Swedish Perspective on the Accelerator-Driven Nuclear System

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1. Introduction

The nuclear power programme of Sweden consists of 12 nuclear reactors (Tab. I) located at four different sites and with a combined capacity of 10 000 MW net electric power. The nuclear power plants generated about 42% of the total Swedish electric power produced in 1993. These nuclear power plants are owned by four companies which has formed the Swedish Nuclear Fuel and Waste Management Company, SKB (SKB - Svensk Kärnbränslehantering AB). SKB duty is to develop, plan, construct and operate facilities and systems for the management and disposal of spent nuclear fuel and radioactive wastes from the Swedish nuclear power plants. On the behalf of its owners SKB is responsible for all handling, transport and storage of the nuclear wastes outside of the nuclear power productions facilities (1). SKB is also in charge of the comprehensive research programme in the radwaste field.

Tab. I Swedish nuclear reactors

Reaktor name and type	Capacity MW(el)	Commerc. Operation	Licensed to
Barsebäck 1 (BWR)	600	1975	Indefinit.
Barsebäck 2 (BWR)	600	1977	2010
Oskarshamn 1 (BWR)	442	1972	Indefinit.
Oskarshamn 2 (BWR)	605	1975	Indefinit.
Oskarshamn 3 (BWR)	1160	1985	2010
Ringhals 1 (BWR)	750	1976	Indefinit.
Ringhals 2 (PWR)	800	1975	1995
Ringhals 3 (PWR)	915	1981	2010
Ringhals 4 (PWR)	915	1983	2010
Forsmark 1 (BWR)	970	1980	2010
Forsmark 2 (BWR)	970	1981	2010
Forsmark 3 (BWR)	1090	1985	2010

A complete system has been planned for the management of all radioactive residues from the 12 nuclear reactors and from the research facilities. The system is based on the projected generation of waste up to the year 2010. For spent fuel a central interim storage facility, CLAB, was taken into operation in July 1985. This facility has a current facility of 5 000 tonnes of spent fuel. The spent fuel will be stored in CLAB for about 40 years. It will then be encapsulated in a corrosion-resistant canister and deposited at depth in the Swedish bedrock. The construction of the deep repository will be made in steps. A first stage of the repository, for 5 - 10% of the fuel, is planned to be put into operation in 2008. The next stage for the full repository will only be built after a through evaluation of the experiences of the first stage and a renewed licensing. The site for the deep repository has not yet been chosen.

The estimated costs for the Swedish deep rock repository amounts to about 40 billion SEK. One attractive option to reduce these costs would be to transmute the most cumbersome components of the spent fuel using accelerator-driven transmutation technology.

2. Accelerators enter nuclear energy field

In recent years new concepts of treating spent fuel from fission reactors have been developed (2). This has initiated rapid growing international research activities in which a number of Swedish, mostly university-linked, groups participate. The technique is in general named accelerator-driven transmutation technology (ADTT) and is aiming to convert the long-lived radioactivity in the burned nuclear fuel, to short lived one and by that reducing the need for geological depositions. The accelerator-driven transmutation technology offers in the long-term a possibility to produce clean fission energy over an indefinite time, a concept which would fit Swedish needs and technological skill. However, due to the environmental requirements the Swedish parliament decided that the two dominating energy sources - the nuclear power and fossil burning - will be either shut down (nuclear power) or its use will be limited (fossil fuels), the Swedish energy supply in the long run is a problem area. The parliament decisions are based on the perceived risks which in the first case are linked to a possible release of radioactivity at a large reactor accident and/or the handling of the highly radioactive spent fuel and also to the proliferation concerns. In the second case - the risk for a global environmental catastrophe through the "green house effect". Although research of alternative renewable energy sources is in progress, no large scale solutions which can meet the future energy demands have come out so far. At the same time the research problems connected with the utilization of fusion energy are still numerous. Today it is difficult to predict when the basic problems in this field will be solved. Finally, import of energy effects negatively the balance of trade and makes Sweden depending on political and economical decisions in foreign countries.

With the twofold aim to find *methods for treating the high level nuclear wastes* which could be more easily accepted by the public than a direct geological deposition, and at the same time *recruit students to the nuclear energy field*, a national collaboration has been initiated on the research of accelerator driven transmutation technologies, particularly accelerator based nuclear waste transmutation systems (ADTW). The ambition to start research in this field was positively influenced by the Specialists' Meeting on "Accelerator-Driven Transmutation Technology for Radwaste and other Applications" which was held at Saltsjöbaden, Sweden on 24-28 June 1991.

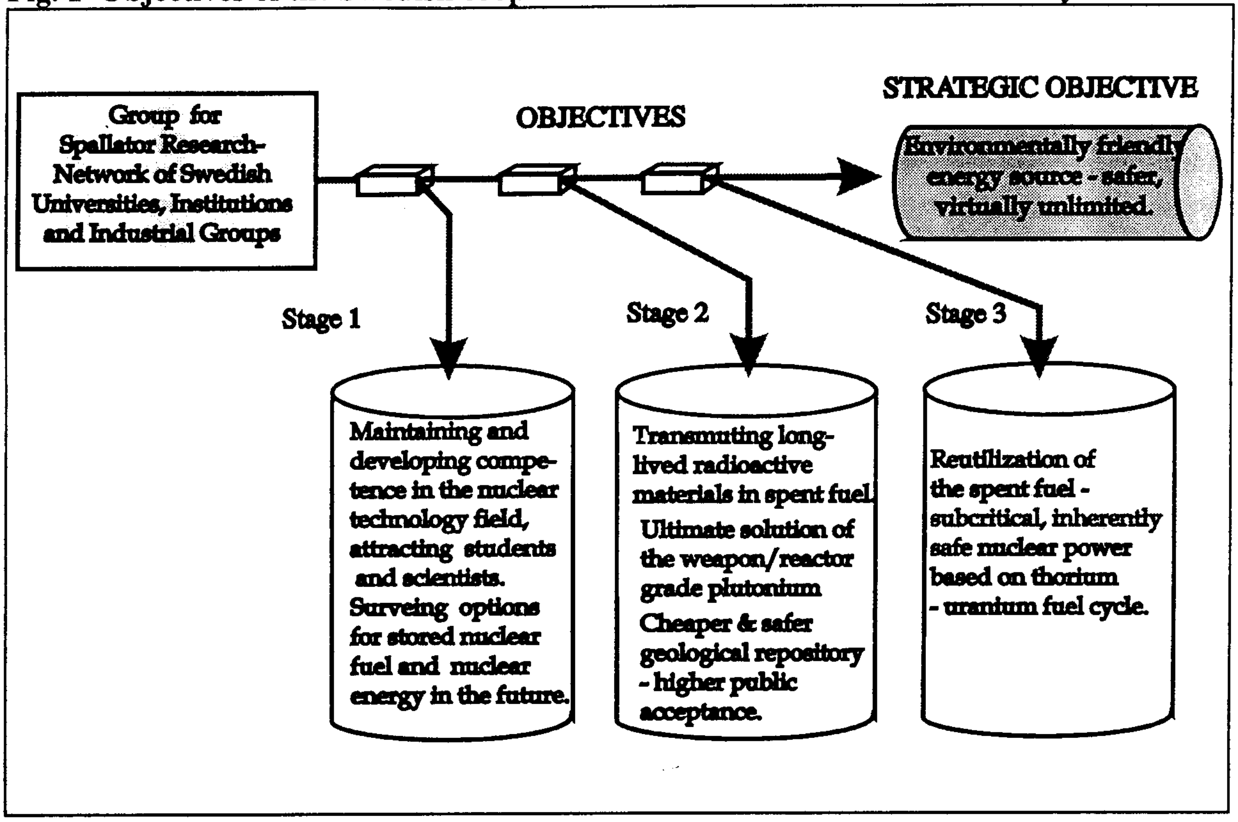
The "Group for Spallator Research" conducts - so far - the concerted research at CTH, KTH, the Manne Siegbahn Laboratory-Stockholm University and the Uppsala University.
The main task of this Group is to stimulate and to coordinate research and development projects in the accelerator driven transmutation technologies. These projects as - shown on Fig. 1 - are aimed to :

1) Practical solutions for accelerator driven transmutation of longlived radioactive material (e.g. plutonium, minor actinides, fission products) into shortlife or stable elements. It may result in cheaper and safer geological repository;

2) Investigation of new options for nuclear energy production with inherently safe systems, either with uranium or thorium fuel and with reduced longlived radioactive waste production. If successful, it will result in a new, environmental friendly, safe, cheap and virtually unlimited source of energy. The proposed systems for transmutation of spent fuel and production of energy are subcritical and inherently safe.

3) Opening new, exciting research and occupation possibilities for students and young specialists, which will ensure the proper level of competence needed for our nuclear power utilities, governmental agencies etc. The existing nuclear power facilities will, namely, need qualified personnel for at least two generations, even in the case of shutting-down of all the Swedish nuclear power plants by year 2010.

Fig. 1 Objectives of the Swedish cooperation in accelerator-driven nuclear systems



3. Research within a collaboration on accelerator based transmutation technologies in Sweden

3.1 Department of Nuclear Chemistry Chalmers University of Technology (CTH)

A research project was initiated at the Department of Nuclear Chemistry at CTH in 1976 to develop a process for separation of actinides from high level radioactive waste from the PUREX process. The project run for about 10 years time and resulted in the so called "CTH-process".

When the US and Japan separation and transmutation programs were presented around 1990 a new interest come into the field. This resulted in the creation of a new separation and transmutation project - SKB financed - at the Department of Nuclear Chemistry at CTH which started in 1991. Initially, a comprehensive survey was made of national and international activities in the field (3). Since 1993, the Department has started a new research project linked to the activities in other countries within the same research area.

The aim of the project is to study separation processes proposed for use in connection with nuclear transmutation. The project conducted in cooperation with research groups in US, Japan and EU contains both experimental investigations as well as modelling of different separation systems. The project is mostly directed towards fundamental research and aim to help judging the realism of different proposed separation and transmutation processes. In particular, the proposed separation systems by LANL and within the OMEGA project in Japan will be screened.

A very important issue in order to get a reasonable reduction of radionuclides through transmutation is a high separation efficiency. In turn, this means that one has to have a good control over what happens in the separation process and the chemistry must tolerate reasonable deviations in operating conditions. The separation process has to be optimized in this concept which requires separation data for a number of different elements and a sensitive analysing technique. The most important elements are the actinides, which are long-lived and highly radiotoxic. The development of analysis techniques for the actinides is, for that reason, an important research area.

The department operates the only large α-box laboratory in Sweden and has facilities to handle substantial activities of β,γ emitting nuclides in shielded cells with master-slave manipulators.

3.2 Department of Neutron and Reactor Physics and Centre for Safety Research, Royal Institute of Technology (KTH)

Alternative nuclear fuel handling has been discussed within a working-group at KTH through a number of years. The group consists of about 25 experts of different disciplines as reactor physics, nuclear chemistry, physics, material sciences, hydrology, geology and risk analysis. The group has worked actively to broaden the interest for transmutation after the Conference in Saltsjöbaden in 1991 and stimulated creation of the small research team fully devoted to study accelerator driven systems (4). The research program conducted by this team is focused on conceptual studies based on computer simulations (computer codes: MCNP, SYSDANT, ORIGEN and CASMO/SIMULATE) aimed to find the answer for some important questions like:

1. Impact of the ADTT on the costs and performance of the geological repository

2. Safety analysis of transmutation systems
    a) Criticality margins and criticality budget
    b) Minimizing the amount of actinides in the system
    c) Neutronics for the ADTW/ADEP systems

3. Safety and system analysis of the synergetic system: nuclear reactors and accelerator-driven waste transmutation system

Very extensive investigations - in collaboration with so called Swedish Industrial Group - were performed on the system proposed by Carminati et al. (5) because of its potential attractiveness: thorium breeding cycle and light water moderation. The conclusions, however, pointed at some very difficult problems with this idea:

1. The reactivity budget analysis of such system shows that it is virtually impossible to construct this device without external reactivity control systems. The idea of the subcritical system with k_{eff} inherently lower than 1 seems to be irreconcilable with the physics of this system and economical requirements

2. Solid fuel and light water moderator require multiple target due to the power density peaked around the targets. It makes the construction much more difficult - if not impossible - and more expensive (multiple cyclotrones, target window problems etc.).

3. To make the construction of such system economically possible it seems to be necessary to reevaluate the requirements of the inherent subcriticality. Instead, better safety mechanism could be invented (or re-invented) and applied to ensure safe operation. Very high k_{eff} of the level of .99 should be reconsider if one wants to proceed with light water and the solid fuel (6).

The research of the group at KTH is performed in very active and close cooperation with the Los Alamos National Laboratory. The common project in calculation of the neutronics of the accelerator-driven plutonium burner and thorium-based energy producer is now expanding into Russia and a common experimental programme becomes realistic.

3.3 Department of Neutron Research and Department of Radiation Science, Uppsala University

Basic and applied experimental neutron and nuclear research at the Uppsala University is centred around two laboratories administrated by the University namely the The Svedberg Laboratory (TSL), Uppsala and the Neutron Research Laboratóry (NFL), Studsvik.

The main facilities of TSL is a cyclotron, a storage ring (CELSIUS) on-line the cyclotron and a tandem van de Graff-accelerator. The cyclotron can operate in an isochronous mode allowing acceleration of protons up to 100 MeV and heavy ions to 196 Q^2/A MeV and in a synchrocyclotron mode which allows acceleration of protons to 180 MeV. The storage ring CELSIUS is equipped with acceleration and electron cooling capacities. It takes both light and heavy ion beams. The maximum proton energy is 1.36 GeV. The tandem is a High Voltage 6 MV EN-tandem mostly used for applied research as C-14 dating, PIXE, ion-surface studies etc.

The NFL is located at the research reactors R2 and R2-0 at Studsvik. The main facility aside of the neutron diffractometers at the R2 reactor is an isotope separator on-line the R2-0 reactor (OSIRIS) for studies of nuclear structure and decay data for fission products and fission yields.

Measurements in progress or planned by different Uppsala groups of relevance for the research on the ATW concept at the TSL and NFL facilities are:

A comprehensive study has been carried out of the yield pattern of fission products formed in the thermal neutron induced fission of U-235 using the OSIRIS facility at NFL. Independent and/or cumulative yields have been obtained for 195 nuclear species, among them 83 isomeric states. Similar studies of the yield pattern have been carried out for the fast fission of U-238, is in progress for the thermal fission of U-233 and is planned for the fast fission of Th-232. At the same laboratory, continuous spectra of beta particles and gamma rays emitted in the decay of short lived fission products have also been measured. The mass range 79-98 and 130-147 was covered by a measurement at OSIRIS and 98-108 by a measurement at the on-line separator LOHENGRIN at ILL. Accurate average beta and gamma energies, obtained from the spectra, are essential input data for summation calculations of the heat developed in nuclear fuel by the decaying fission products.

Cross section measurements for residual nuclide production by proton and neutron induced reactions relevant for Accelerator Driven Transmutation Technologies are in progress within a collaboration between the Universities in Hannover and Cologne, KFA Jülich, ETH Honggerberg, Kossuth University Debrecen, University of Bourdeaux-Gradignan and Uppsala University. It is the aim to measure at TSL thin-target cross sections for the production of residual nuclei from about twenty medium and heavy target elements by proton-induced reactions for energies between 70 and 180 MeV. Radioactive and stable residual nuclei will be measured via gamma-spectrometry ($T_{1/2}$> 15 h) counting techniques (H-3), accelerator mass spectrometry (B-10, Al-26, Cl-36, Ca-41, Mn-53 and I-129) and conventional mass spectrometry (stable rare gas isotopes). The results will be used to test nuclear reaction models of spallation, fragmentation and medium energy fission. Furthermore, feasibility studies are underway of activation experiments with fast neutrons up to 100 MeV.

Model calculations in the intermediate energy region are tested against measurements at TSL of double differential cross section measurements at 100 MeV for (n,p)-reactions in C-12, Fe-54,56, Zr-90 and Pb-208 and of the n-p differential scattering cross section. A reasonable agreement was obtained between the experimental (n,p)-reaction data and the same data from DWA/RPA calculations adding contributions from multistep reactions. On the other hand a disagreement of about 5-10 % was observed between the experimental n-p scattering data at about 180 degrees and recent phase shift calculations. Accurate n-p scattering measurements over a wide angle range is underway to further explore the observed discrepancy.

Measurements of neutron induced fission cross sections for Bi-209 and U-238 have been performed for 100, 130 and 160 MeV at the neutron beam facility of the TSL in a collaboration between the Khlopin Radium Institute, S:t Petersburg and the Uppsala University. The fission fragments were detected by thin film break down counters. The neutron flux was measured relative to the n-p scattering cross section. A reasonable agreement was obtained with calculations using the LAHET code.

Research and development of measuring procedures and instrumentations for isotopic analysis of burned nuclear fuels are underway.
The Uppsala group is also participating in an experiment at SATURNE, Saclay to study the neutron production in thin targets of several elements (Pb, Bi, W, Fe etc) between 0.6 and 2 GeV.

The study is a collaboration between Centre d'Etudes de Bruyeres-le-Chatel, Laboratoire National SATURNE, I.P.N. Orsay, Centre d'Etudes de Saclay, College de France Paris and the Uppsala University.

3.4 Manne Siegbahn Laboratory (MSL) - Stockholm University

The Manne Siegbahn Laboratory has a long tradition in accelerator design and operation. The present main accelerator facility at MSL is a 52-m circumference synchrotron storage ring called CRYRING [4]. It includes both an injection line for light ions, the MINIS separator, and a line for highly-charged heavy-ions, the INIS- CRYSIS electron-beam ion-source system. Intermediate acceleration is provided by a radiofrequency quadrupole structure, RFQ, and the quality of stored ions in the ring is improved by an electron cooler.

Within the collaboration the group at MSL has proposed studies of critical issues connected to the construction of high current accelerators. The issues involve studies of space-charge current-limitation in the low energy part of the accelerator and a minimization of the particle losses due to rest gas collisions in the vacuum system. Furthermore, the injection lines feeding CRYRING allow and can hence be used to investigate how to merge two beams into the RFQ as has been proposed for the high current ATW-facility at Los Alamos. Another research area of concern for the construction of a high power accelerator is ultra high vacuum technology. Experienced scientists in this area are available at both MSL and TSL.

MSL has the competence and experimental resources to measure nuclear reaction data of importance for the spallation concepts. A small van de Graff accelerator (2 MeV) is available near the CRYRING facility for this purpose.

3.5 The Industrial Group

A more industrially oriented group of reactor physicists, formerly at ABB Atom, and neutron physicists from Uppsala University and KTH have investigated the technical and economical possibilities to implement a nuclear reactor construction based on the concept which recently has been presented by C. Rubbia et al (5). As the first goal, this group of reactor and neutron physicists has investigated the technical and economical possibilities to realize a nuclear energy production facility based on **the light-water spallator driven by a smaller scale accelerator**. The strategy chosen by the group was to start with a LWR-construction and to marginally modify the construction, with state-of-the-art technology, and if necessary supplement it with an autogenous rescue cooling system of the PIUS-type or similar.

4. International perspective

The research activities of the Group for Spallator Research has been primarily devoted to system and feasibility studies together with participating in the number of international efforts mainly in US (Los Alamos), Russia (Troitsk), France (Saturne) and in future possibly Japan (PNC-JAERI), CERN and Switzerland (PSI).

Collaborative projects are already in progress with leading international laboratories on ADTT research as described above. In particular, a test experiment of burning plutonium from the present nuclear power plants but also the weapon grade plutonium from warheads of destructed nuclear weapons at the linear accelerator of the Institute for Nuclear Research at Troitsk outside Moscow has been proposed as a collaboration between U.S.A., Russia and Sweden. It is anticipated that the Swedish groups (coordinated and financed through the Centre for Spallator Research) - in similarity to e.g. CERN collaboration - will prepare some part of the experimental equipment and take responsibility for its installation and performance.

The next international conference on Accelerator-Driven Transmutation Technologies and Applications 1996 will be arranged in Sweden, 3 - 7 June in Kalmar.

Group for Spallator Research is also going to work actively to create an international organisation or centre for advancement of ADTT.

5. Final remarks

Accelerator-driven nuclear systems can become an important complement for nuclear reactors opening new options for the nuclear fuel cycle and furthermore, in the countries like Sweden, where the future of the conventional nuclear power has no prospects, these systems can make the nuclear energy again an attractive source of environmental friendly energy. Also the idea of burning weapon grade plutonium in accelerator driven systems has a lot of advantages and should be thoroughly exploited. The best way to achieve these goals is an intensive international cooperation and the common efforts to build the first demonstration facility.

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