP_{inlet} on the C_{mn} coefficients (all the quantities were normalized to their corresponding maximum values).

The second research activity mentioned above, performed in 2012, concerned the reconstruction of the void fraction and void velocity profiles in BWRs from neutron noise measurements. In order to test different methodologies for steam content reconstruction, an earlier developed Monte Carlo model of two-phase flow for simulating digital neutron noise detector signals was used. In this model in order to provide a realistic simulation of bubbly two phase flows, the bubbles were sampled randomly in such a way that the axial void profile corresponded to a real BWR one. Two methods, one based on the break frequency of the APSD, and another on the transit time approach were investigated. The results of the void profile reconstruction from the simulated neutron noise, based on the break frequency method, are shown in Fig. 2a. From this figure, one can see that the reconstructed void fraction profile is in a satisfactory agreement with the true profile except for the subcooling region where the void fraction is significantly overestimated. Similar results for the void velocity profile reconstruction, based on the transit time method, are given in Fig. 2b. From this figure, it can be noticed that both the reconstructed and the true velocity profiles are in a good agreement between each other.

The results in the above two topics resulted in three separate papers. The first one was presented at the ANS Winter Meeting 2012 and the second one at the PHYSOR 2012 conference in Knoxville, Tennessee, USA [4,5,6]. In addition, one more paper was submitted for publication on the effect of propagating perturbations in 4 different reactor systems (PWR, BWR, CANDU and a fast reactor) [7].

On 7th September 2012 Victor Dykin successfully defended his PhD thesis. The opponent for the thesis defense was professor Gumersindo Verdu from Universitat Politècnica de València, Spain.

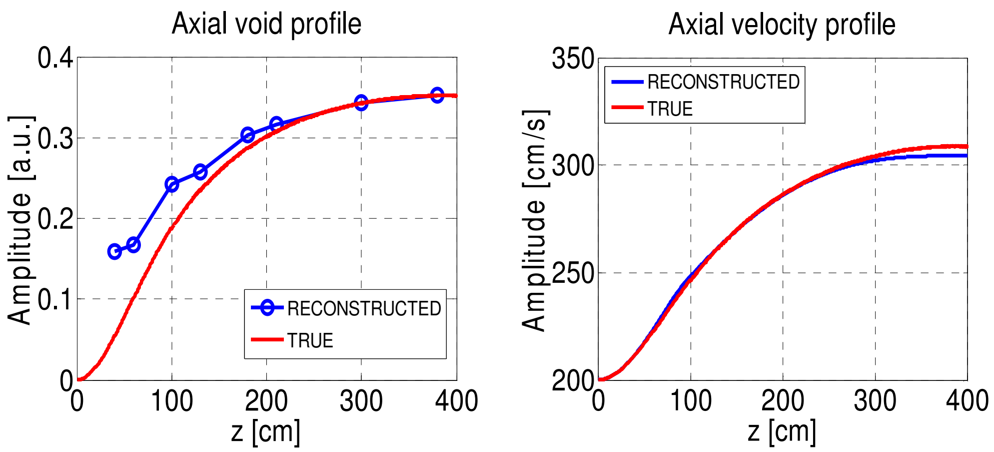


Fig. 2 Left panel: comparison between the reconstructed and “true” void profiles using the break frequency method; Right panel: comparison between the reconstructed and “true” void velocity profiles using the transit time method.

References

1. Dykin V. and Demazière C., Lange C., Henning D., Investigation of global and regional BWR instabilities with a four heated-channel Reduced Order Model, Annals of Nuclear Energy, Vol. 53, pp. 381-400 (2012).

2. Dykin V. and Demazière C., Lange C., Henning D., Investigation of local BWR instabilities with a four heated-channel Reduced Order Model, Annals of Nuclear Energy, Vol. 53, pp. 320-330 (2012).

3. Dykin V. and Demazière C., Simulation of local instabilities with Reduced Order Models, Proc. of PHYSOR 2012, Knoxville, Tennessee, USA, April 15-20 (2012).

4. Dykin V. and Demazière C., Vinai P., On the Possible Dependence of the Decay Ratio on the Void Reactivity Feedback, Transactions of the 2012 ANS Winter Meeting, San Diego, California, USA, 11-15 November (2012).

5. Dykin V. and Pázsit I., Simulation of in-core neutron noise measurements for axial void profile reconstruction in boiling water reactors, Proc. of PHYSOR 2012, Knoxville, Tennessee, USA, April 15-20 (2012).

6. Dykin V. and Pázsit I., Simulation of in-core neutron noise measurements for axial void profile reconstruction in boiling water reactors, To appear in Nuclear Technology, 2013.

7. Dykin V., Jonsson A. and Pázsit I., Qualitative and quantitative investigation of the propagation noise in various reactor systems, Submitted to Progress in Nuclear Energy, 2012.

Neutron fluctuations in zero power systems and power reactors

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

Background

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

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

Goals

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

Organisation

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

Methodology

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

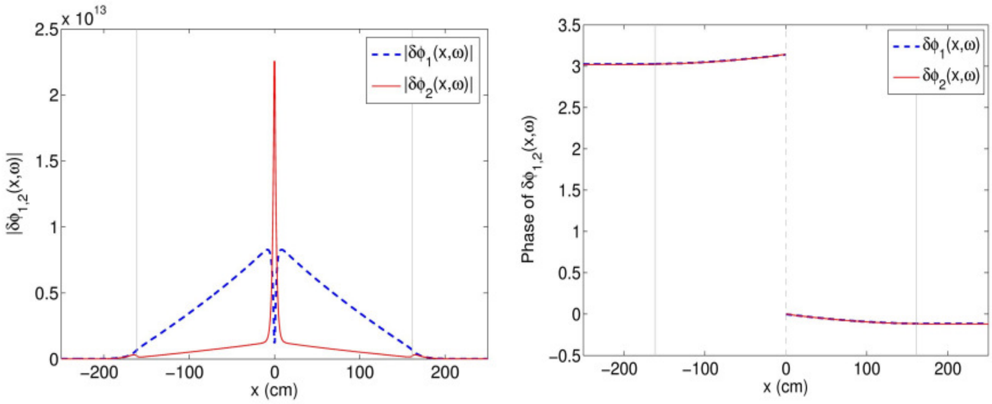
Results in 2012

The research in 2012 was concentrated on finishing up the on-going work as well as to prepare to the PhD exam and writing the thesis. First, the work on the analytic solutions of the Molten Salt Reactor equations was completed. This included a physical interpretation of the integral terms of the equation, the investigation of the validity and applicability of a new approximation (the case of no recirculation), and the investigation of the significance of the zero flux and logarithmic boundary conditions. The manuscript was submitted for publication in February and appeared in the December issue of Annals of Nuclear Energy [1].

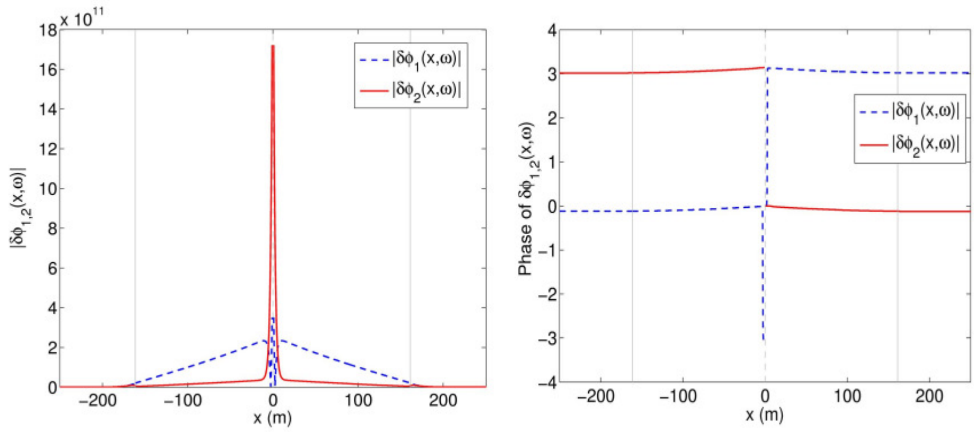
Next the work on the effects of propagating perturbations in four different types of systems was completed. The reactor systems concerned were using stationary fuel, but with different spectral properties, hence two-group theory was used. This work revealed interesting new results on the interference of the effect of the different cross section perturbations on the induced noise. Such effects do not appear in a one-group theory treatement. The manuscript was sent for publication to Progress in Nuclear Energy in March [2].

The third work to finish up was the application of the forward equations for the calculation of the Green's function of the two-group noise problem, and its application for the calculation of the noise induced by a few typical perturbations, such as a variable strength absorber, and the vibrations of an absorber rod. Although this work does not seem to be related to the MSR problem area, in fact it constituted a preparation to the next stage of investigations of an MSR. Namely, in order to handle the core boundary conditions in a more realistic way, and to follow up the decay of precursors and possible further fission events induced by the delayed neutrons, we plan to extend the model from containing only the core to the joint treatment of the core and the auxiliary loop. For this, two-group noise equations have to be handled in inhomogeneous systems (at least in a tw-region system). So far, instead of the direct Green's function, the dynamic adjoint (the adjoint Green's function) was used for such problems. However, as it was demonstrated in this work, with the use of symbolic computations (Mathematica™), it was possible to use forward techniques, which opens up new possibilities in treating inhomogeneous systems. Although application of this method to a more complex model of an MSR with core and external loop could not be started during the present PhD work, this pre-study constituted a useful preparation, as well as supplied new results of its own. It was for instance shown how the sprectral content and the phase of the space-dependent noise can be used to identify the type of the noise source, i.e. whether the vibrating component is an absorber (control rod) or a fuel assembly.

The manuscript was submitted for publication in March 2012 and appeared in print in Kerntechnik in October 2012 [3]. Some results from the paper, showing the noise induced by a vibrating absorber, are shown in Fig. 1.



Vibrating absorber



Vibrating fuel rod

Fig. 1. Upper figures: the amplitude and the phase of the neutron noise induced by a central vibrating control rod. Lower figures: the same for a vibrating fuel assembly at the core centre. The spectral properties of the amplitude (left figures), and in particular the phases (right figures) are different for the control rod and for the fuel assembly, making it possible to find out from the measurements the type of the vibrating component.

Anders Jonsson defended his thesis with the title "Neutronics in reactors with propagating perturbations" [4] on 6 June 2012 with Sandra Dulla of the University of Turin as external examiner.

References

1. Pázsit I., Jonsson A. and Pál L. Analytical solutions of the molten salt reactor equations. Ann. nucl. Energy **50**, 206 - 214 (2012)
2. Dykin V., Jonsson A. and Pázsit I., Qualitative and quantitative investigation of the propagation noise in various reactor systems. Submitted to Prog. nucl. Energy (2012)
3. Jonsson A., Tran H. N., Dykin V. and Pázsit I. Analytical investigation of the properties of neutron noise induced by vibrating absorber and control rods. Kerntechnik **77**, No. 5, 371 - 380 (2012)
4. Jonsson A. Neutronics in reactors with propagating perturbations. PhD Thesis, Chalmers University of Technology, CTH-NT-256 (2012)

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

PhD student: Cheuk Wah Lau
Research leader: Adjunct professor Henrik Nylén.

Background

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

Goals of the project

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

Organization

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

The Division 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. The main purpose of the project is to use thorium with plutonium to reduce the weapon grade and reactor grade plutonium [3]. Mutual interaction between these two projects is thus favoured.

Methodology

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

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

The work has progressed from designing a new innovative fuel assembly, to using the fuel assembly for simulations in CASMO and SIMULATE in order to reach equilibrium core loading conditions [4, 5, 6]. The results showed an improvement in the core pin peak power and the axial offset, as shown in figure 1. Those two parameters clearly showed that, cores using the new innovative fuel assemblies will have a more homogeneous power distribution compared with traditional fuel assemblies, and core safety margins will be improved.

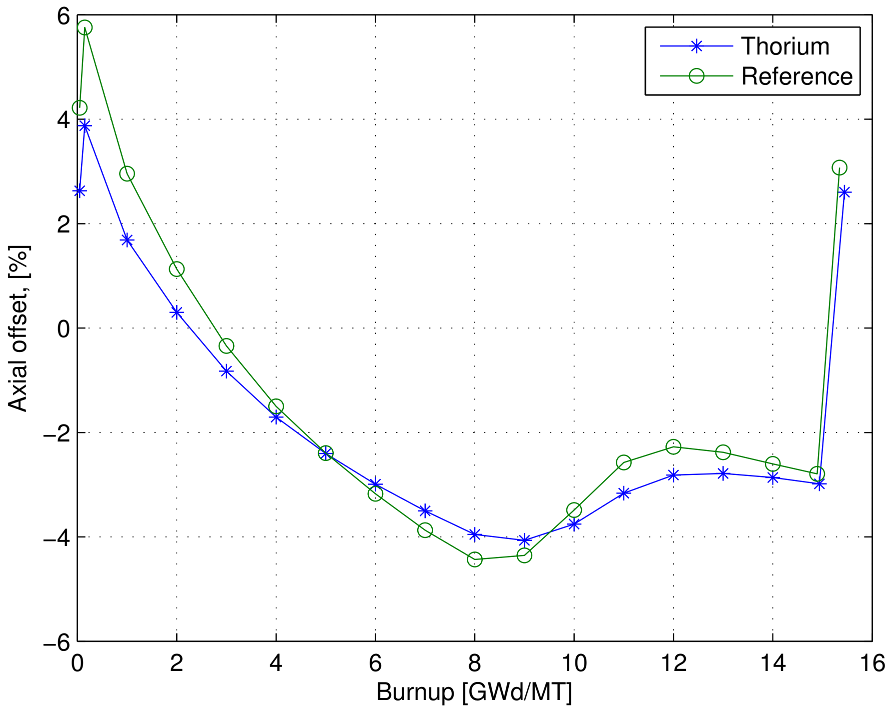


Figure 1. Variation of the axial offset for the Reference- and the Thorium-core (about 60 % of the core is using the uranium-thorium-based fuel assembly) as function of burnup. The axial offset is reduced in the Thorium core compared with the Reference core.

The current work is to evaluate the uncertainty in the infinite multiplication factor of the fuel assemblies. The work is done together with Dr. Augusto Hernández-Solís using the DRAGON code. The next and final step is to make full core transient analysis to evaluate the new innovative fuel assembly by using in-house knowledge of simulating and evaluating full core transients.

As mentioned above, because of the collaboration with Klara Insulander Björk, work has been performed in understanding the behaviour of thorium-plutonium fuel assemblies in the Ringhals-3 PWR core.

Finally, Cheuk Wah Lau was granted scholarship from Chalmers Vänner to present a conference paper at PHYSOR-2012 in Knoxville, Tennessee. This year, he will participate to the ICAPP 2013 to present a paper in Jeju island, South Korea.

References

1. R. Price and J. R. Blaise, “Nuclear fuel resources: Enough to last?”, *NEA Updates NEA News*, 20 (2), 2002.
2. M. Saglam, J. J. Sapyta, S. W. Spetz, and L. A. Hassler, “Core Designs and Economic Analyses of Homogeneous Thoria-Urania Fuel in Light Water Reactors”, *Nuclear Technology*, **147**, *1*, 8-19 (2004).
3. K. Björk, V. Fhager, C. Demazière, ”Comparison of thorium-based fuels with different fissile components in existing boiling water reactors”, *Progress in Nuclear Technology*, **53**, 618-626 (2011).
4. C. W. Lau, C. Demazière, H. Nylén, and U. Sandberg, “Improvement of LWR thermal margins by introducing Thorium” *Progress in Nuclear Energy*, **61**, 48-56 (2012).
5. C. W. Lau, C. Demazière, H. Nylén, and U. Sandberg, “Improvement of the Thermal Margins in the Swedish Ringhals-3 PWR by Introducing New Fuel Assemblies with Thorium” Proc. PHYSOR 2012 - Advances in Reactor Physics - Linking Research, Industry, and Education, Knoxville, TN, USA, April 15-20, 2012.
6. C. W. Lau, H. Nylén, C. Demazière, and U. Sandberg, “Investigation of the Equilibrium Core Characteristics for the Ringhals-3 PWR with Improved Thermal Margins Using Uranium-thorium Fuel”, Submitted to ICAPP 2013, Jeju Island, South Korea, April 14-18, 2013.

Complexation of iodine species with organic molecules under severe accident conditions in LWR`s

PhD student: Sabrina Tietze, Department of Chemical and Biological Engineering, Nuclear Chemistry, Chalmers University of Technology
Supervisors: Professor Christian Ekberg[1], Dr. Mark Foreman[1], Dr. Henrik Glenneskog[2]
[1] Nuclear Chemistry, Chalmers University of Technology, Göteborg
[2] Vattenfall Power Consultant, Göteborg

Background

During severe nuclear accidents significant amounts of gaseous elemental iodine will be formed from uranium fuel in LWR`s. Under the severe accident conditions (heat, irradiation) it can react in complex reactions with the organic substances released from organic materials (paint, cable coatings) in gaseous phase to form highly volatile airborne organic iodine species such as methyl iodide and ethyl iodide. These iodine species cannot be retained with the same efficiency as elemental iodine with the present used safety installations (sprays, charcoal filter, wet-scrubber filter) in Swedish nuclear power plants. The properties of the currently used filter materials are chosen to efficiently retain elemental iodine. However, organic iodides show a different chemical behaviour due to their organic and more hydrophobic characteristics and thus require different filter materials. For example, the currently in wet scrubber used alkaline sodium thiosulfate solution is about 20 times less efficient to retain methyl iodide. Consequently, those organic species have a high potential to cause biological harm to humans when released to the environment.

Since iodine is essential for the human body, it gets concentrated in the thyroid gland and thus increases the risk of cancer. Organic iodides which have been uptaken additionally have an organic rest in their molecule such as a methyl group in methyl iodide which is able to cause methylation effects as known from workplaces with usage of ethyl bromide. Of especially high relevance for the public are ^{131}I containing species. Those have a half-life of circa 8 days which is long enough for harmful bioaccumulation.

Goals of the project

The formation of organic iodides is not well investigated both quantitatively and qualitatively. The formation of those species is studied from different paint products and their solvents used in nuclear installations, as well as from cable plastics under the effects of heat and irradiation.

The distribution behaviour of commonly identified alkyl iodides such as methyl and ethyl iodide is studied in the FOMICAG (Facility set-up for On-line Measurements of the Iodine Concentration in an Aqueous and Gas phase) facility, which is a model of the Swedish BWR Oskarsham 3 and the data are used for a newly developed model (The Chalmers Model) to e.g. estimate the remaining quantity of these species in gaseous phase which could be potentially released into the environment.

While paint surfaces can act as a source for organic iodides, they can as well act as a sink for gaseous iodine species and lead to the formation of new volatile or non-volatile iodine species. Thus, the interactions (sorption and revaporisation) of gaseous inorganic and organic iodine species are studied with differently aged paint surfaces (Teknopox Aqua VA) in comparison with common metal surfaces (Al, Cu, Zn, SS). The interactions on the surfaces are affected by the presence of other fission products such as RuO_4 or radiolysis and pyrolysis products such as hydrochloric acid, nitric acid and ozone.

A fraction of the iodine species will remain in gaseous phase in an accident scenario. To decrease the release of the currently less retained organic species in case of containment venting, a modified scrubber medium is developed.

Organization

The work is performed by the Ph.D. student Sabrina Tietze under the supervision of Prof. Christian Ekberg, Dr. Mark Foreman and Dr. Henrik Glänneskog. The experimental work is performed at the Nuclear Chemistry department, Chalmers University of Technology. Some experimental work on IOx aerosol interactions is performed in collaboration with VTT Technical Research Centre of Finland. Material samples of paint products and cable plastics have been provided from Vattenfall, Ringhals and Forsmark. Analytical support on pyrolysis GC-MS is given by Dr. Barth van Dongen (Manchester University).

The first part of the work is presented in the Licentiate thesis and was successfully defended on September 10, 2012 at Chalmers University of Technology. The opponent of the defense was Per-Olof Aronsson (former Ringhals).

Methodology

The formation (qualitative and quantitative) of organic iodides from organic materials is studied using temperature controlled thermolysis experiments and radiolysis experiments (gamma source, dose rate = 14 kGy/h) together with gas chromatographic equipment (GC-MS, pyrolysis GC-MS).

The distribution and hydrolysis behaviour of e.g. methyl iodide is studied using the FOMICAG (Facility set-up for On-line Measurements of the Iodine Concentration in an Aqueous and Gas phase) facility, which is a model of the Swedish BWR Oskarsham 3. For e.g. this purpose, synthesis methods for ^{131}I labelled organic iodide species have been developed.

The experimental data generated for different temperatures and over solutions of varying pH are used for the development of a mathematical model (The Chalmers Model) to describe the kinetic parameters of the partitioning and hydrolysis behaviour of e.g. methyl iodide to determine their partitioning coefficients.

The sorption and revaporisation behaviour of different inorganic (IOx, I_2) and organic iodine (methyl iodide, ethyl iodide) in and withoout presence of other species under heat, irradiation and humidity is investigated using a HPGe-, LSC- and e.g. autoradiography measurements.

The testing of modified scrubber solutions is performed mainly using the FOMICAG facility and a modification of it, wash-bottle cascades and shaking experiments.

Publications

1. S. Tietze, Formation, partitioning and interactions of organic iodides under severe nuclear accident conditions in LWR containments, Thesis for the degree of Licentiate of Engineering, ISSN: 1652-943X, Chalmers University of Technology, Sweden, September 2012.
2. S. Tietze, M. Foreman, C. Ekberg, Synthesis of I-131 labeled iodine species relevant during severe nuclear accidents in light water reactors, Accepted by Radiochimica Acta, 2012.
3. S. Tietze, M. Foreman, C. Ekberg, B. van Dongen, Identification of the chemical inventory of different paint types applied in nuclear facilities, Journal of Radioanalytical and Nuclear Chemistry, 3, pp. 1981-1999 (2013).
4. S. Tietze, M. Foreman, C. Ekberg, Formation of organic iodides from containment paint ingredients caused by gamma irradiation, Accepted by Nuclear Science and Technology, 2012.
5. T. Haste, A. Auvinen, J. Colombani, F. Funke, G. Glowa, S. Güntay, J. Holm, T. Kärkelä, G. Langrock, G. Poss, B. Simondi-Teisseire, S. Tietze, G. Weber, Containment Iodine Experiments in the SARNET2 project, 5th European Review Meeting on Severe Accident Research (ERMSAR-2012) Cologne (Germany), March 21-23, 2012.

Nitric acid formation and ruthenium chemistry

PhD student: Ivan Kajan, Department of Nuclear Chemistry, Chalmers University of Technology
Supervisor: Professor Christian Ekberg

Background

Formation of nitric acid under severe accident conditions

In the nitrogen (N_2) atmosphere of BWR containments and in steam rich containment air nitric acid (HNO_3) can be produced in large quantities by radiolysis. Produced nitric acid influences the pH of the water pools. Due to the strong oxidizing character of nitric acid the water pool chemistry, e.g. the volatility of iodine, is further influenced. Thus the formation of nitric acid under high dose rates and high temperatures expected in different severe accident scenarios needs to be studied. The formation of radiolysis products is commonly characterized by the so-called G-values, i.e., the number of molecules formed per joule of radiation energy absorbed.

Possible re-vaporisation of ruthenium in the containment

During a severe nuclear accident significant release of ruthenium may occur if the fuel is oxidized during an air-ingress accident. Ruthenium can be released to the containment via the reactor coolant system as different ruthenium oxides. The main species will be ruthenium tetroxide vapor and ruthenium dioxide aerosols. These ruthenium compounds can condensate in the water phase or on different surfaces in the containment. The deposited ruthenium will mainly be in form of solid ruthenium dioxide. Due to a high radiation field in the containment during a severe accident there will be a continuously formation of oxidation agents like ozone via the radiolysis of air. These oxidation agents may react with ruthenium deposits on the surfaces in the containment and reproduce volatile ruthenium species, which can be released from the containment.

Goals of the project

Formation of nitric acid under severe accident conditions

In this work the G-value for nitric acid production will be determined by measuring irradiated air and/or water phases with a ^{60}Co gamma source. First measurements have been performed for 25 °C with a weaker gamma cell at VTT (dose rate of 135 Gy/h, 25 °C). This source does not allow measurements at dose rates expected in the containment during severe accidents. The recently loaded gamma cell (dose rate of 14 kGy/h; app. 45 °C) at Chalmers will be used to achieve dose rates and temperatures according to severe accident scenarios.

Possible re-vaporisation of ruthenium in the containment

In this part of project work will be focused on estimation of re-vaporized ruthenium under radiation. For the experiments will be used gamma cell on nuclear chemistry department with dose relevant to severe nuclear accident scenario. Possibilities and quantity of ruthenium re-vaporisation will be examined on surfaces of copper, zinc and aluminium. As ruthenium in form of ruthenium tetroxide is strong oxidising agent there is possibility of oxidise iodine deposits on surfaces. Iodine in case of nuclear accident is released sooner than ruthenium so it is already deposited on surfaces. As ruthenium tetroxide is then released into the atmosphere it can affect re-volatilising deposits of iodine formed previously. This interaction will be also studied.

Organization

The work is performed by PhD student Ivan Kajan under supervisin of Professor Christian Ekberg. Co-supervision is performed by Mark Foreman. For consultations there are two external co-supervisors Henrik Glänneskog and Joachim holm both from Vattenfall company.

Methodology

Formation of nitric acid under severe accident conditions

G-value for the formation of nitric acid was estimated for different ratios between air and water phase. Impact of amount of received dose on formation of nitric acid was also studied. For determination of nitric acid two different chemical methods were used. Both of them use UV spectrophotometric measurements for concentration of HNO_3 determination.

Possible re-vaporisation of ruthenium in the containment

We performed deposition of metal samples (Al, Zn, Cu) with ruthenium tetroxide. Surface of samples was then analysed with several methods (ESCA, SEM and XRD) to estimate composition of deposited layer. Current work is focusing on re-vaporisation phenomena caused by gamma radiation. As source of gamma radiation we use Cobalt 60 filled source gamma cell 220 producing dose rate of approximately 14 kGy per hour. This dose rate fits well with dose rates expected in severe accident conditions.

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

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

Introduction

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

Objectives and methodology

The objective of this project is to investigate the post-dryout heat transfer and in particular, to study the influence of spacers on the onset of dryout and on the post-dryout heat transfer. The new post-dryout measurements were performed in two-side heated annulus 12.7x24.3.1x3650 mm using pin spacers and various flow obstacles, such as cylinders and unit cells of a commercial BWR grid spacer. The main thermal hydraulic parameters such as mass flux, static pressure, pressure drop over test section, wall temperatures and vapor temperature are measured under different flow conditions. The experimental matrix includes measurements of wall temperature distributions for single and two phase flow for both convective boiling and post-dryout heat transfer. The experimental results include as well pressure drop measurements for single phase flow in the test section in order to obtain the friction coefficient relationship and an expression for local pressure losses for flow obstacles. Investigations include the occurrence of dryout on the inner rod and the occurrence of dryout on the outer tube. Various mass fluxes, inlet sub-cooling values and system pressures have been studied. A major influence on post dryout heat transfer regime is exercised by the presence of the flow obstacles. The main objective of the flow obstacle presence is to improve the heat transfer coefficient in the post dryout region. (Pioro et al. 2002) indicated that the heat transfer coefficients can be increased as much as 120% for various types of flow obstacles.

Results in 2012

Several objectives were achieved during year 2012. In the beginning of the year, main effort was devoted to compare the experimental results with post dryout selected correlations from the literature. A thorough analysis of experimental uncertainties has been performed, along with a study of the influence of the three flow obstacle used in the experiment. Figures 1 show a comparison between measured heat transfer coefficients obtained in the same conditions. Figure 2 indicates an increasing of the quenched drypatch with the increasing of the mass flux. The measured heat transfer coefficient was weighted with the calculated heat transfer coefficient based on post-dryout Groeneveld LookUp Table. Figure 3 present a calculated versus measured heat transfer coefficient in case of Groeneveld Look Up table. It can be noticed an over-predicted calculated wall temperature. A small correction function was proposed based on Saha Model, [11]. The Saha model was chosen because it allows the user to predict the wall temperature starting from the onset of the dryout location, while the other post dryout correlations assume a priori the post dryout regime (without taken into account the transition zone). To elaborate the function, 215 experimental points from test section with pins-spacers were selected. The remained points (464) were used to validate the obtained function. Data analysis showed that the heat transfer coefficient in the dryout point proximity can be calculated with the following relation, where coefficients A=4.8 and B=80.59.

$$\frac{Nu_{\exp}}{Nu_{Saha}} = 1 + Ae^{-B(X_{local} - X_{Dryout})}$$

where X_{dryout}, X_{local} represent quality at the onset of the dryout location and local quality respectively, Nu_{exp}, Nu_{Saha} represents the experimental Nusselt number and Nusselt number calculated with Saha model. This function doesn't take into account the flow obstacle influence, however the prediction of the calculated temperature is improved. Figure 4 shows the improved heat transfer coefficient.

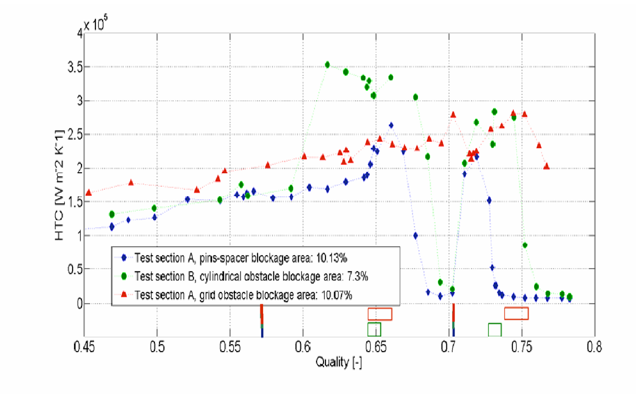


Fig.1 Measured heat transfer coefficients.

Mass flux G=500 kg/m^{2}s, inlet subcooling ΔT=10 K, pressure P= 7 MPa, heat flux on rod q''= 500 kW/m^2

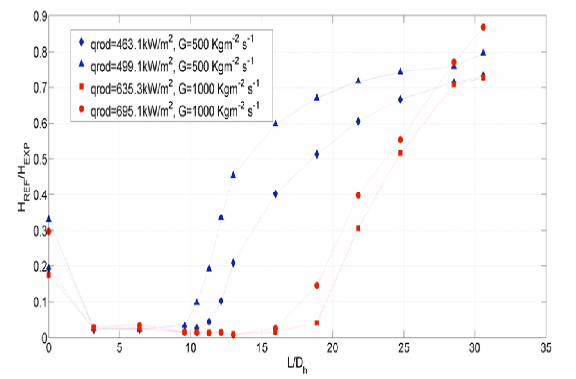


Fig.2 Effect of mass and heat flux on the heat transfer coefficient ratio.

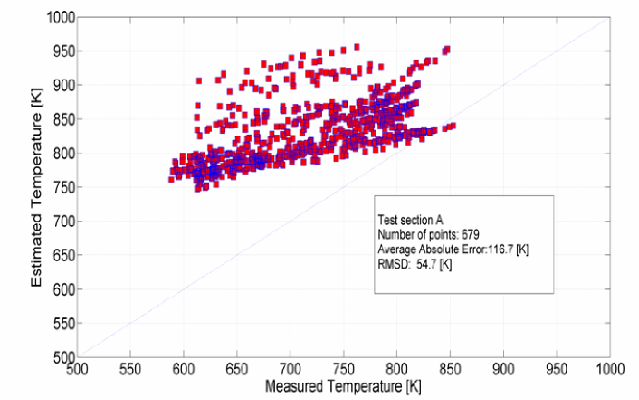


Fig.3 Predicted wall temperature versus measured temperature, test section A (Groeneveld Look Up Tables)

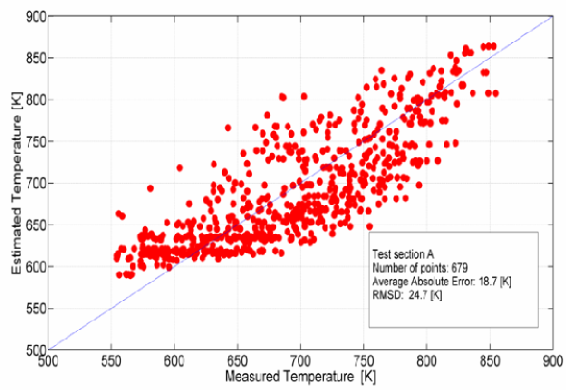


Fig.4 Predicted wall temperature versus measured temperature, test section A

The results of measurements have been presented at such conferences as ICONE-17, IHTC-14, NENE-2010, [1-3], and as an invited lecture at the UK-Japan Seminar on Multiphase Flows, [4]. The results from the project were analysed and published in 2012 a journal paper (International journal of Heat and Mass Transfer), [9] and conference paper, Nureth15,[10] . One additional journal article and the defence of the doctoral thesis are scheduled to be accomplished until June 2013.

References

1. 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, ICONE-17 Brussels, Belgium.
2. Anghel, I., Anglart, H, Hedberg, S., 2010. Study of Post Dryout Heat Transfer in Annulus with Flow Obstacles, Proceedings of the 14th International Heat Transfer Conference, IHTC-14, Washinghton, USA.
3. Anghel, I.G., Anglart, H, Hedberg, S., 2010.Experimental Investigation of Post-Dryout Heat Transfer in Annuli with Flow Obstacles, Proceedings of the International Conference, Nuclear Energy for the New Europe, NENE-2010, Portoroz, Slovenia.
4. Anglart, H., Anghel, I., 2010. 8th Japan-UK Seminar on Multiphase Flows, Otaru, Japan.
5. Anghel, I.G., Anglart, H., 2011. Experimental Investigations of Heat Transfer at Dry Patch Location in Annular Two-Phase Flow, submitted to the International Conference on Nuclear Engineering, ICONE-19, Chiba, Japan.
6. Anghel, I., Anglart, H., 2011. Measurement of Post Dryout Heat Transfer Coefficient in a Double Heated Annulus With Flow Obstacles, 14th International Topical Meeting on Nuclear Reactor Thermalhydraulics, NURETH-14, September 2011, Toronto, Canada.
7. Anghel, I., G., Aglart,H., Hedberg, S., 2012, "Experimental investigation of post-dryout heat transfer in annuli with flow obstacles," Nuclear Engineering and Design, 246, pp. 82-90
8. Anghel, I., 2011. Experimental Study of Post-Dryout Heat Transfer in Annuli with Flow Obstacles, Licentiate Thesis, ISBN-978-91-7501-020-5.
9. Anghel, I., G., Aglart,H, 2012, "Post-dryout heat transfer to high-pressure water flowing upward in vertical channels with various flow obstacles, International Journal of Heat and Mass Transfer , 55(25-26, pp. 8020-8031
10. Anghel, I., Anglart, H., 2012. Experimental Study of Post Dryout Heat Transfer in a Double Heated Annulus with Flow Obstacles, 15th International Topical Meeting on Nuclear Reactor Thermalhydraulics, NURETH-15, September 2011, Pisa, Italy (submitted)
11. P. Saha, A nonequilibrium heat transfer model for dispersed droplet post-dryout regime,Int. J. Heat Mass Transfer, 23 (1980), pp. 483–492.

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

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

Background

Reactor thermal-hydraulic system codes such as RELAP5 and TRACE play an important role in assessing safety analysis for nuclear plants, designing thermal-hydraulic experimental facilities, research and commercial nuclear reactors. Main advantages of these codes are relatively small computational time and reasonably good results for system steady-states and transients. For closures, the codes, however, employ empirical correlations developed from separate effect and integral experiments of different scale. In many codes a two-fluid model with time- and volume-averaged parameters is used for simulation of two-phase flows. Neglected physical effects together with the volume averaging give a concern that the codes will fail in calculating complex system behavior such as strongly oscillating two-phase flows with rapid transitions among flow regimes. An adequate treatment of transient two-phase flow patterns in nuclear reactor thermal-hydraulic system codes is necessary.

Objectives and methodology

First, 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 codes such as RELAP, TRACE, MELCOR.

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

Organization

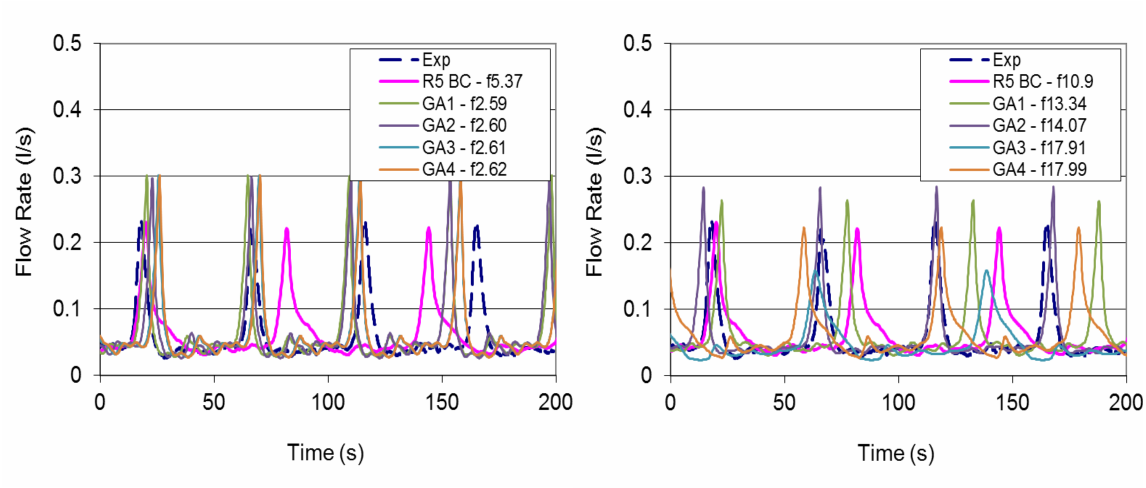
The work is performed by PhD student Viet-Anh Phung under the direction of scientific advisor Associate Professor Pavel Kudinov. The members of the reference group are: Ayalette Walter (SSM), Farid Alavyoon (Forsmark), Claes Halldin (OKG), Henrik Nylén (Ringhals) and Anders Andrén (Westinghouse).

Results in 2012

The main directions of the work during year 2012 were (i) further study of RELAP5 capability in predicting natural circulation and two-phase flow instability in CIRCUS-IV single channel experiments for uncertainty reduction by input calibration and (ii) study of depressurization history effect on core relocation phenomena in a reference Nordic Boiling Water Reactor (BWR) using MELCOR.

In the first part of the work, analysis on identification of flow-regimes during unstable natural circulation in CIRCUS-IV by using RELAP5 and TRACE was finalized and NUTHOS-9 conference paper was submitted.

Then, a genetic algorithm tool (GA-NPO) coupled with RELAP5 was used to calibrate the CIRCUS-IV RELAP5 input. The previous studies showed that RELAP5 can calculate relatively well two-phase flow instability at natural circulation and low pressure for some cases, but the results are sensitive to input parameter uncertainties. Manual input calibration requires a complex procedure, which is time consuming and to some extent involves a user uncertainty. The GA-NPO/RELAP5 results demonstrate that the tool can be applied to automate the input calibration process and to reduce simulation error. Possible model uncertainty space is defined for the GA-NPO. Fitness function of the algorithm compares simultaneously a number of calculated and experimental thermal hydraulic parameters (e.g. flow rate, oscillation period, water temperatures) to guide the tool finding the optimal input model. The result shows that user defined fitness function plays an important role in identifying final optimal input models (figure 1a and 1b).



a) Fitness function 1 b) Fitness function 2

Figure 1: Comparison of experimental inlet flow rate, manually calibrated RELAP5 result and top four GA-NPO/RELAP5 results of CIRCUS-IV during instability (Tin = 93 ^{o}C). For the same defined fitness function, lower value of fitness function is better.

The second part of the work was the analysis of influence of depressurization history on core relocation phenomena in a reference Nordic BWR. The loss of offsite power combined with diesel generator failure leading to station blackout was selected as the reference scenario.

Effect of uncertain parameters in operation of safety relief valves and automatic depressurization system (ADS) was investigated. The analysis provided preliminary range of uncertainty of melt characteristics (composition, thermal conductivity, temperature, etc.), pressure, water level in the lower plenum and event timing. Results show that in-vessel melt progression could be sensitive to ADS activation time and maximum opening area of ADS safety valves. Thermal conductivity of debris mixture in lower plenum could vary from 9 to 16 W/m/K.

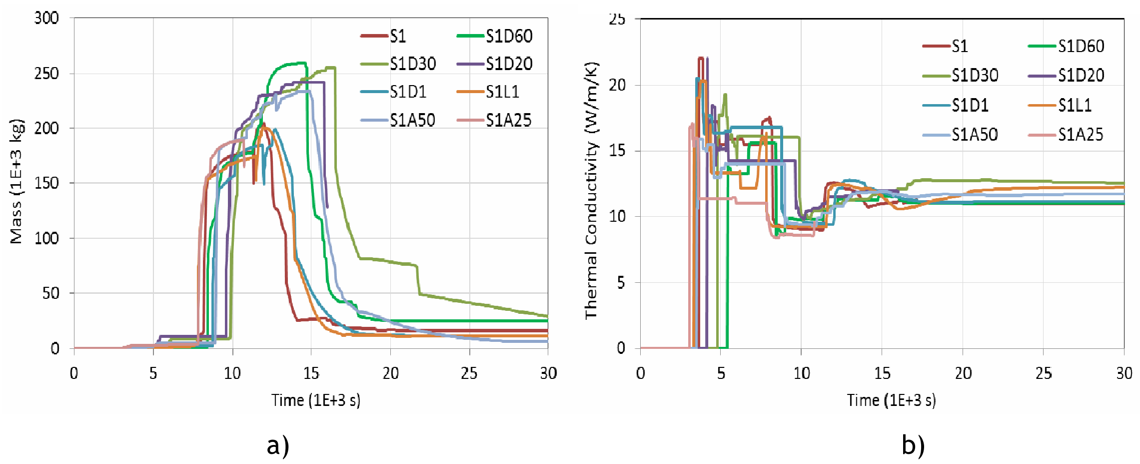


Figure 2: Variation of a) total mass debris and b) thermal conductivity of debris mixture in lower plenum to depressurization history.

References

Phung V. A., Kozlowski T., Kudinov P., Rohde M., Simulation of Two-Phase Flow Instability in CIRCUS Facility Using RELAP5, ANS Transactions, vol 99, 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, vol 101, 2009.

Phung V. A., Kudinov P., Identification of Two-Phase Flow Regimes in Unstable Natural Circulation Using TRACE and RELAP5, International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NUTHOS-9), Kaohsiung, Taiwan, 2012, paper N9P0062.

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

PhD student: Kaspar Kööp, Division of Nuclear Power Safety, KTH
Supervisor: Assoc. prof. Pavel Kudinov

Background

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

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

Project Goals

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

Research Approach

Both probabilistic and deterministic safety analysis methods will be addressed. The research should help establish a procedure to effectively search for credible scenarios and parameter ranges, when individually-tested passive-safety systems interact nonlinearly and fail to perform their pre-defined functions. Such a failure signifies the deficiency of the decomposition (divide-and-conquer) strategy adopted in system design and testing. Consequently, a vulnerability map for a passive system shall be devised for use in probabilistic treatments, similarly to the equipment failure rate of an active system.

Case studies include Generation III plant (AP1000), Generation III+ plant (ESBWR) and Generation IV plant (a passive LFR). The proposed research is expected to lead to recommendations on improving passive safety systems and operating procedures for the advanced plant designs under consideration.

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

Results in 2012

Advanced methodologies for design analysis and performance characterization (mentioned in the project goals) need to be validated against experimental data. A large part of the work in 2012 was continuation of 2011 work on support calculations for TALL-3D facility design and optimization, as this facility will play an important role in validating proposed safety analysis methods for passive systems. Performed system code calculations were instrumental in defining the experimental parameters and validation matrix.

Several advancements in system thermal hydraulic (STH) and computational fluid dynamic (CFD) code coupling were made in cooperation with PhD student Marti Jeltsov. This effort will allow accurate and efficient exploration of the deterministic event space in systems where strong feedbacks between 1D and 3D components exist. In these systems (like pool type reactors) single STH or CFD codes are either not accurate enough or too computationally expensive to be deployed. Coupled codes manage to deliver accuracy without sacrificing efficiency allowing greater number of simulations to be run.

Still the efficiency of coupled codes is not enough to support event space exploration with IDPSA tools (e.g. GA-IDSPA) which require thousands of simulation runs. Therefore development of a surrogate model for TALL-3D test section was started in 2012. This surrogate model is based on physical phenomena identified from the CFD calculations and will replace CFD in the coupled code framework.

Interfacial radiation chemistry

PhD student: Claudio Lousada, Division of Applied Physical Chemistry, School of Chemical Science and Engineering, KTH, Stockholm
Supervisor: Professor Mats Jonsson

Introduction

Interfacial radiation chemistry (radiation induced chemical reactions at solid-liquid interfaces) is crucial for the safety and performance of most nuclear technological applications. Nevertheless, this is still a fairly unexplored field. In most systems of practical importance, the liquid phase is water. Radiolysis of water produces H_2O_2, H_2, OH, H and e^-_{aq}. In homogeneous systems, the radiation chemical yields (G-values) are well known. However, in heterogeneous systems where the solid surface area to solution volume ratio is high, the radiation chemical yields are still unclear. Several studies have shown that the yield for H_2 is significantly higher in heterogeneous systems containing water and solid oxides. The yield appears to depend on the solid surface area to solution volume ratio as well as the nature of the oxide. For the other molecular product, H_2O_2, no such effect has been reported.

The reactivity of the aqueous radiolysis products towards metal and metal oxide surfaces is still not well understood. H_2O_2 has been shown to react with numerous oxide surfaces of relevance in nuclear technology.

Objectives and methodology

The objective of this project is to investigate how aqueous radiolysis products interact with metal oxide surfaces. We have focused our attention on hydrogen peroxide and the hydroxyl radical.

Results

During the course of this project we have investigated the reactivity of H2O2 towards metal oxides as well as the mechanism for this type of reaction. The main reaction route produces molecular oxygen and water. The hydroxyl radical has earlier been proposed to be an intermediate in this reaction. A method has been developed in order to quantitatively scavenge hydroxyl radicals formed in the process of catalytic decomposition of H2O2 on oxide surfaces. The method has also been used successfully to investigate the affinity of hydroxyl radicals for oxide surfaces. The activation parameters for these processes have been determined experimentally. In parallel with the experimental studies, DFT-studies have been performed. The DFT studies have been performed in order to investigate the possible mechanism of these reactions and to determine the energetics of the reaction steps involved. During a stay at the University of Notre Dame (USA), experiments have been carried out in order to identify side reactions. To summarize, we can now describe the mechanisms and energetics of these reactions in detail with the support of experimental and DFT-data. The impact of these processes on nuclear technological applications has been discussed to some extent. Future efforts will focus more on the reactivity of adsorbed radicals of importance in nuclear technology. This work has resulted in 8 publications/manuscripts so far.

References

1. Reijo Pehrman, Martin Trummer, Claudio Miguel Lousada and Mats Jonsson, On the redox reactivity of doped UO2 pellets - Influence of dopants on the H2O2 decomposition mechanism, Journal of Nuclear Materials, Vol. 430, No. 1-3, pp. 6-11, 2012
2. Claudio M. Lousada, Adam Johannes Johansson, Tore Brinck and Mats Jonsson, Mechanism of H2O2 Decomposition on Transition Metal Oxide Surfaces, The Journal of Physical Chemistry C, Vol. 116, No. 17, pp. 9533-9543, 2012

3. Claudio M. Lousada and Mats Jonsson, Kinetics, Mechanism, and Activation Energy of H2O2 Decomposition on the Surface of ZrO2, The Journal of Physical Chemistry C, Vol. 114, No. 25, pp. 11202-11208, 2010
4. Claudio M. Lousada, Martin Trummer and Mats Jonsson, Reactivity of H_2O_2 towards different UO_2-based materials - The relative impact of radiolysis products revisited, Accepted for publication in Journal of Nuclear Materials
5. Claudio M. Lousada, Adam Johannes Johansson, Tore Brinck and Mats Jonsson, Reactivity of metal oxide clusters with hydrogen peroxide and water – A DFT study evaluating the performance of different exchange-correlation functionals. Accepted for publication in Physical Chemistry Chemical Physics
6. Claudio M. Lousada, Jay A. LaVerne and Mats Jonsson, Enhanced hydrogen formation during the catalytic decomposition of H2O2 on metal oxide surfaces in the presence of HO radical scavengers, submitted to Journal of Physical Chemistry C
7. Claudio M. Lousada, Miao Yang, Kristina Nilsson and Mats Jonsson, Catalytic decomposition of hydrogen peroxide on transition metal and lanthanide oxides, Manuscript to be submitted
8. Claudio M. Lousada, Tore Brinck and Mats Jonsson, Application of reactivity descriptors to the catalytic decomposition of hydrogen peroxide at oxide surfaces, Manuscript to be submitted

Mechanical modelling of Stress-Corrosion Cracking in sensitized stainless steel 316 in BWR water

PhD student: Michael Sedlak, Department of Solid Mechanics, KTH, Stockholm
Supervisors: Professor Bo Alfredsson and Adj. Professor Pål Efsing

Introduction

There exists ample laboratory evidence as well as multiple industrial findings in nuclear reactor systems of Stress Corrosion Cracking (SCC) in un-sensitized stainless steel and ultra-clean environments. These conditions have traditionally been thought of as relatively un-sensitive to SCC, but the available results illustrates that such conditions does not exist. It increases the importance of understanding the mechanisms that initiate and propagate cracks in ultra-clean environment and stainless steel with residual stresses. The damage becomes even more detrimental if the material has become sensitized by heat-treatment, for instance welding, or cold work such as grinding.

From experiments and applications the existence of the phenomenon is well documented. The requirements for both crack initiation and propagation are known: a tensile stress that well can be static, some small amount of oxidants in the water and a potential gradient, firstly between positions in the surface and secondly between the crack tip and the outer surface. In some aspects SCC is clearly a fracture mechanical damage phenomenon. On the other hand the crack may branch into multiple cracks that continue to propagate. From a purely fracture mechanical standpoint such branching in a homogeneous and isotropic material at a time invariant and homogeneous stress field is an anomaly. If two crack branches exist, then one branch will sooner or later be slightly longer and more loaded by the Stress Intensity Factor (SIF) than the other. The more loaded crack would then propagate faster and thereafter shield the slightly shorter branch from further growth. If both branches continue to grow, as the experimental evidence in the literature show, then there has to be an additional crack propagating mechanism or process that promotes crack propagation and is related to crack length in such a way that it enhances growth of the shorter crack. The corrosion process is such a process. One key question is: how does the corrosion process communicate through the crack length with the surrounding environment? There seem to be similarities between SCC and hydrogen embrittlement. Another key question that needs to be addressed is: how does the corrosion process affect the material properties at the crack tip? From a fracture mechanical standpoint the research should focus on how changing material properties at the crack tip can propagate the crack at constant SIF.

Objectives and methodology

Micrographs of crack faces from defected components and laboratory samples illustrate that SCC propagation mainly is intergranular in its morphology, although there exists examples when growth has started as transgranular and shifted to intergranular after some short distance. Based on these findings it is reasonable to assume that the process zone in front of the crack tip follows the grain boundaries and it is therefore one-dimensional in the crack cross-section. The working hypothesis will be to model the crack growth with a cohesive zone in front of the crack tip. The cohesive model formulation allows for some damage features: a load threshold below which no damage occurs, a thermally activated crack propagation, stress and environmentally assisted kinetics and a condition for crack propagation. The reaction-rupture mechanism will take place in a narrow band where the locally resisted crack opening exceeds a critical value. The local cohesive zone parameters may be controlled by a diffusion law for the passage of ions through the crack length. A cohesive zone model will aim at describing the local conditions at the crack tip including the corrosion detrimental effects. At a slightly larger length scale the model can be loaded by the generic stress and displacement fields of linear elastic or elastic-plastic fracture mechanics. The suitable field description depends on the load levels. The aim is that the model should be applicable for both long and short SCCs.

There exists a multitude of experimental series that are described in the literature. The crack growth rate is well documented in relation to corrosion potential or time. Therefore, the project utilizes the existing experimental results. Existing experimental results in the literature will be reviewed, give reference data and form a starting point of the analysis.

Results in 2012

Since the Ph. D. student started working on the project after summer period, the main focus so far has been oriented towards his education, both taking courses and being part of the assistant team for the basic courses with the department of Solid Mechanics at KTH. Current activities includes literature studies regarding the phenomenology of Stress Corrosion Cracking in nuclear rector systems as well as modeling of the stresses in front of a crack in a commercially available finite element code to include for better incorporation of the constitutive equations for the specific materials than is the normal case.