SKC Annual Report 2010

Swedish Centre for Nuclear Technology

October 2011
SKC 11-01

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

Summary of 2010

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

The nuclear education steadily grows in Sweden. A new bachelors´programme in nuclear engineering at Uppsala University started august 2010 in collaboration with KSU (Kärnkraftsäkerhet och Utbildning). The Swedish nuclear power plants sponsors the program with 30 MSEK over the first six years.

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

The Sigvard Eklund prize to the best PhD thesis of the year was awarded to Andreas Enqvist for his work on safeguards. Paul Bramson won the prize for the best masters´ thesis for his work on assessment of the potential for separation and transmutation.

SKC Sponsors in 2010

SKC has been sponsored by the following organisations during 2010:

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

The total support from these organisations was 17 million Swedish kronor during 2010.

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 new-build

A message from the director

When looking back at two years as SKC director, it feels like much more time has passed, simply because the situation has rapidly improved so dramatically.

In June, the Swedish parliament voted in favour of allowing new-build of nuclear power reactors, with the condition that new reactors must be erected on existing sites, and that an old reactor should be disconnected from the grid for each new connected. Thereby, a 30 year moratorium on nuclear technology has been terminated. What is even more interesting is that essentially no high-power electricity production has been allowed to be built during this time, with restrictions on new hydro or fossil generation. Hence, nuclear power is now the only generation allowed to be built that has a significant impact on the overall power balance.

Nuclear new-build has gone from utopia to a generally considered option in just a few years. This means that SKC needs to stay alert for new opportunities due to new-build. In fact, SKC needs to be a few years ahead of the development in society, because we operate early in the competence chain. We need to inspire high-school students *now* for new-build projects starting at the end of the present decade. As a consequence, SKC has increased its marketing activities dramatically during 2010, with a doubling of the activities at student recruitment fairs at the universities, extending the ambitions to universities without nuclear power on the curriculum. In addition the marketing in media has increased.

Up to now, SKC has sponsored education on masters' level. During 2010, a bachelors' level nuclear education was started at Uppsala University, being the first of its kind ever in Sweden. It did not take long until plans on two other programs at a similar level were presented, by KTH and notably by Gävle University, the latter in collaboration with Uppsala University. The Gävle program is designed to provide students with a platform for further studies at masters' level studies at Uppsala University, KTH or Chalmers. It seems safe to predict that the nuclear educational landscape will be wider in a few years from now.

In 2009, the administration was reduced in order to free time for activities aiming at increasing the overall funding. This was manifested in the GENIUS project comprising 36 MSEK that was approved late 2009 and started early 2010. GENIUS has become an instant success, leading rapidly to a new collaboration climate between the three SKC universities.

During 2010, an even larger new initiative was established. France has agreed to co-finance the ESS laboratory to be built in Lund. Sweden has agreed to counter-finance this contribution by giving a special grant to the Swedish universities for collaboration with France in nuclear technology. The deal comprises funding for:

- Participation of Swedish scientists and PhD students in the design and safety analysis of the prototype reactor ASTRID, amounting to 2.8 M€.
- Access for Swedish researchers and PhD students to French laboratory facilities for joint development of fuels and materials to be tested in JHR and ASTRID, amounting to 2.0 M€.
- Access for Swedish students to French education and training reactors (ISIS and MINERVE), including costs for travel and accommodation, amounting to 2.1 M€.
- Transfer of one instrument from Uppsala University to the GANIL facility in Caen, and access for Swedish researchers to the facility for establishing the instrument and future joint work with the instrument amounting to an in kind contribution of 2.6 M€.
- Access for Swedish researchers and PhD students to the Jules Horowitz Reactor (JHR; partly owned by Vattenfall), amounting to 1.8 M€.

Thus, the program comprises in total 11.3 M€, i.e., three times the GENIUS project, which already that was the largest academic nuclear project in Sweden after 1980. About 15 new PhDs are expected as outcome, and 10 postdocs that might become new teachers at the universities as well.

The second SKC annual symposium was organized at Uppsala University in September with over 100 participants. The symposium had an unusual frame, because IAEA held its Technical Meeting on Nuclear Education and Training in parallel with the SKC meeting. The reason is that IAEA want to learn from the Swedish model on how to rejuvenate nuclear education. A joint session was organized, as well as the banquet at Uppsala Castle, in which a special guest appearance by the late Dag Hammarskjöld was one of the highlights.

The SKC director has been deeply involved in the creation of the European Nuclear Energy Leadership Academy (ENELA), an initiative by six European companies with support from the EU. ENELA will offer education that can become of large interest to Swedish nuclear power industry, to SSM, and to academic students. The first courses will start March 2011, with Sweden sending the strongest participation team.

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

With the combined efforts of the new program and GENIUS, Sweden has in just two years increased its ambition level and visibility dramatically in future reactor technology. Three years ago I would have deemed the idea that Sweden should host a GenIV research facility to be moonshine; today I see it as a possibility. In parallel, the prospects of nuclear new-build in the Swedish industry are in progress. Expect some interesting years ahead!

Jan Blomgren

SKC director

Organization and funding

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

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

The funding organizations are:

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

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

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

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

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

The advisory council has consisted of:

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

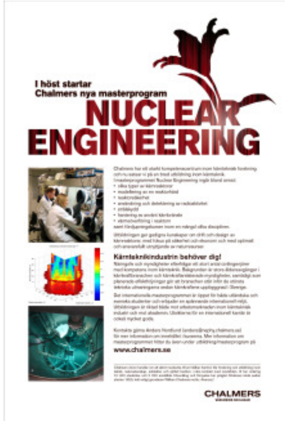
In addition, Jan Blomgren has attended the meetings as secretary.

The SKC Board has consisted of:

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

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

Chalmers University of Technology



Overview of Activities in 2010

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

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

Nuclear Engineering

Research in:

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

Facilities, tools and other data:

- Access to all major system codes for neutronic and thermal-hydraulic calculations.
- A pulsed beam for variable energy slow positrons.
- A portable 14 MeV pulsed neutron generator.
- 13 PhD students (5 with SKC support, 1 jointly with Nucl. Chemistry). 1 PhD exam and 4 licentiate exams during 2010.

Highlights of the year:

Expanding the department with one research associate (J. Anderson), one post-doc (S. Moradi) and one PhD student (A. Mollén);
Andreas Enqvist received the Sigvard Eklund Prize for best PhD thesis;
The chapter on neutron noise techniques by I. Pázsit and C. Demazière appeared in the 5-volume Handbook of Nuclear Engineering by Springer in October 2010.
The EU-financed project FREYA on fast hybrid reactor systems has been approved;
Our long-term collaborating partner, Prof. Emeritus Kojiro Nishina from Nagoya University was promoted to Honorary Doctor in Chalmers.

Nuclear Chemistry

Research in:

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

Facilities and other data:

Laboratories for low activity α, β, γ experiments and activity measurements; hot cell laboratory for γ activity.
In 2010 a special laboratory for research on advanced nuclear fuels (collaboration with KTH) has been built.
The ^{60}Co irradiation facility was upgraded and re-installed. It now gives about 20 kGy/h.
13 PhD students (2 with SKC support, 1 jointly with Nuclear Engineering). 3 licentiates during 2010.

Highlights of the year:

The EU-project CROCK dealing with chemistry in a repository environment was approved.
An SKB project dealing with nuclear fuel dissolution and radiolysis of water was also approved.
The construction of the new nuclear fuel lab was finished
The upgraded ^{60}Co source was put into routine operation

Education

In autumn 2010 the second year of the international master programme in Nuclear Engineering was started at Chalmers. As opposed to earlier courses in nuclear engineering the new program is more engineering oriented and aims at students with backgrounds in physics, chemistry, mechanical or electrical engineering. The new master programme is the only nuclear education in Sweden combining physics and chemistry in one educational program. The philosophy of this programme is to have a "top-down" approach in teaching the physics of nuclear reactors, i.e. starting with an overview of how nuclear reactors work, followed by a detailed description of the main governing physical phenomena and corresponding equations, and finally elective and specialized courses.

The master programme has currently 17 students in the second year and 13 students in the first year. There has also been a large interest in taking the introductory courses as elective courses from other master programs. One of the introductory courses has as much as 55 registered students. About 2/3 of the students are Swedish speaking. New study material, focusing more on the engineering approach and the application of nuclear reactors, had to be developed within a very short time. KSU is greatly acknowledged for helping with simulators, pictures and suggestions for study material. The amount of students taking courses in nuclear engineering has greatly increased and this has put high demands on the departments of Nuclear engineering and Nuclear chemistry.

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

- A. Nordlund, "Introduction to nuclear reactors", Chalmers University of Technology, 2009;
- C. Demazière, "Physics of nuclear reactors", Chalmers University of Technology, 2009;
- C. Demazière, "Modelling of nuclear reactors", Chalmers University of Technology, 2010.
- G. Skarnemark, "Solvent extraction", Chalmers University of Technology, 2009
- G. Skarnemark, "Lanthanide, actinide and super heavy element chemistry"
- G. Skarnemark, "Radiopharmaceutical chemistry", Chalmers University of Technology, 2010
- G. Skarnemark, "Radioecology and radioanalytical chemistry", Chalmers University of Technology, 2010
- T. Fülöp, G. Papp and I. Pusztai: "Fusion Energy", Chalmers University of Technology, 2010

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

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

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

KTH – Royal Institute of Technology

Overview of Activities in 2010

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

Reactor physics
Reactor technology
Nuclear power safety
Nuclear chemistry
Nuclear physics
Surface and corrosion science
Applied materials science
Materials processing science
Computational thermodynamics
Solid mechanics
Philosophy

The six latter groups have started their activities during 2010, thanks to grants from the science council (GENIUS) and support from Vattenfall.

Staff

In total 18 senior scientists are employed full time in the nuclear engineering field, out of which 4 are full professors, 2 associate professors and 2 assistant professors.

In addition, one adjunct professor works half-time at the department of solid mechanics. Three associate professors at the materials science department and one research associate at the division of surface and corrosion chemistry are actively involved in the GENIUS project.

At the division of philosophy, two professors and one research associate are developing courses in safety of nuclear power systems.

PhD education

30 PhD students were active in 2010. Four PhD theses and two licentiate theses were presented:

Calle Berglöf: ”On Measurement and Monitoring of Reactivity in Subcritical Reactor Systems”, PhD thesis in reactor physics.

Roberta Concilio Hansson: ”An experimental study on the dynamics of a single droplet vapor explosion”, PhD thesis in nuclear power safety.

Anders Puranen: ”Near field immobilization of selenium oxyanions”, PhD thesis in nuclear chemistry.

Sandra Garcia Garcia: ”Generation, stability and migration of montmorillonite colloids in aqueous systems”, PhD thesis in nuclear chemistry.

Ivan Gajev: "Sensitivity and Uncertainty Analysis of BWR Stability", Lic. Eng. thesis in nuclear power safety.

Andrei Fokau: ”Transmutation of Americium in fast neutron facilities”, Lic.Eng. thesis in reactor physics.

Milan Tesinsky: ”MCNPX Simulations for Neutron Cross Section Measurements”, Lic.Eng. thesis in reactor physics.

Undergraduate education

A total of 20 courses in nuclear engineering are given regularly at masters level.

In fall 2010, 16 students enrolled into the nuclear energy engineering masters programme, out of which 6 were engineering physics students at KTH. Many courses attract other students, in particular exchange students from southern Europe (Spain, Italy and France). The largest courses (reactor physics and thermal hydraulics in nuclear engineering) were attended by over 40 students. In addition the freshman course in environmental physics, which contains 25% nuclear engineering topics, was taken by 110 open entrance programme students.

During 2010, it was decided to start a nuclear power technology specialisation as a 3rd year option in the bachelors programme in mechanical engineering in Södertälje. First students will be enrolled in 2011.

Research highlights

The fuel fabrication lab succeeded in producing the first batch of uranium nitride pellets in april 2010, using a highly innovative spark plasma sintering technique. Densities up to 96% of the theoretical maximum were achieved.

National and international projects

KTH is coordinating the GENIUS project (Generation IV research in Swedish universities), where KTH, Chalmers and Uppsala University are participating.

KTH is now an official member of the ESNII task force of SNE-TP.

KTH participated in the following EU-projects during 2010: HPLWR2, NURISP, SARNET2, EUROTRANS, ELSY, HeLiMNET, MICADO, GETMAT, FAIRFUELS, THINS and LEADER. In addition the FREYA project was approved.

Six SKC funded PhD projects have been in progress during 2010. A summary description of these projects is provided in the following pages.

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

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

Six SKC funded PhD projects have been in progress during 2008. A summary description of these projects is provided later on in this report-

Uppsala University

Division of Applied Nuclear Physics

The strategy that generated a lot of inspiring events during 2009 was successful also during 2010 and it may be concluded that many interesting opportunities was offered for presenting Swedish nuclear technology research and education nationally as well as. Several of these events have resulted in new international collaborations in which the Division functions as the centre of gravity.

Another event of interest is the fact that the research programme, Ion Physics, now is merged with Applied Nuclear Physics. This opens up for new exciting experimental possibilities regarding materials research, especially when taking into account the increasing collaboration the Division has with the research programme Material Theory at UU. It is foreseen that the concentration of material related activities around the Division will form an important support for research in materials for Gen IV.

External contacts have become increasingly important for the Division and a simple strategy has been formulated in order to expand the contact area against the surrounding world, which can be divided into a few items:

a) Attending conferences with the main objective to connect research and educational activities at UU with corresponding activities internation-ally.
b) Continue to attend public debates, writing articles directed towards the public sphere and in other ways supplying information to the society at large.
c) Initiating dialogues with the objective to collaborate with well-reputed actors around the world.

The account below gives a few examples of what has been achieved during 2010 in these respects:

a) During the INMM conference in July it became clear that the Los Alamos National Laboratory (LANL) in the USA was eager to initiate collaboration with the Division. A first step in this direction is that Sophie Grape now is assigned as a member of a review committee on 14 NDA techniques for determining the plutonium and fissile content of spent fuel, in a network led by LANL. The objective is to find a few technologies that can form a basis for research and development within this field at LANL. Further on, it is anticipated that the Division will become an integral part in such research where typically one senior researcher and one or two Ph.D. students will participate.

b) Several debate articles were written during 2010. Ane Håkansson and Mattias Klintenberg wrote an article for Dagens Nyheter 2010-06-21 in response to an article by the leaders of the Green Party. A joint article was written in Svenska Dagbladet by Janne Wallenius, Jan Blomgren, Calle Berglöf, Ane Håkansson and Christian Ekberg. Another article was written by Ane Håkansson, Janne Wallenius, Christian Ekberg and Mattias Klintenberg in Ny Teknik 2010-12-08.

   Additionally, several interviews have been conducted during 2010. Among others, Dagens Nyheter, Svenska Dagbladet and the Swedish Radio and television have performed interviews with the staff at the Division.

c) Several international collaborations have been initiated during 2010:

   As mentioned above, collaboration has been initiated with the LANL regarding safeguards research. It is also anticipated that this collaboration will be extended towards research on materials for Gen IV which will, in that case, involve UC Berkeley as well.

   The dialogue with IAEA initiated during 2009 resulted in some interesting ideas: Ane Håkansson was invited to United Arab Emirates in March 2010 to speak at the IAEA conference on “International Conference on Human Resource

Development for Introducing and Expanding Nuclear Power Programmes". During this event it was concluded that the Division and UU as a whole could play an educational role in the build-up of the nuclear programme of UAE.

The continued discussions with IAEA also led to that UU hosted a "Technical Meeting on Training and Educational Systems for Nuclear Industry" in Uppsala 28 September to 1 October 2010. The meeting gathered participants from 22 countries representing universities, academia, nuclear facilities, ministries, regulatory bodies, R&D organizations, training organizations, NPP vendors, and suppliers of training tools.

Together with IAEA, UU has also started a process with the objective to create a regional competence centre for nuclear safety, offering education and training to, in the first place, northern Europe. However, countries such as UAE have shown interest to send people in a "train the trainers" programme. The main focus of the centre is on the non-technical issues e.g. psychology, economy, legal affairs and MTO. Although the centre will be coordinated by UU, the very idea is to attract collaborators in Sweden and the Nordic countries, in the first place, to form a network. To that end, KSU and the IFE/OECD in Halden are interested to get involved in this network. Obviously Swedish universities should also be offered to be a part of this network. In addition, discussions with ENELA to include part of the centre's competence into their management education in Munich have been initiated.

Collaboration with the IFE in Halden was initiated during 2010. Here several fields will be considered such as safeguards, core simulators, fuel diagnostics, materials and core monitoring. One concrete item for the collaboration is the on-going PhD project on emission tomography of nuclear fuel assemblies, where the PhD student, Scott Holcombe from Westinghouse, will spend the forthcoming two years in Halden, adapting the tomographic technique to fuel assemblies from the OECD Halden reactor.

The safeguards group at SCK·CEN in Mol works with issues quite similar to the safeguards group at UU. It was therefore reasonable to start discussions of collaboration between these two groups. Especially interesting here is to find surfaces between SCK·CEN, UU, Halden and LANL.

The nuclear reactions group initiated collaboration with GANIL, France, for performance of measurements at NFS beamline. The Medley facility currently installed at TSL will be moved to NFS for, e.g., measurements of fission cross sections.

The nuclear reactions group furthermore initiated collaboration with University of Jyväskylä, Finland, for measurements of fission yields for various nuclei from both thermal and fast neutrons.

As can be seen, much of the work at UU during 2010 has been focussed on external relations and network building. Parallel to these activities, research and education have been conducted in a regular way with the exception of two new items: the new Bachelor program for nuclear technology and UU:s four projects included in the Genius programme.

Below is an account on the part of the Division's activities that has a direct relevance for SKC.

Education

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

Bachelor's program in nuclear engineering

Following the agreement between KSU and Uppsala University (July 1, 2009) regarding: "Högre utbildning inom kärnkraftindustrin", where the Swedish nuclear power industry, in a long-term perspective, supports a new bachelor program in nuclear engineering both financially and practically, UU has been hard at work establishing the new program which was started in September 2010. The idea behind this unique program is to allow students with at least two years previous studies in bachelor of engineering programs all over Sweden to apply for this education. Priority is given to students within mechanical engineering and electrical engineering. The objective of the one year program is to cover most non-site specific issues and it is believed that such an education will 1) increase the volume of employable people to the nuclear industry and 2) decrease the industry's total training cost. The latter is due to the fact that almost a year of training, that otherwise would charge each power plant individually, would be centrally funded without the need to provide salaries etcetera to course participants.

The program, which comprises 60 hp, contains the following courses:

- Introduction to nuclear engineering (5 hp)
- Reactor physics (5 hp)
- Nuclear thermal hydraulics and steam turbine technology (5 hp)
- Light water reactor technology (5 hp)
- Chemistry, materials and fuels for reactor applications (5 hp)
- Nuclear power safety (5 hp)
- Power Engineering (5 hp)
- Nuclear power operation (5 hp)
- Future nuclear energy systems (5 hp)
- Degree project in nuclear power technology (15 hp)

In most courses experts from industry and authorities are involved as guest teachers, collaborating with UU teachers. Most courses include study visits to nuclear power relevant facilities and also laboratory exercises are performed in KSU's simulators in Studsvik and at VTT's TRIGA reactor in Helsingfors. 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 professional network Women in Nuclear (WiN) provides a mentoring program that runs in parallel with the program courses. Each student is assigned a personal mentor working in the nuclear industry and over the course of the study year, WiN organizes six meetings for all students and mentors with seminars on various topics, e.g. career planning, radiation safety and protection and the nuclear fuel disposal. In between these meetings students and mentors meet on an individual basis.

Considerable effort has been devoted to student recruitment activities during the first half of 2010. This included advertising in various media, mailings and lunch lectures at several engineering colleges around Sweden. One observation from these activities is that although many students have a general interest in nuclear engineering it is a big step for them to make a career decision and elect to study nuclear engineering. As a result of the marketing efforts 80 students applied to the program, 48 were found to fulfil the prerequisites and in the end 32 students were admitted. Of the students admitted, 24 commenced the education and at the time of writing (feb. 2011) 21 students are active within the program.

Master of Science in engineering programs

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

At present, the following courses are 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 program for Energy Systems. About 30 students per year.
- ”Energy System Physics”: A general course on energy-related issues with some chapter on nuclear power. Given within the Master of Science in Engineering program for Sociotechnical Systems Engineering. About 45 students per year.
- ”Complex Systems – Technology”: A course on risk assessment with one focus on nuclear energy (PSA). Given within the Master of Science in Engineering program for Sociotechnical Systems Engineering. About 45 students per year.
- ”Energy Physics I”: A course similar to ”Energy System Physics”. Given within the Master of Science in Engineering program in Engineering Physics and the Bachelor Program in Physics. About 40 students per year.
- ”Energy Physics II”: Advanced course with focus on nuclear energy. Given within the Master of Science in Engineering program in Engineering Physics. About 25 students per year.
- ”Project in Applied Physics”: Within this course, the division offers projects on energy-related questions, including nuclear energy, in collaboration with Vattenfall. About 15 students per year.

Contract education for the industry

Following the high pace of recruitment within the Swedish nuclear industry during the last couple of years, parts of the industry entered a period of recruitment freeze and cost cutting measures during 2010. This is reflected in the demand for courses given within UU’s contract education agreement with KSU, exhibiting a slight decrease from 29 weeks in 2009 to 26 weeks in 2010.

During 2010, courses have been conducted on 12 occasions:

- Kärnkraftteknik, H1 (12 hp), 3 occasions, one at OKG
- Tillämpad reaktorfysik (7,5 hp), 1 occasion
- Fördjupad strålskyddsutbildning FS1, 2 occasions
- Fördjupad strålskyddsutbildning FS1, 1 occasion
- Värme- och strömningslära (KGP), 2 occasions (OKG)
- Reaktorfysik fördjupad (KGP), 1 occasion (FKA)
- Material och konstruktion, 1 occasion

The course Material och konstruktion was developed and given for the first time in the autumn of 2010. For two of the courses, Kärnkraftteknik H1 and Tillämpad reaktorfysik, the attendees can be registered as students at Uppsala university and get academic credits after passing the examinations.

Theses presented during 2010

John Loberg: “Novel Diagnostics and Computational Methods of Neutron Fluxes in Boiling Water Reactors”, Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology, ISSN 1651-6214; 715 (2010) (Doctoral Thesis).

Richard Fridström: ” Response of the Gamma TIP Detectors in a Nuclear Boiling Water Reactor” (Masters) – in collaboration with Westinghouse.

Cecilia Larsson: “Upgrade and validation of PHX2MCNP for criticality analysis calculations for spent fuel storage pools” (Masters) – in collaboration with Westinghouse

Viktor Sivertsson: " Hydrogen production using high temperature nuclear reactors: A feasibility study" (Masters) - in collaboration with Vattenfall R&D

Matilda Åberg Lindell: "Safeguards Licensing Aspects of a Future Generation IV Demonstration Facility: A Case Study" (Masters).

Jonas Isaksson: "Påverkan på torrkokningsgränsvärden vid avvikelse från planerad drift" (Masters) - in collaboration with FKA.

Axel Rudling: "Mechanistic modeling of dryout in fuel assemblies with complex spatial power distribution" (Masters) - in collaboration with Westinghouse

Mikael Ewing & Mattias Lindgren: LCA av en natriumkyld snabbreaktor med avseende på koldioxidutsläpp(Bachelor thesis)

Diploma works started during 2010

John Johnsson: "Boron depletion in the top of CR99 control rods" (prel. title) - the work is performed in collaboration with Westinghouse.

Isbel Llerena Herrera: "Tool for calculation of residual heat in spent nuclear fuel" (prel. title) - the work is performed in collaboration with SKB.

Filip Gottfridsson: "Simulation of Reactor Transient and Design Criteria of Sodium-cooled Fast Reactors" - the work is performed in collaboration with Vattenfall.

Mathias Hareland: "Key issues of the lead-cooled fast reactor design" - the work is performed in collaboration with Vattenfall.

Publications and conferences

T. Lundqvist, S. Jacobsson Svärd, A. Håkansson, "Recent progress in the design of a tomographic device for measurements of the power distribution in irradiated nuclear fuel assemblies", *Nuclear Science and Engineering*, **165** (2), June 2010.

L. Bläckberg, A. Ringbom, H. Sjöstrand and M. Klintenberg, "Assisted self-healing in ripped graphene", *Physical Review B*. **82** (19), November 2010.

P. Andersson, H. Sjöstrand, S. Jacobsson Svard, "Effects of proton escape on detection efficiency in thin scintillator elements and its consequences for optimization of fast-neutron imaging", *Nuclear Instruments and Methods in Physics Research Section A*, accepted for publication in 2011.

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

P. Andersson, S. Jacobsson Svärd, H. Sjöstrand, "Neutron tomography for void distribution measurements", European Nuclear Conference (ENC), Barcelona, Spain, May 30 - June 2, 2010.

G. Wallin, C. Gustavsson, S. Pomp, H. Sjöstrand, M. Österlund, et al., "Massive Computation Methodology for Reactor Operation (MACRO)", European Nuclear Conference (ENC), Barcelona, Spain, May 30 - June 2, 2010.

S. Jacobsson Svärd, "Nuclear education in collaboration between university, industry and authorities", IAEA Technical Meeting on Training and Educational Systems for the Nuclear Industry, Uppsala, Sweden, September 2010.

H. Sjöstrand, "Integration of nuclear engineering education into existing engineering programmes - Uppsala experiences", IAEA Technical Meeting on Training and Educational Systems for the Nuclear Industry, Uppsala, Sweden, September 2010.

P. Andersson, S. Jacobsson Svärd, H. Sjöstrand, "Neutron Response Distortion due to Recoil Proton Escape - Effects on Fast Neutron Tomography" 9th World Conference on Neutron Radiography (WCNR), Kwa Maritane, South Africa, October 3-8, 2010.

S. Grape, S. Jacobsson Svärd, B. Lindberg, A. Hjalmarsson, "Modelling Cherenkov light from irradiated nuclear fuel assemblies using GEANT4", The IAEA Symposium on International Safeguards, Vienna, Austria, November 1-5 2010.

M. Åberg Lindell, S. Grape, A. Håkansson, S. Jacobsson Svärd, "Safeguards Licensing Aspects of a Future Gen IV Test Facility: A Case Study", The

IAEA Symposium on International Safeguards, Vienna, Austria, November 1-5 2010.

J. Loberg, M. Österlund, K.-H. Bejmer, J. Blomgren, "Neutron, Detection-Based Void monitoring in Boiling Water Reactors", Nuclear Science and Technology, 164, pp. 69-79 (2010).

J. Loberg, M. Österlund, K.-H. Bejmer, J. Blomgren, "A Method for Channel-Bow Indication by Neutron Flux Measurements", Proceedings of Physics of Reactors, Pittsburgh, ANS, USA (2010).

J. Loberg, M. Österlund, K.-H. Bejmer, J. Blomgren, J. Kierkegaard, S.-Ö. Lindahl, "Simulations and Models of Neutron Fluxes in BWRs intended for depletion calculations of Withdrawn Control Rods", accepted for publication in Nuclear Science and Technology (2010).

M. Österlund, A. Håkansson, E. Tengborn, "Strategy for nuclear technology education at Uppsala university", The IAEA Symposium on International Safeguards, Vienna, Austria, November 1-5 2010.

G. Ericsson, S. Pomp, H. Sjöstrand and E. Traneus, "Piezonuclear reactions - do they really exist?", Phys. Lett. A 374 (2010) 750.

A. Al-Adili, F.-J. Hambsch, S. Oberstedt, S. Pomp}, Sh. Zeynalov, "Comparison of digital and analogue data acquisition systems for nuclear spectroscopy", Nucl. Instr. Phys. Res. A 624 (2010) 684.

A. Al-Adili, F.-J. Hambsch, S. Oberstedt, S. Pomp, "Investigation of ^{234}U(n,f) as a function of incident neutron energy", Seminar on Fission, Het Pand, Gent, Belgium, 17-20 May 2010, World Scientific, eds. Cyriel Wagemans, Jan Wagemans, Pierre D'hondt, p.99-105.

Personnel

During 2010, four positions as lecturers were appointed in order to cover the educational research efforts at the Division. From a large number of applicants, the positions were given to Staffan Jacobsson Svärd (senior lecturer), Matthias Weiszflog (senior lecturer), Cecilia Gustavsson (lecturer) and Henrik Sjöstrand (lecturer).

In addition, the research staff was extended by two new appointments: Mattias Lantz (starting in June 2010) and Peter Jansson (starting January 1, 2011).

Additional safeguards activities on behalf of SSM

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

Discussions and planning are ongoing about arranging the 8th course on nuclear safeguards and non-proliferation in Uppsala during September 2011.

Sophie Grape is co writing a text book on nuclear forensics techniques. This work is done together with SIPRI in Stockholm.

Sophie Grape has written a report: "Statistical grounds for determining the ability to detect partial defects using the Digital Cherenkov Viewing Device (DCVD)". This report treats the evaluation of the DCVD instrument's capability to be used for partial-defect verification (sent to SSM in December 2010).

More information is available at:

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

SKC financials in 2010

The following table summarises the SKC financials for 2010

Received from financing parties		17 000 000 SEK
Saved from previous years		-140 927 SEK
Interests etc		35 213 SEK
KTH	7 288 000 SEK	
Chalmers	5 292 000 SEK	
Uppsala University	3 020 000 SEK	
SKC centrally	3 427 647 SEK	
Balance at year's end		-2 133 361 SEK

The contributions from the financing organizations are split as follows:

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

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

Winners of the Sigvard Eklund Price in 2010

Andreas Enqvist, Chalmers Institute of Technology, was awarded the prize for the best PhD thesis, which has the title "Safeguards: Modelling of the Detection and Characterization of Nuclear Materials". His work is characterized by the review committee:

This outstanding dissertation is the result of an original investigation through the safeguards methods and tools. The multiplicity theory is revisited and extended to combinations of neutrons and gamma rays, and the use of neural networks. An analysis of the scintillation light pulses generated by fast neutrons serves as a basis for the modeling of organic scintillation detectors. The theoretical tools developed are successfully used for measuring coincident neutrons and gamma rays using fast scintillation detectors. The thesis opens new perspectives in the determination of characteristics of nuclear materials. The nine attached papers form a consistent and impressing set towards the objectives of the thesis. The quality of the presentation is optimum: the objectives, the methods, the results, the conclusions, suggestions for future work are clearly explained. Everything is clear and pleasant to read: text, equations, figures."

Andreas Enqvist (right) and Jan Blomgren at the prize ceremony.

Paul Bramson, Royal Institute of Technology, was awarded the prize for the best Masters' thesis, which has the title "Transmutation Strategies – a Swedish Perspective". His work is characterized by the review committee:

"The oldest nuclear power plants in Sweden are approaching the time when they have to be replaced. In this master thesis future scenarios for nuclear power in Sweden are studied, taking both economical and environmental aspects into account. Different reactor concepts are compared, including fast reactors and accelerator driven systems, with the focus on reducing the amount of radioactive waste. The thesis is well written and of considerable current interest."

Paul Bramson.

Research projects

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

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

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

Background

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

Goals of the project

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

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

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

Organization

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

Methodology

Since 2008, Chalmers has been part of the OECD/NEA BWR Full-Size Fine-Mesh Bundle Test (BFBT) benchmark, which offered a good opportunity to evaluate many of the POLCA-T code features in predicting steady-state and transient void fractions, pressure drops and critical powers under a wide range of system conditions [1]. During the first trimester 2010, the validation process (based on a statistical uncertainty and sensitivity analysis using Latin Hypercube Sampling (LHS)) of the BFBT cases modelled with POLCA-T was completed, and sent for publication [2]. Such work formed the basis of the Licentiate thesis, which was defended in May, 2010. Afterwards, attention has been put on performing uncertainty analysis applied to the prediction of the reliability of BWR macroscopic cross-sections, using an inverting procedure based on actual plant neutron flux measurements. The unfolding procedure is relying on perturbation theory and the use of adjoint fluxes [3], and utilizes as input data differences between core-calculated and measured thermal and fast fluxes. The unfolding technique was tested on real plant measurements performed in the Ringhals 1 BWR, from which the uncertainties in macroscopic cross-sections were obtained. In Fig. 1 and Fig. 2, the uncertainties in the macroscopic cross-sections derived from the thermal and fast neutron fluxes at a certain axial level of the core are shown. The uncertainty pattern for different burn-up points and during successive reactor cycles will be studied in the future, so that possible trends in the macroscopic cross-section models used in core calculations can be highlighted. This new methodology opens the possibility of validating macroscopic cross-section models used in core simulators, without any need of propagating the uncertainties in the nuclear data libraries via many tedious lattice physics calculations; thus, not only a space dependant uncertainty can be derived but also a burn-up (i.e. time) dependant uncertainty of the overall macroscopic cross-sections.

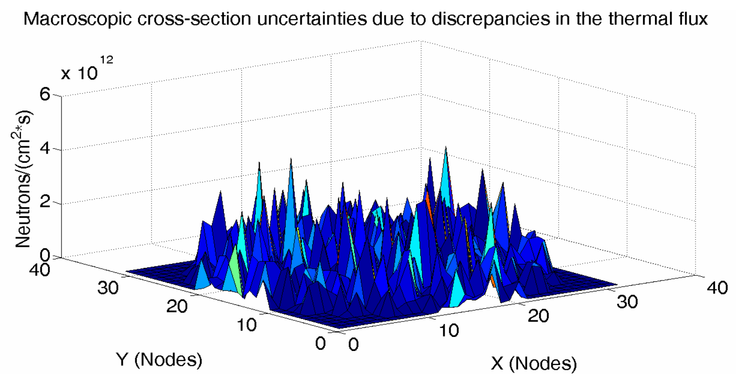


Figure 1. Macroscopic cross-section uncertainties due to discrepancies in the thermal flux.

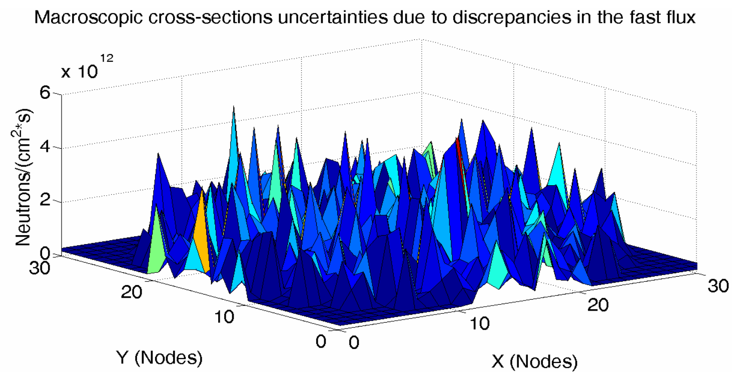


Figure 2. Macroscopic cross-section uncertainties due to discrepancies in the fast flux.

References

1. A. Hernandez-Solis, P. Vinai, U. Bredolt. (2009), *"An Assessment Study of the POLCA-T Code Based on NUPEC Data". ANS Annual Meeting Transactions*, 2009. Vol. 100. pp. 750-751
2. Hernández-Solís A., Ekberg C., Demazière C., Ödegaard-Jensen A., Bredolt U.*"Uncertainty and sensivity analyses as a validation tool for BWR bundle thermal-hydraulic predictions"*. Submitted to Nuclear Engineering and Design, 2010.
3. Hernández-Solís, A. *"A Review of Methodologies for Uncertainty and Sensitivity Analysis"*. (To be published as an internal report), 2011.

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

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

Background

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

Goals of the project

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

Organization

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

Methodology

In 2010, the work with the Analytical Nodal Method was continued and resulted in one contribution at PHYSOR in Pittsburgh, USA [3] and in one article [4]. A comparison between calculations using ANM and finite differences was also conducted and the results will be presented at M&C 2011 in Rio de Janeiro. The main result from this study is that the gain of using ANM in practical cases is not sufficient to motivate the extra computational effort.

The next step of the PhD-work was to construct a simple thermal-hydraulic model and to couple this to the existing neutronic model. As a start, a single phase model for PWR applications was developed and the results from the coupled calculations will be presented at RPCNC in Helsinki, Finland [6]. The model is currently under further validation and testing

The contributions to both of the mentioned conferences are supposed to be further extended to journal publications during the spring. The PhD thesis is planned to be defended before the end of this year.

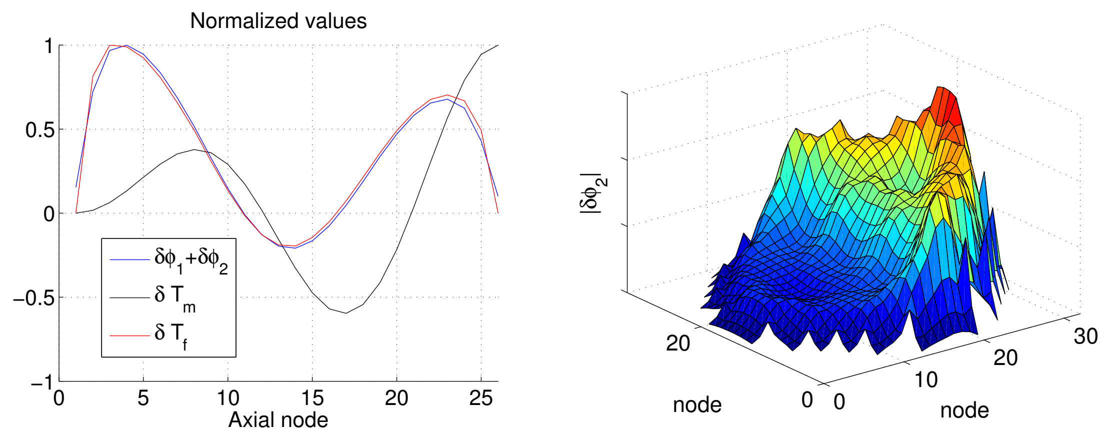


Figure 1: Amplitude of the noise calculated by the coupled neutronic/thermal-hydraulic model in a realistic PWR core. (To the left, an axial plot of the temperature and neutron noise; to the right, a radial plot of the thermal neutron noise.)

Publications

1. C. Demazière, “Development of a 2-D 2-group neutron noise simulator,” *Annals of Nuclear Energy*, **31**, pp. 647-680 (2004).
2. C. Demazière and I. Pázsit, “Numerical tools applied to power reactor noise analysis,” *Progress in Nuclear Energy*, **51**, pp. 67-81 (2008).
3. V. Larsson and C. Demazière, “Neutron noise calculations using the Analytical Nodal Method,” Presented at *PHYSOR2010 – Advances in reactor physics to power the nuclear renaissance*, Pittsburgh, PA, USA, May 9-14, 2010.
4. V. Larsson, C. Demazière, I. Pázsit and H. N. Tran, “Neutron noise calculations using the Analytical Nodal Method and comparisons with analytical solutions”, *Annals of Nuclear Energy*, **38**, pp. 808-816 (2011).
5. V. Larsson and C. Demazière, “Neutron noise calculations in three-dimensional systems,” Submitted to *The International Conference on Mathematics and Computational Methods applied to Nuclear Science and Engineering (MC 2011)*. Rio de Janeiro, Brazil, May 8-12, 2011.
6. V. Larsson and C. Demazière, Development of a numerical tool for calculating the neutron noise in a PWR. Submitted to *XV Meeting on reactor physics calculations in the Nordic countries*. Helsinki, Finland April 12-13 2011.

Reactor diagnostics with advanced signal analysis (READS)

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

Background

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

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

Goals

The goal of the project is to give contributions for method development both regarding advancement of modelling the system and the various normal and abnormal regimes, and to apply them to solve relevant diagnostic problems in collaboration with the power plants. The work in the thesis is focused 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 will be performed on both simulated signals as well as measurements taken in Swedish power plants.

Organisation

The reactor diagnostic group is led by Prof. Imre Pázsit, who is also the leader of this SKC-project. Assoc. Prof. Christophe Demaziere, senior lecturer, acts as a deputy adviser. Other PhD students at the department, and some of our foreign collaborating partners, primarily Assoc. Prof. Tatiana Tambouratzis, also support the project.

Methodology and results

The project started during the summer of 2008 with the analysis of BWR stability in a model system driven by a driving force with a non-white power spectrum. As a continuation, the space-dependent noise, induced by propagating perturbations, i.e. by density and/or temperature fluctuations was investigated in 2009. This work resulted in a journal publication [1].

In 2010 the activity was mainly pursued on a different line, namely the investigation of past instability events, using a nonlinear analysis approach, such as Reduced Order Models (ROMs), was started. Several types of ROMs have been developed in the last decades, but only the first two neutronic modes (fundamental and first azimuthal modes) were taken into account. From our perspective, it is necessary to include the second azimuthal mode to correctly model the regional instability behaviour of a BWR. For that reason a four-heated channel ROM was developed which allows to reconstruct the behaviour of first three modes.

The ROM consists of three sets of time only -dependent equations: neutron-kinetic equations which describe the neutron production; 2) thermal hydraulic equations, which describe the flow dynamics; and 3) heat transfer equations which describe the heat exchange between the fuel and the coolant. These equations were derived from 3D time/space-dependent equations, applying special reduction procedures. The main benefit of ROM analysis is its simplicity which gives a deeper understanding of the processes, taking place in BWR instabilities, and the possibility of describing any non-linear behaviour.

One of our intentions for the newly-developed ROM is to identify new BWR stability indicators that are differrent from the traditional ones, such as Decay Ratio (DR), which is mostly applicable in linear theory. The problem with the DR is that it does not always provide the true information about the reactor core behaviour.

Another goal of the ROM simulation is to reconstruct some specific features of complicated instability patterns, for example the oscillating symmetry line between two azimuthal modes which were observed in several instability events, involving regional oscillations. Some results of ROM simulations are presented in *Fig. 1*.

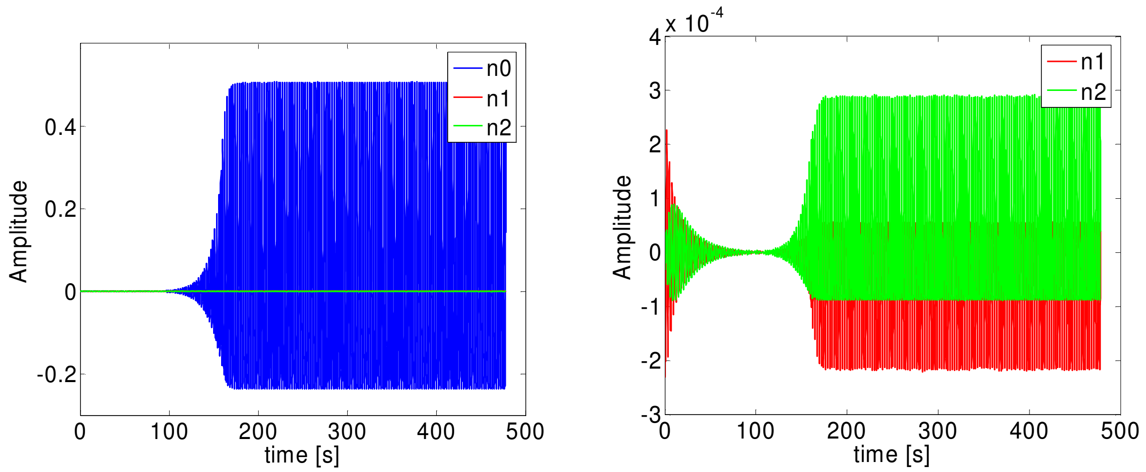


Figure 1. Time evolutions of the fundamental (unstable)), the first and the second (stable) azimuthal modes, calculated for the Forsmark-1 Instability Event of 1996/1997.

The ROM was further extended to include the effect of local oscillations. This resulted in a paper submitted to the coming M&C conference in Rio de Janeiro, Brazil [3]. The results of this work are also a part of the Licentiate thesis [2] which was sucsessfully defended in September 2010 with Imre Pazsit, as an examiner, and Vasily Arzhanov, KTH, as opponent.

References

[1] Pázsit I. and Dykin V. Investigation of the space-dependent noise induced by propagating perturbations. Annals of Nuclear Energy, vol.37, pp. 1329–1340, 2010.

[2] Dykin V. The Effect of Different Perturbations on the Stability Analysis of Light Water Reactors, Lic. Thesis, CTH-NT-235, Chalmers University of Technology, Gothenburg, 2010.

[3] Dykin V., Demaziere C., Lange C., Hennig D., Simulation of local instabilities with the use of reduced order models, Submitted to the M&C conference, Rio de Janeiro, Brazil, 2011.

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 on power reactor noise analysis 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 eqation. This equation is usually solved with the Green's function technique, which gives insight into the dynamics of the system in general. To calculate the noise induced by perturbations, one has to integrate the Green's function with the noise source. Due to the differring physics of the MSR (moving delayed neutron precursors), new solution methods and new kinetic approximations have to be found.

Activities in 2010

The research in 2010 continued to be focused on the kinetics, dynamics and netron noise in Molten Salt Reactors (MSR). MSR is one of the six selected Generation-IV reactor types, in which the fuel is in a liquid molten salt state and it passes through the core and returns in a closed loop. The main difference between the MSR and a traditional reactor is that the delayed neutron precursors travel with the fuel and hence are not stationary. This changes the structure of the equations, but also the physics and the static and dynamic properties of the core. Some of the precurcors in addition decay outside the core, which leads to a loss of reactivity.

The work this year focused on two areas that had not previously been covered: extending the treatment of the MSR to a two-group theory, and using realistic data for a thorium-fuelled MSR as well as data from traditional reactors. The focus was again on investigating the noise emanating from inhomogeneities in the fuel, propagating through the core. This was done through the Green's function technique, which also reveals several properties of the system transfer properties independent of the final solution of the neutron noise.

This work confirmed the findings from the one-group treatment, and also revealed some new, interesting features:

1) To describe the static flux of the MSR, both of the basic solutions of the static equation are needed. This means that asymptotic reactor theory can not be applied to a MSR, and that the energy spectrum will be weakly space dependent.

2) The more point kinetic-like behaviour of an MSR as compared to traditional reactors means that the local component in the Green's function is less pronounced. This is even more pronounced in a thorium reactor, where the local component is hardly visible at low frequencies.

3) The interference between the point kinetic and pure space dependent components of the induced noise, which leads to noise amplitudes with spatial oscillations in the core and which was found already in one-group theory and in traditional reactors, was found also in two-group theory and with e.g. fast reactor systems. Furthermore, some interesting features were found in the frequency dependence of the induced noise, which have not been observed before and which will be studied for traditional reactors.

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

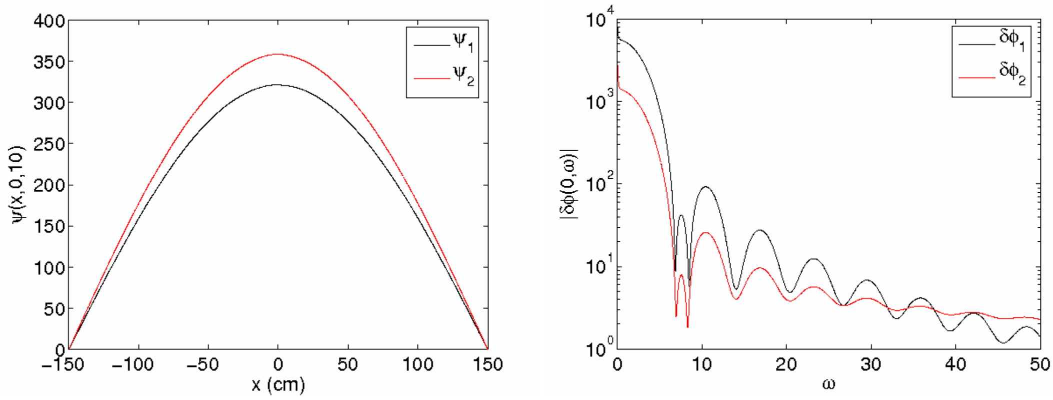


Fig. 1. Left figure: the space dependence of the dynamic adjoints $\Upsilon(z, z_0, w)$ *of a thorium-fueled MSR for a central perturbation* $(x_0 = 0)$ *at* $w = 10$ *rad/s. Notice the lack of a discernible local component, and that the thermal flux is larger than the fast one. Right figure: the frequency dependence of the amplitude of the noise induced by propagating perturbations of the absorption cross section in a Uranium-fuelled reactor with a core size of 366 cm and* $x = 0$. *The oscillations come from the point-kinetic term, but the addition of a space dependent term means that the amplitude is exactly zero (the sharp sinks) only at very low frequencies.*

The work was written up in an article and has been accepted for publication [1]. It was also included in the Licentiate thesis presented in December [2]. The licentiate degree was obtained on 13 December. The external examiner was Prof. Gábor Por, Technical University of Budapest.

References

[1] Jonsson A. and Pázsit I. Two-group theory of neutron noise in Molten Salt Reactors. To appear in *Annals of Nuclear Energy* (2010)

[2] Jonsson A. Neutronics in Molten Salt Reactors. Thesis for the degree of Licentiate of Engineering (2010) CTH_NT-237.

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

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

Background

There has been a renewed interest in the use of thorium as a nuclear fuel in the recent years. The main isotope of thorium is thorium 232, which is very abundant in nature. Thorium 232 is not fissile, but fertile. By neutron capture, its leads to thorium 233, which decays into protactinium 233, which itself leads to uranium 233 by decay. Uranium 233 is a fissile isotope, i.e. can undergo fission by thermal neutrons, and as such has a big potential in thermal reactors. It is estimated that the resources in thorium would be sufficient to last between 17000 and 35500 years when used in a thermal spectrum [**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 232 compared to uranium 235 in commercial reactors has to be carefully checked in terms of proliferation resistance, radiotoxicity of the waste, and reactor safety.

Goals of the project

The PhD project aims at investigating the use of thorium in nuclear reactors (both existing and future designs). Emphasis will be put on the best utilization of thorium. The first part of the project focuses on existing thermal systems, whereas the second part of the project will most likely focus on future reactor designs. During the first part, an innovative use of thorium in LWR fuel assemblies was investigated. Namely, thorium is used for controlling the excess 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 Associate Professor Christophe Demazière. Prof. Imre Pázsit, Dr. Henrik Nylén, and Dr. Jan Dufek also support Cheuk Wah Lau on some aspects of the project. The members of the reference group are: Ninos Garis and Elisabeth Rudbäck, SSM, Urban Sandberg, Ringhals, Tommy Einarsson, Forsmark, Christer Netterbrant, OKG, and Per Seltborg, Westinghouse.

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

Methodology

Since the start of the project, emphasis has been put on thermal systems and on the investigation of the use of thorium as a “burnable absorber”. Today’s light water reactors use gadolinium as a burnable poison. The use of burnable poisons is meant 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 thorium has a higher absorption cross section than U-238, thorium could be inserted instead of gadolinium as a burnable poison. The use of thorium as a burnable poison 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 poison are conducting on the Ringhals-3 PWR core.

The project is divided into 3 phases. The first phase was to design a fuel assembly using CASMO-4E or CASMO-5. The fuel has the same structural design as the traditional uranium-based fuel assemblies. The changes are only made in the composition of the fuel pellets, where some of the fuel pellets contain a mixture between uranium and thorium oxides. The thorium/uranium-based fuel assemblies were designed so that they achieve the same discharge burnup as the uranium-based fuel assemblies. The fuel assemblies were optimized to even the power distribution in the fuel assembly at beginning of life, as shown in figure 1. A paper presenting the results of these investigations has been accepted to the ICAPP 2011 conference in Nice, France [2].

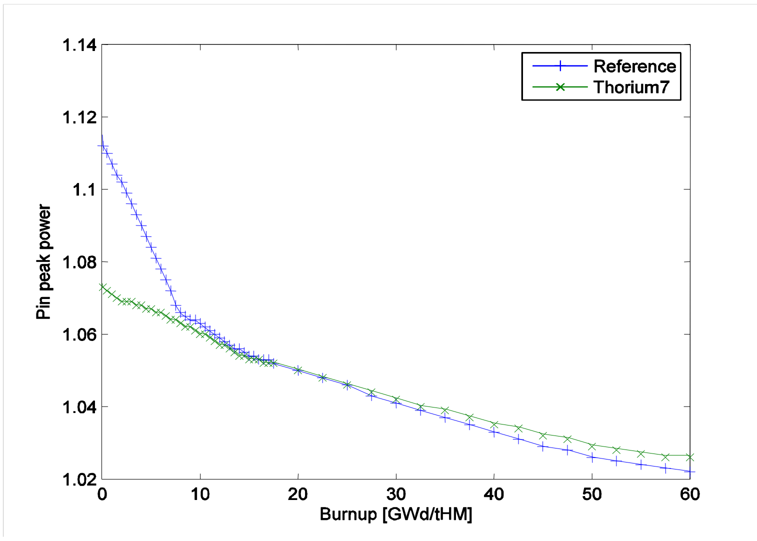


Figure 1. Variation of the pin peak power for the traditional uranium fuel assembly (Reference) and the thorium/uranium-based fuel assembly (Thorium7) as function of burnup.

The second phase of the project is to simulate the use of the thorium/uranium fuel assemblies in the core of Ringhals 3. Only one third of the fuel assemblies are replaced in the first cycle, following the same reloading strategy as for traditional uranium-based fuel assemblies. The core configuration is optimized by XIMAGE and SIMULATE-3. The EBBA-script, earlier developed at Ringhals AB, is used to calculate all the safety/performance parameters of the reactor such as the ITC, the MTC, the consequences of a postulated large break loss of coolant accident (LOCA), the fraction of delayed neutron, the radial form factor, etc. If the core configuration does not fulfil all the design parameters, a new core or new fuel assembly will be redesigned. This second phase is currently under way.

The third phase of the project will be to analyze the safety/performance parameters of the core with the thorium/uranium fuel assemblies during equilibrium conditions. This core will be compared to a core using traditional uranium based fuel assemblies at equilibrium.

Cheuk has also attended the 2010 Frederic Joliot/Otto Hahn Summer School in Cadarache, France.

References

1. R. Price and J. R. Blaise, "Nuclear fuel resources: Enough to last?", *NEA Updates NEA News*, 20 (2), 2002.
2. C. W. Lau, C. Demazière, H. Nylén, and U. Sandberg, "Innovative use of Thorium in LWR fuel assemblies," accepted to the *International Congress on Advances in Nuclear Power Plants (ICAPP 2011)*, Nice, France, May 2-5, 2011.

Iodine chemistry in the reactor containment during a severe accident

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

Background

Iodine is a volatile fission product, which is formed during normal operations in the nuclear core. During a severe accident iodine is transported from the melted fuel mainly as CsI to the containment. Iodine is distributed in the containment pool as non-volatile iodide ions. However, several processes will produce volatile iodine species, like elemental iodine (I_2) and methyl iodide (CH_3I). Thermal and radiolytic oxidation of iodide is the main processes for production of airborne iodine in the containment during a severe accident. Radiolysis products like ·OH, formed due to the expected extensive gamma radiation field, will react with iodide ions and produce I_2. The radiolysis product may also produce organic radicals, because of organic impurities. These organic radicals may react with iodide ions and produce organic iodine like methyl iodide, which is even more volatile than I_2. The volatile iodine species can be released to the environment from the containment via e.g. leakage and pressure relief.

Recently different experiments have shown that airborne inorganic iodine, both inorganic and organic iodine, may be depleted from the gas phase in the containment [1] [2].

Objectives

The aim of this project was to investigate the reaction between methyl iodide and ozone and the behaviour of methyl iodide in a radiation field of UVC-radiation. This project is a continuation of the experiments done in 2009 [2]. Several different parameters and conditions were thought to be investigated, like temperature, humidity, ozone concentration and radiation intensity. The most interesting was the eventual depletion of methyl iodide from the gas phase when both ozone and UVC radiation were present in the system. The speciation of the eventual formed particles was also prioritized. These experiments were performed at VTT, Finland.

A comparison study was also performed at Chalmers. In these experiments gamma radiation was used as a radiolytic oxidation tool for methyl iodide instead of UVC-radiation and ozone. A gamma cell loaded with ~900 TBq ^{60}Co, which generated a dose rate of 20 kGy/h, was used for theses experiments. The objectives of the experiments were to resemble real severe accident conditions even more, with high gamma radiation levels in the containment.

Organisation

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

Methodology

The experiments are performed in the experimental set-up, which can be seen in Figure 1. The set-up consists of several parts. A production bottle for gaseous iodide, a UV-furnace where the methyl iodide is exposed to UV-radiation and/or ozone, a sampling furnace which is connected to several measurement devices for on-line analysis of the particles and the gas species.

The gas species are analysed with a FTIR device (Fourier Transform Infra Red). The formed particles were analyzed with CPC (Condensation Particle Counter), SMPS (Scanning Mobility Particle Sizer), ELPI (Electrical Low Pressure Impactor) and TEOM *(*Tapered Element Oscillating Microbalance). The ratio between the iodine particles and iodine gas species is determined by trapping the particles on paper filter and the gas species are trapped in gas washing bottles. The filters and gas washing bottles are placed a separate stream from the sampling furnace. The iodine content on the filters and in the gas washing solutions are determined by ICP-MS (Inductively Coupled Plasma Mass Spectroscopy).

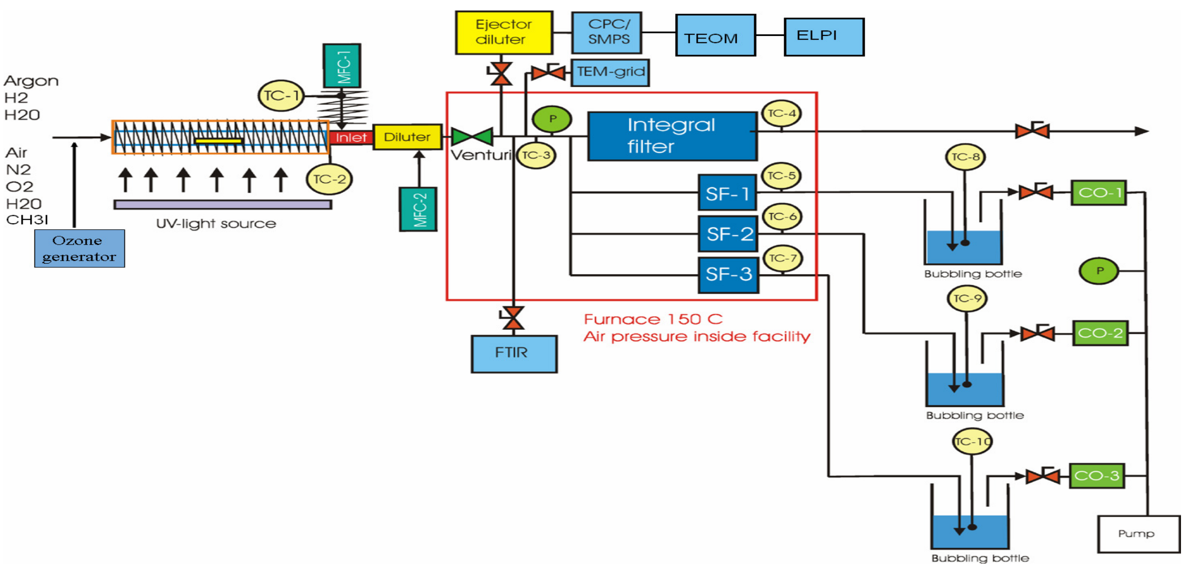


Figure 1: The experimental set-up, the EXSI facility.

In the experiments performed at Chalmers the UV-furnace is replaced with a ^{60}Co gamma cell.

Results

Experiments performed at VTT - UV-radiation and ozone

In totally 6 experiments were performed and several parameters on the formation of iodine particles were investigated, like temperature effect (50 °C, 90 °C and 120 °C), ozone concentration and UV-radiation present in the system and humidity.

Dry experiments

When ozone and UV-radiation were present in the system, the formation of particles is instant and extensive. As can be seen in Figure 2, the particle is increasing with temperature and the ozone level production. Observe also the additive effect of UV-radiation present in the system. The iodine particle mass is significant larger when the methyl iodide and ozone are exposed to UV-radiation.

The changes of the particle concentration and the size of particles are behaviour the same as the particle mass when the temperature, the ozone concentration and the UV-radiation are increased.

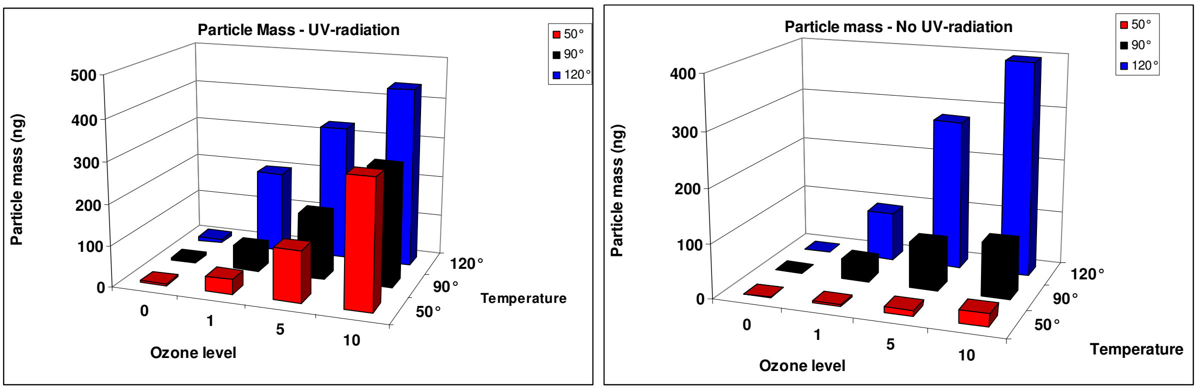


Figure 2: The particle mass depending on temperature, ozone level production and UV-radiation.

The methyl iodide concentration is decreasing with increasing temperature in the system, regardless UV-radiation present or the concentration of ozone, as can be seen in Figure 3. At 120°C and 90°C the CH_3I concentration was significant lower compared to at 50°C.

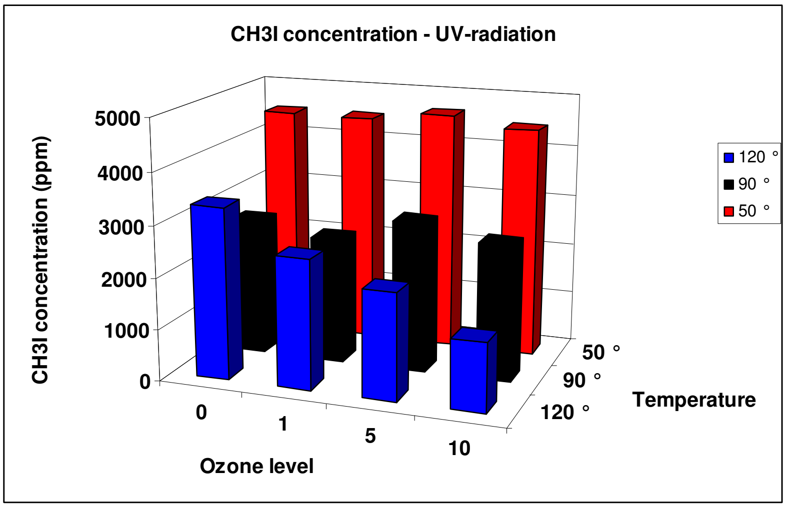


Figure 3: The methyl iodide concentration at different temperatures and at different ozone concentrations.

Humid experiments

The particle formation was even more extensive when the gas atmosphere was humid. The mass and the size of the particles were significant larger compared with the results for the dry experiments. Severe problems with clogging of the systems (because of to extensive particle formation and agglomeration) was appearing at the highest ozone concentrations used in the experiments. Therefore is some of the data complicated to interpret.

The humidity effect on the methyl iodide concentration was investigated. The methyl iodide concentration is decreasing with increasing, as can be seen in Figure 4.

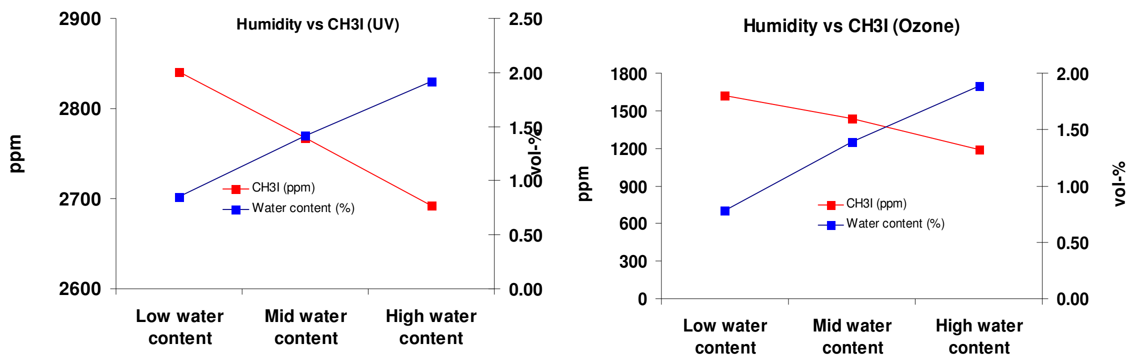


Figure 4: The methyl iodide concentration at water content for experiment with UV-radiation or ozone present in system.

Experiments performed at Chalmers - Gamma radiation

In total were 4 experiments performed, but the analysis of the data is still in progress. Measurements of the particles from these experiments showed on a significant formation of iodine particles. However, the formation of the particles was no as extensive as the formation when UV-radiation and/or ozone were present in the system. A reason for this can be the relative short residence time inside the gamma cell.

The data from methyl iodide concentration measurements is complicated to interpret, more processing of the data is needed to do accurate interpretations.

References

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

[2] Teemu Kärkelä, Joachim Holm, Ari Auvinen, Riitta Zilliacus, Unto Tapper, Tuula Kajolinna, Henrik Glänneskog, Christian Ekberg, Gas Phase Reactions of Organic Iodine in Containment Conditions, Proceedings of ICAPP 10, San Diego, USA, 13-17 June, 2010.

Other publications

Teemu Kärkelä, Joachim Holm, Ari Auvinen, Riitta Zilliacus, Unto Tapper, Tuula Kajolinna, Henrik Glänneskog, Christian Ekberg, Gas Phase Reactions of Organic Iodine in Containment Conditions, Proceedings of ICAPP 10, San Diego, USA, 13-17 June, 2010.

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

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

Introduction

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

Objectives and methodology

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

Results in 2010

In 2010 the main effort was devoted to carry out experimental tests in case of two kinds of flow obstacles. For this purpose, in addition to the pins-spacer, two different flow obstacles, namely a cylindrical obstacle and a grid obstacle were inserted into the test section. Over 110 experimental runs were carried-out in both cases. Variations in pressure (5 and 7 MPa) and mass flux (500-750) kg/(m^2s) were investigated and the local quenching effect was compared for each type of the flow obstacles. One of the conclusions that can be drawn from the experimental data is that the pin-spacers are most effective from all types of flow obstacles due to their biggest blockage area. The analysis of the experimental results revealed discrepancies with selected correlations, in both pre and post-dryout region. Figure 1, 2 and 3 show the temperature distributions and the measured heat transfer coefficient with uncertainties for the various runs. 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]. New results have been submitted to ICONE-19 and NURETH-14 and are planned to be presented during 2011.

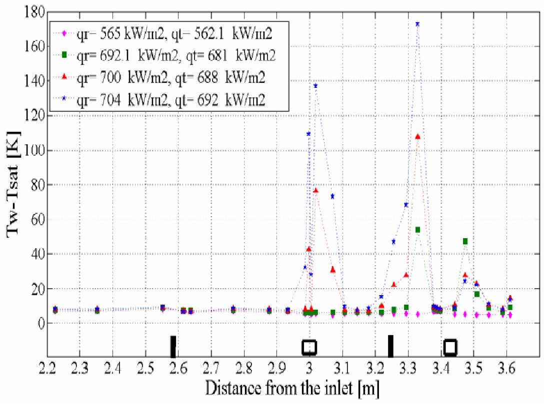


Figure 1. Measured superheat of rod wall surface for various heat fluxes. Mass flux G=750 kg/m^{2}s, inlet subcoolig ΔT=10 K, pressure p= 7 MPa. (Pin-spacers + grid obstacles).

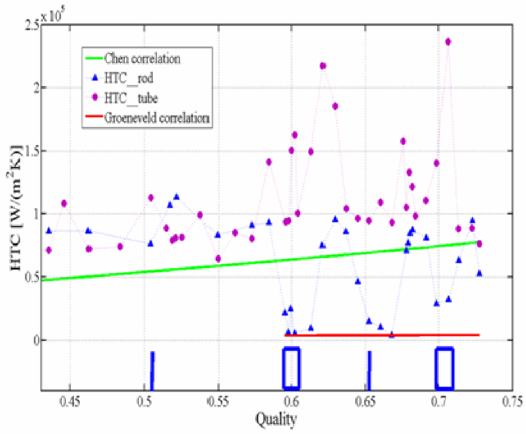


Figure 2. Measured heat transfer coefficient. Mass flux G=750 kg/m^{2}s, inlet subcoolig ΔT=10 K, pressure P= 7 MPa (pin-spacers + grid obstacles).

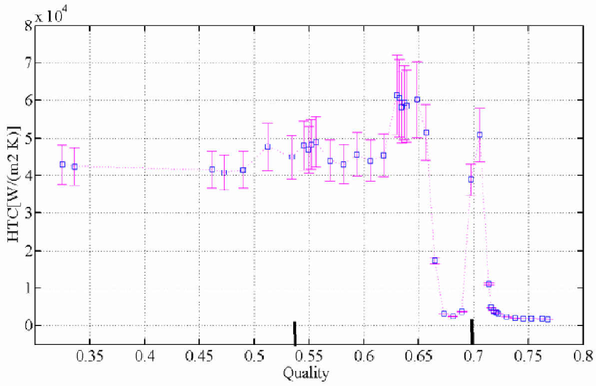


Figure 3. Measured heat transfer coefficient with uncertainties. Mass flux G=750 kg/m^{2}s, inlet subcoolig ΔT=10 K, pressure P= 7 MPa (pin spacers).

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, abstract accepted to the 14th International Topical Meeting on Nuclear Reactor Thermalhydraulics, NURETH-14, Toronto, Canada.

Influence of power distribution on dryout occurrence in heated channels

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

Background

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

Objectives and methodology

Simulations are run using commercial CFD-code CFX v12.1. Simulations in single phase flow in an annulus with wire wrap spacer were carried out in connection with earlier research performed at the division in order to establish functional parameters for boundary conditions and post-processing. Inhomogeneous boundary conditions (primarily with an eye on power distribution) in single phase flow have been implemented for simple geometries (pipes). Current work is focussed on validation, by means of experimental results and analytical approaches, of a variety of turbulence models with different axial power distribution profiles.

In the long term, two phase flow simulations are planned with the implementation of new wall functions to capture the correct heat transfer behaviour.

Results in 2009

Results for wire wrapped annuli appear to be in good agreement with other methods that were tried concurrently elsewhere. Validation of the effects of axial power distribution are a work in progress, initial results show acceptable agreement with experiments and analytical approach. The work on validation and comparison of various turbulence models under different axial power distributions is intended for publication at NURETH 14.

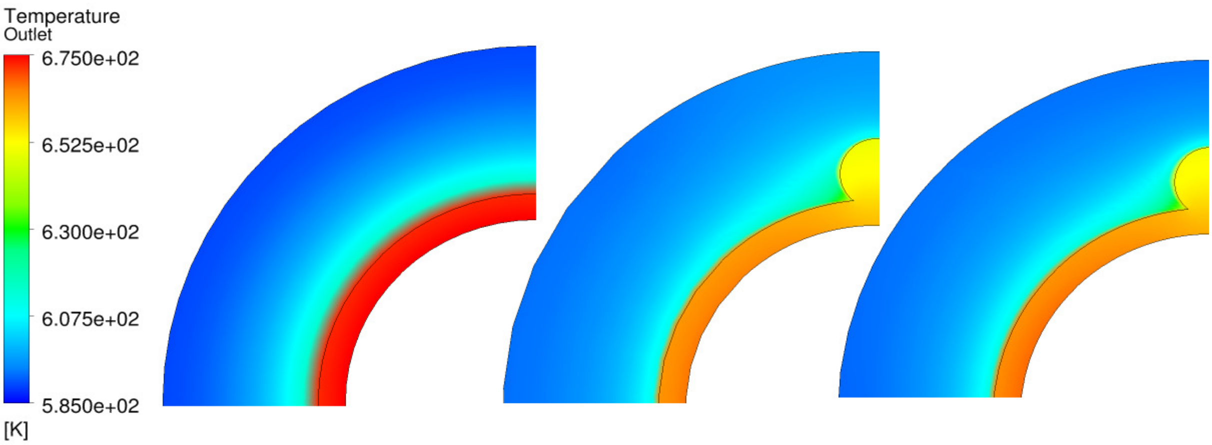


Figure 1: Comparison of temperature profiles in coolant and cladding with, respectively, no wire, a straight wire, a twisted wire.

Organisation

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

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

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

Background

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

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

Goals of the project

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

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

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

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

Organization

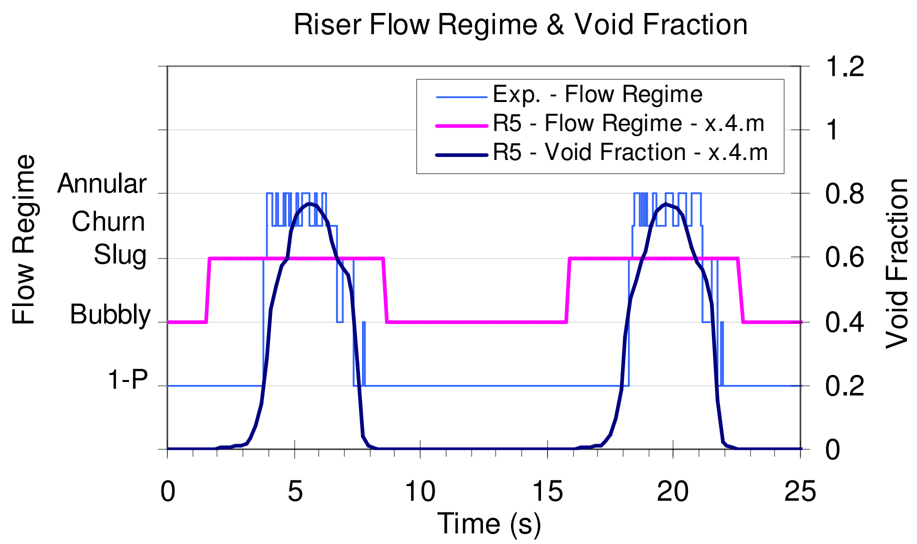
The work is performed by PhD student Viet-Anh Phung under the direction of scientific advisor Associate Professor Pavel Kudinov and scientific co-advisor Dr. Tomasz Kozlowski. The members of the reference group are: Ayalette Walter (SSM), Farid Alavyoon (Forsmark), Claes Halldin (OKG), Henrik Nylén (Ringhals)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

Methodology

In 2010, the first part of the work was the further analysis of single channel experiments at the CIRCUS-IV facility (Delft University of Technology, the Netherlands) that provides representative conditions for natural circulation systems at low pressure.

In the CIRCUS-IV high frequency and high amplitude instability case, significant discrepancy was found between experimental and calculated flow regime. The analysis showed that the RELAP5 has problem with identification of the bubbly-to-slug flow regime transition. The code considers CIRCUS-IV riser a small diameter tube in which the bubbly flow regime only exist at void fraction lower than 10^{-3}. The small diameter tube flow regime map contradicts observation in the CIRCUS-IV and other experiments.

To investigate the effect of the flow regime identification, sensitivity analysis of the RELAP5 flow regime transition boundaries (bubbly-to-slug, slug-to-annular) on simulation results was performed. The sensitivity results became worse as the transition boundaries were modified from RELAP5 original values. Therefore, it is probable that RELAP5 flow regime map was non-physically adjusted to compensate errors from code's correlations.



(a) (b)

Figure 1: Calculated riser flow regime and void fraction in comparison with experimental flow regime (CIRCUS-IV)

The second part of the work was the continuation of the flow regime transition relaxation time model development.

We proposed a concept to implement the flow regime transition relaxation time with transport equation into the system codes for two-phase flow transient calculations. The concept is based on the idea of interfacial area transport equation method. Depending on characteristics of the flow (velocity, acceleration), the model will use steady state flow regime map or the transition relaxation time model to provide correction to the flow regime identification.

We performed calculation and analysis of the relaxation time in bubbly-to-slug flow regime transition based on experimental data from the literature. Initial results of the estimated relaxation time from three independent experiments agree with each other. The estimated relaxation time will be used later to provide guidelines for the model development (identify area where flow regime transition should be corrected), and to provide data for model validation.

Publications

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

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

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

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

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

Background

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

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

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

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

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

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

Goals of the project

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

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

Organization

The work is performed by Ph.D. Student Francesco Cadinu under the direction of Associate Professor Pavel Kudinov and co-supervision from Dr. Walter Villanueva. The contact reference group consists of Wiktor Frid and Oddbjörn Sandervåg (SKI), Lilly Burel-Nilsson and Thomas Probert (OKG), Farid Alavyoon (Forsmark), Anders Andren (Westinghouse), Henrik Nylen (Vattenfall).

Methodology

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

Most multi-scale methods found in the literature are problem specific. The reason is the impossibility to devise a general multiscale method if both accuracy and computational efficiency have to be targeted. This means that, depending on the problem features, several coupling techniques can be developed. For the CFD/STH coupling problem, we can introduce a classification building on the concepts of coupling in space and coupling in time. Coupling in space refers to the nature of the quantities exchanged by the codes. They can be either boundary conditions or closures. Coupling in time refers to the mechanism used to transfer information between the codes for the simulation of a given transient. We envision three cases: the codes run in parallel and exchange information on the fly, one code is used in pre-processing mode (coupling-by-closure), one code allows reinitialization at any point during the transient, thus paving the way for the use of the gap-tooth method (which bears some relationship to the Equation Free Method and the Heterogeneous Multiscale Method, both standard multiscale techniques).

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

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

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

Finally, the issue of verification and validation of coupled codes is considered. Clearly, it is not sufficient that the single components of a coupled code are independently verified and validated. From the verification point of view, one must ensure that the exchange of information takes place exactly as it is required by the coupling algorithm. From the validation point of view, experimental facilities expressly conceived for coupled codes are needed. The instrumentation should allow validation both at the STH and the CFD level and the transients used for validation should be characterized by two-way, system-to-component feedbacks, which are a fundamental feature of multiscale systems. The development of such experimental facility and experimental matrix are carried out as a part of this project and in the framework of the EU's project THINS.

Publications

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

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

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

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

F. Cadinu, T. C. Thanh, P. Kudinov *, Analysis of In-Vessel Coolability and Retention with Control Rod Guide Tube Cooling in Boiling Water Reactor*, Proceedings of the Workshop on in-vessel coolability, NEA Headquarters, NEA/CSNI/R(2010)11.

P. Kudinov, F. Cadinu, *Coupling Strategies and Approaches to Validation of Coupled CFD and STH Codes*, Verification and Validation Workshop for Nuclear Systems Analysis, Myrtle Beach, South Carolina, USA, (2010).

Radiation-induced processes at liquid-solid surfaces

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

Background

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

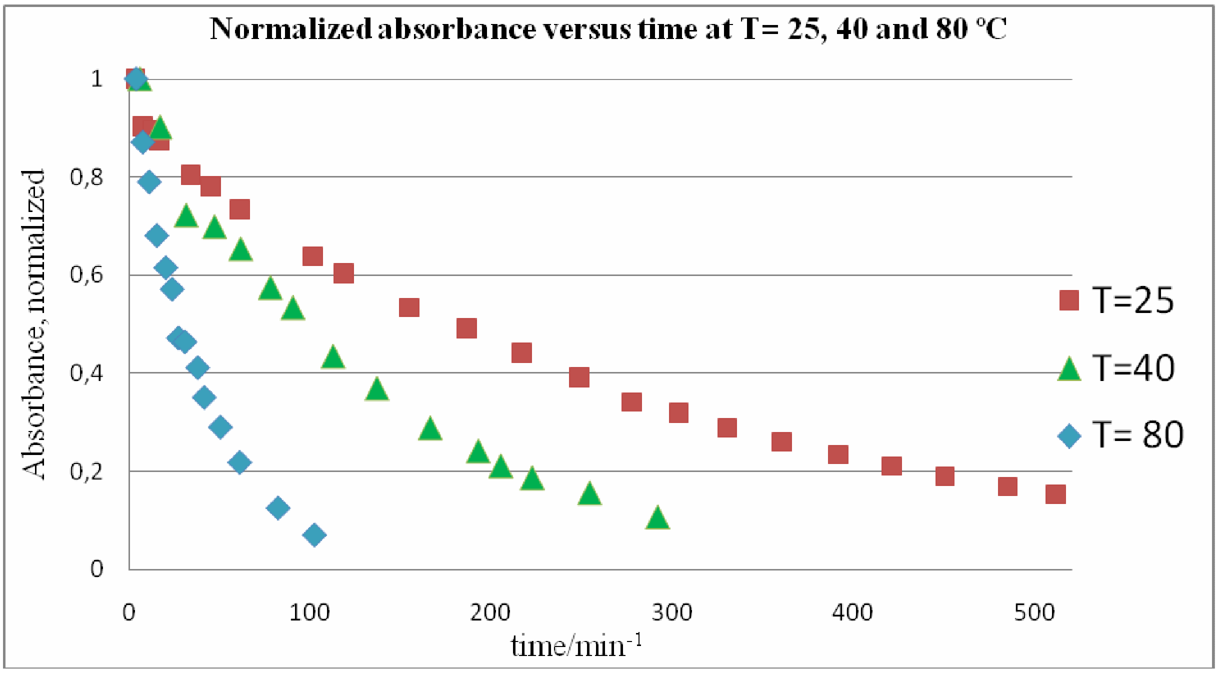


Figure 1. Plot of the normalized absorbance vs reaction time at different temperature values. This procedure was repeated for temperatures between 25 and 80 ºC with steps of 5ºC.

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

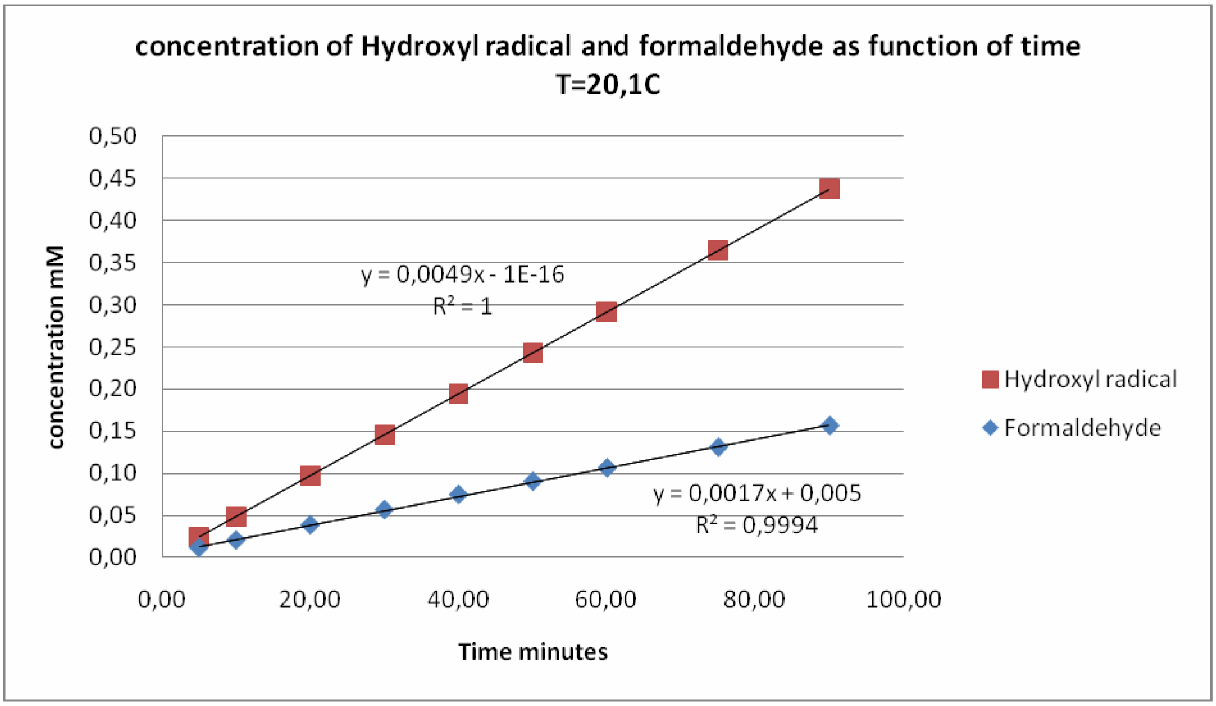


Figure 2. Formaldehyde and hydroxyl radical concentrations evolution with time during reaction of ZrO_2 with H_2O_2.

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

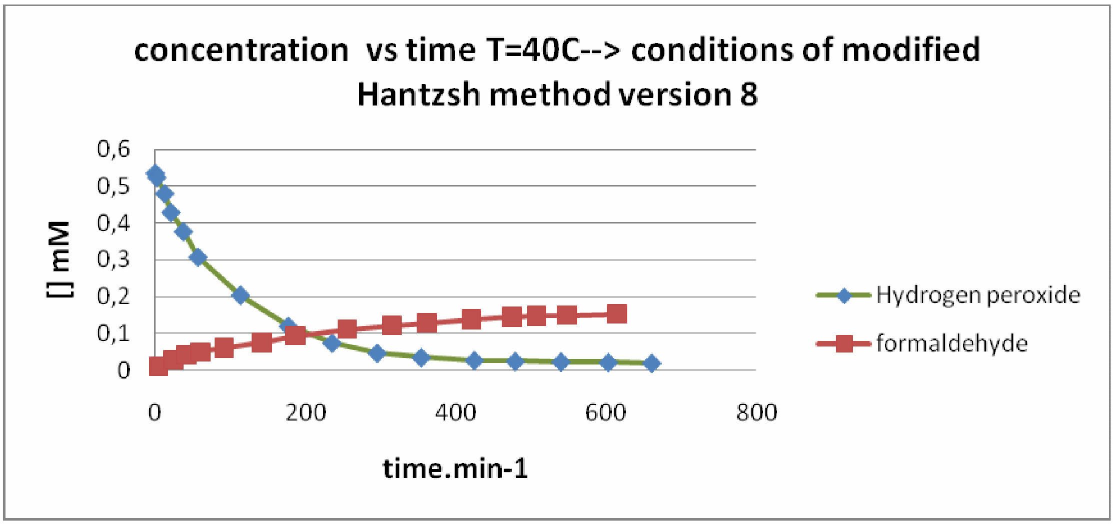


Figure 3. Formaldehyde and hydrogen peroxide concentrations evolution with time during reaction of ZrO_2 with H_2O_2.

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

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

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

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

Results in 2010

Our study of reactions of hydrogen peroxide with materials of relevance in nuclear technology lead to a publication entitled: Kinetics, Mechanism, and Activation Energy of H_2O_2 decomposition on the Surface of ZrO_2. In this study we did a comprehensive research on the reaction of H_2O_2 with ZrO_2 in terms of kinetics, energetics and mechanism. We also devised a method that allows us to study, with ease and inexpensively, the dynamics of formation of HO radicals during the course of this type of reactions. This method was already applied by us to other metal oxide/H_2O_2 systems with success and the research done will soon be submitted to publication. We are doing DFT calculations to better understand the mechanisms and energetics of the reactions mentioned above. The first findings that we had in this study will also be submitted to publication.

High performance nitride fuels for LWRs

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

Background

Nitride fuels have a higher actinide density than oxide fuels. They also feature a much higher thermal conductivity than the oxides which gives some advantages in terms of margin to melt and smaller rates of diffusion . A "flatter" temperature profile in the fuel pin gives mainly less fission gas swelling which in turn means that a higher burn-up can be achieved compared to the oxides. Also the crystal structure of nitrides is simpler with fewer phase transformations and the actinide nitrides are mutually soluble in each other. Associated problems with the nitrides are their sensitivity to oxygen, mainly in powder form. Moreover, even if the uranium nitride has a high melting point, it can, in the absence of a nitrogen partial pressure, dissociate to liquid uranium and nitrogen gas above 1800 °C. By adding an additive such as zirconium nitride the thermal stability is increased so that the dissociation problem can be decreased. Nitride fuels are mainly discussed in the context of transmutation of MAs (Minor Actinides) in fast reactors. These Gen-IV (Generation 4) reactors are typically cooled by liquid sodium or lead. The present SKC- project includes research to modify the nitride fuel so that it could be rendered suitable also for LWRs (Light-Water Reactors).

Figure 2: SPS sintered pellets, from left to right; UN pellet, (U,Zr)N pellet, ZrN pellet

Project objectives

- Synthesise high-quality uranium nitride powder; the method chosen was *hydriding, then nitriding*. By hydriding the metal, a fine powder is produced which then reacts very well with nitrogen gas. XRD (X-ray Diffraction) and SEM (Scanning Electron Microscope) is used to confirm the content and the purity of the product.
- Manufacture pellets by compacting and sintering the synthesised powder. Here the final and most important analysis is done by XRD, SEM and LOM (Light Microscopy) to confirm the content, the purity and for the mixed nitrides also whether the material is in solid solution.
- Stability tests in water at LWR conditions (~ 300°C).

The project has reached a certain maturity in that we can produce and analyse the material on a regular basis. The sintering capacity has been somewhat limited because of the lack of an adequate sintering furnace. Nitrides requires a high sintering temperature, here at least 1800 °C but preferably 2000 °C or more. This should be done in a protected atmosphere like argon or nitrogen gas. Instead of conventional sintering SPS (Spark Plasma Sintering) has been utilised. High-density pellets of up to 97.0 % of the theoretical density have been produced with this sintering method (see figure 1). For the mixed (U,Zr)N pellets solid solution is still to be achieved.

Some results during 2010

- To get solid solution in the mixed nitride pellets different methods have been under consideration and some are under evaluation. Tests are conducted by alloying uranium and zirconium and then synthesising the alloy to mixed (U,Zr) nitride. Alloying by induction furnace and arc melting have been tried out. The last step by sintering remains to be done.
- Improved control of the synthesis by flow difference measurements. By measuring the inflow and outflow by sensitive electronically-controlled flow meters two benefits is achieved. Firstly, that the synthesis today can be controlled from a computer and with a higher precision of the flow than before. Secondly, by comparing the difference between the out- and inflow of the reaction gas knowledge about the chemical gas-solid reaction is obtained during the synthesis. Figure 2 shows how uranium hydride is reacting with nitrogen gas, according to the reaction;

$4\ UH_3 + 3\ N_2 \rightarrow 2\ U_2N_3 + 6\ H_2$, which is producing hydrogen gas and consuming nitrogen gas.

- Some conclusions from autoclave tests has been made on (U,Zr)N pellets and will result in an article to come.

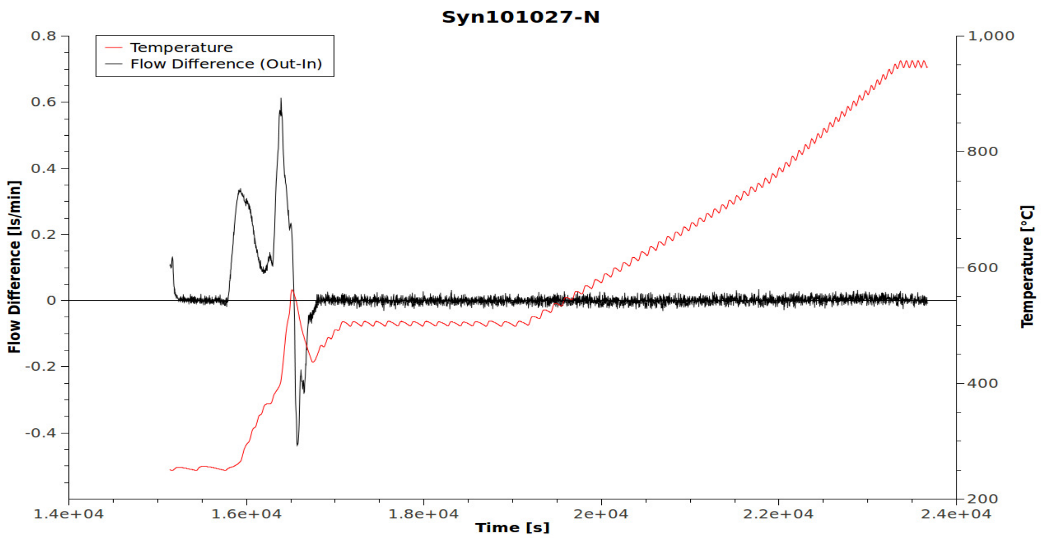


Figure 3: Flow difference and temperature measurements of uranium hydride powder reacting with nitrogen gas.

Future work

- Solid-solution nitride production by heat-treatment of mixed nitride SPS pellets.
- Calorimetric measurements of heat capacity, thermal diffusivity and the thermal conductivity is planned for nitride pellets of UN, ZrN and (U,Zr)N.
- Water compatibility tests of UN, ZrN and (U,Zr)N pellets at 300°C.

Novel diagnostics and analysis of neutron fluxes in boiling water reactors (AVKOK)

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

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

Summary

The PhD project AVKOK is composed of two distinct and separate parts, where the first concerned neutron-detection based void monitoring in boiling water reactors. This first part was described in the SKC 2008 annual report. The results have been published in international journals, and have constituted a licentiate thesis. The second part of the PhD project have been devoted to the studies of simulations of neutron fluxes in boiling water reactors for depletion of withdrawn control rods described below and investigations of axial power gradients near unsymmetrical control blade tips.

The project was brought to a successful finish on December 16, 2010 when John Loberg defended his doctoral thesis “Novel Diagnostics and Computational Methods of Neutron Fluxes in Boiling Water Reactors”. The opponent was Dr. Thomas Smed, Studsvik Scandpower AB. The complete thesis can be downloaded from

http://uu.diva-portal.org/smash/get/diva2:360604/FULLTEXT01

From January 2011 John Loberg has taken up a position with Vattenfall Nuclear Fuel AB where he will continue working within the field of core calculations.

Results in 2010

Models of the neutron flux shape in a withdrawn control rod in a BWR bottom reflector has been constructed from simulations with the Monte Carlo code MCNP. So-called G factors are created that are intended for coupling the neutron flux models to a conventional nodal code via the core bottom neutron flux. The neutron flux models and G factors are found to be very insensitive; the neutron flux models predict the simulated neutron flux in the withdrawn control rod from MCNP over a variety of reflector configurations with an error $< 3.0\%$. This implies that the neutron flux models constructed in this work are generally applicable for BWR reflectors.

BWR bottom reflector calculations in lattice codes such as CASMO are presently only used in order to produce accurate boundary conditions for core interfaces in nodal diffusion codes. Homogenized cross section constants and discontinuity factors are calculated in 1D without explicit presence of the control rod absorber. As a result, only the average neutron flux is known in the reflector, not the spatial. If the spatial flux in a BWR bottom reflector is required, e.g., for depletion calculations of withdrawn control rods, the homogenization of the reflector must be based on a representation of the 3D geometry and material composition that is as true as possible.

Differences in cross section and discontinuity factors from 1D calculations in CASMO has been compared to 3D Monte Carlo calculations of a realistic bottom reflector model in MCNP5. The cross section and discontinuity factors from CASMO and MCNP5 are furthermore implemented in the nodal diffusion code SIMULATE5 in order to investigate the effect on the neutron fluxes in the bottom reflector.

The results show that for the case investigated, the 1D homogenization in CASMO5 produces a 26 % overestimation of the homogenized thermal absorption cross section in the reflector and a 62 % underestimation of the homogenized fast absorption cross section. Furthermore, the resulting reflector side fluxes in SIMULATE5 are over predicted by 280 % with CASMO5 input data compared to the results with MCNP5 input data. However, if homogenized cross sections and discontinuity factors from MCNP are used in the nodal code SIMULATE5, the resulting spatial neutron flux agrees within ± 3%.

Also control rod withdrawal in BWRs has been studied with MCNP5. Control rod withdrawal in BWRs induces large power steps in the adjacent fuel assemblies. The ability to predict pin power gradients accurately is important for safety considerations whereas large powers steps induced by control rod withdrawal can cause pellet cladding interaction. The computation of axial pin power gradients axially around a control rod tip is a challenging task for any nodal code. On top of that, asymmetrical control rod handles are present in some BWR designs. The lattice code CASMO requires diagonal symmetry of all control rod parts. This introduces an error in computed pin power gradients that has been evaluated by calculations with the Monte Carlo code MCNP5. The results show that CASMO5/SIMULATE5, despite the asymmetrical control rod handle, predicts maximum axial pin power gradients within ±1%/cm on average, for axial nodal sizes of 15 cm to 3.68 cm compared with MCNP5 with the same nodal sizes. However, the results also show that the magnitude of the pin power gradient increases with decreasing nodal size, i.e., if conventional node sizes are used, ~15 cm, pin power gradients can be underestimated by over 50 % compared with 1 cm nodes.

Studies of void distributions using neutron tomography

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

Background

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

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

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

Objectives and methodology

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

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

Personnel, collaborations and reference group

In addition to the PhD student, the project group at Uppsala University comprises five senior researchers. Contacts are established with KTH and Westinghouse in order to adapt the technique to be useful at the HWAT and FRIGG facilities. Furthermore, FOI has offered to host the experiments at their experimental facilities in Stockholm, comprising a DT (deuterium-tritium) neutron source.

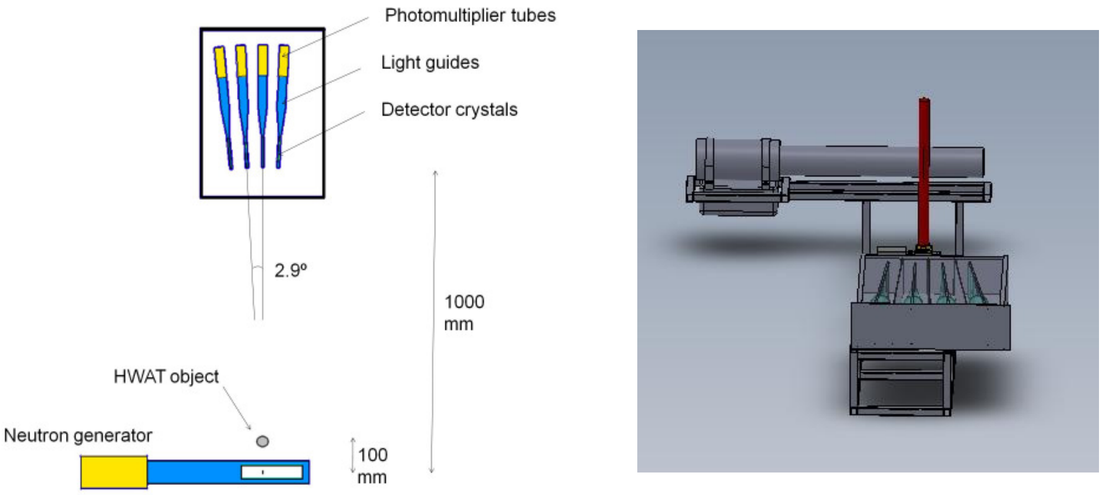
The SKC reference group consists of Uffe Bergmann (Westinghouse), Jesper Ericson (Forsmark), Elisabeth Rudbäck (SSM), Jonas Lanthén (OKG) and Fredrik Winge (Ringhals). In addition, Henryk Anglart (KTH) has accepted to join the group. A reference group meeting was kept in Uppsala on December 7, 2010.

Results in 2010

The project was started in May 2008. During the first half of the PhD project, various simulations have been performed of different measurement setups in order to study various properties of importance for the practical implementation of the technique, such as the level of scattered neutrons in the detectors and their energy distribution and also the background of neutron-induced gamma radiation. Furthermore, two types of accelerator-driven neutron sources have been considered, namely DT, giving neutrons at 14 MeV, and DD (deuterium-deuterium), giving neutrons at 2.5 MeV.

During 2010, focus has been put on the achievable spatial resolution and its dependence on incident neutron energy and on the detector size. In addition, the expected performance using a detection system with spectroscopic properties to enable energy discrimination has been studied, including a study on the energy loss due to recoil proton escape from thin scintillator detector elements. As accounted for below, the results have been presented at two international conferences, and one scientific paper has been accepted for publication in a peer-reviewed journal.

The overall design of an experimental setup to be used with the DT source at FOI has been completed, and parts of the instrumentation have been purchased. The instrument design is shown in Figure 1.



Cross section of the planned measurement geometry.

Figure 1. The instrument design to be used in experiments at the DT neutron source at FOI. The setup comprises four scintillation detectors connected to PM tubes and light guides, contained in a light-tight box. An HWAT model is included, which can be rotated and translated relative to the neutron source in order to make tomographic measurements possible.

In addition to the investigations accounted for above, the student has completed courses of totally 26 hp and courses of yet another 18.5 hp have been started. Furthermore, the work has comprised teaching at the undergraduate level to an extent of about 20%.

Peter Andersson will present his licentiate thesis during spring 2011. Finally, it can be noted that Peter has been accepted for the 2011 Young Generation program for young employees in the nuclear business.

Scientific publications and conference presentations

During 2010, one scientific paper has been accepted for publication:

P. Andersson, H. Sjöstrand, S. Jacobsson Svärd, "Effects of proton escape on detection efficiency in thin scintillator elements and its consequences for optimization of fast-neutron imaging", accepted in *Nuclear Instruments and Methods in Physics Research Section A*,

In addition, presentations have been given at two conferences during 2010:

European Nuclear Conference (ENC), Barcelona, Spain, May 30 – June 2: "Neutron tomography for void distribution measurements".

9th World Conference on Neutron Radiography (WCNR), South Africa, October 3-8: "Neutron Response Distortion due to Recoil Proton Escape – Effects on Fast Neutron Tomography"

Additional reference

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

Evaluation methodology for the safeguards aspects of a demonstration lead-cooled fast reactor

PhD student: Matilda Åberg Lindell, Dept of Physics and Astronomy, Uppsala University.
Supervisor: Dr. Sophie Grape

As a pre-study for a PhD project within work package 3 of GENIUS, a master thesis (urn:nbn:se:uu:diva-129232) was written by Matilda Åberg Lindell on the topic of identifying the safeguards requirement for a demonstration facility consisting of a lead-cooled fast reactor, a storage facility and a reprocessing plant with fuel fabrication. The work was finished in the beginning of the autumn and presented at the IAEA Safeguards Symposium in Vienna in November 2010. The results were also used as a starting point for the doctoral studies within the GENIUS project that Matilda proceeded with.

The doctoral studies are closely related to the same facility as in the pre-study, but the focus is now to develop a methodology for estimating the systems proliferation resistance based on facility design, material flows and processes. The development of a simulation tool is also foreseen. The aim is to use the tool for optimizing the facility design, for identifying the ideal placement of relevant safeguards equipment and for evaluating, and if possible prevent or at least decrease, the risks of various diversion scenarios. In the future, the simulation tool could also be used by IAEA inspectors to facilitate a smooth and easy way to assess and/or evaluate whether diversion has taken place or not.

Discussions are ongoing with SCK·CEN in Mol (Belgium), Los Alamos National Laboratories (USA) and the OECD Halden Reactor Project (Norway) regarding possibilities to use existing Virtual Reality codes as a starting point for further development.

Nuclear safeguards span a broad spectrum including technical as well as non-technical issues and Matilda Åberg Lindell devoted most of her time during 2010 to get a grasp of this comprehensive field of research. She is now in a position to formulate the basic principles for the project and the first paper is anticipated during 2011.

Core monitoring in Gen-IV reactors

PhD student: Peter Wolniewicz, Dept of Physics and Astronomy, Uppsala University.
Supervisor: Prof. Ane Håkansson

The GENIUS sub-project " Core Monitoring in the Lead-Cooled Fast Reactor, ELECTRA" is carried out as a Ph.D. project at Uppsala University. The Ph.D. student, Peter Wolniewicz, has been active within the project since the end of 2009. The aim of the projects is to evaluate the possibilities to use core monitoring systems that are sensitive to the neutron energy spectrum to monitor not only the power distribution in the core but also vital reactor parameters such as voiding of the coolant and geometric perturbations such as assembly bow. In particular, one may note that coolant void is of particular interest since a positive void coefficient may be a concern in Gen IV reactors.

The first year has been committed to simulations of the properties of predominantly SFR cores using the MCNP simulation code. In addition, modelling has also been started using the SERPENT code. The simulations show notable changes in the neutron spectrum for various cases of coolant voiding and assembly bow. The results are promising for reaching the project goals, and an abstract titled "*Detection of coolant void and fuel-assembly dislocations in fast reactors using changes in the neutron spectrum*", has been sent to the **IAEA Technical Meeting on Fast reactor physics and technology** to be held in Kalpakkam, India, March 21-25 2011.

In addition to the work on SFR cores accounted for above, modelling has also been started on LFR cores, and the work performed so far is expected to result in the submission of two articles to scientific journals during 2011 and the presentation of a licentiate thesis late 2011/early 2012. Furthermore, during 2010 the student has been introduced to the Gen IV research community by taking part in several courses and workshops on Gen IV issues nationally as well as internationally.

During the coming year, the project will focus more on instrumentation issues, with the scope to evaluate the spectroscopic capabilities obtainable using a combination of fission chambers with different isotopic contents having different neutron - energy fission thresholds. Furthermore, the monitoring capabilities of coolant void and geometric perturbations using such a system will be studied.

Detector development for test ban verification

PhD student: Lisa Bläckberg, Dept of Physics and Astronomy, Uppsala University.
Supervisor: Dr. Mattias Klintenberg

Lisa Bläckberg joined the Division of Materials Theory, Department of Physics and Astronomy on 1 August 2009 as a graduate student. Bläckbergs project is in collaboration with FOI (Totalförsvarets Forskningsinstitut) and concerns the memory effect in the SAUNA system. SAUNA is used to verify the compliance of the comprehensive nuclear test ban treaty and the memory effect is related to that a fraction of the Xe isotopes diffuse into the plastic scintillator used in the SAUNA system. Bläckberg has mainly work with a coating hypothesis and it now appears that she has solved the memory effect problem by coating the plastic scintillator with 400 nm Al2O3 using ALD (atomic layer deposition). Very exciting indeed. Bläckberg has published one paper and will submit her second paper before spring.

Produced papers

”Assisted self-healing in ripped graphene” L. Bläckberg et al. Phys. Rev. B82, 195434 (2010).

"Investigations of surface coatings to reduce memory effect in plastic scintillator detectors used for radioxenon detection". L. Bläckberg et al. In manuscript (2011).

Novel detector materials for monitoring and safeguards applied to Gen-IV technology

PhD student: Anna Shepidchenko, Dept of Physics and Astronomy, Uppsala University.
Supervisor: Dr. Mattias Klintenberg

Anna Shepidchenko joined the Division of Materials Theory, Department of Physics and Astronomy on 1 November 2010 as a graduate student. Schepidchenkos project (part of the GENIUS VR) aims at identifying possible functional replacements of HPGe detectors that function under ambient conditions. During these first few months of the project Shepidchenko has mainly focused on two parallel tasks:

1) In order to get jump-started in the art of electronic structure calculations a number of VASP tutorials have been completed. These tutorials contain the essentials for carrying out and analyzing as well as visualizing electronic structures.

2) Apply what is learnt from (1) on CdTe. Within this task we expect Shepidchenkos first publication to be produced during 2011.

Neutron-induced fission of ^{234}U

PhD student: Ali Al-Adili, Dept of Physics and Astronomy, Uppsala University.
Supervisor: Dr. Stephan Pomp

The aim of the project is to investigate the fission-fragment properties for ^{234}U as a function of incident neutron energy. This process is relevant the understanding of so-called second-chance fission of ^{235}U. Furthermore, ^{234}U is used in BWR monitors to breed ^{235}U.

The PhD student, Ali Al-Adili, is based at the Joint Research Centre (JRC) of the European Commission in Geel, Belgien until the end of 2011. Measurements are performed at the JRC neutron beam using a Frisch-grid ionization chamber. For the last year of his PhD studies, Ali will return to Uppsala and present his thesis in autumn 2012.

Produced papers

A. Al-Adili, F.-J. Hambsch, S. Oberstedt, S. Pomp}, Sh. Zeynalov, “Comparison of digital and analogue data acquisition systems for nuclear spectroscopy”, Nucl. Instr. Phys. Res. A 624 (2010) 684.

A. Al-Adili, F.-J. Hambsch, S. Oberstedt, S. Pomp, “Investigation of ^{234}U(n,f) as a function of incident neutron energy”, Seminar on Fission, Het Pand, Gent, Belgium, 17-20 May 2010, World Scientific, eds. Cyriel Wagemans, Jan Wagemans, Pierre D'hondt, p.99-105.

Massive computation methodology for reactor operation (MACRO)

PhD student: Gustav Wallin, Dept of Physics and Astronomy, Uppsala University.
Supervisor: Stephan Pomp

The project started in spring 2010 and aims at studying uncertainties of various reactor parameters based on the uncertainties of in the nuclear reaction models which in turn depend on uncertainties in the underlying nuclear data measurements. In collaboration with scientists from NRG, Petten, Holland, a recently developed state-of-the-art nuclear model code, Talys, is used to vary the ingoing model parameters. The results are then feed into reactor core simulation codes and, by means of a series of simulations propagated to uncertainties in macroscopic reactor parameters.

This project bears relevance for both todays LWR and future so-called GenIV systems. It is currently financed by the Swedish Research Council with focus on LFR reactors but an extension of the project towards LWR is planned.

Produced papers

G. Wallin, C. Gustavsson, S. Pomp, H. Sjöstrand, M. Österlund, et al., "Massive Computation Methodology for Reactor Operation (MACRO)", European Nuclear Conference (ENC), Barcelona, Spain, May 30 – June 2, 2010.