SKB rapport R-97-04

February 1997

Safety analysis and neutronics of accelerator-driven transmutation of wastes with concurrent energy production

Annual report for the year 1996

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ISSN 1402-3091
SKB Rapport R-97-04

SAFETY ANALYSIS AND NEUTRONICS OF ACCELERATOR-DRIVEN TRANSMUTATION OF WASTES WITH CONCURRENT ENERGY PRODUCTION

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ABSTRACT.

The research activities in the project *"Safety analysis of accelerator-driven systems for transmutation of nuclear waste and for nuclear power production"* have significantly expanded compared to the earlier period and were concentrated in 1996 on the following major objectives: ATW system studies, simulations, optimization and design of spallation target, benchmarking of the calculational tools in the frame of IAEA coordinated research project, development of the computer codes for ADS and some experimental activities on subcritical reactor MASURCA.
Under 1996 a very extensive international collaboration network has been further developed and many collaborative research projects have been launched.

1. INTRODUCTION.

The project on Accelerator-driven Transmutation at the Royal Institute of Technology aims to assess the potential of the Accelerator-driven Systems (ADS) for the nuclear waste transmutation on the safe and economical way. ADS has a potential to overcome the drawbacks with the reactor based transmutation of nuclear waste and at the same time diminish the need for geological deposition. The Accelerator Transmutation of Wastes (ATW) concept has as its goal the realization of a high-power nuclear system, driven by a powerful neutron source, external to its subcritical core, not relying on delayed neutrons and reactivity changes for its power management.

Even though the very first concepts of nuclear systems from 1940's involved the use of subcritical devices, none of them was really developed or tested to any significant degree.

ATW system consists of an intense neutron source which is driven by a high power proton accelerator (1-2 GeV, 20-200 mA). The neutron source is surrounded by a subcritical blanket containing the nuclear waste to be transmuted. The neutron flux in the blanket (10^{15-16} $cm^{-2}s^{-1}$) is 5-100 times higher than in a ordinary reactor which means that the fissile inventory in the blanket can be reduced accordingly compared to the conventional reactors. The waste is dissolved in e.g. molten lead-bismuth or molten salt (mixture of Li- and Be-fluorides) in different proposed Accelerator-Driven Transmutation Technologies (ADTT) concepts with fast or thermal neutron spectrum, respectively. Special proliferation resistant processes have been proposed to prepare the fuel for the ATW system from spent nuclear fuel or weapons plutonium and to remove the fission products (volatiles, transition metals and lanthanides) from the molten salt.

There are several options for utilization of accelerator-driven transmutation technologies, however, our project is concentrated on the economical way of destruction of nuclear waste. The economical way in our reality implies in principle concurrent energy production. ATW concept takes full advantage of the larger neutron availability and flexibility of operations it enjoys with respect to critical reactors, to destroy materials that for a number of reasons cannot be incinerated in critical reactors. ATW offers very flexible option to complement and improve the presently available geological storage solution.

2. THE ACCELERATOR-DRIVEN TRANSMUTATION RESEARCH

2.1 System studies

Since 1992 different ATW systems have been studied in order to optimize transmutation performance, safety requirement, and economical and technological constraints. First systems based on heavy water moderator and fuel suspensions / solutions have been assessed [1]. Those systems had, however, significant problems to fulfill basic safety requirements concerning performance safety and economics. Then the molten-salt based thermal neutron systems have been extensively studied showing promising results [1,2]. In the mean time Japanese program

OMEGA was focused on using fast neutron spectrum in liquid fuel molten-chloride systems or fast-breeder like subcritical devices with solid fuel and sodium cooling [1,3,4]. In 1995 Carlo Rubbia and his CERN-based group proposed the system based on solid fuel (Th fuel cycle for energy production and Pu/ minor actinide fuel for transmutation) and liquid lead coolant [5]. CEA-Cadarche has also started a broad research project (ISAAC and GEDEON) to assess the feasibility of ADS based on the fast neutron spectrum [1]. It became a clear necessity to investigate very carefully the transmutation performance of ADS depending on the neutron spectrum of the system. Our system studies in 1996 were therefore focused on the impact neutron spectrum on the performance of ATW. An extensive analysis of the simulation results were performed and it is now being prepared for publications [6]. The results of this analysis show that liquid lead as a coolant and neutron propagator opens interesting possibilities to keep the constant transmutation rates for many isotopes in a wide range of concentration in the fuel. It makes it also possible to reach the resonance cross section region for some cumbersome fission products like ^{99}Tc and ^{129}I.

2.2 Simulations, optimization and design of spallation target.

One of the most important component of an accelerator-driven transmutation system is a high efficient target for neutron production. In principle, the most efficient neutron production is obtained when the high power proton beam from the accelerator is stopped in a heavy material like e.g. lead, bismuth, tungsten or uranium. The protons split the atoms of the heavy materials by a number of complex nuclear reactions (spallation reactions). Each proton produces a large number of neutrons (about 30 neutrons/ 1 GeV proton) which number depends on the energy of the incoming proton and to a less extent the type of heavy material.

Being a part of the extensive international collaborative effort we have decided to concentrate a part of our research and management activities to the spallation target design and manufacturing. In a close collaboration with H. Condé (Uppsala University), C. Mileikowsky (Spallator Group) and our international partners: Los Alamos (USA), CEA-Cadarache (France) and PSI (Switzerland) we formulated, supervised and finally lead to the approval decision an ISTC (International Science and Technology Center in Moscow) project to manufacture the 1 MW liquid lead-bismuth. The title of the project is : **Pilot flow lead-bismuth target of 1 MW for accelerator-based systems** (ISTC project # 559). The cost for this project is 1 M$ and is fully covered by ISTC.

The purpose of the project is to develop a heavy metal flow target which posses the best features for producing neutrons at a high power proton accelerator. Thus, the technical key problems of a flowing lead-bismuth 20 MW-power target should be investigated. Such a technical base will be established by the design of a pilot lead-bismuth 1 MW-power target. It is proposed and agreed that the pilot target will be tested at the LANSCE accelerator at LANL (LANSCE: 800 MeV, 1.5 mA linear proton accelerator) or as an alternative at the Paul Scherrer Institute (PSI), Villigen, Switzerland.

Extensive simulations have been performed to optimize the size and neutron production for this target using FLUKA-96 [7] high energy transport code. Also the radiotoxicity of the spallation products were investigated in the frame of Master of Science thesis work done by J. Carlsson [8].

The calculations of heat generation and potential material damages around the active part of the target are being performed in collaboration with Politecnica Torino as MSc thesis by our guest student Alberto Talamo.

2.3 Coordinated research project (CRP): "Potential of Th-based Fuel Cycles to Constrain Pu and Reduce Long-term Waste Toxicities"

The IAEA CRP to benchmark the calculational tools used in the ADS simulations started in the middle of 1996 and is in its final phase. Extensive calculations comprising spallation neutron source simulations (with FLUKA-96 [7]), neutron transport (MCNP) and burnup simulations have been performed in order to compare the results of the simulations of the relatively simple ADS with the results of other groups participating in this CRP (France, Italy, CERN, Germany). These calculations are carried out by J. Wallenius and K. Tucek, who is a postgraduate guest student from Czech Republic.

The results of this CRP will be published in few months.

2.4 Development of the computer code systems.

The work has been started to develop the integral computer code system to simulate fully the accelerator driven system beginning from the ingoing proton beam and ending on the radiotoxicity of the residual waste. This project which is planned to continue for several years in collaboration with Dubna (Russia), Karlsruhe (Germany), CEA-Cadarache (France) and LANL (USA) will give us the powerful tool to perform the feasibility studies of ADS and could be the basis for conceptual design of demonstration experiment.

2.5 Experimental activities.

In 1996 we started the collaboration with CEA-Cadarache in order to participate in their experimental program on MASURCA reactor in the subcritical configurations. The MASURCA zero-power critical facility in Cadarache allows to set up a wide range of critical or subcritical configurations with fast neutron spectrum, using a variety of different fuels and simulated coolant materials (like Na), in different proportions. For the MUSE-1 experiment an existing loaded core was used (fueled with UO_2 - PuO_2; ratio of Pu/(Pu+U) approximately equal to 0.25, and with simulated Na coolant). In the central channel of the core it was possible to load a ^{252}Cf neutron source, which was located successively at three axial position. Starting from a critical configuration without external source, the core was made subcritical , by unloading some peripheral fuel elements.

The following measurements have been performed :

- sub-criticality level,
- ^{235}U fission rate radial and axial distributions,
- φ^* measurement [1].

The experiments on MASURCA will be continued and the results will be published in 1997. Our intention is to extend this collaboration.

2.6 Organisation of the 2nd International Conference on Accelerator-Driven Transmutation Technologies and Applications, Kalmar 3-7 June, 1996

Royal Institute of Technology was one of the main organizers of the Kalmar Conference. 207 participants from 24 countries took part in the 2nd International Conference on Accelerator Driven Transmutation Technologies and Applications in Kalmar. It is interesting to conclude that countries with the very different nuclear policies were represented on this Conference. Beginning from the countries which are or have been intensively developing nuclear power like Japan, South Korea and France, through countries which seriously consider the development of the large scale nuclear power like China and ending with countries which shut-down or are planning to shut-down the nuclear power (Austria, Italy, Sweden). It indicates that ADTT have attractive solutions to offer for the back-end of the nuclear fuel cycle including the management of the reactor-grade and excess weapon plutonium and possibly for the future development of nuclear power systems [9].

3. COLLABORATION

Sweden

Swedish cooperation in 1996 conducted as concerted projects consisting of the representatives from universities and industry was focused on arranging the Second International Conference on Accelerator Driven Transmutation Technologies and Applications, Kalmar, June 3-7, 1996 (see ref. [1]). Moreover the so called Spallator Group (H. Condé, C. Mileikowsky, J-O Liljenzin and W. Gudowski) was formed to coordinate Russian activities in Accelerator-Driven Systems financed by Sweden in the frame of the International Science and Technology Center in Moscow.

In October 1996 ISTC board approved the project "Pilot flow lead-bismuth target of 1 MW for accelerator-based systems (ISTC project # 559)" which will result in designing and manufacturing of the spallation target for the international experiment on the Los Alamos linear accelerator. The Spallator Group has initiated and conducted this project until the approval decision. RIT is one of the international collaborators and coordinators of this project and will actively participate in the manufacturing of the spallation target.

The participating universities and industries in the Swedish coordinating group are:

- **Royal Institute of Technology**, Stockholm, T. Thedéen, W. Gudowski, J. Wallenius, E. Möller and J. Carlsson.
- **Chalmers University of Technology**, Göteborg, J.O. Liljenzin, M. Skålberg, A. Landgren, L. Spjuth and I. Hagström.
- **Uppsala University and The Svedberg Laboratory** H. Condé, E. Traneus, A. Bäcklin, S. Carius (Kalmar University) and J. Thun.
- **Manne Siegbahn Laboratory**, Stockholm, M. af Ugglas
- **Experts on reactor technology**, K. Hannerz, C. Sundkvist, C. Pind, E. Tenerz and C. Mileikowsky.

IAEA

W. Gudowski has accomplished his work as an editor of the IAEA Status Report on Accelerator-Driven Systems (see ref. [1])
Royal Institute of Technology is participating in the IAEA Coordinated Research Program on the Hybrid Systems. The project is in progress and will be published in May - June 1997.

EC

A collaboration with CEA Cadarache/FR, ECN Petten/NL, KFA Jülich/DE, ENEA Casaccia/IT, FZK Karlsruhe/DE, JRC-ITU Karlsruhe/DE, AEA Techn Harwell/UK, Univ. Uppsala/SE, ENEA Bologna/IT, Chalmers Tekniska Högskola (CTH)/SE started on 1 st of May 1996. The project is funded by the EC (IABAT project, FI4I-CT96-0012) in the IV Framework Programme.
W. Gudowski is coordinator of this project.
Half-year progress report is already available and can be obtained from EC.

France
A close and broad collaboration has been established with CEA-Cadarache. The collaboration has several platforms: in the frame of the EC-IABAT project, bilateral collaboration between RIT and CEA (e.g. participation in the subcritical experiments on Masurca experiments - see paragraph Experimental activities) and international collaboration with LANL, CERN and some smaller partners. This international collaboration has as a main objective to design and accomplish first demo-experiment on the accelerator-driven system, to collaborate and coordinate international effort in Russia in the frame of ISTC-funding.

It is worthwhile to note that France has a very dynamic development of ADS projects. ISAAC (CEA) and GEDEON (CEA+CNRS) projects reached the financing level of about 30 millions FF and there are further plans to get funds for a major experimental activities.

USA
Collaboration between LANL and RIT which was initiated in 1992 has further developed under 1996. We have regular exchange of researchers, exchange of the research results and we are coordinating some our research activities. Manufacturing of spallation target in Obninsk Russia is one of the spectacular good results of our collaboration. We continue preparations for the international collaboration and experiments (under the title LIFT-1) in the field of liquid lead/bismuth technology, subcritical reactor design, transmutation optimization and safety assessments.

Russia
A collaboration with Russia which was initiated 1994 in the frame of the ISTC Project 17 "Feasibility Study of Principal Technologies in Accelerator Based Conversion of Military Pu and Long-Lived Radioactive Waste" and has developed into several important projects: manufacturing of the spallation target (Obninsk - ISTC), medium energy cross-section measurements (St. Petersburg - ISTC), development of the code system for high energy charged particle transport and neutronic calculations (Dubna - bilateral collaboration).

Italy
Besides the collaboration in the frame of EC IABAT project, research projects has been established with Politecnic in Turin. The graduate student is doing his MSc thesis at our Institute on heat deposition, material damages and radiotoxicity of spallation products.

Japan
A collaboration which was initiated in 1993 between our Institute and JAERI-group involved in OMEGA-project has continued under 1996. This collaboration includes information exchange an coordination of some research activities mainly in the spallation process area.

Czech Republic
The postgraduate student from Czech Republic has conducted some research in our institute on Monte-Carlo simulations of ADS systems and on burnup optimization calculations. Moreover we coordinate our activities in the molten salt investigations which are under preparations at the institute in Rez.

4. SCIENTIFIC EXCHANGE. TRAVELING AND GUEST RESEARCHER VISITS AT THE ROYAL INSTITUTE O TECHNOLOGY

Visits to at the Royal Institute of Technology:

1996-01-03-07	Visit of Dr. V. Kazaritsky (Institute of Theoretical and Experimental Physics). Seminar given at Royal Institute of Technology.
1996-05-22-29	Visit of Dr. F. Venneri (Los Alamos National Laboratory). Seminars given at Swedish Defence Research Institute (FOA), Royal Institute of Technology, Uppsala University.
1996-06-10-14	Visit of Dr. H. Takahashi (Brookhaven National Laboratory). Seminar given at Royal Institute of Technology.
1996-10-15-18	Visit of Dr. F. Venneri (Los Alamos National Laboratory). Seminars given at Royal Institute of Technology and Uppsala University.

International conferences, meetings etc. :

Nuclear Methods for Waste Transmutation , Workshop at Joint Institute for Nuclear Research, Dubna, Russia May 29-31, 1996 (Appendix I)
"Accelerator-Driven Systems - Survey of the Research Programs in The World", Waclaw Gudowski (invited speaker)

2nd International Conference on Accelerator Driven Transmutation Technologies and Applications, Kalmar, June 3-7, 1996.
"ADTT Safety Aspects", T. Thedéen (invited speaker) (Appendix III)
"Conference Wrap-Up", Waclaw Gudowski (invited) (Appendix II)

General Assembly of the International Union of Pure and Applied Physics, Uppsala, September 19-20, 1996
"Accelerator-Driven Systems - New Perspective for Fission Energy", W. Gudowski (invited speaker)

International Symposium "New Generation of the Nuclear Power Plants", Warszawa, September 23-25, 1996.
"Computer Simulations of the Accelerator-Driven Systems", W. Gudowski (invited lecture)

NATO-Workshop on Advanced Nucelar Systems Consuming Excess Plutonium, Moscow October 13-16, 1996.
"Accelerator-Driven Systems - New Perspective on Fission Energy", Waclaw Gudowski (invited speaker)

International Peer Review Workshop of the Accelerator-Driven Transmutation Technologies Project at the Los Alamos National Laboratory, Los Alamos, October 15-16 1996.
"Accelerator-Driven Systems - Swedish and European Research Activities", W. Gudowski (invited speaker)

ISTC P#17 Workshop : **Feasibility Study of Principal Technologies in Accelerator Based Conversion of Military Pu and Long-Lived Radioactive Waste,** Moscow, December 2-4, 1996.
"Review of the Results of ISTC P#17 Project", W. Gudowski (invited).

IAEA Consultancy on Hybrid Concepts for Nuclear Energy Generation and Transmutation, Vienna, December 16-17 1996. W. Gudowski (invited expert)

Waclaw Gudowski became a member of programme committees for two international conferences:
International Conference: Nuclear Data for Science and Technology (Trieste, 19-24 May, 1997) and International Conference on Future Nuclear Systems Global-97 (Yokohama, October 5-10, 1997)

February 1996 T. Thedéen, W. Gudowski and E. Möller gave seminar at SKB presenting this research project.

5. REFERENCES

[1] W. Gudowski (editor), IAEA Status Report on Accelerator-Driven Systems, Vienna 1997 (in print - see also network edition of this report at http://www.neutron.kth.se)

[2] W. Gudowski, "Accelerator-driven Systems - Survey of the Research Programs in the World", Nuclear Methods for Transmutation of Nuclear Waste: Problems, Perspectives, Cooperative Research, World Scientific 1997 (Appendix I)

[3] YOSHIDA, H. et al.: "A Strategic Study of the Partitioning and Transmutation System being Developed at JAERI", Proc. Int. Information Exchange Meeting on Actinide and Fission Product Separation and Transmutation, ANL (1992).

[4] Takizuka, T. et al.: "Conceptual Design Study of an Accelerator-based Actinide Transmutation Plant with Sodium-cooled Solid Target/Core", ibid.
Katsuta, H. et al.: "A Continuous Transmutation System for Long-lived Nuclides with Accelerator-driven Fluid Targets", ibid.

[5] Rubbia, C., Buono, S., Gonzales, E., Kadi, Y., and Rubio, J. A., A Realistic Plutonium Elimination Scheme with Fast Energy Amplifiers and Thorium-Plutonium Fuel, CERN/AT/95-53, 1995.

[6] E. Möller and W. Gudowski, "Impact of the neutron energy spectrum on the performance of the Accelerator-driven transmutation of waste" (to be published in Kalmar Conference Proceedings).

[7] A. Fasso, A. Ferrari, P. Sala and J. Ranft, FLUKA-96, e.g. CERN manual, 1996. Also: http://www.hut.fi/...../prfluka.html.

[8] J. Carlsson, "Optimisation of the neutron production in spallation target with FLUKA", Msc-thesis at the Department of Nuclear and Reactor Physics, Royal Institute of Technology, Stockholm 1996.

[9] W. Gudowski, "2nd International Conference on Accelerator Driven Transmutation Technologies and Applications - Conference Wrap-Up", Proceedings of the 2nd International Conference on Accelerator Driven Transmutation Technologies and Applications, Kalmar 3-7 June, 1996. (Appendix II)

Appendix I

ACCELERATOR-DRIVEN SYSTEMS - SURVEY OF THE RESEARCH PROGRAMS IN THE WORLD

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ABSTRACT

An overview of the projects in accelerator-driven nuclear technologies is presented together with short characteristics of these projects. Possible impact of accelerators on nuclear energy production and transmutation of nuclear wastes is preliminary assessed.

1. Introduction

Intense, external neutron sources combined with nuclear reactors into so called hybrid systems (frequently called Accelerator-Driven Systems - ADS), can very significantly improve the neutron economy of the conventional nuclear reactors. Improved neutron economy gives consequently an excess of neutrons which may be usefully utilized to convert non-fissile materials into nuclear fuel as well as for transmutation of some long-lived radioactive isotopes into short-lived or even nonradioactive ones. Fissile material breeding in Thorium fuel cycle and possibilities for extended burnup are also attractive options for these hybrids.

The first practical attempts to promote accelerators to generate potential neutron sources were made in the late 1940's by E.O. Lawrence [1] in the United States, and W.N. Semenov in the USSR. The first application proposed was the production of fissile material in the frame the MTA project at the Lawrence Livermore Radiation Laboratory [2]. This project was abandoned in 1952 when high grade Uranium ores were discovered in the United States. The Canadian team at Chalk River always has been strong proponent of such a producer of fissile material which could be used in conjunction with a conversion-efficient CANDU reactor [3].

When US administration decided to slow down the development of the fast breeder in the United States to promote the non-proliferation of weapon fissile material, Brookhaven National Laboratory presented several proposals for accelerator breeders such as the Na-cooled fast reactor target, the Molten Salt target, the He-gas-cooled target, as well as the LWR fuel regenerator [4].

This concept of the accelerator breeder also has been studied by Russian scientists.

Under the guidance of V.I. Goldanski, R.G. Vassylkov made a neutron yield experiment in depleted Uranium blocks using the accelerator at Dubna [5].

The original idea of exploiting the spallation process to transmute actinide and fission products directly soon was abandoned. The proton beam currents required were much larger than the most optimistic theoretical designs that an accelerator could achieve, which are around 300 mA. Indeed, it was shown that the yearly transmutation rate of a 300 mA proton accelerator would correspond only to a fraction of the waste generated annually by a LWR of 1 GW_{el}.

In last few years hybrid systems were proposed for different purposes. ADS on fast neutrons for the incineration of higher actinides was proposed at Brookhaven National Laboratory (PHOENIX-project) and now is carried out in Japan as a part of OMEGA-programme. Los Alamos National Laboratory has developed several ideas - under the common name: Accelerator-Driven Transmutation Technologies (ADTT) - to use the hybrid system on thermal neutrons with a linear accelerator for incineration of Plutonium and higher actinides as well as for transmutation of some fission products in order to reduce effectively long-term radioactivity of nuclear waste. Three years ago Carlo Rubbia and his European group at CERN proposed cyclotron based hybrid system to produce nuclear energy based on the Thorium fuel cycle. This is an attractive option reducing the concerns about higher actinides in the spent fuel and opening the possibility to utilize cheap and abundant Thorium. Some preliminary experiments were already performed by the CERN-group

The more detailed description of these projects will be presented in the next chapters.

Accelerator-Driven Systems with their transmutation potential are considered to be an alternative approach for the nuclear waste management compared to the final geological repository projects. Separation of the long-lived nuclei from the high-level waste and transmuting them into short-lived or non-radioactive wastes would ease a lot of constraints for geological repositories, may significantly reduce their costs and increase the public acceptance.

ADS can also address the safety issues associated with criticality, which are perceived as serious for nuclear reactors. ADS operates in non self-sustained chain-reaction mode and therefore minimizes the criticality concern. ADS is operated in a subcritical mode and stays subcritical, regardless of the accelerator being on or off. The accelerator provides a convenient control mechanism for subcritical systems than that provided by control rods in critical reactors, and subcriticality itself adds an extra level of operational safety concerning criticality accidents. As described later, a subcritical system driven with an accelerator decouples the external neutron source (spallation neutrons) from the fissile fuel (fission neutrons). Accelerator driven systems can in principle work without safe-shutdown mechanisms (like control rods) and can accept fuels that would not be acceptable in critical systems.

The technology of accelerating a charged particle to high energy has been well demonstrated in recent years, as has the technology of the target. However, extension of this capability to high-current beam-acceleration is required.

2. Transmutation and Spallation

The basic process of accelerator-driven nuclear systems is nuclear transmutation. The nuclear transmutation was first demonstrated by Rutherford in 1919, who transmuted ^{14}N to ^{17}O using energetic α-particles. I. Curie and F. Joliot produced the first artificial radioactivity in 1933 using α-particles from naturally radioactive isotopes to transmute boron and aluminum into radioactive nitrogen and oxygen. It was not possible to extend this type of transmutation to heavier elements as long as the only available charged particles were the α-particles from natural radioactivity, because the Coulomb barriers surrounding heavy nuclei are too great to permit the entry of such particles into atomic nuclei. Transmutation processes can be induced efficiently - as shown on Fig.1 - mainly by photons, neutrons and charged particles. However, due to small cross-sections, the use of photons is very limited; charged particles bombarding directly the transmutation target are also of very limited use due to the Coulomb barrier. Neutrons are by far the most efficient transmutation tool. The conventional nuclear reactors, specially those types with a good neutron economy, can be used as a neutron source for transmutations purposes. Accelerator-Driven Systems are also one of the options. High power accelerators coupled with the spallation process can be used to produce large numbers of neutrons, thus providing an alternative method to the use of nuclear reactors for this purpose. Spallation offers exciting new possibilities for generating intense neutron fluxes for a variety of purposes.

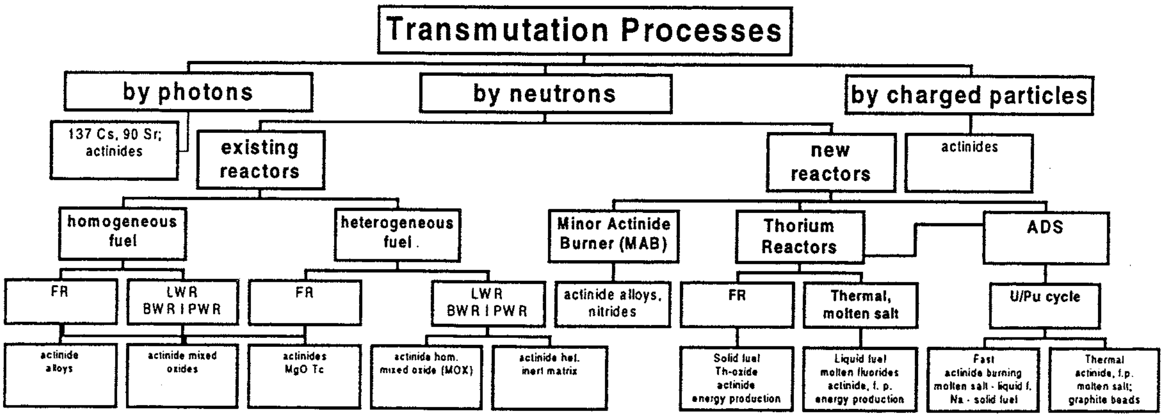

Fig. 1 Classification of the transmutation processes

Spallation refers to nuclear reactions that occur when energetic particles (e.g. protons, deuterons, neutrons, pions, muons, etc.) interact with atomic nucleus - the target nucleus. In this context "energetic" means kinetic energies larger than about 100 MeV per nucleon. At such energies the nuclear reactions do not proceed through the formation of a compound nucleus. The initial collision between the incident projectile and the target nucleus leads to a series of direct reactions whereby individual nucleons or small groups of nucleons are ejected. At energies above a few GeV per nucleon, fragmentation of the nucleus can also occur. After the initial phase, the nucleus is left in en excited state and subsequently relaxes to its ground state by "evaporating" nucleons, mostly neutrons [6].

The spallation process is illustrated in Fig. 2, showing two stages of the process (intranuclear cascade and evaporation). For thick targets, high energy (>20 MeV) secondary particles (and their progeny) can cause further spallation reactions in the target. For some targets materials, low energy (<20 MeV) spallation neutrons can enhance neutron production through (n,xn) reactions. For heavier nuclei, high energy fission will compete with particle evaporation from highly-excited nuclei, see Fig. 2. Tantalum, tungsten, lead and bismuth are examples of potential targets.

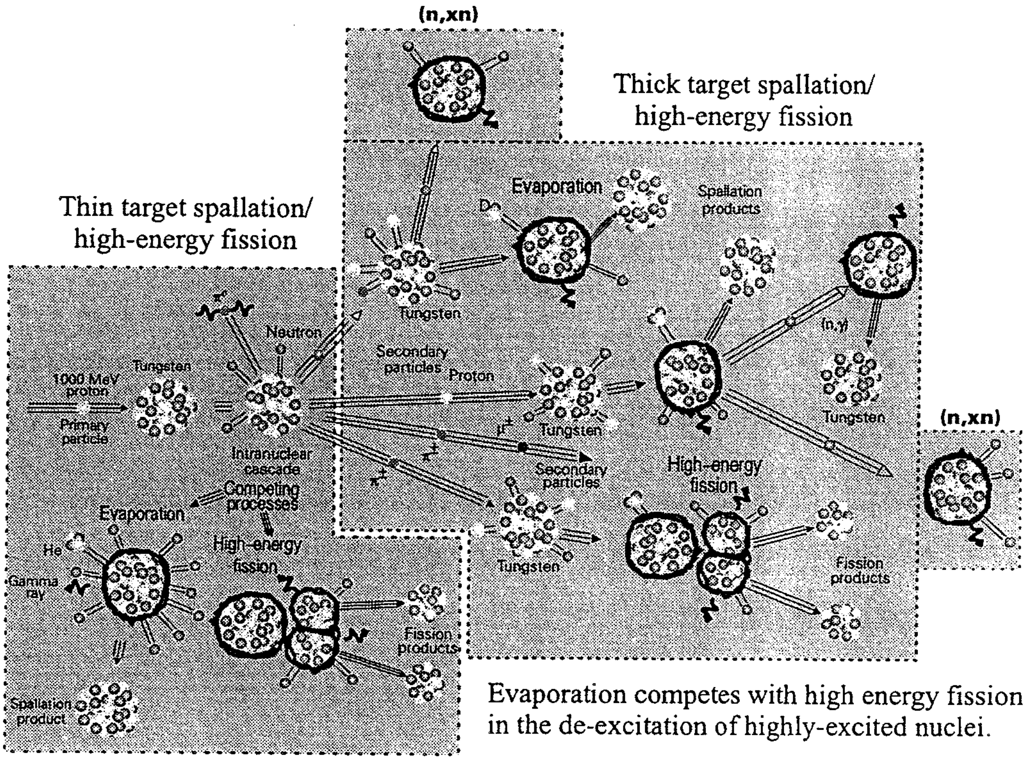

Fig. 2 Illustration of high-energy processes in a spallation target [6].

Some target materials, such as ^{232}Th and ^{238}U, can also be fissioned by lower energy (~1 MeV to ~20 MeV) neutrons. Spallation, high energy fission and low energy fission produce different nuclear debris (spallation and fission products).

The high power accelerator technology required for ADS has been under continuous development for the past decades. Linear accelerators, linacs, have been developed into highly reliable and efficient research (and military) tools. There is confidence in that a high power (200 mA, 1.6 GeV), continuous wave (CW) accelerator can be built at a reasonable cost (In October 1995 the US DOE committed to the demonstration of the accelerator technology for application to tritium production). On the other hand the technology the of circular proton accelerators, such as the segmented cyclotron or synchrotron recently improved so that a proton beam of 10-15 mA is achievable. The cyclotron does not require a large physical area and has some other benefits compared to linac. In recent evaluations it was found that the most efficient operation current for a cyclotron-type machine would be ~10 mA and for a linear accelerator ~100 mA.

The function of the spallation target in the ADS is to convert the incident high energy particle beam to low energy neutrons. These requirements can be summarized as:

1. Compact size to enable good coupling to the surrounding blanket,
2. High power operation, on the order of 10 to 100 MW,
3. High neutron production efficiency,
4. Reliable and low maintenance operation,
5. Safe and low hazard operation,
6. Small contribution to the waste stream.

It is believed today that molten lead or molten lead-bismuth eutectic (LBE) are the best target choices, meeting most of the requirements above. A problem with LBE, however, is the production of radioactive and highly mobile polonium isotopes, especially ^{210}Po, from high energy proton and neutron reactions on lead and bismuth. This will be a concern because the polonium in the LBE will be rapidly released at operating temperatures. Pure lead, on the other hand, has a lower polonium production, but higher operating temperatures. Further assessments are needed in order to make a choice between these target materials.

The thermal cross-sections for transmuting MA and FP are larger than the fast neutron cross-sections. However, the thermal neutron cross-sections of the transmutation products are also large. It is therefore desirable in thermal systems to remove the products in order to reduce unproductive losses of neutrons. The capture of fast neutrons by the fission products and by the structural material is smaller than for thermal neutrons and, from the point of neutron economy, a fast reactor is better than a thermal reactor. Also, one would like to take advantage of the high η-values for ^{239}Pu and the other actinides to produce extra neutrons by high-energy fission for use in transmutation of the long-lived fission products.

As mentioned above the Thorium-Uranium fuel cycle is very attractive for future ADS. It has at least two advantages over the traditional Uranium-Plutonium cycle used in most nuclear reactors:

1. The Thorium-Uranium cycle produces a smaller amount of higher actinides than the Uranium-Plutonium cycle, because of the small capture to fission ratio in ^{233}U and because of the presence of two other fissionable isotopes of Uranium (^{235}U and ^{237}U) in the chain leading to Plutonium and the other heavier actinides
2. The Thorium-Uranium cycle is perceived as safer than the Uranium-Plutonium cycle from a nuclear weapons proliferation standpoint, because of the presence of the hard-γ emitter ^{232}U as a minor product of the cycle, and because it is imagined that an isotopic dilution of ^{233}U with depleted or natural Uranium in the feed, or in the start-up fuel, would make ^{233}U difficult to extract in pure form.

The very generic scheme of the Accelerator-Driven System is presented on Fig. 3.

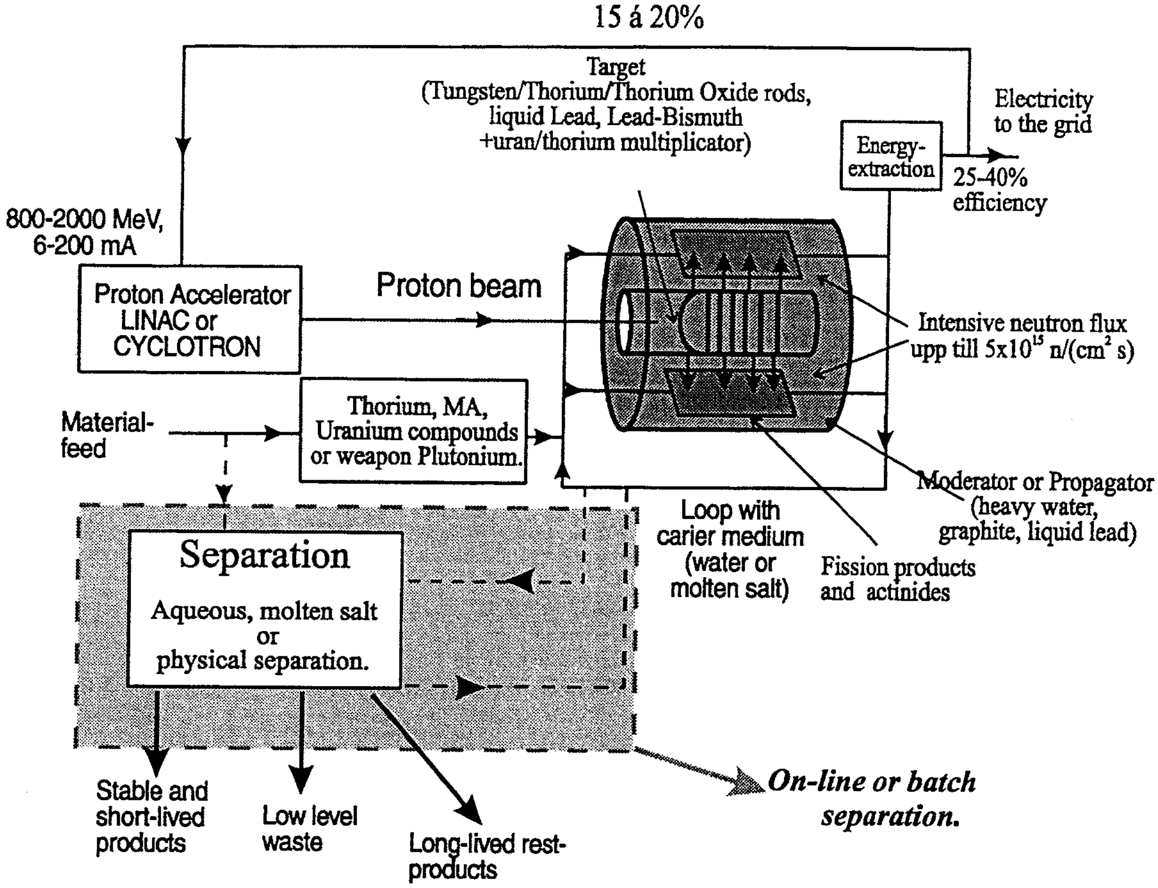

Fig. 3. A generic scheme of the Accelerator-Driven System.

3. Review of the existing projects

Fig. 4 shows a classification of existing ADS concepts according to their physical features and final objectives. The classification is based on neutron energy spectrum, fuel form (solid, liquid), fuel cycle and coolant/moderator type, and objectives for the system. ADS systems - like reactors - can be designed to work in two different neutron spectrum modes - on fast or on thermal neutrons. The CERN-group headed by C. Rubbia investigates the possibilities (CERN application to EC, 1995) to design a system which will exploit the neutron cross-section resonances in what could be classified as a "resonance neutron" mode. Both, fast and thermal systems are considered for solid and liquid fuels. Even quasi-liquid fuel has been proposed based on the particle fuel (pebble bed) concept developed by BNL.

The objective for some nuclear transmutation systems is to transmute existing nuclear wastes from light water reactors, mainly Pu and minor actinides, with or without concurrent

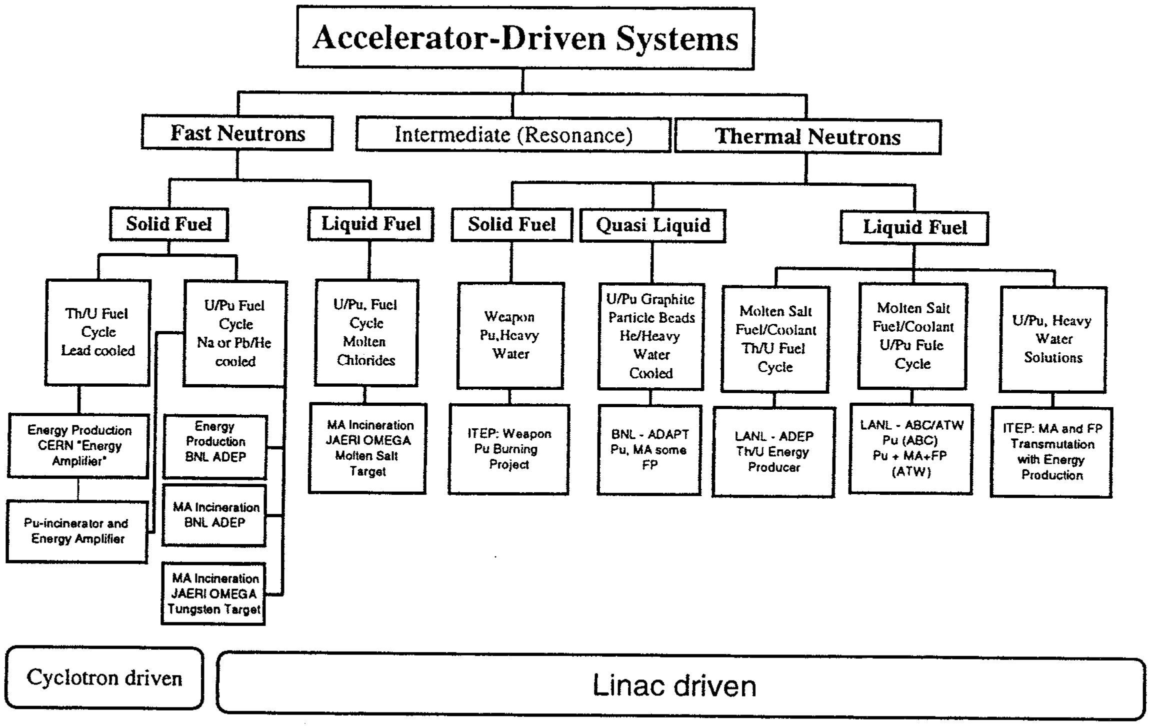

Fig. 4 Classification of existing ADS concepts

energy production. These projects can be classified as an attempt to close the LWR-fuel cycle. Other systems are designed to take advantage of the Thorium fuel cycle for energy production. As can be seen in Fig. 4 most concepts are based on linear accelerators. The CERN-group and BNL propose to use a proton cyclotron.

3.1 Los Alamos National Laboratory ADTT-program

Nuclear systems under study in the Los Alamos Accelerator-Driven Transmutation Technology program (ADTT) have multiple objectives: the transmutation of nuclear spent fuel and weapons-return Plutonium, as well as the production of nuclear energy from the Thorium cycle, without a long-lived radioactive waste stream. LANL claims that ADTT can phaseout production and eliminate world inventory of reactor and excess-weapons Plutonium in 30 years [7] and can provide an alternative to conventional nuclear reactors and allow the complete utilization of fertile fuel (Thorium) without excess breeding or the use of enriched material at any time in the cycle [8]. Finally ADTT systems can reduce the requirements for long-term storage of radioactive waste [9]. LANL uses general ADTT nuclear design in all three basic applications of the concept. ADEP (Accelerator-Driven Energy Producer) is a Thorium based energy producer, ATW (Accelerator Transmutation of Waste) feeds on spent fuel, ABC (Accelerator Based Conversion) burns weapons-return Plutonium. All these systems produce electricity and short-lived or stable fission product isotopes only (Fig. 5).

The subcritical systems proposed by the ADTT program represent a departure from traditional nuclear concepts (reactors), yet they strive to keep the best that the technology developed over the years, within a sensible conservative design envelope.

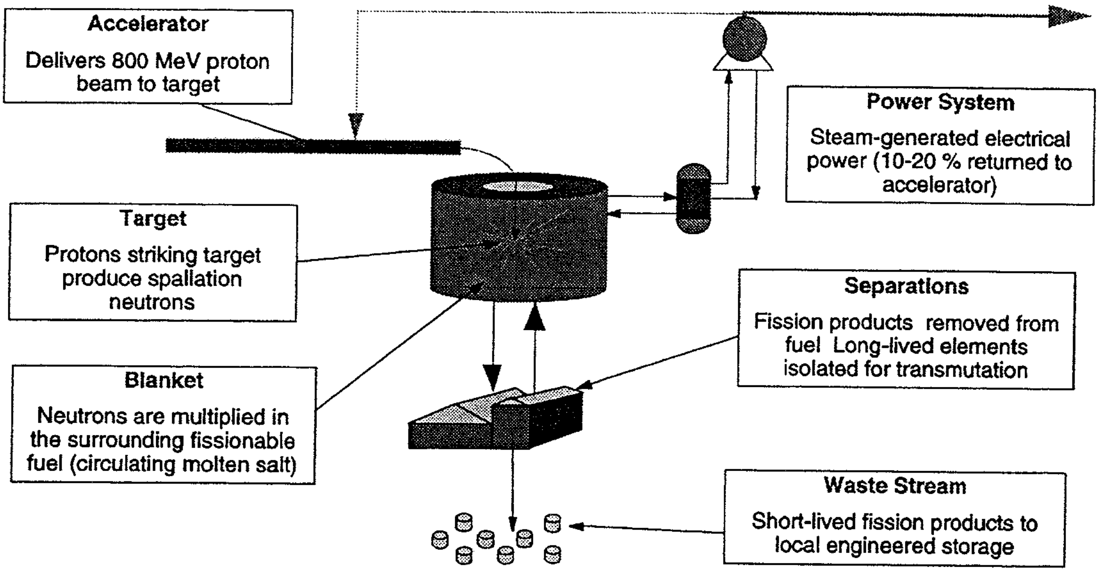

Fig. 5. The main elements and functions of a Los Alamos ADTT system.

The main elements and function of a Los Alamos ADTT system are illustrated in Fig. 5 for a system which generates nuclear energy from Thorium and destroys its long-lived high-level fission product waste. The system starts with ^{232}Th and converts it by neutron absorption into the fissile fuel ^{233}U from which energy is produced. The system consists of a reactor referred to in the figure as the target-blanket which contains the fissile material and the waste to be transmuted. For a reactor each fission on average produces enough neutrons after losses to cause another fission so that the chain of fissions is continuous. For all ADTT systems, the losses are made somewhat larger by the loss of neutrons for waste transmutation so that there is no self-sustained chain reaction. Therefore by itself the system is passive and inoperative. However, by making up for the 5-10 % loss of neutrons from an external neutron source, the system would function effectively even though the chain reaction would not be self-sustaining.

3.1.1 *ABC*

The Los Alamos National Laboratory has proposed an accelerator-driven subcritical system in which fission product poisons are allowed to build up until not only sufficiently to consume the excess fission neutrons from ^{239}Pu fission, but also the supplemental neutrons from the accelerator [10]. The system achieves very high burn up without fuel reprocessing or fuel fabrication and refabrication. Also no fission product removal is required. The General Atomics Corporation has proposed a program with a similar objective. Its helium-cooled graphite-moderated reactor with ^{239}Pu fuel particles suspended in the graphite has been proposed as the first stage of ^{239}Pu destruction. After the Pu has been burned sufficiently that it will not sustain criticality, the fuel is transferred to an accelerator-driven assembly which continues to destroy the Plutonium using accelerator-generated neutrons until k_{eff} of the system has dropped to about 0.6. The burn-up of the Los Alamos and the General Atomics systems are similar and are the highest of any of the proposed Pu-burning systems.

3.1.2 *ADEP*

Perhaps the most important element of the ADTT project over the long term is Accelerator-Driven Energy Production (ADEP) which uses Thorium as a nuclear fuel. The system is based on the Th-U cycle in which ^{232}Th is converted by neutron capture to fissile ^{233}U. This cycle has been studied extensively for use in commercial nuclear reactor power generation [11]. The primary objective of the molten salt reactor experiment was to show that an effective breeder reactor could be built on this cycle which produced more ^{233}U than it consumed. The introduction of the accelerator in ADEP helps to improve the neutron economy and largely reduces the problem of breeding efficiency which critical reactor design has to face. The accelerator-driven spallation source supplements the number of available neutrons over that which can be achieved in a critical reactor by converting some of the electric power generated into neutrons. This neutron increase allows ADEP designs to produce energy using natural Thorium as feed, without highly enriched fuels and even without chemical extraction of the protactinium precursor to ^{233}U while at the same time transmuting the internally generated radioactive wastes. To do the equivalent functions, a critical reactor would require the use of highly enriched fuels.

ADEP systems should be able to transmute most of the cumbersome long-lived fission products. ^{99}Tc and ^{129}I are the most bothersome of the fission products regarding the risk of migration out of the geological storage. Fortunately, these isotopes have high thermal neutron capture cross-sections and are easily transmuted to stable ^{100}Ru and ^{130}Xe respectively. The third most important long-lived nuclide is ^{135}Cs; to make effective use of the neutrons in the transmuter isotopic separation of the cesium nuclides is required before burning the ^{135}Cs. However, isotopic separation of ^{135}Cs and ^{137}Cs as well as ^{89}Sr and ^{90}Sr can be obtained naturally by radioactive decay in the ADEP system, exploiting the possible fast removal of their noble gas precursors from the liquid fuel. The small quantities of ^{126}Sn and ^{79}Se produced as fission products can also be readily transmuted. ^{90}Sr and ^{137}Cs are major components of the waste and are more difficult to transmute because of their very low thermal capture cross-sections. Today it seems most feasible to transmute ^{99}Tc, ^{129}I, ^{135}Cs, ^{126}Sn and ^{79}Se, which together constitute 4.5% of the total fission products generated by the ADEP during power production. The remaining fission products are made up of stable nuclides, short-lived isotopes, and long-lived isotopes that do not present significant hazards. It is unnecessary to transmute ^{93}Zr and ^{107}Pd because their radioactivity is very small, their decay modes have very low energies, and as noble metals they are not readily transported by natural means through the environment. ^{137}Cs and ^{90}Sr cannot be effectively transmuted inside the low-flux ADEP blanket because of their small cross-sections.

The design of the ADEP plant consists of various systems, or facilities, categorized as:

1. The target-blanket system, in which source neutrons generated by the interaction of a ion beam with the molten salt target are thermalized and multiplied; the fission heat generated in the fuel salt in its passage through a graphite moderated region is removed in primary heat exchangers
2. A coolant-salt circulating system, steam generators, and a turbine-generator plant for converting the thermal energy into electric power
3. An off-gas system for purging the fuel salt of fission product gases and gas-borne particulates and an associated electrolytic system for plating out noble and semi-noble metals.
4. A separation processing facility for fuel salt cleanup and recycle; this facility would continuously process a slip stream of molten salt.
5. Auxiliary salt handling equipment
6. General facilities and equipment, including controls and instrumentation, maintenance tools, auxiliary power equipment, waste management, storage and disposal systems, condensing water systems, electrical switchyard, stacks, etc.

3.1.3 *ATW*

The objective of the Accelerator Transmutation of Waste (ATW) sub-project of ADTT is to destroy the actinide and long-lived fission product waste from commercial nuclear reactor spent fuel. If the separations can be done sufficiently well, the amount of long-lived radionuclides in the remnant waste will be substantially reduced compared to LWR-wastes.

The ATW system also aims for continuous feed of waste from commercial light water reactors. Thanks to the excess neutrons provided by the accelerator, front end reprocessing is limited to the removal of the zirconium cladding and the Uranium. All of the other actinide and all of the fission product can be fed into the blanket, because the capabilities for removal of the fission product already exist in the back-end separations system.

The front-end removal system has not been selected but there are at least two options under consideration. One would involve the crushing of the spent fuel assemblies which contain mostly UO_2 and the oxidation of this to U_3O_8 Another means of removing the cladding might be to burn the spent fuel assemblies in a chlorine atmosphere over a plasma torch converting the zirconium to volatile $ZrCl_4$.

In contrast to the standard aqueous reprocessing system developed over many years and now in common use, the processes proposed for ATW do not produce a pure stream of "naked" Plutonium. The Plutonium is never separated from the highly radioactive components of the spent fuel, but only from zirconium and Uranium. The front-end separation required for the ATW therefore produces a stream which is mostly highly radioactive fission product and separation of the Plutonium from this fission product and from the other actinides would be required before it could be used in weapons.

Commercial nuclear power plants are typically sized at 3000 MW_{th} and leave about 300 kg of Plutonium and other higher actinide per year in the spent fuel while fissioning 1200 kg of fissile material per year. Therefore an ATW system operating at the same fission power level of the LWRs could burn the waste from four LWRs if its operating life were the same as the LWRs. Destroying the LWR waste arising from all LWRs in Sweden using ATW systems would require the deployment of about three 3000 MW_{th} ATW systems if the waste were to be destroyed in about 30 years. Unless the income from electric power sales were sufficient to offset the capital and operating costs of the ATW system, the cost of destroying the waste by this means could be prohibitive. The economic picture for the ATW system will be less favorable than for the Thorium-based energy producer (ADEP) system because the ADEP system need only destroy its own waste and only a modest accelerator is required for the modest neutron supplement. However the ATW system must destroy not only its own waste but also that from the three-four LWRs. Substantially more accelerator-produced neutrons are required with greater capital cost for a larger accelerator and for the additional power to the accelerator.

However, the growing concern about the increasing stock of the reactor grade Plutonium in spent fuel might change our perspective on this issue in the future.

3.2 CERN

C. Rubbia developed his early ideas to design the accelerator-driven system (so called Energy Amplifier - EA) based on the Thorium fuel cycle with solid fuel assemblies [12]. However, it was later realized that a subcritical system with solid fuel and thermal neutrons moderated in light water would be impossible to construct except for very low power units. The problem with power peaking due to the very short neutron diffusion length in light water would require very sophisticated solutions like a distributed target, permanent fuel shuffling, many accelerator beams and so on. As the result CERN-group is now investigating a system based on a fast neutron spectrum.

An Energy Amplifier (EA) module consists of a 1500 MW_{th} unit with its dedicated 1 GeV proton accelerator of 12.5 mA, see Fig. 6. A compact, reliable and modular cyclotron has been designed. A plant may consist of several such modules. The EA is a large, passive device into which a proton beam is dumped and the heat generated by nuclear cascades is extracted, without other major elements of variability. The delivered power is controlled exclusively by the current of the accelerator. There are no known major technological

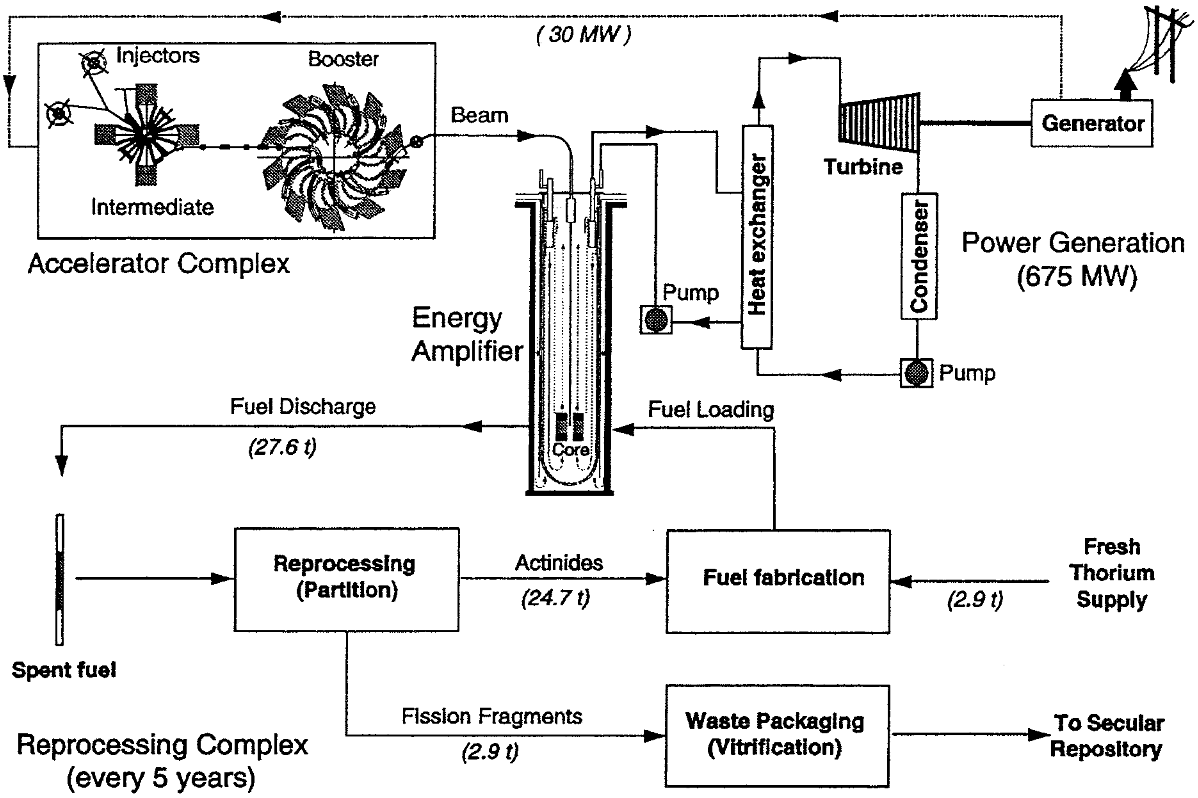

Fig. 6 Energy amplifier system according to Rubbia.

barriers to build a demonstration facility.

Rubbia estimates that after ≈700 years the radio-toxicity left is about 20 000 times smaller than the spent fuel from an ordinary Pressurized Water Reactor (PWR) for the same energy production. Geological storage (10^6 years) can be virtually eliminated or at least strongly reduced ($\leq 600\ \mu Bq/J_e$ after 1000 years). It could be further reduced ($<40\ \mu Bq/J_e$) by "incinerating" some of the nuclides. The radiation dose to individuals, truncated to 10 000 years, emanating from a given energy production is about 1/330 of the one from spent PWR fuel and about 1/33 of the dose from coal burning [13][14].

The liquid lead cooled system is partially based on Russian work and experiences with liquid lead/liquid and lead-bismuth eutectic cooled reactors (e.g. Russian submarine reactors). This system has very good safety feature ensuring large safety margins and very good neutronics. However problems connected to chemistry - especially corrosive properties of high temperature liquid lead and of the Pb/Bi eutectic put significant constraints on this concept.

The CERN-group already performed a demonstration experiment proving to a certain degree the feasibility of the Energy Amplifier concept [15]. The experiment consisted of heat measurements in 3.6 tons of natural Uranium irradiated by a high energy proton beam (1 - 3 GeV). The most interesting result of this experiment is the optimal proton energy for n-production by spallation processes in the thick target.

3.3 JAERI "OMEGA" concepts

In Japan, a national program called OMEGA was started 1988 for research and development of new technologies for P-T of nuclear waste. Under the OMEGA program, the Japan Atomic Energy Research Institute (JAERI) is carrying out research and development for proton accelerator-driven transmutation, together with transmutation based on a fast reactor burner and an advanced partitioning technology.

The project on proton accelerator-driven transmutation at JAERI includes a conceptual design study of transmutation systems and the development of an intense proton accelerator. Two types of accelerator-driven transmutation system are proposed: a solid system and a molten-salt system. Both are specifically designed for nuclear waste transmutation purposes. In either system, an actinide loaded subcritical blanket is driven by a proton accelerator and utilizes the hard neutron spectrum to burn actinides.

JAERI R&D includes the conceptual design study of accelerator-driven transmutation plant, the development of a spallation simulation code system [16], [17] and spallation integral experiments [18].

A partitioning process has been developed to separate elements in the HLW into four groups; transuranium elements (TRU), Sr-Cs, Tc-platinum group metals and the other elements . A series of laboratory-scale tests with the actual or synthesized HLW indicated that the proposed partitioning process was promising. The hot test of the entire process is to be conducted with the actual HLW at the Nuclear Fuel Cycle Safety Engineering Research Facility (NUCEF), Tokai. The chemical engineering test is also planned to start in 1996.

A special transmutation device designed to operate with a very hard neutron energy spectrum and high neutron flux can be very efficient and effective for MA transmutation. In this context, JAERI has been pursuing the concepts of an actinide burner reactor (ABR) and an accelerator-driven system as dedicated transmuter, rather than transmutation schemes based on MA recycling to commercial power reactors.

JAERI has proposed construction of an intense proton linear accelerator called the Engineering Test Accelerator (ETA) with 1.5-GeV beam energy and 10-mA average current. The main objective of ETA is to perform various engineering tests for accelerator-driven transmutation and other possible nuclear engineering applications. Toward this end, accelerator components have been developed and tested.

JAERI R&D includes the conceptual design study of an accelerator-driven transmutation plant, the development of a spallation simulation code system and the spallation integral experiments.

A small delayed neutron fraction in actinide fuel and a short neutron life-time, coupled with a small Doppler coefficient, tend to make the consequences of reactivity-initiated transient severe in critical fast reactors. The accelerator-driven subcritical system that is driven by external spallation neutrons can mitigate this safety problem and provide large margins for increasing flexibility in the design and operation. It also has an advantage in that the power of the subcritical blanket can be easily controlled by adjusting the power of incident proton beam.

The goal of the conceptual design study is to develop technically feasible concepts of the accelerator-driven transmutation system. The proposed plant is designed as a dedicated system that transmutes about 250 kg of MAs per year, which corresponds to the actinide production rate from operation of about 10 units of 3,000 MW_t light water reactor. The capacity of the unit transmutation plant was chosen tentatively based on a preliminary strategic study of the partitioning and transmutation system. The subcritical blanket is required to operate at a multiplication factor of around 0.9 to reduce the scale of the proton accelerator and improve the energy balance of the total system.

3.3.1 SOLID SYSTEM

A schematic diagram of the proposed transmutation system concept is shown in Fig. 7

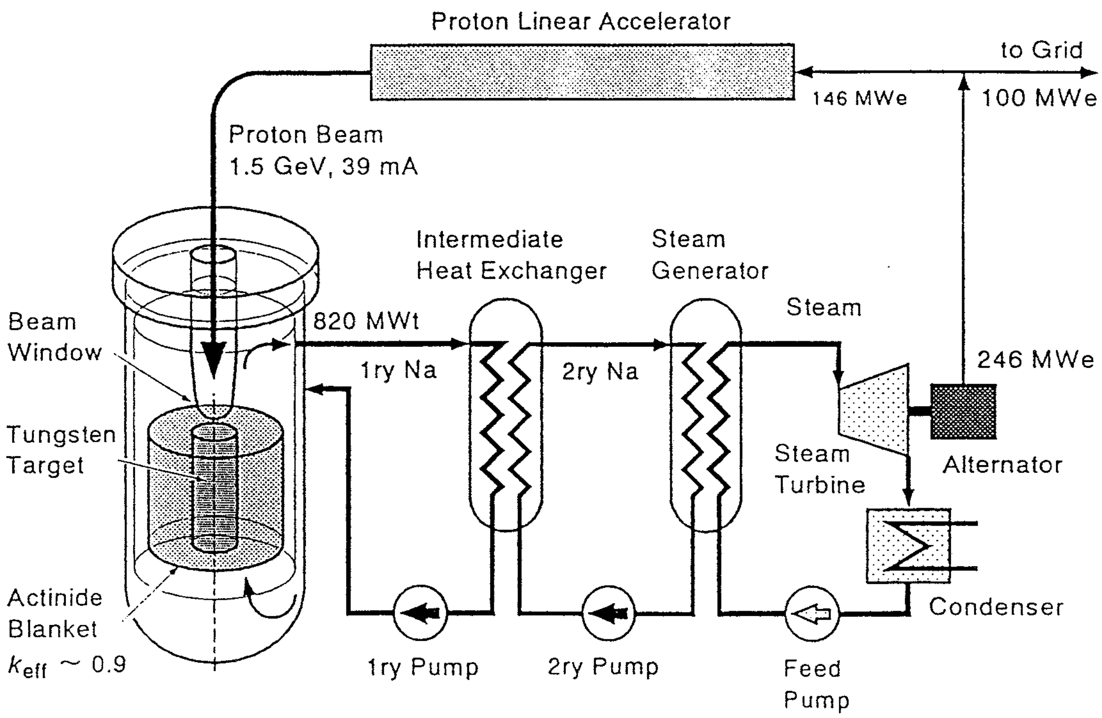

FIG. 7. Concept of accelerator-driven transmutation system with solid fuel.

[19]. The design of the system is based on the state of the art technology for a sodium-cooled fast reactor. The target/blanket operating parameters are given in Table I.

The accelerator injects a 1.5 GeV proton beam through the beam window into the target located at the center of the target/blanket. The target is made of solid tungsten. Surrounding the target is the subcritical blanket loaded with actinide alloy fuel.

TABLE I. SOLID SYSTEM TARGET/BLANKET OPERATING CONDITION

Proton Beam Current	39 mA
Actinide Inventory	3160 kg
Effective Multiplication Factor	0.89
Spallation Neutrons per Proton	40 n/p
Fissions per Proton	
(> 15 MeV)	0.45 f/p
(< 15 MeV)	100 f/p
Neutron Flux	4×10^{15} n/cm^2/s
Mean Neutron Energy	690 keV
Burnup	250 kg/y
Thermal Output	
Fuel Region	800 MW
Target Region	20 MW
Total	820 MW
Power Density	
Maximum	930 MW/m^3
Average	400 MW/m^3
Linear Rating	
Maximum	61 kW/m
Average	27 kW/m
Coolant Outlet Temperature	
Maximum	746 K
Average	703 K
Fuel Temperature	
Peak	1163 K
Surface Maximum	821 K
Clad Temperature	
Inside Maximum	801 K
Outside Maximum	757 K

A large number of neutrons are released by spallation reactions in the target, and induce further fission in the actinide blanket region. The target/blanket generates a total thermal power of 820 MW, and is cooled by the forced upward flow of sodium primary coolant. Heat is transported through the primary and the secondary loops to the power conversion system. In the energy conversion system, thermal energy is converted into electricity. A part of electric power is supplied to the systems own accelerator.

3.3.2 MOLTEN-SALT SYSTEM

A preliminary conceptual design study is being performed on an 800-MW$_t$ molten-salt target/blanket system as an advanced option for an accelerator-driven nuclear waste transmutation system [20]. Figure 8 schematically shows the proposed molten-salt system concept. Chloride salt with a composition of 64NaCl-5$PuCl_3$-31$MACl_3$ (where MA represents Np, Am, and Cm) is chosen for the molten-salt system based mainly on the consideration of actinide solubility. The molten-salt acts both as fuel and as target material, and at the same time it also serves as coolant in the molten-salt system. This significantly simplifies the target/blanket system configuration.

A high energy proton beam at 1.5 GeV is injected into the central target/blanket region through the beam window. The target/blanket region is surrounded by an internal reflector. Intermediate heat exchangers and salt pumps are installed in the annular region around the internal reflector. This in-vessel heat exchanger design minimizes the total actinide inventory in the system.

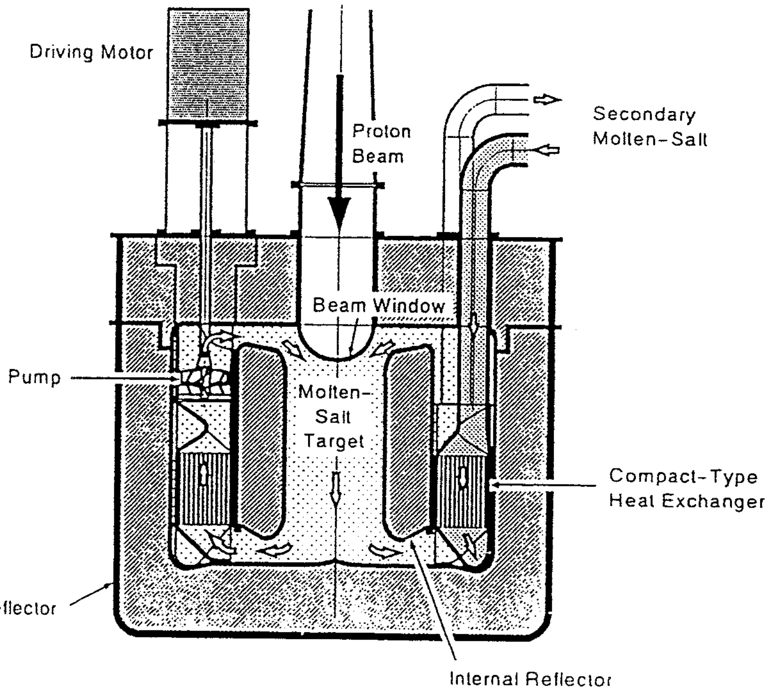

FIG. 8. Concept of molten-salt target/blanket system.

Table II shows the major parameters of molten-salt target/blanket system.

TABLE II. MAJOR PARAMETERS OF MOLTEN-SALT TARGET/BLANKET SYSTEM

Fuel	Chloride Salt $64NaCl\text{-}5PuCl_3\text{-}31MACl_3$ (MA: Np, Am, Cm)
Target	Chloride Salt
Coolant	Chloride Salt
Actinide Inventory	5430 kg
Neutron Multiplication Factor	0.92
Spallation Neutrons per Proton	38 n/p
Proton Beam	1.5 GeV - 25 mA
Thermal Power	800 MW
Burnup	250 kg/y (4.6 %/y)
Power Density	
Maximum	1660 MW/m^3
Average	310 MW/m^3
Coolant Temperature	
Inlet	923 K
Outlet	1023 K
Coolant Maximum Velocity	3.6 m/s

3.4 RESEARCH ACTIVITIES IN SWEDEN

The research interest in Sweden is driven by the conviction that the accelerator-driven transmutation technology offers a possibility to produce cleaner fission energy over an indefinite time (comparable to fast breeder reactors), a concept which would fit Swedish needs and technological skill. Although research of alternative renewable energy sources is in progress, no large scale solutions which can meet future energy demands have emerged. 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 of spent fuel, 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.

The "Group for Spallator Research" conducts - so far - concerted research at Chalmers

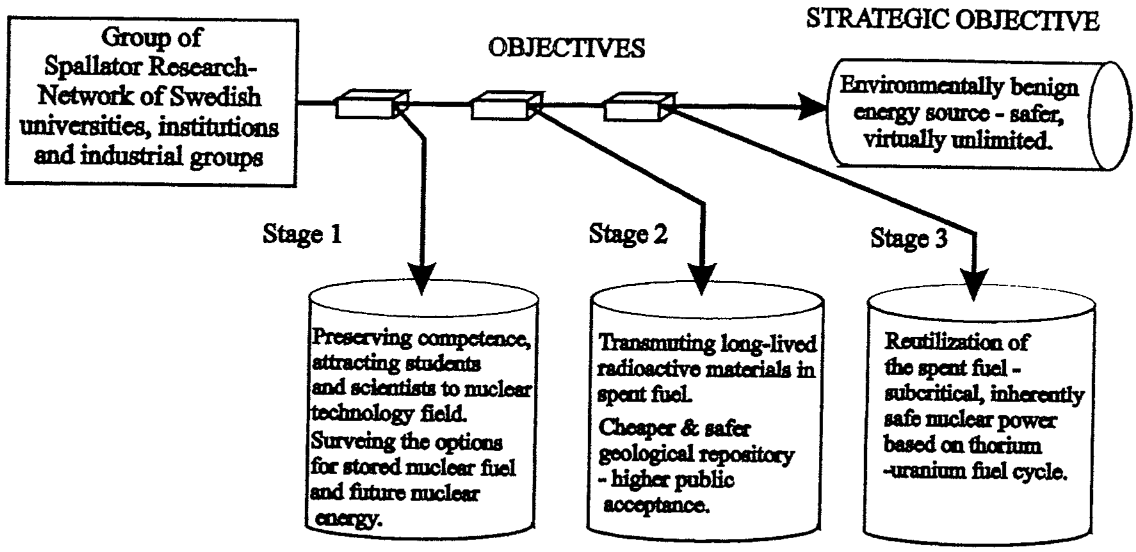

Fig. 9. *Objectives of the Group for Spallator Research.*

Technical University (CTH), Royal Institute of Technology (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 in Fig. 9 are aimed to:

1. Practical solutions for accelerator driven transmutation of longlived radioactive material (e.g. Plutonium, minor actinides, fission products) into shortlived 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.

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 (Moscow, Obninsk), 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.

The Spallator-group conducts also negotiations with the Russian institutes concerning possible ADS research projects financed in the frame of the Swedish ISTC-contribution.

3.5 SOME EUROPEAN ACTIVITIES

Some institutes and research centers from different European countries (Sweden: KTH, CTH, UU; Germany: KFK, KFA; France: CEA, Italy: ENEA, Politecnica Torino; Netherlands: ECN, Great Britain: AEA and European Institute of Transuranium Elements, Karlsruhe) applied to EC for a shared-cost project funding in 4th Framework Programme of the European Community 1995-1998, Programme Activity 1, Field: V. ENERGY, RTD and Demonstration Programme: 12. Nuclear Fission Safety, AREA A: "Exploring Innovative Approaches", Sub-area A.2: "Fuel Cycle Concepts (Partitioning and Transmutation)", A.2.1:"Strategy studies". Title of the project: IMPACT OF THE ACCELERATOR BASED TECHNOLOGIES ON NUCLEAR FISSION SAFETY (IABAT). The application has been accepted by CEC and contract negotiations are under way.

The overall objective is to make a European assessment of the possibilities of accelerator-driven hybrid reactor systems from the point of view of safe energy production, minimum waste production and transmutation capabilities. In particular:

a. to perform system studies on accelerator driven hybrid systems

b. to assess the accelerator technology

c. to study the radiotoxicity of the fuel cycle for ADS and its nonproliferation aspects

d. to provide basic nuclear and material data for ADS by means of evaluation and experiments

The final objective is to concentrate and coordinate different efforts from member states to create the European scientific and technological basis for eventual further projects aimed to develop environmental friendly, more public accepted and safer nuclear fission energy source. Models, tools, validated routines and some new experimental data for the future experimental activity on a larger scale will be the final results.

4. Conclusions

A brief summary of technical disadvantages of the different ADS from the Swedish perception point of view is presented in Table III.

Finally one can conclude that ADS can complete and broader the nuclear power option, there are specific objectives, mainly in fuel inventory toxicity reduction, nuclear waste toxicity reduction and LLFP incineration. Most of them can be addressed successfully with ADS:

TABLE III. TECHNICAL DISADVANTAGES AND PUBLIC PERCEPTION FOR ADS

ADS type	**Technical Disadvantages**	**Public Perception (Swedish perspective)**
Solid fuel and thermal neutrons	Flux/power density distribution make system unfeasible. Serious safety concerns with "beam-on" power transients(e.g. unprotected loss of flow accidents)	Similar to LWR (subcriticality advantages important)
Aqueous system with liquid/quasi-liquid fuel	Pressurized system can not meet the "blow-down" criterium(Low pressure drives the economy to the bottom).Radiolysis of the water creates serious problems	Too risky, no technology developed, difficult safety in depth!
Solid fuel and fast neutrons	Very high inventory/burnup ratio (e.g. 3160 /250 for Japanese minor actinide burner). Liquid sodium cooling (with all the odds). Very powerful accelerator (BNL Phoenix) if electrical energy is to be produced. Radiation damage problems.	Low acceptance for fast neutron spectrum - but subcriticality can balance this. No experiences in fast reactors, sodium questionable. TOO LARGE INVENTORY
Liquid fuel and fast neutrons	Even worse inventory / burnup ratio - 4.5% (e.g. 5460 /250 for Japanese actinide burner) Problems with chloride salts (corrosion)	As above. Can liquid lead help?
Liquid fuel and thermal neutrons	High thermal neutron flux - radiation damage and activation problems. Separation chemistry on- or quasi on-line. Difficult safety in depth.	Low inventory, low pressure and high transmutation rate are attractive. No technology developed for liquid fuel.

:

- by minimizing the core inventory and allowing high neutron fluxes and "exotic" (not well behaving) fuels (thermal systems but not exclusively),
- thorium breeding without excess breeding or the use of enriched material.

Different paths exist for ADS development :

- utilization of existing spent LWR fuel should be of interest from the environmental conservation point of view, could be a joint effort for weapon-grade and reactor-grade Pu burning,

- Thorium fuel cycle should be the strategic objective for the future nuclear power (both reactor and ADS), it requires, however, 20-30 years of an intensive development.

ADS will not eliminate completely the necessity of the geological repository, it can make it cheaper, more acceptable and safer. Could pay for transmutation costs itself through energy production. Moreover ADS open new possibilities for the nuclear technology and can contribute to the environmental restoration

Future of ADS and the nuclear technology in general will be probably based not on its technological feasibility (we can master it today) but it will be rather a moral choice for the society. To make this choice, all the alternative technologies have to be put "on equal footing". Today all the technologies for energy production carry global threats.

Acknowledgments

This paper is partially based on materials prepared for the IAEA "Accelerator-Driven Systems - Status Report" which is to be published in 1996.

References

[1] E.O. Lawrence and N.E. Edlefsen, "On the Production of High Speed Protons", Science, LXXII, NO. 1867, 376, October 10, 1939.

[2] C.M. van Atta, "A Brief History of MTA Project", ERDA Information Meeting on Accelerator Breeding , January 19-19 (1977).

[3] G.A. Bartholomew and P.R. Tunnicliffe, Eds, "The AECL Study for an Intense Neutron generator", Atomic Energy of Canada Limited, Report No. AECL-2600 (1966).

[4] G.Van Tuyle, M.Todosov, M.Geiger, A.Aronson and H.Takahashi, "Accelerator-Driven Subcritical Target Concept for transmutation of Nuclear Wastes, Nucl. Tech. p.1, Vol. 101, 1993.

[5] R.G. Vassylkov, V.I. Goldanski et al., Atomnaya Energiya 48, 329 (1978).

[6] G.J. Russel, E.J. Pitcher and L.L. Daemen, "Introduction to Spallation Physics and Spallation Target Design", International Conference on Accelerator Driven Transmutation Technologies and Applications, Las Vegas, NV, July 25-19 1994.

[7] Bowman, C.D., Venneri, F., High Value use of Weapons Plutonium by Burning in Molten Salt Accelerator-Driven Systems or Reactors, International Seminar on Nuclear War and Planetary Emergencies, 18th Session, pp. 400-411, Erice, Italy, 1993.

[8] Venneri, F., Bowman, C.D., Heighway, Ed., Accelerators add a new option to our energy future, Los Alamos Unclassified Report LA-UR-94-3905.

[9] Venneri, F., Bowman, C.D., Jameson, R., Accelerators address nuclear waste problems, Physics World 6,8 p.40, Aug. 1993.

[10] The Los Alamos Accelerator-Based Conversion Concept for Plutonium Disposition, transparency set prepared for review by the JASON Group in January 1994, available from The ADTT Project Office, Los Alamos National Laboratory, Los Alamos, New Mexico; and C. D. Bowman, "Weapons and Commercial Plutonium Ultimate Disposition Choices...Destroy Completely or Store Forever," in Managing the Plutonium Surplus: Applications and Technical Options, pp 125-138, Kluwer Academic Publishers, Dordrecht, The Netherlands, 1994.

[11] Weinberg, A. M., Molten Salt Reactors, in Nuclear Applications and Technology 8, 102-219 (1970

[12] Carminati, F., et al., An Energy Amplifier for Cleaner and Inexhaustible Nuclear Energy Production Driven by a Particle Accelerator, CERN/AT/93-47 (ET) (1993).

[13] Rubbia, C., Rubio, J. A., Buono, S., Carminati, F., Fiéter, N., Galvez, J., Kadi, Y., Klapisch, R., Mandrillon, P., Revol, J. P., and Roche, Ch., Conceptual Design of a Fast Neutron Operated High Power Energy Amplifier, CERN/AT/95-44 (ET), 1995 and Status Report on Accelerator-Driven Systems, IAEA, 1996 (in preparation).

[14] Rubbia, C., Buono, S., Gonzales, E., Kadi, Y., and Rubio, J. A., A Realistic Plutonium Elimination Scheme with Fast Energy Amplifiers and Thorium-Plutonium Fuel, CERN/AT/95-53, 1995.

[15] Rubbia, C., et al, Elegant Demonstration Successful, Europhysics News, Vol. 26, No. 1 (1995).

[16] Nishida, T., et al., Improvement of Spallation Reaction Simulation Codes NMTC/JAERI and NUCLEUS", 2nd Int. Symp. on Advanced Nuclear Energy Research, Mito (1990).

[17] Nakahara, Y., and Tsutsui, T., NMTC/JAERI - A Simulation Code System for High Energy Nuclear Reactions and Nucleon-Meson Transport Process, JAERI-M 82-198 (in Japanese) (1982).

[18] Takada, H., et al., Production of Radioactive Nuclides in a Lead Assembly with 500 MeV Protons, Proc. Specialists' Mtg. on Accelerator-Based Transmutation, PSI (1992).

[19] YOSHIDA, H. et al.: "A Strategic Study of the Partitioning and Transmutation System being Developed at JAERI", Proc. Int. Information Exchange Meeting on Actinide and Fission

Product Separation and Transmutation, ANL (1992).

[20] Takizuka, T. et al.: "Conceptual Design Study of an Accelerator-based Actinide Transmutation Plant with Sodium-cooled Solid Target/Core", ibid.
Katsuta, H. et al.: "A Continuous Transmutation System for Long-lived Nuclides with Accelerator-driven Fluid Targets", ibid.

Appendix II

2nd International Conference on Accelerator Driven Transmutation Technologies and Applications - Conference Wrap-Up.

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Royal Institute of Technology
Kalmar, Sweden
3-7 June 1996

207 participants from 24 countries took part in the 2nd International Conference on Accelerator Driven Transmutation Technologies and Applications in Kalmar. Fig. 1 shows the statistics over the participants of Kalmar Conference. It is interesting to conclude that countries with the very different nuclear policies were represented on this Conference. Beginning from the countries which are or have been intensively developing nuclear power like Japan, South Korea and France, through countries which seriously consider the development of the large scale nuclear power like China and ending with countries which shut-down or are planning to shut-down the nuclear power (Austria, Italy, Sweden). It indicates that ADTT have attractive solutions to offer for the back-end of the nuclear fuel cycle including the management of the reactor-grade and excess weapon plutonium and possibly for the future development of nuclear power systems.

It is worth to notice that thanks to the support of the International Science and Technology Centre in Moscow the participation of the Russian scientists was unprecedently large. This fact reflects the amount of work which has been done in Russia in this field during last two years. Excellent attendance also from Sweden, USA, France, Germany, Switzerland and Czech Republic is very pleasing and reflects strong scientific interest for ADTT in these countries.

What has been achieved since Las Vegas Conference?

1. Impressive conceptual designs have been presented during the Kalmar Conference. To the most comprehensive belonged CERN's Fast Energy Amplifier (presented by C. Rubbia), Los Alamos Accelerator-Transmutation of Waste Systems (ATW) with very interesting chemistry and a set of Russian presentations reviewing the ISTC project P#17.
2. Real good news in molten salt chemistry for ADTT fuel cycle - it looks like feasible (for a physicist!) - presentation of M. Williamson and N. Li from Los Alamos National Laboratory.
3. Accelerator development in the energy and current ranges interested for ADTT has its own drivers in other research branches: linac has APT-driver (APT - Accelerator Production of Tritium), cyclotrons can benefit from activities at PSI and CERN.
4. Molten lead revisited - most of the ADTT conceptual designs for fast neutron spectrum are based on the molten lead as coolant and "neutron diffuser". These concepts can clearly benefit from the vast Russian experiences in molten Pb-Bi and molten Pb reactors.

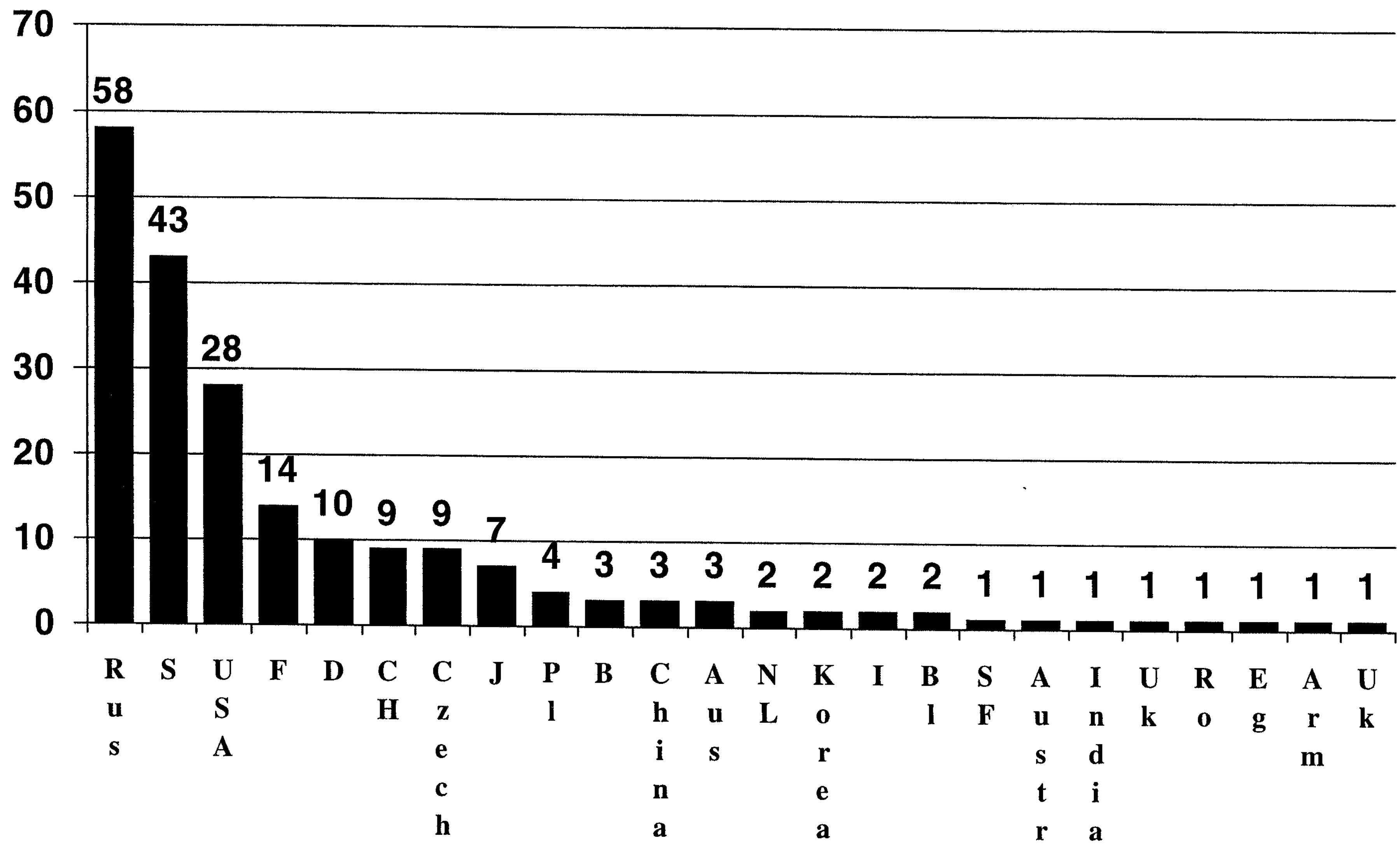

Figure 1 2nd International Conference on Accelerator Driven Transmutation Technologies and Applications in Kalmar - Participation statistics

5. Extensive work on radiotoxicity and fuel cycle analysis was presented.

6. Interesting experiments and work on spallation and basic data

7. Some international and national projects have been successfully launched:
   - ISTC-role in Russia acknowledged
   - European Community has launched system studies on ADTT (3 EC projects have been started in the 4th Framework Programme including some basic experiments)
   - French ISAAC/GEDEON programs reported
   - CERN group with C. Rubbia´s leadership has showed important work
   - US national labs have clearly shown interest in a broad international cooperation
   - smaller countries like Sweden and Czech Republic have very active research projects in ADTT, seeking also for international cooperation

8. Liquid Pb-Bi spallation target work reported, launching manufacturing in Obninsk (Russia) (in the frame of the ISTC-project)

9. Further computer code development including kinetics with emphasis on subcriticality.

10. Aqueous systems have no significantly interest any more, except for some Russian groups

11. Molten salt and thermal systems seem to leave the field for the fast systems based on molten lead. Different designs presented on the Conference are shown on Fig. 2.

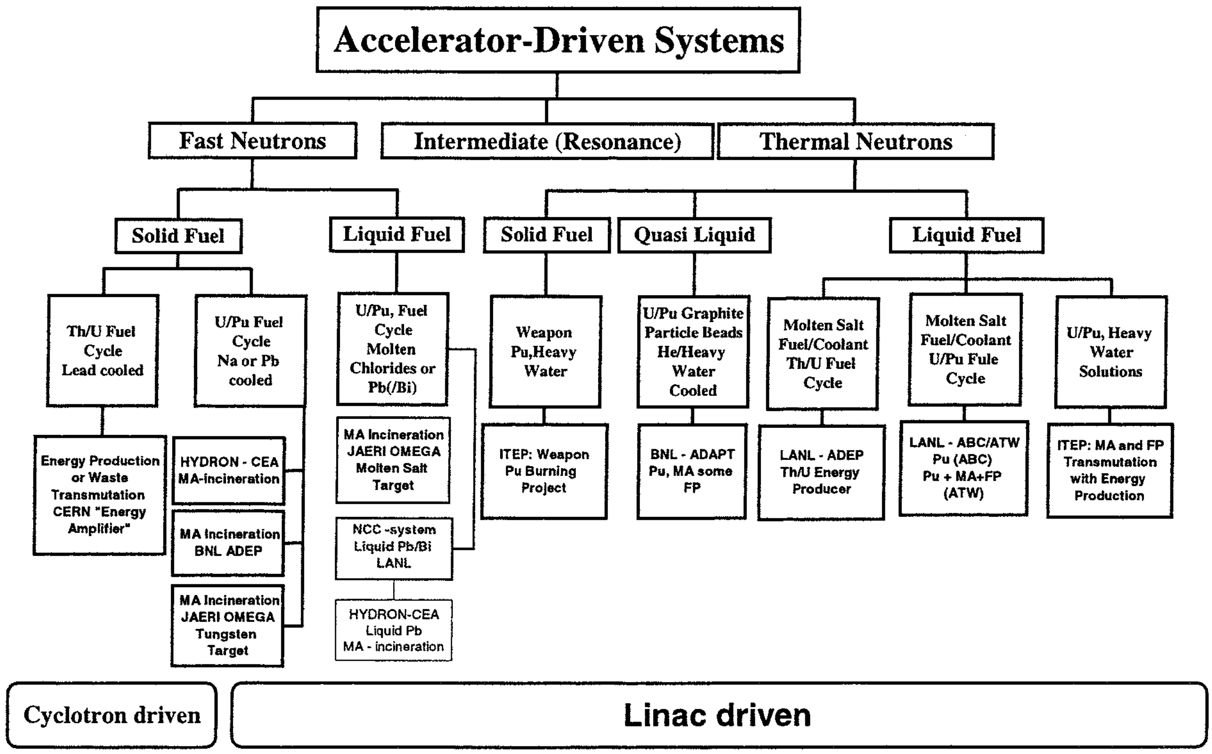

Figure 2 Accelerator-Driven Systems presented on Kalmar Conference

12. Transmutation of transuranium elements is the shorter term objective, new nuclear systems for energy production using accelerators have the longer time perspective.

Some conclusions from the Conference pointed out during the Panel Discussion.

1. Too much emphasis on Pu-fear was put in some presentations. It seems for the majority of participants that ADS have sufficient "positive" driving force for the future development. We should not advertise it through:

   Pu-thriller scenario

   Discrediting geological repository

2. We should not neglect difficulties with ADTT and we should not promise too much and too fast. (It should not be a COLD FISSION story)

What has to be done in the nearest future:

1. Time for the limitation of "conceptual design space". Now, mainly experiments can push forward our knowledge. It was clear during the Conference that many research groups from different countries (France, US, CERN, Japan, Sweden, Russia etc.) can relatively easily agree on common experiment. A simple accelerator with a few milliampere current at few hundreds of MeV and liquid lead coolant/fuel carrier could be a common nominator. The Conference put many research groups closely together.

2. We should try to use more extensively the existing accelerators (LAMPF, PSI, Troitsk?) and perform experiments.

   A lot of interesting experiments can be done on reactors and other neutron sources (generators, ^{252}Cf etc.)

3. We should take advantage of other ongoing projects (APT, ESS etc.) and ensure information and experience exchange

4. No serious safety assessment can be done without a more specific design. Again - one should try to define the "base line ADTT design" to perform some necessary assessments.

5. MORE EXPERIMENTS are necessary:

   Material investigations (intense radiation always degrades materials!).

   Materials chosen primarily on the basis of neutronic properties are frequently those found to be most prone to either environmental and/or radiation induced degradation (F. Garner) when sufficient attention has been paid to materials development early in the program, an acceptable solution has almost always been found.

   Corrosion and chemistry experiments badly needed

6. Further code development required (e.g. spallation product calculations, coupling spallation-

neutronics - burnup - decay)

General Comments

- 2nd Conference on ADTT showed an increased interest in ADTT, excellent attendance and remarkable enthusiasm
- More technical and detailed work compare to the 1st ADTT Conference
- Synergy with conventional nuclear power and geological repository programs stated as an important issue
- Transmutation of existing nuclear wastes from LWR fuel cycle is gaining priority compare to new nuclear energy production systems (Plutonium first, Thorium later)
- Strong appeal for a broad international cooperation. First seeds already exist and have very good prospects for the near future. Liquid Pb-Bi spallation target ISTC project can be a strong driver for this cooperation
- Fast neutron systems have today stronger drivers in many countries than thermal neutron systems. More studies definitely needed
- Safety and economical assessments require better defined ADTT systems
- ADTT is entering consequently experimental reality: CERN and CEA are conducting neutronic experiments, basic nuclear data experiments are under way on few accelerator sites, spallation target for ADTT is manufactured.

Next ADTT conference will take place in Czech Republic in 1998.

Appendix III

ADTT Safety Aspects

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Abstract. Beside the technical problems of ADTT which remain to be solved it is crucial for the ADTT progress that safety and economical aspects are considered already during the research and planning phases. Safety here stands for the converse of risk, negative consequences for human life and health and the environment together with the corresponding probabilities. The system to be considered includes all phases of an ADTT plant, a life cycle analysis- LCA. The risk analysis is useful for two purposes: comparison with other ways of handling nuclear waste, e.g. geological repository and for valuation of different construction designs. Due to lack of precise plans and adequate data the analysis will be more of a qualitative than quantitative type. The main risks appear in connection with repair and replacement work

Introduction

In the start phase of a technical project it is quite natural to concentrate on the technical feasibility and that is the case with the ADTT projects. But it is essential also to take into account the economic and safety aspects from the very beginning. Dealing with anything ´nuclear´ it is even more important to consider safety aspects. We shall in the following restrict ourselves to ADTT in the treatment of nuclear waste- Accelerator driven Transmutation of nuclear Waste, ATW- and further not go into the proliferation aspects, which will be taken up in some other papers at this conference. We shall further let risk stand for the combination of uncertain or random events with negative consequences for human life, health and the environment and some measure- the probability- for the likelihood of the events to occur. Let us note that we avoid the common definition of risk as expected consequence being too narrow and separated from people´s risk perceptions.

We presume that risk here is of interest in a decision setting. Involved in decision situations are essentially three groups: The decision makers, the benefit (and cost) receivers and the risk takers. These groups can be more or less separate. In the case of modern technology they are often very separate and that makes risk analysis even more important. That is certainly the case for nuclear waste management. Here the decision has to be taken by the political bodies of now living generations, the benefit receivers of nuclear energy are the now living generations and the risk has to be taken by personnel, and living and coming generations around the sites for energy production and waste handling and placement.

System limits

The decision making group and the alternatives to be considered mainly determines the system. When one considers waste handling the following options are available:

- Reuse of the material, recirculation.
- Transforming the waste into a ´safe´ material. (For nuclear waste- transmutation.)
- Dispersion of the waste in such a way that the concentration is ´safe´.
- Putting the waste in a repository which is separate from the biosphere.

For nuclear waste, geological repository is a combination of the two last alternatives; the repository shall keep the waste separate from the biosphere but if some waste comes out of a capsule it should disperse at such a slow pace that it will be safe for the public.

The purpose of the risk analysis for nuclear waste transmutation is, from Swedish perspective, twofold:
- to compare different ATW designs from a safety point of view
- to compare ATW with other nuclear waste handling methods, e.g. geological repository.

In other countries when ADTT is meant for burning weapon plutonium and/or energy production the relevant comparison might be with other ways to take care of the Pu and conventional LWR.

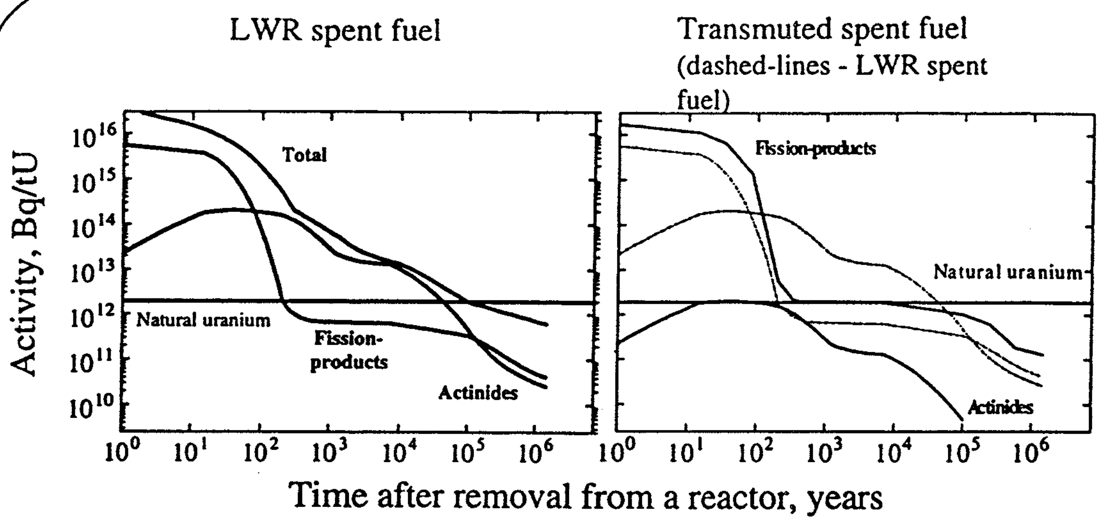
The ATW system to be considered should include:
- transportation of the waste from the reactors to the ATW plant
- prestorage and preparation of the waste material for transmutation
- the ATW plant with accelerator, window and target, blanket, partitioning and separation
- storage of stable or short-lived material-
- handling and storage of longlived products.

In time we should consider the following phases:
- construction
- production
- maintenance, replacement of components
- destruction of the plant.

One can also find arguments to enlarge the system to include production of components and corresponding risks. This should be done if the alternatives considered have different risk profiles in the production of respective components.

Risk aspects

The main reason for transmutation of nuclear waste instead of placing the waste in a repository is safety related. In the latter case there is a very small risk for radioactive material to reach the biosphere through corrosion of capsules followed by seepage of contaminated groundwater through the rock. Even if small that possible effect some thousands years after the use of nuclear energy has caused public concern. Here we encounter a clear separation of the benefit receiving group- the now living generation- and the risk takers- the human population in a distant future, which was considered in the introductory section. A safety advantage of ATW is then the exchange of small uncertain risks in a distant future by mainly plant related risks now and in the near future. It should however be added that even ATW includes a rest part of long-lived products which can give rise to effects in the distant future. Figure 1 below illustrates the remaining radioactivity as a function of time for different alternatives.



Radioactivity of spent fuel and what is expected from transmutation process

- Assumptions for transmutation:
  - Normalisation for intial, fresh fuel loaded into LWR
  - Actinide partitioning/separation factor 0.01
  - Activation radioactivity neglected

Figure 1

A risk analysis of a technical system will start by identifying the hazards- risk identification. After that a quantitative analysis, i.e. estimation of the risksshould be done. And in order to make decisions we must valuate the risks. Even if we as analysts like to provide the decision makers with 'objective' data for their decisions, we must know about and take into account the subjective- 'irrational'- opinions of the public opinion and political bodies.

Today there are just some different ideas- plans about ATW designs. As was pointed out above all these plans contain some main common parts as accelerator, window and target, blanket, reprocessing and partitioning, and rest product handling. But the concrete design of these parts differ considerably: linear vs cyclotron accelerators, fluid lead or molten salt as target, fast vs thermal neutrons, water slurry vs molten salt in the blanket, on line or batchwise separation of the transmuted waste etc. That uncertainty of the ATW detailed design makes it for the time being very difficult to perform the quantitative part of the risk analysis. Some very rough estimates of the overall safety should however be possible by comparing with risks in existing LWR and reprocessing plants (Cf oral presentation in Stockholm May 1996 by Fransesco Anselmo).

Those who will take the largest risks are the personnel of the plant, where reprocessing and repairments will be dangerous tasks. The pipes etc. will be subject to molten salt at high temperature together with radioactivity. In contrast to waterborne systems where the material properties are rather well known, here very much research and experimental work has to be done in order to find good materials. Necessary repairment and replacement of wornout components will be difficult and dangerous, cf. [1].

Albeit the difficulties to perform a risk analysis of ATW it is essential for its success that risk studies accompanies the technical research and development of the system. I like to argue that such a work should be coordinated at an international level. A network of interested safety analysts should be formed. Modern IT for exchange of information and data together with workshops shall be used to coordinate the work. I am willing to act as a ´mailbox´ for exchange of emails in such a group, address: tort@ce kth.se.

References

[1] Gudowski, W., Pettersson, K., and Thedéen, T. "Acccelerator Transmutation of Wastes (ATW)-Prospects and Safety.". SKB Report 93- 23. Stockholm 1993.

[2] Thedéen, T. "Risk Aspects on Nuclear Waste Handling - Transmutation vs. Deep Geological Repository." In Proceedings of the 50th Session of the International Statistical Institute, Beijing 1995.