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19. Status of Nuclear Transmutation Study

Takakazu TAKIZUKA

Center for Neutron Science, Japan Atomic Energy Research Institute
Tokai-mura, Naka-gun, Ibaraki-ken 319-1195 Japan
e-mail: takizuka@omega.tokai.jaeri.go.jp

Abstract

JAERI is carrying out R&Ds on partitioning and transmutation under the OMEGA Program. The R&Ds include the design study of accelerator-driven transmutation systems and the development of transmutation experimental facilities. Accelerator-driven systems have received much interests due to their potential role as dedicated transmuters in the nuclear fuel cycle for minimizing long-lived waste. Principles of accelerator-driven system, its history, JAERI proposed system concepts, and the experimental program are overviewed.

1. INTRODUCTION

Management of high-level radioactive waste (HLW) arising from reprocessing of spent fuel from nuclear power stations has become one of the top priority issues in the development and utilization of nuclear power. Since HLW includes long-lived radioactive nuclides such as minor actinides (MA), it should be isolated from the human environment for a very long time period. In Japan, HLW is to be solidified into a stable form, stored for 30 - 50 years to reduce the decay heat, and then disposed of permanently in a deep geological formation several hundreds meters below the ground level.

In 1988, the Japan Atomic Energy Commission launched a long-term R&D program on partitioning and transmutation, called the OMEGA Program. The program is aiming at developing technologies to improve the efficiency and safety in the HLW management. JAERI is carrying out the research on accelerator-driven transmutation within the framework of the Program. JAERI has proposed dedicated transmutation system concepts with a hard neutron energy spectrum for efficient MA burning. To demonstrate the technical feasibility of the accelerator-driven transmutation and to verify the system design concept. JAERI is setting up a plan of engineering experiments plan to verify the system design concept and under the Neutron Science Project to demonstrate the technical feasibility of the accelerator-driven transmutation and to verify the system design concept.

Accelerator-driven systems have attracted continuing interest because of their unique features of subcritical mode operation and excess neutron availability. These features offer the advantages of a safe and efficient means for nuclear waste transmutation.

This paper discusses about the principles of accelerator-driven transmutation, brief history of accelerator-driven systems, the status of R&Ds, technical challenges, the proposed concepts of accelerator-driven system, and the experimental plan under the Neutron Science Program.

2. PRINCIPLES OF ACCELERATOR-DRIVEN TRANSMUTATION

2.1 Accelerator-Driven Systems

The concept of accelerator-driven systems (frequently called hybrid systems) combines a particle accelerator with a subcritical core (or blanket). Most proposals assume proton accelerators, delivering continuous-wave beams with an energy around 1 GeV and a current of several tens mA. The accelerator will be either a linear accelerator (linac) or a circular accelerator (cyclotron). High-intensity proton beam are injected onto a spallation target to produce source neutrons for driving the subcritical core. The target will be made of heavy metal of solid or liquid state. Spallation reaction in the target emits a few tens of neutrons per incident proton, which are introduced into the subcritical core to induce further nuclear reactions. The subcritical core will be very similar in principle to that of a critical reactor. It can be designed to operate either with a thermal or fast neutron spectrum.

2.2 Transmutation of Nuclear Waste

The term "transmutation" denotes the nuclear process where a nuclide transforms into another by nuclear reaction or radioactive decay. In the context of nuclear waste management, it is used specifically to mean artificial nuclear transformation of the long-lived radioactive nuclides into either short-lived or stable ones.

Major target nuclides addressed for transmutation are Np, Am, and Cm; they are collectively called minor actinide (MA). The next priority target nuclides may be fission products with very long half-lives such as ^{129}I and ^{99}Tc.

A variety of nuclear reactions can be applied for transmutation of MAs and long-lived FPs. Neutrons induce reactions (n, f), (n, γ), (n, 2n), (n, p), etc. Charged particles such as high energy protons can induce spallation reaction (p, xpyn). Photons induce photo-nuclear reactions (γ, n), and (γ, f).

From a practical point of view, neutron is considered as the most useful for transmutation. Technologies are well developed or under development to efficiencly produce a large amount of neutrons through fission, fusion, and spallation reactions.

Neutron is electrically neutral and thus it can reacts with an atomic nucleus even at a very low energy. Spallation reaction when used directly for transmutation is less favorable because of worse energy balance The least favored option is to use photo-nuclear reaction.

2.3 Spallation and Fission

Accelerator-driven transmutation systems make use of both spallation reaction and fission reaction. There are several differences in the nature of spallation and fission, which will have impact on the system designs.

One difference is in the number of neutrons released. Fission produces 2.5 - 2.9 neutrons per event, and at least one of the neutron produced is not useful since it is consumed to sustain the chain reaction. Spallation produces 30 - 40 neutrons per incident proton when strikes a tungsten target at 1.5 GeV.

Another difference between spallation and fission is in the energy spectrum of emitted neutrons. The energy distributions of spallation and fission are similar in the low energy range. Spallation neutron spectrum has a high energy tail in the forward direction. High-energy neutrons above 20 MeV are less than 10% of emitted neutrons, the highest reaching to the energy of incident protons.

The amounts of energy deposition per neutron produced are different for spallation and fission. Fission deposits about 120 MeV per useful neutron as heat, whereas spallation deposits about 25 MeV per neutron.

Other differences are in the amount of γ-ray energy produced, in the mass distribution of residual reaction products, and in the degree of radiation damage to materials.

Fission reaction produces a few neutrons, but deposits large amount of thermal energy. On the other hand, spallation is an efficient reaction for neutron production, but is endothermic. Neutron balance, energy balance and heat removal requirements generally set fundamental limitations in system designs. Complementary nature of spallation and fission makes a new opportunity of hybrid systems which can take full advantage of combining both reactions.

2.4 Features of Accelerator-Driven System

Accelerator-driven systems operate in a subcritical mode and stays subcritical, regardless of the beam being on or off. Accelerator-driven systems can address the safety issues associated with criticality, which are often perceived as serious problems for critical reactors. Subcriticality improves the controllability of the system. The accelerator provides a much simpler, more reliable control mechanism for subcritical systems than that provided by control rods in conventional critical reactors. An accelerator-driven system can in principle work without safe-shutdown mechanisms.

Subcriticality also provides substantial flexibility in fuel processing and managing as well as in system operation. Criticality in a conventional reactor imposes tight constraints on the specifications of fuel and cycle length of the reactor. Accelerator-driven systems can accept such fuels that would be impossible or difficult to use in critical reactors, and can extend their cycle length if necessary.

Accelerator-driven systems can provide more excess neutrons compared to critical reactors. The excess neutrons can be usefully utilized for transmutation purpose. Transmutation potential of a system is, in brief, a matter of availability of excess neutrons. Light water reactors have almost zero excess neutron per fission, thus leading to a very limited transmutation potential. In fast reactors, about 0.6 excess neutron is available per fission. This is utilized for breeding in case for fast breeder reactors. In accelerator-driven systems, about one excess neutron is available per fission. Even it is possible to yield more than one excess neutron per fission in some designs.

One notable drawback of an accelerator-driven system is the additional costs associated with the construction and operation of the accelerator.

3. BRIEF HISTORY OF ACCELERATOR-DRIVEN TRANSMUTATION TECHNOLOGIES

The idea of accelerator-driven nuclear energy systems is not new. The history can be traced back to the early stage of the nuclear power development.

In 1941, G. T. Seaborg produced the first man-made element Pu with a deuteron accelerator and a natural U target. In the late 1940's, experimental studies were performed by E. O. Lawrence, B. B. Kinsey, H. York, W. N. Semenov et al., aiming at application of accelerator-driven neutron sources.

3.1 MTA Project, USA

The first proposal of ADS application was production of Pu (and tritium). The MTA Project [1] was initiated in 1949 at Lawrence Livermore (at that time the Livermore Research Laboratory). The objective is to develop anew process for ^{239}Pu (and tritium) production from depleted uranium and to design the accelerator-breeder facility called the Material Testing Accelerator.

R&D activities under the Project covered such areas as measurements of nuclear data, development of calculation model, design and technology development of intense accelerator, nuclear design of subcritical core, and design of plant and processes including reprocessing and power conversion. A system designed assumed a 500 MeV-320 mA deuteron accelerator, a Be primary target, a NaK-cooled ^{238}U secondary target, and a water-cooled ^{238}U core, producing 564 kg of ^{239}Pu per year.

The Project was abandoned in 1952. The reasons was difficulties in construction of the system based on the technologies at that time. The MTA was considered far from being a practical application.

3.2 ING Project at CRNL, Canada

At Chalk River in Canada, a concept of accelerator-breeder (AB) had been pursued from 1950's. The project called ING (Intense Neutron Generator) was aiming at production of ^{239}Pu and ^{233}U from natural uranium and thorium respectively as fuel for CANDU reactors [2-4].

The program plan consisted of four stages:

- 1st stage: construction of 10 MeV-300 mA proton accelerator , 3-MW target , (ZEBRA; Zero Energy Breeder Accelerator)
- 2nd stage: upgrading up to 200 MeV-70 mA, 14-MW target, material testing, experiments of target/blan-

ket, CCL development, (EMTF; Electronuclear Material Test Facility)
- 3rd stage: 1000 MeV-70 mA, 150-MWe target/blanket (mid 2010's)
- 4th stage; 1000 MeV-300 mA, pilot plant (mid 2020's)

Studies were done for various target/blanket concepts, such as Pb-Bi (Pb) target and Na-cooled blanket, fluoride molten-salt system, D_2O (or H_2O) cooled CANDU system, etc. The project ended in 1980's.

3.3 Accelerator-Driven Breeder Systems

In the late 1960's into the early 1970's, there were some activities on accelerator-driven breeder systems in Russia, Japan and Europe. In Russia, conceptual studies of AB [5, 6] were performed by V. G. Vasil'kov, V. A. Davidenko, et al. V. G. Vasil'kov et al. measured the spallation neutron yield in ^{238}U traget at Dubna [7]. In Japan, a conceptual study of AB [8] was made by K. Furukawa et al. at JAERI. The proposed system called Accelerator Molten Salt Breeder was composed of a 1 GeV-300 mA proton linac and fluoride molten-salt target/blanket.

Apparently, accelerator-driven breeders was not considered to be cost competitive with LMFBRs. LMFBR technologies had been conceived as well developed and ready to be demonstrated at that time.

3.4 NASAP Program in the U.S.

In the late 1970's, to promote the non-proliferation of weapon fissile material, U.S. administration decided to slow down the development of FBR in the U.S. and launced an R&D program called NASAP (Nonproliferation Alternative System Assessment Program) for development of alternative nuclear systems to FBR.

Under this Program, studies of AB were conducted at BNL [9-12], ORNL [13-15], LANL [16, 17], ANL [18], and LLNL [19]. BNL presented several proposals for AB such as Pb-Bi target,/H_2O cooled U oxide core, and H_2O cooled U (Th) oxide target/core. ORNL proposed a system concept with Pb-Bi (Pb) target/fluoride molten-salt core. LANL made a conceptual study and experiments with 800 MeV protons.

The NASAP Program ended in 1982.

3.5 Accelerator-Driven Transmutation Systems

Since the middle of 1980's, transmutation have attracted increasing interests rather than breeding.

In 1987, a group from CERN, JRC, and BNL proposed a concept of accelerator-driven fast neutron system. They combined a 13 - 28 MW proton cyclotron, a Na or He cooled TRU oxide target/fuel for transmutation, and a Th oxide blanket for ^{233}U breeding. The system has a thermal power of 900 MW and transmutes minor actinides from 10 LWRs.

In 1989, JAERI started a study on ADTS within the framework of the OMEGA Program and presented a concept of the Solid System. JAERI also proposed an advanced concept of the Molten-Salt System in 1992. Both systems are specially designed for transmutation purpose and utilize fast neutrons.

BNL proposed an ADTS concept called PHOENIX in 1990. The system consists of a Na-cooled oxide fuel target/core and a 1.6 GeV-104 mA proton linac. The target/core design is patterned after the U.S. experimental fast reactor FFTF.

LANL developed a new idea of minor actinide transmutation in a very high thermal neutron flux around 10^{16} n/cm^2/s and proposed an ADTS concept called ATW in 1991. The ATW system is composed of a 100 - 180 MW proton linac, Pb-Bi (Pb) target, a heavy water moderator, and actinide fuel in a form of slurry or fluoride molten-salt. The idea received substantial interests as an attractive option for transmutation but it was soon recognized that there are insurmountable technical difficulties to generate and utilize such a high thermal flux. LANL updated their concept frequently and presented several variations as follows:

- W target, D_2O moderator, slurry or aqueous solution fuel, CANDU type,
- Pb-Bi (Pb) target, graphite moderator, fluoride molten-salt fuel, He coolant,
- Li (+ ^{238}U) target, graphite moderator, fluoride molten-salt fuel, Li coolant,
- Pb-Bi (Pb) target, graphite moderator, fluoride molten-salt fuel/coolant.

In the latter versions, the thermal fluxes was decreased to a moderate level where efficient transmutation can not be expected. In 1996, they eventually abandoned the thermal neutron system with liquid fuel and turned to a fast neutron system with metal solid fuel and Pb-Bi coolant.

In 1993, C. Rubbia and his group in CERN presented a concept of ADS, so called Energy Amplifier (EA) [20], for energy production based on Th-U fuel cycle. The original system concept followed the conventional LWR design. Protons from a 0.8 GeV-6.25 mA cyclotron are injected upward into a ^{238}U target at the center of the light water cooled Th-U oxide fuel core. It was realized that the combination of solid fuel and thermal neutrons moderated in light water is least favorable for subcritical systems. In the next year, they turned to a fast neutron system comprising of a 1.0 GeV-12.5 mA cyclotron, a Pb target, and a Pb-cooled Th-U oxide fuel core.

In 1991, CEA launched the ISAAC Program within the framework of the French national R&D program on partitioning and transmutation called the SPIN Program. So far, CEA has not presented their own system concepts, but has been investigating various ADTS concepts.

4. REVIEW OF THE EXISTING PROJECTS

Active projects for the accelerator driven transmutation systems exist in France, Japan, USA, at CERN. Furthermore, there are a number of research activities in many other countries as well as within the international programs of OECD/NEA, IAEA, and EC.

4.1 Belgian MYRRHA project

The MYRRHA project has been started at the end of 1996 as a conceptual study aiming at the development of a new radiation source based on accelerator driven neutron generation for multiple purposes. The accelerator would be a proton-cyclotron with an exit energy of 250 MeV and a current of 2 mA to be upgraded to 10 mA. The multipurpose research facility would be used in materials research, radioisotope (^{99}Mo) production, proton therapy and last but not least for the study of transmutation. The total energy would not exceed 30 MWt. The fast neutron flux could reach 1.5×10^{15} n/cm^2/s in a core volume of 0.035 m^3.

The spallation source would be a windowless liquid Pb (Pb-Bi) target surrounded by a subcritical assembly. The basic engineering study is currently going on.

4.2 Czech Activities [21]

The Czech Republic started a national R&D program on accelerator-driven transmutation technologies. The Nuclear Physics Institute, the Nuclear Research Institute plc., and Skoda Nuclear Machinery Ltd. are involved in the program. A project LA-0 is proposed for testing the subcritical modular assemblies with fluoride salts on the experimental reactor LR-0.

4.3 CEA Project, France

The CEA ISAAC program has been setup to investigate the physics of subcritical accelerator-driven systems, in particular in the following areas: (a) high-intensity accelerators, (b) methods, data and validation, (c) target technology, (d) subcritical source-driven multiplying systems, and (e) system studies for different applications. The program includes the MUSE experiments at MASURCA [22] to validate the physics of subcritical systems and the spallation experiments at SATURNE to validate the modeling codes [23].

Recently, a research group GEDEON made up of the CNRS, CEA and EDF has also been set up to intensify and coordinate research in these areas. A preliminary proposal of an experimental fast system called HADRON is made for experimental validation and demonstration of an accelerator-driven system. The HADRON concept is based on a subcritical core with an effective multiplication factor around 0.95 and a thermal power of 50 - 100 MW, fed by a proton beam of 2 - 5 MW.

R&Ds for the linear accelerator providing a 600 MeV-40 mA CW proton beam is being conducted under the TRISPAL Project.

4.4 German Activities [24-26].

In Germany some small activities related to the application of ADSs for the backend of the nuclear fuel cycle are in progress since several years. The first main objective was to establish reliable calculational procedures in order to be able to compare ADS capabilities with those of critical reactors. Exploratory ADS investigations have been performed for thermal systems with dispersed fuel in lead coolant at KFA Jülich and for PHOENIX like fast systems at FZK Karlsruhe.

At the Technical University Munich, the design of a separated-orbit cyclotron with superconducting channel magnets and superconducting RF cavities for 1 GeV proton beams of up to about 10 MW beam power is under development (TRITRON).

4.5 ENEA-INFN Project, Italy

R&Ds on acceletor-driven transmutation system is underway by jointly ENEA and INFN. ENEA is investigating neutronics, thermal hydraulics, safety, beam window, and materials for a Pb (Pb-Bi) cooled subcritical system, and INFN is involved in design and R&D for a 1 GeV-30 mA proton linear accelerator.

4.6 JAERI Project, Japan

JAERI is carrying out studies on accelerator-driven transmutation systems and development of a high-intensity proton accelerator [27, 28] in the framework of the Japanese OMEGA Program. The systems are designed as dedicated transmuters to burn MA efficiently using a proton linac. Two types of system concept, a solid system and a molten-salt system, are being investigated in the conceptual design study.

Engineering tests for accelerator-driven transmutation are planned under the JAERI proposed Neutron Science Project based on a superconducting linac. The linac will deliver a 1.5 GeV beam with a maximum power of 8 MW. Technology demonstration tests will be made on an integrated target/core system at a thermal power around 30 MW to be upgraded to around 60 MW. Technical feasibility of the target will be also tested with a 7-MW beam power.

4.7 KAERI HYPER Program, Korea

A study on the transmutation has been initiated since 1992 at KAERI [29]. KAERI is now setting up a long-term research program called HYPER on accelerator-driven systems. The program is scheduled to develop basic key technologies in 1997 - 2001, and then to design a small bench-scale test facility. KAERI is trying to launch a program for the development of a multi-purpose linear accelerator called KOMAC. The design target of the accelerator is to generate a 1 GeV-20 mA proton beam.

4.8 Russian Activities

Several research institutes in Russia are involved in a partitioning and transmutation program directed by MINATOM [30]. Russia holds excellent technologies relevant to accelerator-driven transmutation. Russian activities in this field, however, do not seem to be well coordinated. Most of activities are carried out within the framework of ISTC projects.

4.9 Swedish Activities [31]

A "Group for Spallator Research" conducts some concerted research at CTH, KTH, the Manne Sigbahn Laboratory-Stockholm University and the Uppsala University. The main task of this group is to stimulate and to coordinate R&D projects in the accelerator-driven transmutation technologies. The activities have been primarily devoted to system and feasibility studies together with participating in some international efforts.

4.10 PSI Activities, Switzerland

PSI is performing the ATHENA experiments [32] and analytical studies [33]. In the experiments, actinide targets are irradiated with 0.6 GeV protons from the PSI cyclotron, with the objective of providing a relevant database for the validation of high-energy fission model. Analytical studies are aiming at verifying the neutronics, comparing the transmutation effectiveness, and identifying the data and code requirements.

4.11 UK Activities

There are little activites in the field of nuclear waste transmutation in UK. Tritium production based on a ~35 MW proton accelerator is being pursued. Feasibility study has been completed and R&Ds on the accelerator is underway.

4.12 BNL PHOENIX Project and LANL ATW Project, USA

Phoenix is an accelerator-driven transmuter concept developed by BNL. The system consists of a set of FFTF-like subassemblies of MA oxide fuel arranged in separate modules. The proton beam from a 1.6 GeV-104 mA linac is spread and impinges on the modules directly. The 3,600-MWt system transmute 2,600 kg of MA (1,050 kg to fission and 1,550 kg to convert into Pu) and 300 kg of Iodine.

LANL has been studying accelerator-driven systems under the Accelerator-driven Transmutation Technologies (ADTT) program for applications of waste transmutation, Pu burning, and energy production. General system concepts for these applications had common features of using thermal neutrons and fluid fuel such as aqueous solution, slurry, and fluoride molten-salt.

ATW is a sub-project for transmutation of commercial and military waste in the ADTT program. Originally proposed ATW [34, 35] was a unique concept in burning MA using the so-called two-step reaction. The system had a heavy water blanket and an intense proton beam over 100 MW to produce a required very high thermal flux of the order of 10^{16} n/cm^2/s.

Recently, the ATW project has abandoned its initial concept of using thermal neutrons to change to a fast neutron system. The system is cooled by Pb-Bi and loaded with metal fuel. The present interest of the ADTT program focuses on reducing the amount and long-term hazard of the spent fuel from commercial reactors.

The superconducting proton accelearator providing a 1.6 GeV-250 mA class beam is being developed under the Accelerator Tritium Production (APT) program.

LANL is proposing an experimental program called LIFT. The LIFT experiments will be carried out using 1 MW proton beam at LANSCE, starting with liquid Pb loop tests followed by integrated target/blanket tests at a thermal power up to 5 MW.

4.13 CERN EA Project

CERN is working on the conceptual design of a so-called Energy Amplifier (EA) with a main objective of power generation based on Th-^{233}U fuel cycle. The present EA concept is an oxide fuel, fast subcritical system driven by a 1 GeV-12.5 mA cyclotron. The effective multiplication factor is 0.98 [36], and the thermal power of 1500 MW is removed by natural circulation of liquid Pb. This system was also proposed as an efficient burner for Pu destruction [37]. The first demonstration EA plant is planned to run with a superconducting linac [38].

The CERN group performed an experiment for proving the feasibility of the concept [39]. Measurements were done on the heat in 3600 kg of natural U irradiated by 1 - 3 GeV proton beams.

A plan has been proposed to construct the first demonstration EA plant with a thermal power of 100 MW to be upgraded to 250 MW in Aragon, Spain. To this end, an internatinal consortium LAESA was established in 1997.

4.15 OECD/NEA Programs

OECD/NEA coordinates a series of meetings related to accelerator-driven transmutation. The OECD/NEA activities include the construction of nuclear data libraries and the benchmark of codes, an emphasis being placed on the intermediate energy region relevant to accelerator-driven transmutation.

4.16 IAEA Programs

IAEA is preparing to publish a status report [40] on accelerator-driven system to provide an overview of ongoing development activities and different concepts being developed. A benchmark of accelerator-driven system is underway in the CRP on the "Potential of Th-based Fuel Cycles". Ongoing acitivites include preparation of the database on existing and planned experimental facilities for ADS related R&Ds.

4.17 EC Projects

An EC project called IABAT is underway to assess the impact of the accelerator based technologies on nuclear fission safety. The objectives are to perform system studies on the accelerator-driven system, to assess the accelerator technology, to study the radiotoxicity of the fuel cycle and its nonproliferation aspects, and to provide basic nuclear and material data. Several institutes and research centers in Europe participate in the project.

4.18 ISTC Projects

Ex-USSR countries have long-standing and continuous interests in accelerator-driven systems for transmutation of nuclear waste and burning excess Pu. There are a number of ongoing ADS related projects supported by ISTC.

5. TECHNICAL CHALLENGES

5.1 High Intensity Accelerator

The high-intensity accelerator technology required for industrial applications has been under continuous development for the past decades. Beam powers in the range 10-100 MW are assumed in the current proposals of full-scale accelerator-driven systems. The maximum beam power that could be achieved within a decade would be up to around 100 MW for a linac and around 10 MW for a cyclotron.

LANL is developing a linear accelerator with a beam power of hundreds of MW under the APT (Accelerator Production of Tritium) Program. The proposal of the program has had many independent reviews. The conclusions of the reviews were positive regarding about the technologies of the accelerator as well as target , but pointed out the need for an appropriate R&D program. [41]. The LANSCE accelerator at LANL is the highest power operational linac (around 1 MW) in the world. This linac is operated in pulsed mode (10% duty), and well below the limits of space charge and RF bucket filling. It is estimated that 40 - 160 MW CW (100% duty) beam is possible in principle by simple extension of proven technologies.

Cyclotrons have the advantages of much smaller physical size and lower cost over linacs with the same beam power. The PSI accelerator is the highest power operational cyclotron (around 1 MW) in the world. The PSI group made a preliminary design of a cyclotron with a relatively modest beam power of 10 MW [42].

In the high-intensity accelerator, beam loss should be minimized to avoid resultant damage and activation of accelerator hardware. For industrial applications, primary issues are the stability, efficiency, reliability, operability and maintainability of the accelerator. To improve them to a great extent, further R&Ds and operational experiences is required. Capital cost and size of the accelerator should be also included in the design priorities.

5.2 Beam Window and Spallation Target

Reliable nuclear data and codes for the intermediate energy region is required for the design of an accelerator-driven transmutation system. At present, most of the data and the codes are available to make an approximate evaluation for conceptual designs and feasibility studies. Detailed designs will need much higher accuracy. If a ±2% accuracy on the system energy balance would be required, the spallation neutron yield should be calculated with an accuracy of ±2%. Uncertainties still seem large in predicting the spallation product yields and the high energy component of neutron spectrum to evaluate activation and damage in material and long-term radiotoxicity of waste. High energy neutrons also have impact on the shielding requirements.

Injection of intense proton beam into the target causes high fluxes of protons and fast neutrons in the section of the beam window, target, and wall material surrounding the target. Their materials particularly for the beam window suffer irradiation damage and are degraded in mechanical properties and dimension stability. The beam window is the boundary that separates accelerator vacuum and system operating pressure. The exposure of the materials would be more severe in terms of fluxes and energies than what is experienced in normal reactors. Therefore, rather frequent replacement of these components would be required for a system driven by a high-current accelerator.

An intense proton beam deposits considerable heat in the target and the beam window. The heat deposition in these component may cause overheating or excessive thermal stresses and deformations. Even after the beam shut down, decay heat lasts for a while. Heat removal requirements for these components are essentially identical to those for the reactor fuel.

Fluctuations and trips of the incident proton beam may be inevitable in an accelerator-driven system. These changes in beam intensity will cause changes in temperatures and thermal stresses in the target and the beam window. Resultant thermal cyclings and thermal shocks may degrade the structural integrity and shorten the life-time of these components.

The beam window suffers from the stress due to the differential pressure between the accelerator vacuum and system operting pressure.

Liquid Pb or molten chloride salt targets may present material compatibility problems. Technologies should be developed to prevent the structural materials from errosion and corrosion.

5.3 Subcritical Core

A subcritical core can be the very similar in principle to a critical core except that the effective neutron multiplication factor is less than unity. A major difference is that the operating pressure in the subcritical core is limited to be relatively low because of the presence of the beam window and/or target vessel. The low operating pressure practically rules out use of water or gas as a primary fluid. A subcritical core cooled by liquid metal can fully utilize existing LMFBR technologies.

The problems of thermal fatigue caused by beam trips and material compatibility with coolant in the core components are similar for the case of the beam window and spallation target.

MA fuel technology is a key to dedicated transmutation systems. Reliable nuclear data of MAs are necessary to evaluate the system performance. Technologies should be developed for fabrication and reprocessing of MA containing fuel.

5.4 Safety [43]

The accelerator-driven subcritical system has clear safety advantages for severe reactivity accidents. It can cope with fast ramp rate accidents which could occur too rapidly for scram systems in critical reactors. This ability to overcome fast reactivity insertions is important to avoid Chernobyl type accidents caused by power excursions. This is a particularly important feature in MA fuel dedicated transmutation systems.

The consequences of cooling-failure accidents, such as loas of force circulation, loss of heat sink, and loss of coolant or depressurization, for accelerator-driven systems are not so different from the case for critical reactors. Therefore, a reliable beam shutoff system is required for an accelerator-driven system - just as a reliable scram system is required for a critical reactor. Also, of general importance is a reliable emergency decay heat removal system.

6. ACCELERATOR-DRIVEN TRANSMUTATION SYSTEM CONCEPT

JAERI is developing the concepts of accelerator-driven transmutation systems (ADTS). The systems are specially designed for transmutation purpose as dedicated transmuters. With dedicated transmuters, an entire fuel cycle would be of strata sturcture as proposed as the concept of the double-strata fuel cycle (Fig. 1).

ADTS is designed to have a hard neutron spectrum and a high neutron flux for efficient and effective transmutation of MAs. The fuel feed consists of MAs in a form of mononitride or chloride molten salt, Pu beeing added in the initial feed only. One unit of ADTS supports about 10 unit of 1000-MWe LWR. The accelerator is a superconducting CW proton linac with a final energy of 1.5 GeV and a current of several 10s mA. Power generation is involved to supply electricity to operate its own accelerator. The conceptual layout of the ADTS plant is shown in Fig. 2. In the conceptual design study, two types of system concepts are being investigated. One is the solid system consisting of tungsten target and solid fuel core cooled by liquid Na. Another option is the advanced molten-salt system with flowing chloride fuel.

The experimental plan in the Neutron Science Project addresses the solid system concept. The design of the solid system is based on the well-demonstrated technologies for LMFBR, whereas the molten-salt system needs further research efforts before designing large-scale experiments.

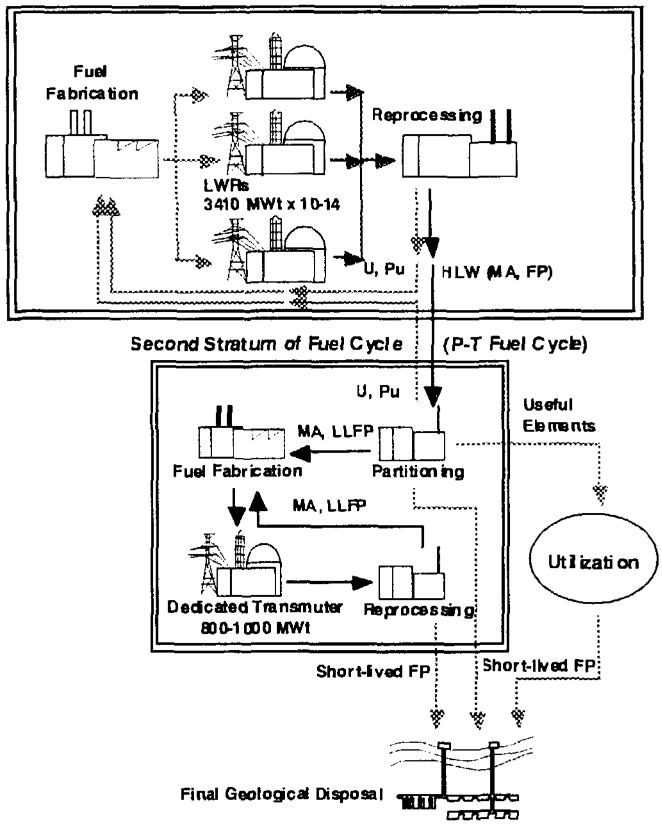

Fig. 1 Concept of Double-strata Fuel Cycle

6.1 Solid System

The solid system consists of an intense proton accelerator, tungsten target, and a MA fuel subcritical core. The accelerator injects proton beam downwards through a beam window into the target. Surrounding the target is the subcritical fast-spectrum core. The target consists of ducted target subassemblies. Each target subassembly has multiple layers of tungsten disk with through holes for coolant passage. The subcritical core consists of pin-bundle ductless type fuel subassemblies. The fuel is MA mononitride. The target and fuel subassemblies are cooled by forced upward flow of primary Na. The whole target/core including reflectors is contained within a steel ves-

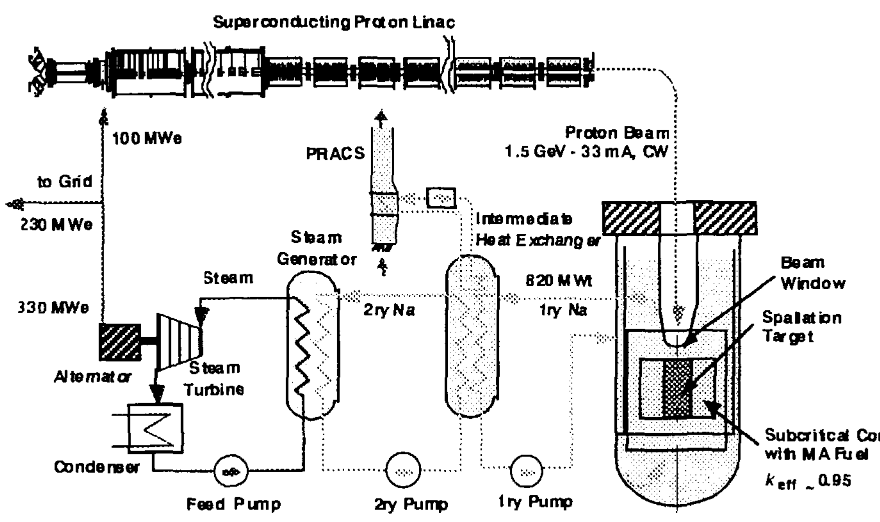

Fig. 2 Concept of Accelerator-driven Transmutation System

sel as shown in Fig. 3.

With a 1.5 GeV-33 mA incident proton beam, the target/core having an effective neutron multiplication factor of around 0.93 produces a thermal power around 820-MW. The net MA transmutation rate is approximately 250 kg/y, or 12% of MA inventory per year, at a load factor of 80%. A Pb-Bi cooled system with nitride fuel is also under investigation as an alternative possible option.

6.2 Molten-salt System

In the molten-salt system design, the molten salt acts both as fuel and as target material, and also servcsas coolant. This eliminates the physical and functional separation of target and core, and thus significantly simplifies the target/core configuration as shown in Fig. 4. Chloride salt with a composition of $64NaCl$-$5PuCl_3$-$31MACl_3$ is chosen based on the consideration about actinide solubility and hard neutron energy spectrum. One of the attractive features of the molten-salt fuel is the possibility of on-line fuel feed and reprocessing.

The molten-salt target/core with 5430-kg actinide inventory produces 800 MW thermal power. The MA burnup is approximately 250 kg/y or 8 %/y at a load factor of 80%.

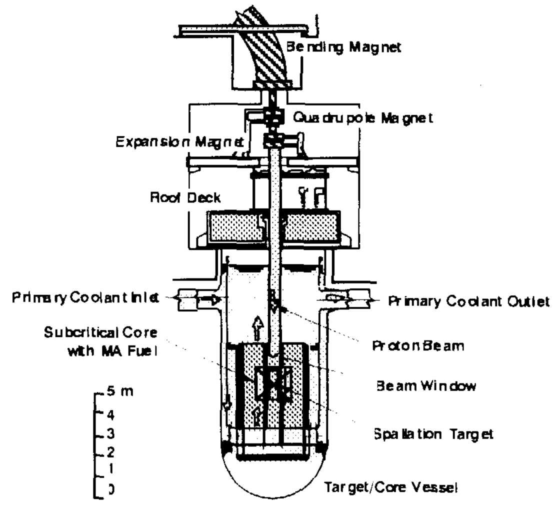

Fig. 3 Solid ADTS

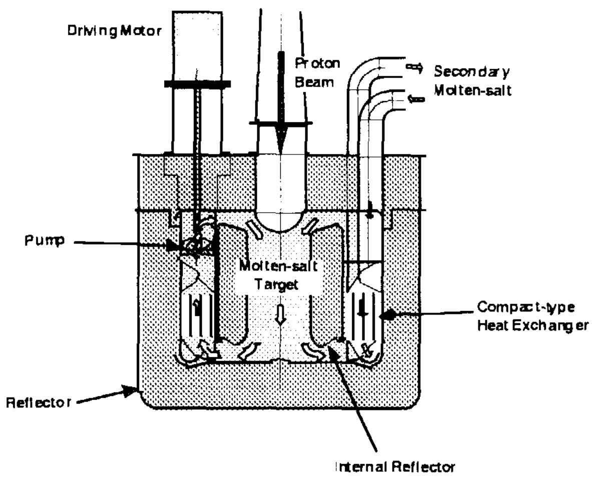

Fig. 4 Molten-salt ADTS

7. EXPERIMENTAL PROGRAM

The Neutron Science Project aims at engineering experiments for ADTS and various experiments in the field of basic science using an intense proton accelerator. The experimental program for development of ADTS was planned. The program is to be proceeded in two phases, according to the available beam power and the operating mode (1st phase: 1.5 GeV-1 mA pulsed beam, 2nd phase: 1.5 GeV-4.5 mA CW beam). Preliminary experiments on reactor physics and target engineering are planned for the first phase. Transmutation system experiments and high-power target experiments are planned for the second phase to demonstrate the technology of ADTSs.

The preconceptual study and preliminary analyses for the transmutation experimental facilities is underway. Preliminary neutronics, thermal-hydraulics, and structural analyses were performed for the experimental transmutation system and the high-power target. Undue difficulties were not found at this stage in the design of the experimental facilities.

7.1 Transmutation System Experiments

The preconceptual design study is being conducted for the experimental system that is a reduced-scale mockup of the proposed 800-MWt practical system. The experiments are planned to be made with a 30-MWt UO_2 core for the first step and then with a 60 MWt UN core for the second steps.

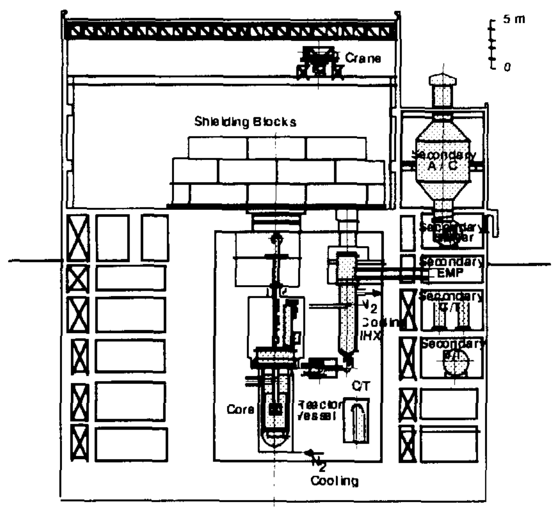

Fig. 5 30 - 60 MWt Experimental ADS

The main goals of the experiments are: to demonstrate the integrated operation of spallation target and subcritical fast-spectrum core driven by an intense proton beam, to demonstrate the MA transmutation performance, to test the instrumentation and control system, to test the integrity of MA fuel, to verify the system design concept, and to verify the operational safety of the system.

The spallation target of the experimental system consists of multiple layers of tungsten disk. The subcritical core is loaded with UO_2 fuel for the first-step experiments. The target and core are cooled by liquid Na. Liquid Pb or Pb-Bi coolant is under evaluation as an option. The system is driven by 2.3-MW CW beam to generate 30-MW thermal power at an effective neutron multiplication factor around 0.93. MA target pins are placed to test the integrity and transmutation capability. The subcritical core for the second-step experiments is loaded with UN core that generates a thermal power of 60 MW at an incident proton beam power of 4.5 MW. MA fuel is irradiated in a form of subassembly to demonstrate the technical feasibility of MA transmutation. The experimental system has no power conversion unit to produce electricity. The heat generated in the target/core is transferred to a secondary Na loop and then dumped to the atmosphere through forced-air coolers. The major parameters of the experimental systems are listed in Table 1. Figure 5 shows the vertical cutaway view of the experimental system.

Table 1 Parameters of the experimental transmutation system [2nd step]

Fuel	UO_2 [UN], 20% U-235
Target	Solid Tungsten, Multi-Layer Disk Type
Coolant	Liquid Sodium
Proton Beam	1.5 GeV-1.5 mA [1.5 GeV-3.0 mA], CW
Initial keff	~0.93
Thermal Power	30 MW [60 MW]
Coolant Temperature, In/Out	623/723 K

7.2 High-power Target Experiments

High-power target experiments are planned to be conducted in the second phase of the Project. The experiments will demonstrate the technical feasibility of the spallation target and beam window. These components constituting an interface between the proton accelerator and the subcritical core are new to nuclear power systems. Their stractural integrity is vital for the reliability and safety of the sysetm. The experiments will use the full beam power of the accelerator. Lower degree of scalability of these components requires higher degree of similitude as compared with the subcritical core.

The main goals of the experiments are: to demonstrate the structural integrity of the spallation target and beam window, to demonstrate the thermal-hydraulic performance of the target and window, to test materials exposed to a high proton and neutron fluxes, to demonstrate the maintainability and replaceability, to verify the target and window design concept, and to verify the operational reliability and safety.

The preliminary analyses were made on thermal-hydraulics and stractural strength for both the steady state condition and transients caused by turning beam on and off. An alternative option of liquid Pb or Pb-Bi target was evaluated. The major parameters of the high-power experimental target are listed in Table 2.

Table 2 Parameters of the high-power target (solid target)

Target	Solid Tungsten, Multi-Layer Disk Type
Coolant	Liquid Sodium
Proton Beam	1.5 GeV-4.7 mA, CW
Thermal Power, Max.	7 MW
Coolant Temperature, In/Out	623/723 K

8. CONCLUDING REMARKS

The features of subcritical operation of ADSs offer the advantages of a safe and efficient means for nuclear waste transmutation. Major ADS projects in the world have shown a convergence toward a common objective (nuclear waste transmutation) and similar technology (fast neutron systems). Fuel breeding and energy production with ADSs have not yet strong incentives. Most of system concepts use fast neutron spectrum that offers significant neutronics advantages.

The conceptual design study of ADTSs and related R&D are in progress at JAERI under the OMEGA Program. JAERI has proposed a solid system concept based on the current LMFBR technology and a molten-salt system concept as an advanced option. The ADTS is designed as a dedicated transmuter to burn MAs from about 10 LWRs and generate enough electricity for the accelerator operation.

A plan of experiments has been proposed in the JAERI Neutron Science Project as crucial steps toward the demonstration of accelerator-driven transmutation technologies. The experiments will test the technical viability of accelerator-driven subcritical systems and the capabilities of MA transmutation with an assembly at zero power level firstly and then with an integrated target/core system at 30 - 60 MW thermal power. Technical feasibility of the accelerator interface will be tested at high beam power levels up to 7 MW. Preconceptual design study is being made for the experimental facilities.

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