Nonproliferation and nuclear fuel cycle back-end research at UU, Sweden

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Special Seminar at PNNL

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Abstract

A brief overview of Uppsala University and the Department of Physics and Astronomy will be followed by a presentation of current research activities within the Division of Applied Nuclear Physics. Special attention will be given to on-going research in two sub-groups; Research for Nuclear Nonproliferation and research for the needs of the Swedish Nuclear Fuel and Waste Management company that is responsible for managing all the used nuclear fuel in Sweden, including encapsulation and deep geological disposal.

After the more organizational overview, the research performed within the research group regarding single photon gamma emission tomography (GET) of nuclear fuel assemblies will be presented both from a historical perspective and from the perspective of what is currently ongoing. Specifically, the work currently ongoing within the Swedish support program to IAEA Safeguards regarding GET will be presented.
Outline

● Overview of…
  ○ Uppsala University
  ○ Disciplinary Domain of Science and Technology (Faculty)
  ○ Department of Physics and Astronomy
  ○ Division of Applied Nuclear Physics

● A focus on two research areas:
  ○ Nuclear fuel cycle back-end issues
    ■ The Swedish nuclear situation
    ■ Safety and Safeguards needs of the operator and regulating authority
  ○ Nonproliferation

● Gamma emission tomography
  ○ Tomographic principles
  ○ History at UU
  ○ Ongoing R&D

Acknowledgements:
Some images kindly donated by Dr Anders Sjöland with The Swedish Nuclear Fuel and Waste Management company (SKB) and Prof. Gabriella Andersson, Ass. Prof. Sophie Grape, Dr Peter Andersson and Ass. Prof. Staffan Jacobsson Svärd with Uppsala University.
This is Uppsala University
Science and Technology

- Biology
- Computer Science
- Physics
- Earth Sciences
- Chemistry
- Mathematics
- Engineering Science
The Faculty by the numbers

**Staff 2015**
1 533 (35% women)
- Technical staff 155
- Administrative staff 286
- Professors 240 (17% women)

**Teachers and researchers** 852 (29% women)

**Students number 2015**
ca 11 500 (40% women)
- Bachelor level 7 700
- Master level 2 800
- Doctoral level 900

**Finances turnover 2015**
2 200 million SEK
- Externally funded research 965
- Education 465
- Faculty funded research 770
The Department of Physics and Astronomy is the second largest at Uppsala University with more than 370 employees and 9 different divisions.

The department of Physics and Astronomy is situated at Ångström Laboratory in Uppsala.
Physics and astronomy - from micro to macro
Div. of Applied Nuclear Physics: 4 research groups

**Nuclear reactions**

This group is doing fundamental research about nuclear reactions.

**Ion physics**

Ion beams of high energy are utilized for material analysis.

**Nuclear fission diagnostics and safeguards**

Non-destructive assay of nuclear fuel and monitoring for power operation. In nuclear safeguards, the group is developing methods for ensuring that nuclear material is used in accordance with international treaties.

**Fusion diagnostics**

Developing instrumentation for monitoring and analysis of fusion reactions.
The nuclear fission diagnostics and safeguards group

- Members, sorted by family name:
  - Dr Peter Andersson (Researcher)
  - Dr Klaes-Håkan Bejmer (Adjunct from Vattenfall AB)
  - Martin Bengtsson (PhD Student, Vattenfall AB)
  - Erik Branger (PhD Student)
  - Prof. Em. Anders Bäcklin
  - Dr Li Caldeira Balkeståhl (Post Doc)
  - Dr Zsolt Elter (Post Doc)
  - Ass. Prof. Sophie Grape (Researcher)
  - Dr Carl Hellesen (Researcher)
  - Prof. Ane Håkansson
  - Ass. Prof. Staffan Jacobsson Svärd (Lecturer)
  - Dr Peter Jansson (Researcher)
  - Dr Dinesh Kumar (Post Doc)
  - Matilda Åberg Lindell (PhD Student)

(Arrows are indicating research leader.)
The Swedish nuclear situation

- 8 (12) operating reactor units at 3 (4) sites
- ~45% electricity
- 12,000 tonnes of spent fuel total program

- **SFR**: Final Repository for Short-lived Radioactive Waste
- **Clab**: Central Interim Storage Facility for Spent Nuclear Fuel
## The Swedish nuclear situation

### Reactors

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Status</th>
<th>Location</th>
<th>Reference Unit Power [MW]</th>
<th>Gross Electrical Capacity [MW]</th>
<th>First Grid Connection</th>
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<td>963</td>
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Above data are from the PRIS database. Last update on 2018-01-22
Funding of decommissioning and waste management in Sweden

Owners

VATTENFALL
FORSMARKS KRAFTGRUPP
e-on
okg

Financing

0.05 SEK per kWh of nuclear electricity

About 59 billion SEK in 2015
The KBS-3 system

- Developed by Swedish SKB
- Adopted by Finnish Posiva
Canister in deposition hole

**Bentonite clay:**
Natural clay with very special swelling properties
Montmorillonite (around 80%) + secondary minerals

**Swedish bedrock:**
More than 900 million years old
Clab – Central Interim Storage Facility for Spent Nuclear Fuel
Clab – Central Interim Storage Facility for Spent Nuclear Fuel

Clab 2 increases the capacity from 5,000 to 8,000 tonnes

In the unloading pool the fuel assemblies are lifted out and placed in a storage canister

Graphic art: Mats Jerndahl
Clab contains all used fuel from the whole country
Clab + Encapsulation plant = Clink
Clink – An integrated encapsulation and interim storage facility
The Nuclear Fuel Repository

- Final disposal of all spent fuel from the present Swedish nuclear energy programme
- Design capacity 6,000 canisters corresponding to 12,000 tonnes of spent fuel
- 15 years of planning, design, construction and commissioning
- 60 years of operation followed by decommissioning and closure

Planned surface facilities at Söderviken, Forsmark

The repository at 470 m depth, when fully built-out
License application submitted by SKB in March 2011 for...

Spent Fuel Repository at Forsmark

Encapsulation plant in Oskarshamn
SKB is applying for...

- To continue **interim storage** of spent nuclear fuel and reactor core components. The amount of spent nuclear fuel may reach a maximum of 8000 metric tons (calculated as uranium).

- To **construct and operate** a facility (Clink) to **store** spent nuclear fuel and core components and for **encapsulation** of spent nuclear fuel. Capacity of approximately 200 canisters per year.

- To **construct and operate** a facility for **final disposal** of spent nuclear fuel and nuclear waste (construction material in the fuel assemblies)
  - Final disposal of the spent fuel that is currently stored in Clab and
  - future fuel that will arise from operating the reactors that currently have a permit to operate

- Final disposal according to **the KBS-3 method** with vertical placement of the canisters (KBS-3V)

- **Water operations** that are needed to build and operate the facilities

- Storage for **rock aggregate**
Licensing review according to Nuclear Act and Environment Code

SKB’s applications

One according to Environmental Code
Two according to Nuclear Act

Review/Court hearings

Approves or disapproves

Permit and conditions

Review

Approves Safety Report
Need for back-end characterization of SNF

- Decay heat – fulfil temperature requirement on canister and bentonite; optimization of repository; transport; intermediate storage pools or dry casks
- Radiation doses: gamma and neutrons; radiation protection – design, final repository, transport, intermediate storage pools or dry casks
- Criticality – multiplicity; avoid criticality everywhere at all times, final repository, transport, intermediate storage pools or dry casks
- Radionuclide inventory: goes into the long term safety analysis
- Safeguards:
  - identify correct fuel,
  - missing pins
  - contents of fuel – amount of fissile material
  - Burn-up (BU), Initial enrichment (IE), Cooling time (CT)
Need for back-end characterization of SNF: Accuracy

- Decay heat: *very high accuracy, order of few percentage uncertainty*
- Radiation doses: *high accuracy – maybe 10%*
- Criticality: *very high accuracy < 10%*
- Radionuclide inventory: *for most nuclides fairly low accuracy need; <100% (for some higher accuracy is needed)*
- Safeguards: *intermediate accuracy*
Fuel characterisation activities

At SKB: Various activities aiming at:

- sufficient measurement methods,
- calculation codes,
- fuel data and
- knowledge and understanding of the nuclear fuel for operational and safeguards issues, and
- in the end for long term safety; have sufficient competent available human resources

All to be in place at the time of start of operation of the encapsulation plant.
Safeguards, nuclear physics and nuclear chemistry different aspects of same things in these respects – more collaboration, avoid division!
More about collaboration...

In Europe: Often relative small, under-critical, research teams. ⇒ Collaboration important

Euratom: Funding via Work Programme.

Previously in RWMD: “Small, individual” EU projects. Budgets in the order of 5 M€. Call cycle every ~2 years.

Now in RWMD: One EU Joint Programme including research for deep geological disposal. ~5 year cycle. Programme budget: 52-65 M€

One R&D work package in programme, out of seven, deals with Spent Nuclear Fuel Characterization and Evolution until Disposal.

Collaboration with organisations world-wide is encouraged!

Read more: www.joprad.eu
Nonproliferation

Non-destructive assay using gamma scanning since late 1980’s; Studies of using measured gamma spectra to determine safeguard related parameters.

More recently (last decade):

- Studies of the DCVD instrument. Enhancing its associated prediction models.
- Multivariate analysis techniques (using gamma spectra) to determine safeguard related parameters.
- Studies of causes and effects of measurement uncertainties on safeguards applied to an encapsulation facility.
- Safeguards for Gen-IV.
- Tomography for partial defect testing/verification.
Instrument for verification of irradiated nuclear fuel based on Cherenkov light detection:

- Non-destructive, non-intrusive, quick, no fuel movements

Gross and partial defect verification

- Gross defect: is this a nuclear fuel?
- Partial defect: fraction of fuel manipulated?
  - Template matching
  - Comparison predicted/measured Cherenkov light intensity

Predictions crucial!

Images by Channel Systems and Clab.
Multi-year effort + PhD project:

- Simulations to understand and describe Cherenkov light emission from nuclear fuel (assemblies)
- Improved prediction software. Parameterization includes IE, BU, CT, irradiation history
- Possibilities offered by image analysis

Applications now include

- Fast and accurate predictions
- Verification of short cooled fuel
- Description of and correction for near-neighbour fuel assemblies
Predict and compensate for near-neighbour effect. Simulations performed on:
• 8x8, 7x17 fuel
• Tightly packed, sparsely packed

Validation against Forsmark data shows good agreement!

Project will continue to investigate:
• The validity of the Cherenkov light emission model wrt CT
• The relation between Cherenkov light emission and detection
• Partial defect detection using the DCVD
  • What is the impact on light intensity?
Multivariate Analysis

- Construct fuel library with varying IE, BU and CT
- Identify isotopes suitable for analysis
- Analysis identifies most important isotopes
- Analysis shows that it is possible to determine IE, BU and CT

Multivariate Analysis

Experimental validation using two PWR fuel assemblies (CT = 5.4 and 14.3 y)

<table>
<thead>
<tr>
<th></th>
<th>Fuel 1</th>
<th>Fuel 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Declared</td>
<td>Measured</td>
</tr>
<tr>
<td>CT (y)</td>
<td>5.4</td>
<td>5.3 ± 0.3</td>
</tr>
<tr>
<td>BU (MWd/kg)</td>
<td>52.6</td>
<td>56 ± 4</td>
</tr>
<tr>
<td>IE (%)</td>
<td>4.0</td>
<td>4.7 ± 0.6</td>
</tr>
</tbody>
</table>
Multivariate Analysis

Can we use MVA techniques to verify partial defects and atypical fuel (assemblies and dissolved fuel)?

Images: Z. Elter et al., Partial defect identification in PWR spent fuel using Passive Gamma Spectroscopy. PHYSOR 2018
Safeguards for Gen IV

- Proliferation resistance assessed
- LFR fuel cycles with multiple recycling processes
  - Weak points
- 2 operational phases in recycling facility
  - Material flows
  - Material Balance Areas, Key Measurement Points, measurement techniques
- Iterative proliferation resistance assessment

Pre-conceptual design
Rudimentary design information
TOPS
Redesign of facility
PR of pathways
PR&PP
Weak points
Safeguards for Gen IV

- Reception area of recycling facility
- Verify UOX/MOX before dissolution
- γ-spectroscopy with multivariate data analysis (MVA)
  - Classify fuel
  - IE, BU, CT using regression models
Tomography is imaging by sections or sectioning, through the use of any kind of penetrating wave. The method is used in radiology, archaeology, biology, atmospheric science, geophysics, oceanography, plasma physics, materials science, astrophysics, quantum information, and other areas of science. The word tomography is derived from Ancient Greek τόμος tomos, "slice, section" and γράφω graphō, "to write" /…/ A device used in tomography is called a **tomograph**, while the image produced is a **tomogram**.
1. Measure collimated $\gamma$-rays emitted from the object from many positions around the object.

2. Using some assumed properties of the object and mathematics, reconstruct the distribution of $\gamma$ activity within the object.

Two classes of reconstruction:

a) Analytic reconstruction
b) Algebraic reconstruction

\[ I = W A \]
Algebraic image reconstruction vs Direct quantitative reconstruction

**Algebraic image reconstruction:**
The image area is divided into standard, square-shaped pixels.
Attenuation may (or may not) be included when defining the system matrix.

**Direct quantitative reconstruction:**
Algebraic methods enable use of *a priori* information on geometry, allowing for detailed modelling of gamma-ray transport.
Adapting pixel pattern to object also enables direct reconstruction of quantitative measures. (Here: pin-wise data.)
Analytic vs algebraic methods

**Analytic (transform-based):**

Pros:
+ Fast
+ Widely used for imaging
+ Software implementations available

Cons:
– Sensitive to noise
– Artifacts, e.g. due to attenuation
– Loss of quantification

**Algebraic:**

Pros:
+ Less sensitive to noise
+ Handle incomplete data
+ Enable accurate physical representation, e.g. attenuation
+ Quantitative capabilities

Cons:
– Computationally intensive
– Require modelling and thus custom software
The history of GET applied to nuclear fuel @ UU

● 1990’s: SSM funded feasibility study on detecting partial defect in nuclear fuel.
https://www.iaea.org/iniis/collection/NCLCollectionStore/_Public/30/014/30014753.pdf?r=1

● 1998 → ~2003: Swedish and Finnish nuclear power industry funded tomographic validation of calculations of pin-level power distribution in weeks before the measurement.
http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-77336

● 2007 → ~2009: Development of GET for the needs of the core calculator.
http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-146740

http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-235124

● 2014 → 2016: IAEA support program “UGET”: SSM funded UU’s part in a viability study of gamma emission tomography for spent fuel verification.
http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-306584

● 2017: IAEA support program “GET”: SSM funds UU’s part in constructing software to be used by inspectors to analyze tomographic measurements with the PGET device.
Fig. 10. The experimentally obtained reconstructed activities using the 1274-keV gamma-ray energy from $^{154}$Eu. Note the small value in the position of the removed rod, (E,5). The activities are normalized to a mean value of 1.0.
Halden tomograph

Figure 22. Overview of the HBWR gamma tomography system with cutaway views showing components housed inside the radiation shielding.
Figure 38, Reconstructed images of the rod-wise $^{137}$Cs distribution in the fuel (left) and the rod-wise $^{85}$Kr distribution in the plenum (right).

Figure 39, Reconstructed images of the rod-wise $^{60}$Co distribution in the plenum region (left) and the rod-wise $^{125}$Sb distribution in the plenum region (right).
Ongoing GET research at UU

- Halden Reactor Project: LOCA tests
  (high power → rod ballooning → fragmentation)
  - Axial scanning of rods + tomography of rods
  - Development of reconstruction techniques

- IAEA Support:
  - Software for determining rod positions and fuel assembly position from tomographic images
  - Software for algebraic reconstruction
  - ⇒ Components in the IAEA “GET toolbox”

- Now at PNNL:
  - Learning RADSAT and applying it to “hard Monte Carlo problems”
  - Exploring challenging situations for tomography with
    (high burnup, short cooling time) or (low burnup, long cooling time)
The Halden Tomography system uses a single spectroscopic detector to scan the fuel laterally and rotationally.

A mathematical reconstruction is performed of the emission intensity of selected radionuclides.
Halden LOCA test series

1) During LOCA transient fuel and cladding temperatures rise.

2) The cladding expands to a balloon formation in the most affected location.

3) Fuel may relocate to the free volume of the balloon, adding additional local heat load.

4) In high-burnup fuel, fragmentation has been observed to cause higher degree of relocation and higher packing fraction in the balloon.

5) The cladding balloon may burst, leading to dispersal of fuel in the coolant.
Halden tomograph
Uncertainty evaluation

Random fuel distributions have been modeled using MCNP to estimate the accuracy and precision of the self-attenuation correction procedure.

RMS Error = 2.6 percent units (i.e. currently not the dominating uncertainty.)
Tomography – PGET @ UU

Reconstruction, Analysis, Evaluation

- Initial Reconstruction
- Determine Fuel Location
- Attenuation Correction
- Initial Analysis
- Advanced Reconstruction and Analysis Tools

- Interactive
- Uniform Attenuation
- Automated 1
- Automated Pin Location and Scoring

- Filtered Backprojection
- Automated Shape
- Non-uniform Attenuation
- Automated 2
- High-Fidelity System Response Function

- UGET (SWESP)
- Automated Pin Location
- Algebraic Reconstruction
- Advanced Algebraic

- UGET (USSP)
Assembly location
Pin location

Current status: Being tested at IAEA.
Algebraic reconstruction software development

- Object oriented (C++)

  ⇒ Abstract base for generic algebraic reconstruction

  - Pixels of any shape
  - Arbitrarily shaped collimator- and detector system
  - Arbitrarily shaped measurement objects (fuel assemblies)
  - Generic gamma-ray transport

- Initially specialized:

  - PGET geometry and materials
  - “Photo peak ray tracing” with attenuation
  - Intrinsic instrument response (without measurement object) calculated with MCNP.

Current status: Work In Progress
Thank you for your attention!