Overview of Physics Aspects of

Different Transmutation Concepts

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1. INTRODUCTION

Partitioning and transmutation (P-T) of actinides and fission products is currently one of the important subjects of long term research and development in several OECD countries and also in Russia,from the viewpoints of its perspectives of potential utilization of resources and possible advances in waste management.

In the P-T, undesirable nuclides in spent fuel are first separated and then incinerated in a nuclear reactor or other transmutation device. The nuclides that would be incinerated by the P-T are generally considered to be the transuranium (Np,Pu,Am and Cm) and certain long-lived fission-products,such as I-129 and Tc-99. Implementation of the P-T concept would involve intensified processing (partitioning) to remove long-lived radionuclides from the waste stream and subsequent use of a transmutation device to convert transuranium to fission and fission-products to shorter-lived radionuclides.

Various P-T concepts for high-level radioactive waste (HLW) are currently being proposed or under investigation at many organizations in the world. Partitioning technologies for spent fuel from light-water reactor and fast reactor include aqueous and pyrochemical processes. Transmutation technologies include application of light-water reactor,fast reactor and proton accelerator-driven transmutor.

Most of the assessment and research performed to date has focused on the fundamental processes or the system design the transmutation device or the partitioning process rather than the

integration of a P-T system into nuclear fuel cycle. Under these circumstances, the OECD/NEA Nuclear Development Committee (NDC) decided to initiate a system study on P-T as international collaboration program to identify advantages and disadvantages of introduction of P-T technologies into nuclear fuel cycle.

With regard to transmutation,various transmutation concepts are under investigation by using their own data and methods. However,their physics characteristics are not necessarily predicted well,because of insufficient accuracy in used data for the transuranium and long-lived fission-products. In this context,the OECD/NEA Nuclear Science Committee (NSC) decided to form a task force to review the physics aspects of various proposed transmutation concepts. The task force requested about 30 specialists working for transmutation to inform the physics aspects of their concepts, including objectives of transmutation, fuel cycle concepts with P-T, physics characteristics of proposed transmutors with used data and methods (see Appendix). The present report overviews the physics aspects of different transmutation concepts ,based on the above mentioned information.

2. R&D PROGRAMS ON PARTITIONING AND/OR TRANSMUTATION

2.1 R&D Programs and Their Principal Objectives

(1) French SPIN program [1]

In order to respond to the public concern about wastes and in particular the long-lived high level ones,a French law issued on December 30,1991 identified the major objectives of research for the next fifteen years,before a new debate and possibly a decision on final wastes disposal in Parliament. To comply with the requirements of the management of long-lived high level wastes, the CEA has launched an important and long term R&D program. A part of this program called SPIN is devoted to separation and incineration of these wastes and it includes two sub-programs:

a) In short and mid term perspectives (1991-2000), PURETEX aiming primarily at reducing the volume of wastes from reprocessing from 1.5m3 to 0.5m3 per ton of reprocessed heavy metal. This result will be obtained by modifying the PUREX process in order to be able to eliminate bitumen and by improving the conditioning of solid wastes.

b) In a long term perspective,ACTINEX devoted to the separation and transmutation of long-lived elements in view of reducing wastes toxicity by a factor 100 and then 1000 compared to direct disposal within 20 and 40 years respectively. With regard to transmutation,the feasibility of actinide incinera

tion by PWR and fast reactor are investigated. In parallel the possibilities of advanced systems such as specific nuclear reactors and accelerators are also investigated.

The objective of this program is to limit volume and potential radiotoxicity of minor actinides in deep storage and also the quantities of long-lived fission-products for the outcome of deep storage.

(2) **Japanese OMEGA program** [2]

The Japan's Atomic Energy Commission launched in October 1988 a comprehensive basic research program (OMEGA) to explore the feasibility of utilizing HLW as useful resources and widening future options for waste management by releasing the report entitled "Long-Term Program for Research and Development on Nuclide Partitioning and Transmutation". In the partitioning technology development, following scopes are to be studied;

- Partitioning from HLW or in main reprocessing process.
- Recovery of useful metals from insoluble residue.
- Technology to make use of separated nuclides.

The development of transmutation technology falls into following two major R&D categories;

- Application of nuclear fission reactors.
- Application of high-intensity accelerators.

Fission reactors include fast breeder reactor power plants ,and specially designed actinide burner reactors,which would be a very effective mean to transmute long-lived TRU. High-intensity accelerator aims at transmuting TRU and other long-lived FP.

The program is planned to be carried out in two phases. The first phase (1988-1996) will be dedicated in general for basic studies and testings to examine feasibilities, to develop fundamental technologies, and to conduct overall assessment for various candidate concepts. In the second phase, engineering scale tests will be conducted to verify the systems and technologies evolved by that time. Because of the exploring nature of the program, several potential methods or concepts are being investigated in parallel in both partitioning and transmutation areas by the Japan Atomic Energy Research Institute (JAERI), the Power Reactor and Nuclear Fuel Development Corporation (PNC), and the Central Research Institute of Electric Power Industry (CRIEPI).

The objective of the program is to significantly reduce the source term of the long-term potential hazard which arises from HLW.

(3) ALMR Actinide Recycle Program [3]

The Advanced Liquid Metal Reactor (ALMR) Actinide Recycle System is being developed in the United States for application early in the 21st century. The system is expected to have the ability to fulfill multiple missions including: (1) the conversion of excess Pu to produce power, (2) utilizing the tremendous energy potential associated with spent LWR fuel, (3) providing long-term energy security,and (4) achieving a significant reduction in the heat load and time constant associated with processed waste. The ALMR is a fast reactor design,and its plant design and development program is a national program involving wide partici-

pation by US industry as well as national laboratories, universities,and international organizations. The ALMR utilizes the metal fuel cycle being developed by Argonne National Laboratory (ANL) which inherently recycles actinides to the reactor in the reference breakeven/breeder and burner designs.

The objectives of the program include potential reduction of major long-lived toxic actinides and removal of heat-producing radionuclides.

(4) Los Alamos ATW Program [4]

The Accelerator Transmutation of nuclear Waste (ATW)is being developed by the Los Alamos National Laboratory (LANL) in the US. The ultimate goals of the ATW development effort concern creation of a system that can destroy long-lived migratory fission-products and high toxicity actinides associated with high-level waste storage, and creation of an advanced energy production concept that can rectify major obstacles facing nuclear power.

Application of an ATW system to HLW management programs can have a significant impact. An ATW system applied to cleanup of long-lived defense HLW at a DOE site could provide management options that minimize or eliminate HLW leaving the site. Long-lived nuclide destruction could also aid creation of more robust on-site waste storage forms. The impact of an ATW system on geologic repository storage could be significant. It could delay or potentially avoid altogether the need for a second geologic repository. It could also reduce the performance required of a geologic repository, e.g. reduce the waste isolation period from

10000 years to a period of around 500 years.

ATW application development involves a staged approach. Specific technology development allows components to be developed for a next application stage. A relevant example is that of defense waste application. The ATW system components developed for it share a high degree of commonality with that could be applicable to destruction of commercial high level waste.

(5) R&D Program at BNL [5,6,7]

Brookhaven National Laboratory (BNL) in the US has proceeded research programs on transmutation by using large proton linear accelerator (PHOENIX program), small power accelerator and high-flux thermal reactor. The objective is to substantially reduce some of the most significant challenges in building a waste repository,by transmuting key elements,such as Pu,minor actinides and a few of the long-lived fission products.

(6) R&D Program at ENEA [8]

A research program on accelerator-driven transmutation is being proceeded at ENEA under the close collaboration with LANL in the US. The objective of transmutation is the radiotoxicity reduction of minor actinides potentially introduced into the biological sphere with a not very significant increase of the KWh cost, and in the case of Pu, straight forward reduction of its stockpiles as a solution of Pu problem.

(7) R&D Program at Toshiba Corporation [9]

Future contribution to overall energy production by nuclear power depends on the development of efficient transuranic elements recovery system for spent fuel reprocessing. The system is expected to lead to optimum resource utilization and substantial reduction in HLW associated with large scale energy production.

The objective of transmutation is:

a) Substantial reduction in volume and long-term radiotoxicity of HLW in fuel recycling system,and
b) Simplification of future TRU-recycling technology in LWR and FBR aiming at total cost competitiveness, including reactor, reprocessing and storage in the total nuclear energy system.

(8) R&D Program at Royal Institute of Technology [10]

A research program on accelerator-driven transmutation is going on at the Royal Institute of Technology in Sweden, under the collaboration with LANL.

The objective of transmutation is:

a) Reduction of radiotoxicity in the geological storage, drastic reduction of the duration of radiotoxicity,
b) Combination of transmutation of waste with energy production, i.e.effective fissioning of transuranic isotopes,and
c) Opening a new "subcritical nuclear option" for energy production.

(9) R&D Program at IPPE [11]

A research of transmutation with fast reactors is being conducted at the Institute of Physics and Power Engineering (IPPE) in Russia. The objective is reduction of radiotoxicity in the deep storage,and finally reduction of health and environmental risks. Recycling of Pu in fast reactors could reduce the long term radiotoxicity of TRU up to 10 times. And recycling of Pu,Np, and Am would reduce it up to 100 times. The reduction of health and environmental risks is still uncertain.

(10) R&D Program at ITEP [12]

A research of accelerator-driven transmutation is being conducted at the Institute of Theoretical and Experimental Physics (ITEP) in Russia. The objective is the radiotoxicity and mass reduction of HLW before deep (underground) storage and the energy production in the blanket of an accelerator-driven transmutation system.

2.2 Nuclear Fuel Cycle Consideration on Partitioning and Transmutation

The nuclides to be transmuted have to be recycled many times to incinerate them sufficiently, since the considered transmutation cross-sections may be relatively low and the highest achievable neutron flux is limited. This means that the transmutation

technology has a strong correlation with the partitioning technology and also with nuclear fuel cycle. If the transmutation efficiency in one cycle is low, the partitioning efficiency must be high to achieve the overall required reduction factor during several cycles. This may give large influence to the overall nuclear fuel cycle concepts. In this context,the proposed nuclear fuel cycle concepts with the P-T technology are illustrated here, although it is out of scope of the present discussion.

(1) SPIN Program

The SPIN program consists of two major projects: PURETEX and ACTINEX, as mentioned above. The ACTINEX project aims at separating Pu, Np, Am, Cm as well as long-lived fission products in an advanced reprocessing system,and furthermore at incinerating them by using thermal or fast reactor, or accelerator. One of the nuclear fuel cycle concepts with the P-T technology considering in the ACTINEX is illustrated in Fig.2.1 {(Pu+Np+Am+Cm) balanced scenario}.

(2) OMEGA Program

The OMEGA program is composed of two major R&D areas: the transmutation technology development and the partitioning technology development. Since several potential methods or concepts in both R&D areas are being investigated in parallel by the JAERI ,PNC and CRIEPI as seen in Fig.2.2, these organizations propose their own nuclear fuel cycle concepts.

1) JAERI

The JAERI aims to develop a partitioning process of TRU and long-lived fission products from HLW and their subsequent transmutation system based on a specially designed fast burner reactor or an intense proton linear accelerator. A double strata nuclear fuel cycle concept is proposed as shown in Fig.2.3, in which the first cycle is the conventional fuel cycle and the second is the P-T cycle. Another concept under investigation is concerned with TRU recycling in LWR as seen in Fig.2.4.

2) PNC

The PNC's approach is to develop a partitioning process as a part of advanced reprocessing system where the improved PUREX process is closely combined with TRUEX-like TRU separation process with emphasis on TRU recycling in a MOX fueled FBR system. The nuclear fuel cycle concept is given in Fig.2.5.

3) CRIEPI

The CRIEPI aims at a concept to separate TRU from HLW by dry process with pyrometallurgical methods and then to transform them to the nuclides with shorter half-lives in a metallic fuel FBR. The nuclear fuel cycle concept is shown in Fig.2.6.

(3) ALMR Actinide Recycle (IFR) Program

The IFR is the entire reactor system consisting of reactor, fuel cycle and waste process. In the IFR pyroprocessing, minor

actinides accompany the plutonium stream and therefore actinide recycling occurs naturally in a metallic fuel LMR. The schematic picture of the IFR concept is given in Fig.2.7.

(4) LANL ATW Program

The feed to the ATW system is the separated actinides,Np,Pu, Am and Cm plus the long-lived fission products (LLFP's),Tc-99 and I-129. Chemical separation capacity is assumed to allow the LWR spent fuel to be partitioned into various streams before ATW is feasible. The ATW target/blanket converts the LLFP's to stable species by neutron capture and the actinides to fission products by capture and fission. There is a small chemical facility to remove any LLFP's created by fission for recycle, and to continuously recycle the actinides. Material flow in the ATW is shown in Fig.2.8.

(5) BNL Program

While not tied to a specific fuel reprocessing/recycling technology, much of the PHOENIX concept is based on the clean use of reactor energy (CURE) approach proposed by the Westinghouse Hanford [13], which is a waste partitioning process based on the well-known Purex process and the newer Truex process. The waste partitioning and transmutation system shown in Fig.2.9 is common in all the transmutation concepts including the PHOENIX concept proposed by BNL.

(6) Consideration at ENEA

The present fuel cycle will be completed adding, after the reprocessing, two new steps : partitioning (recovery of minor actinides from HLW) and transmutation (destruction of TRU). This last step can be carried out in different ways: Pu burning separated from minor actinide burning or the two together. The first strategy can be developed using the IFR for Pu burning and the ATW system for minor actinide burning or the two tasks can be performed by means of the latter strategy.

(7) Consideration at Royal Institute of Technology

The transmutation strategy is aimed to propose an energy producing transmutation system based on thorium fuel cycle. The Institute would try to design a proliferation safe system which will minimize chemistry requirements, possibly only one to the end-of-life stage.

(8) Program at Toshiba Corporation

An integrated nuclear energy production system should be developed to minimize impact on the global environment in future. The recovered minor actinides will be used as fuel together with Pu in LWRs and FBRs. The considered nuclear fuel cycle is shown in Fig.2.10.

(9) Program at IPPE

The considered nuclear fuel cycle includes followings:

- Closed fuel cycle with recycling of Pu mainly in fast reactors with breeding ratio of nearly unity,
- Partitioning of minor actinides, and recycling of Am and Np-237 together with Pu in fast reactors with breeding ratio of nearly unity,
- Long-term storage of Cm,and recycling of accumulated Pu-240,and
- Burning of excess of Pu and minor actinides in special burner reactors including one cycle of Pu in thermal reactors.

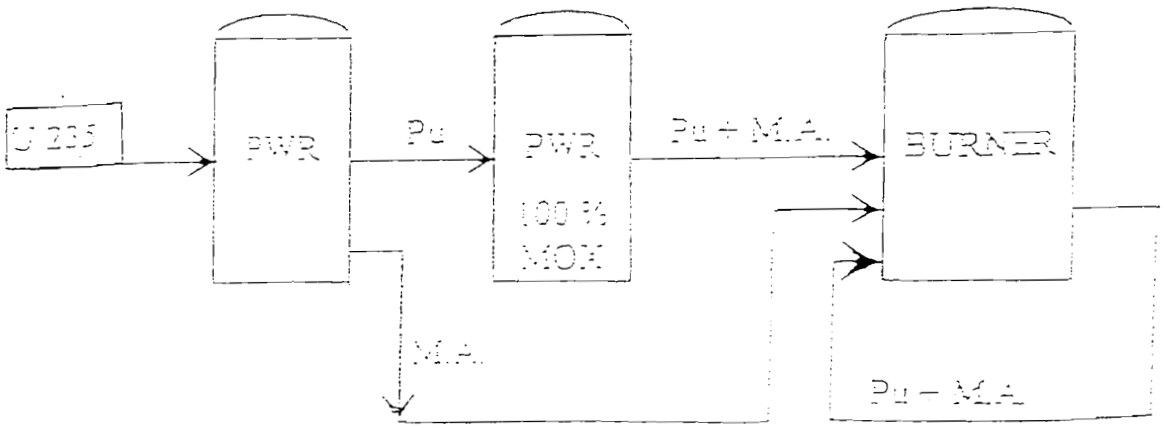

Fig. 2.1 One of Pu and MA Recycling Scenarios (CEA)
- (Pu+Np+Am+Cm) Balanced Scnario -

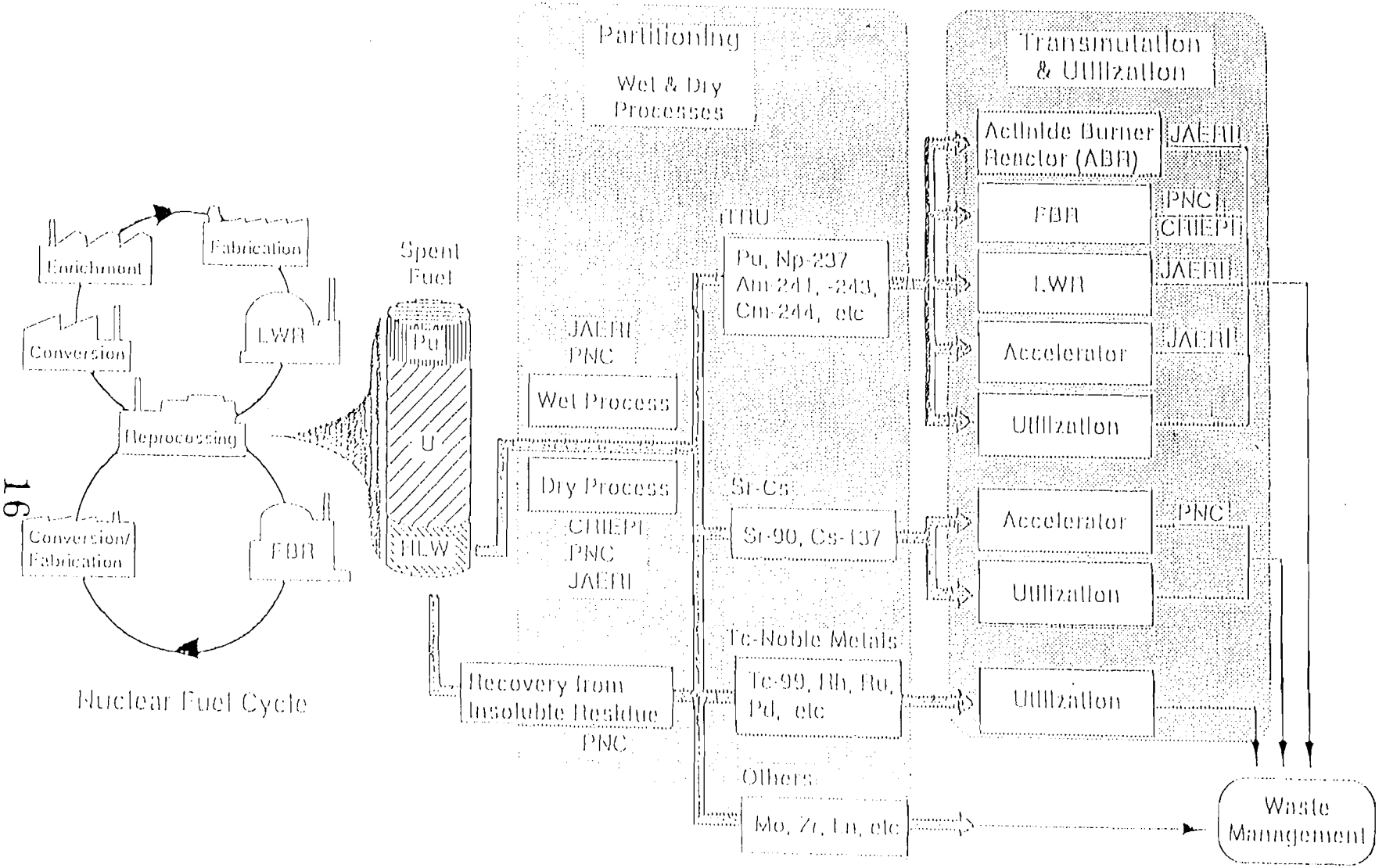

Fig. 2.2 R&D Activities under OMEGA Program on Partitioning and Transmutation (Japan)

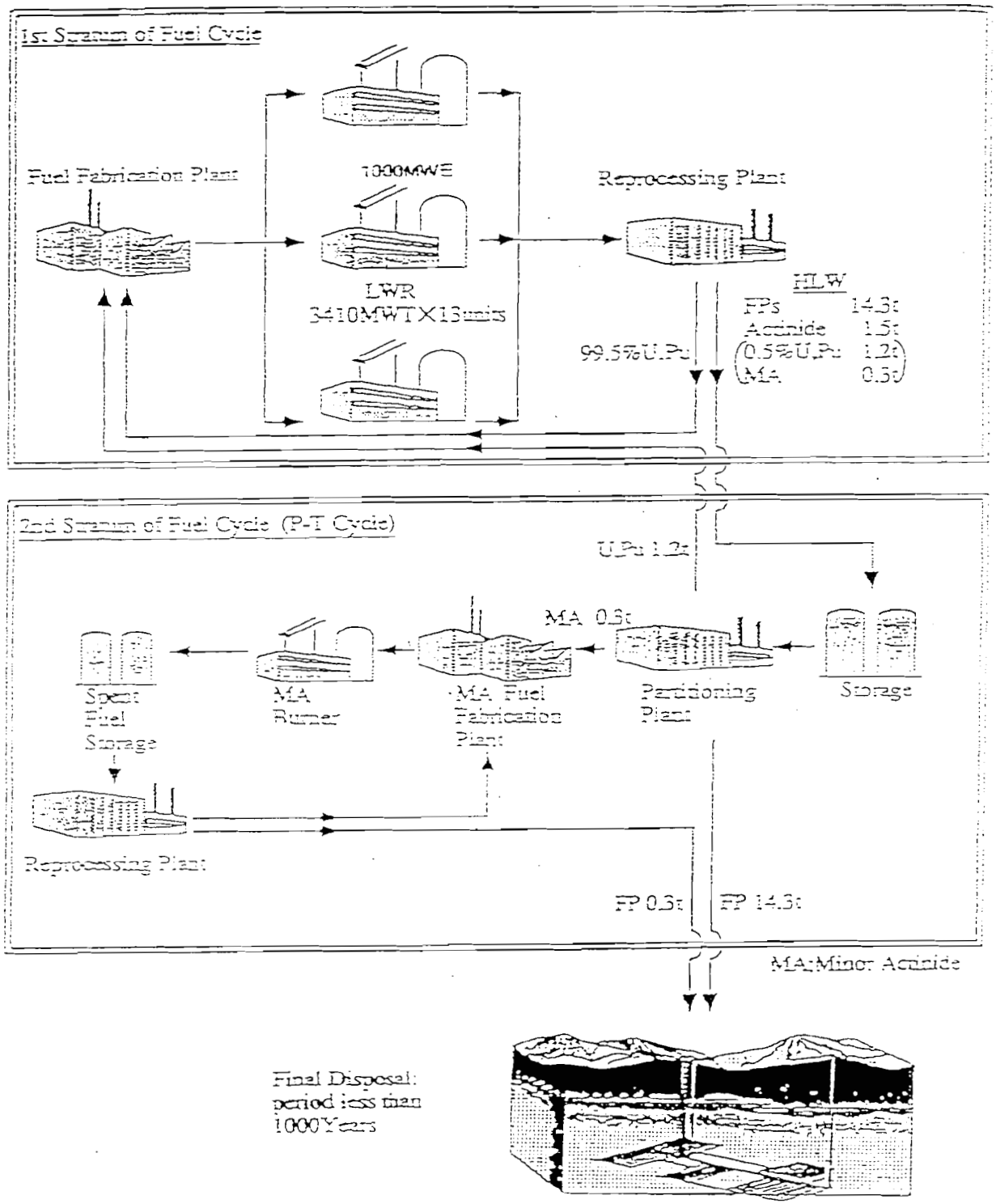

Fig. 2.3 Flow of High-level Radioactive Waste per Year Throuh Double Strata Fuel Cycle Conbined with Partitioning and Transmutation (JAERI)

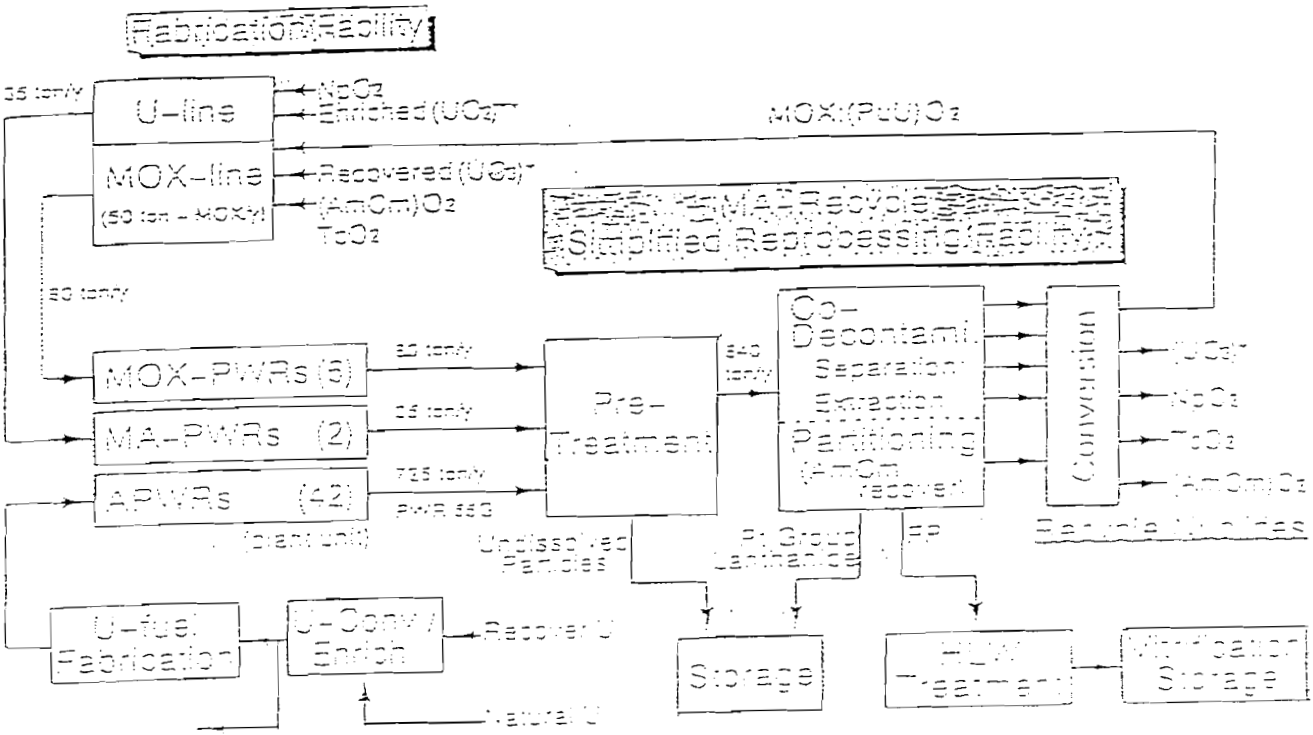

Fig. 2.4 A Concept of Pu and MA Fuel Cycle in LWRs (JAERI)

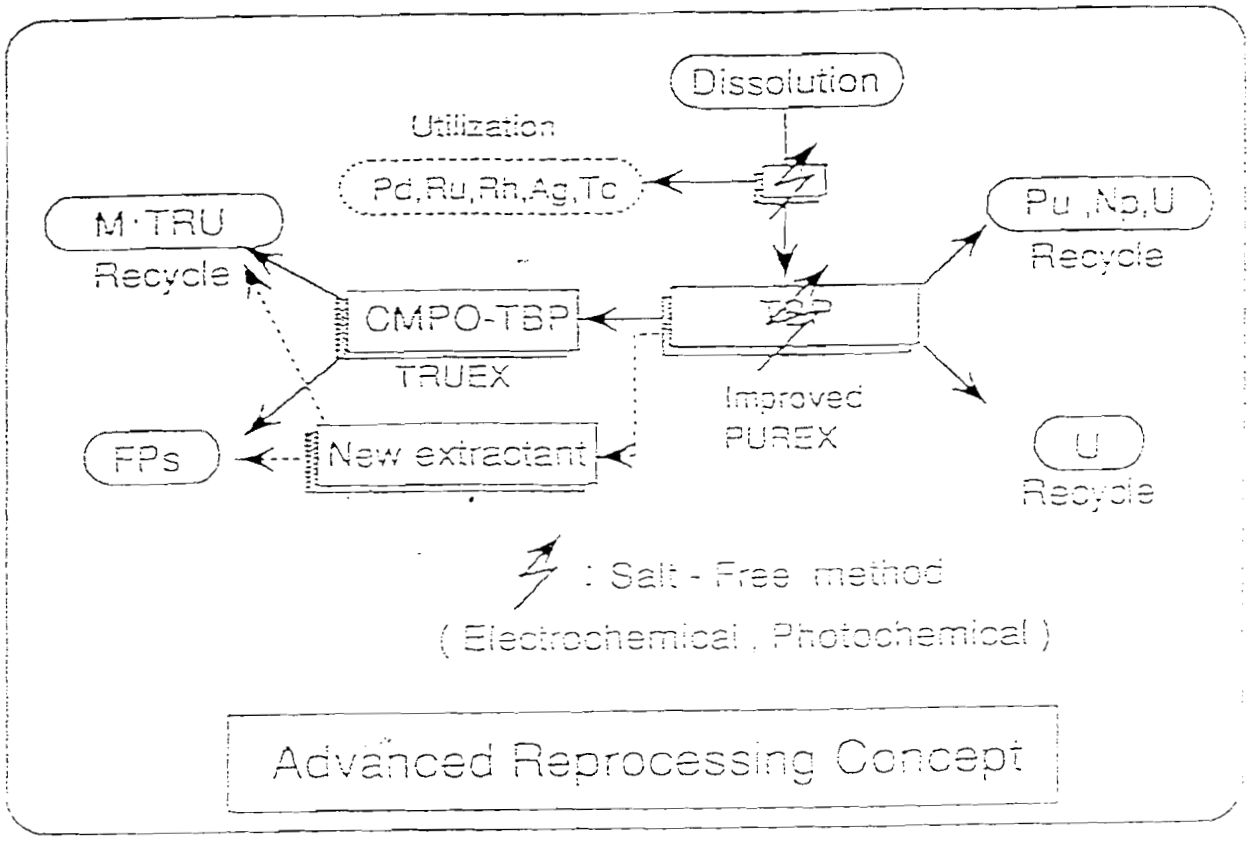

Fig. 2.5 Advanced Reprocessing Systems (PNC)

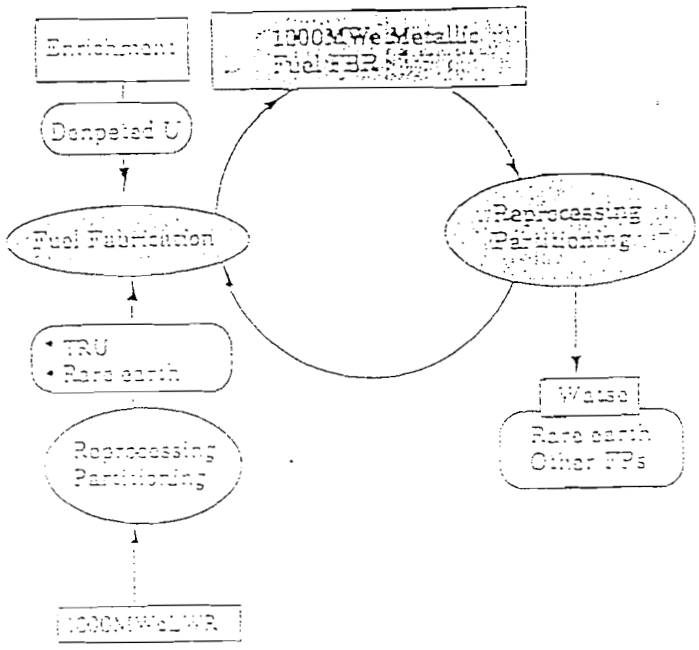

Fig. 2.6 Scheme of TRU Partitioning and Transmutation with Metallic Fuel FBR Recycle (CRIEPI)

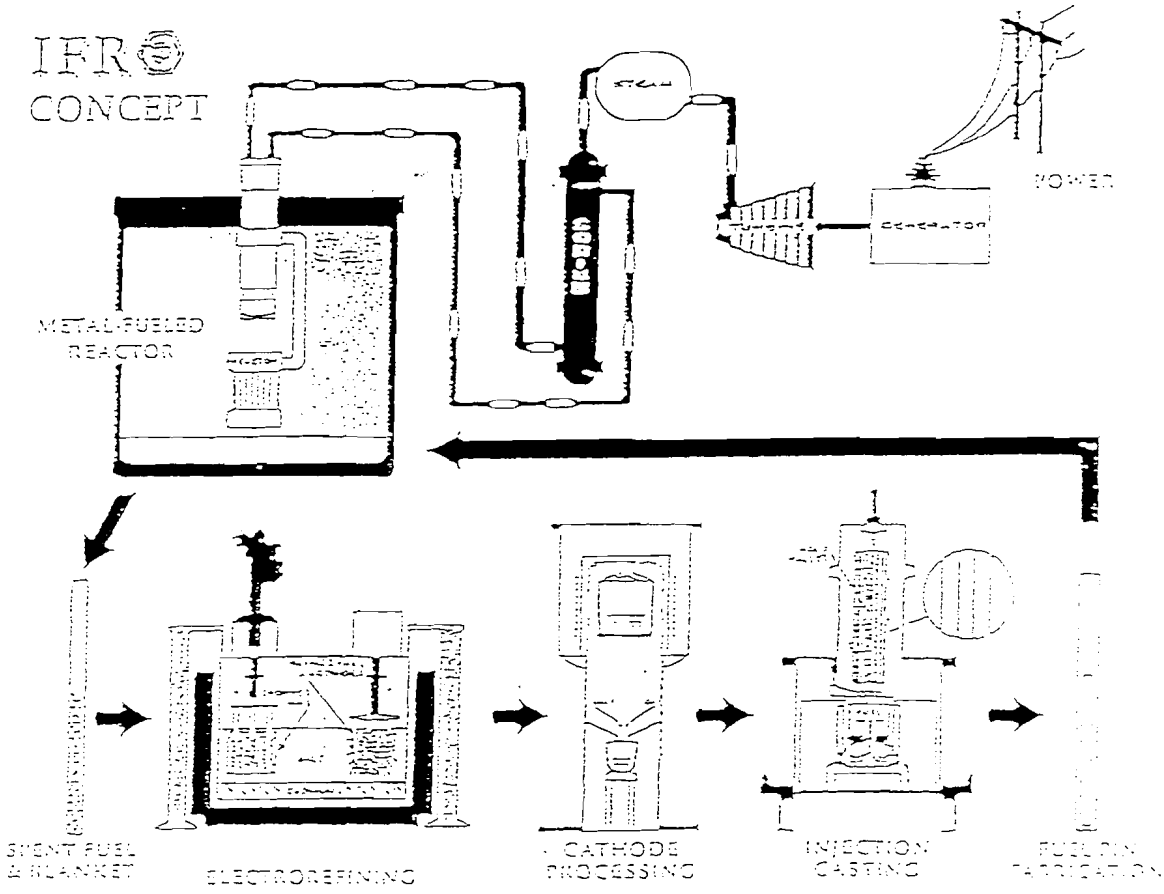

Fig. 2.7 A Schematic Picture of the IFR Concept (ANL)

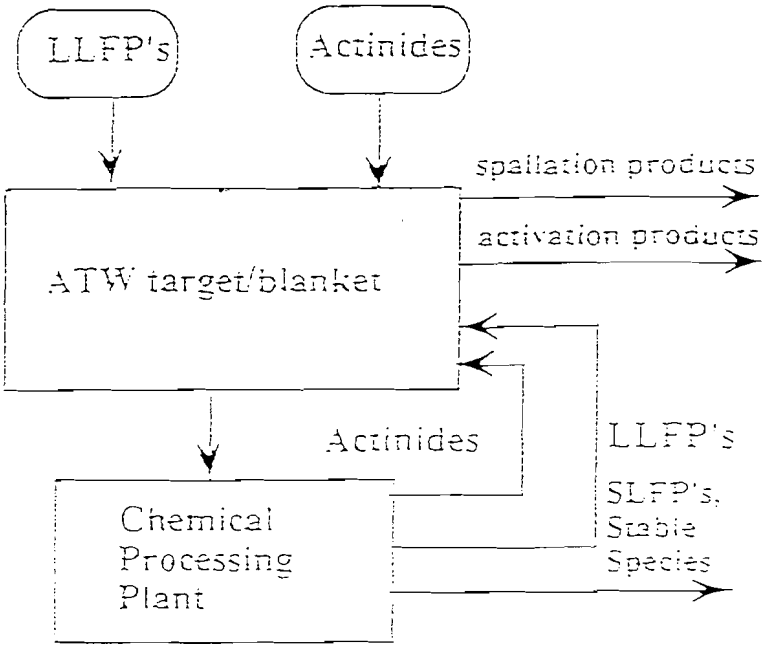

Fig. 2.8 General Concept of ATW System (LANL)

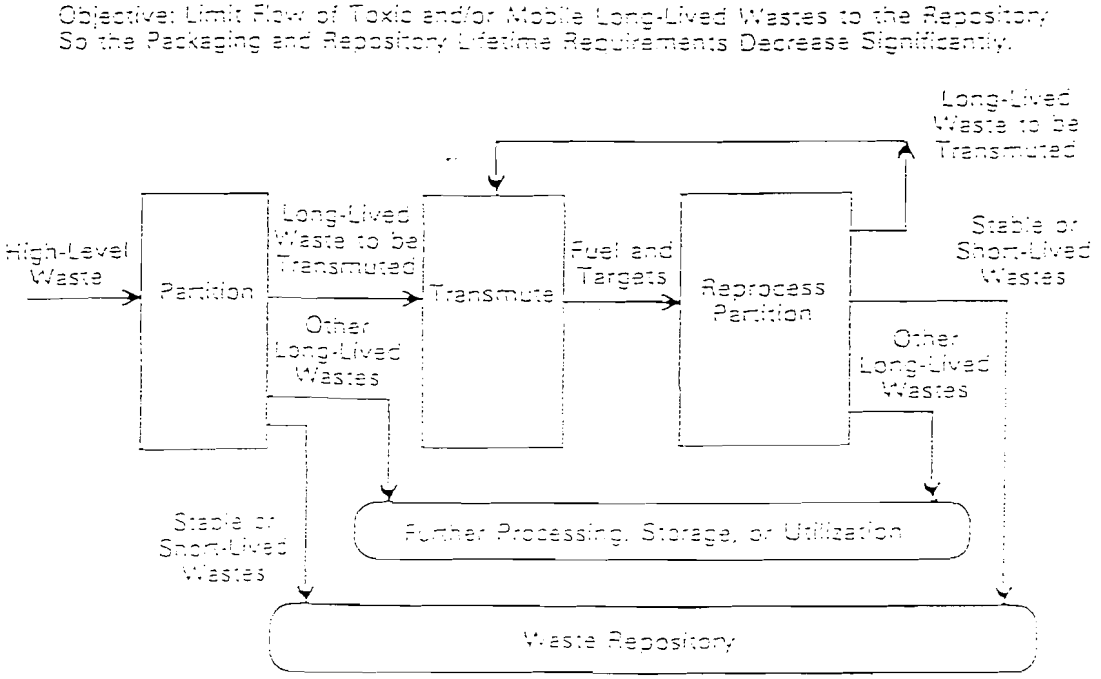

Fig. 2.9 Waste Component Flows through Partitioning and Transmutation System (BNL)

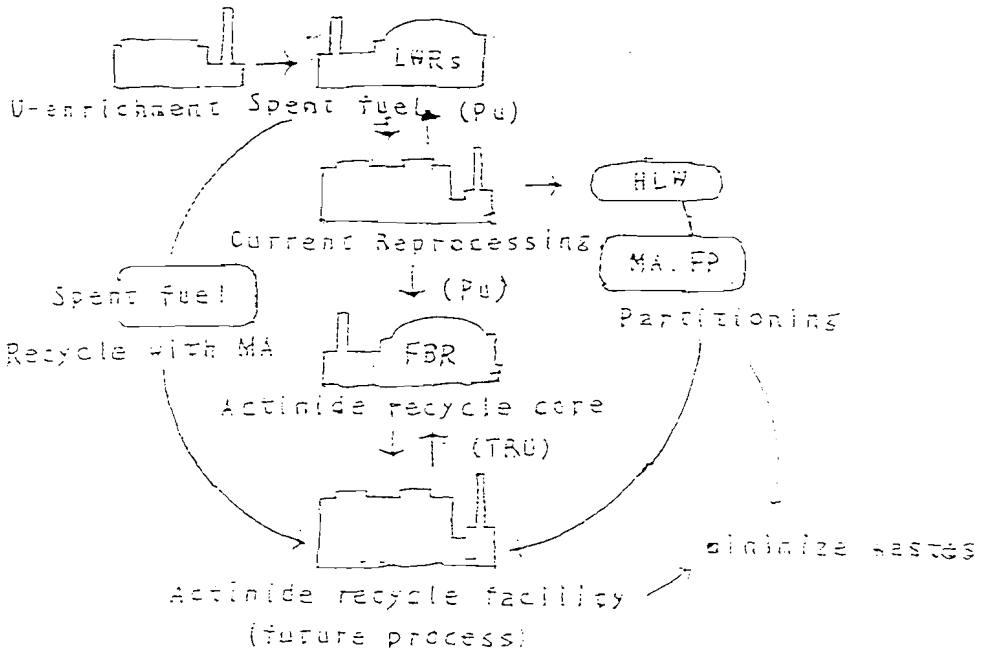

Fig. 2.10 Fuel Cycle with Partitioning and Transmutation under Investigation (Toshiba Corporation)

3. THE ACTIVITIES OF NEA ON TRANSMUTATION

The NEA has been involved since the late 1980s in various activities on Actinide and Fission Product Partitioning and Transmutation.

3.1 Activities of the NSC and Data Bank

The program of work of the Nuclear Science Committee (NSC) covers several items related to transmutation. Some of these programs have been performed within the NSC's own program of work, whereas others have been carried out using the voluntary contributions from the Japanese government to the NEA.

The main emphasis has so far been on different nuclear data needs for accelerator and reactor transmutation applications. A number of projects have been or are being pursued in the field of intermediate energy nuclear data. Three studies were recently completed: one on the availability of experimental data and nuclear model codes, one on the requirements for an evaluated nuclear data file, and one on the international comparison of the performance of compute codes used in intermediate energy data calculations. A data base of available experimental data will be set up, as well as a cooperative project on an evaluated nuclear data file.

(1) Completed Program

1) Review of Fission Product Yields and Delayed Neutron Data from the Actinides (July 1990)

A critical review of available fission product yields and delayed neutron data for the actinides of interest to transmutation, i.e.,Np-237, Pu-242, Am-242m,Am-243, Cm-243 and Cm-245 was performed. The study has identified gaps and inconsistencies in the existing data base and also identified priority areas for further experimental,theoretical and evaluation efforts.

2) Review of High Energy Data and Model Codes for Accelerator-Based Transmutation (December 1992)

This study investigated the availability of experimental intermediate energy data. The need for a comprehensive compilation effort of these data was stressed. The most important nuclear theories and some of the associated nuclear model codes were described, and their applicability to intermediate energy nuclear data calculations was discussed.

3) Requirements for an Evaluated Nuclear Data File for Accelerator Based Transmutation (June 1993)

The importance of evaluated intermediate energy nuclear data files as part of a global calculation scheme for accelerator-based transmutation was discussed. The resulting report contains

a proposal for setting up the following three data libraries:

- a data library from 0 to 100 MeV (first priority),
- a reference data library from 20 to 1500 MeV,
- an activation library from 0 to about 100 MeV.

4) Comparison of Codes for Calculation of Intermediate Nuclear Data (February 1994)

An international comparison study was coordinated. The aim was to assess the predictive ability of computer codes used in calculating intermediate energy charged particle data. Two cases were defined: one where thin target data of Zr-90 and Pb-208 should be calculated and one with the objective to predict the neutron yield and mass distribution of spallation products from 800 MeV proton bombardment of W. The results, to be compared to experimental data, were collected and analyzed. A specialist meeting on Intermediate Nuclear Data will be held on 30 May-1 June 1994 to discuss the result of the study.

(2) On-Going Programs

1) International Evaluation Co-operation

The NSC Working Party on International Evaluation Co-operation has started an activity to evaluate intermediate nuclear energy data. The project will partly build on the results from the above study on the Requirements for an Evaluated Nuclear Data File for Accelerator-Based Transmutation. The

Working Party has established a subgroup (Subgroup No.13) on this subject. The Subgroup has started to inquire data needs and is planning a start-up meeting on 11th May, in Gatlingburg. The Group will discuss items such as the type and format of the data to be included in the library, before starting the actual evaluation effort. The first data files are expected to be ready for testing in 1994.

2) A Data Base for Experimental Intermediate Energy Data

According to a recommendation in the above report on Review of High Energy Data and Model Codes for Accelerator-Based Transmutation, the Data Bank has started to set up a special purpose "transmutation" data base combining relevant material from existing numerical and bibliographic data bases and supplementing the information with the data of essential interest to transmutation needs. This program has been approved by the Steering Committee as the activity reinforced by the voluntary contribution of the Japanese Government. The result of the above program, Comparison of Codes for Calculation of Intermediate Nuclear Data, will provide the basis for identifying the needs in improving the computer programs used for the modeling. At the Specialist Meeting on Intermediate Energy Nuclear Data, it will be discussed on which data compilation and evaluation will be needed in order to complement the data base.

3.2 Activities of the NDC

The Nuclear Development Committee (NDC) performs "Actinide Information Exchange Program". Under the program,an International Information Exchange Meeting on Partitioning and Transmutation (P-T) was held in 1990 and 1992, with the guidance of Liaison Officers nominated by member countries. This program is supported by the voluntary contribution by the Japanese Government. This program was started in 1989 as a five year program. It is expected that the NDC will extend its activity on P-T at the end of 1994 for an additional,possibly 5 years,period.

(1) Completed Programs

1) 1st International Information Exchange Meeting
(Mito City,Japan,November 1990)

A number of papers were presented both on policy orientations and scientific aspects. The discussion ,which concentrated on wide ranging ideas regarding future technologies, led to the conclusion that several disparate approaches had already been taken.

2) Specialist Meetings

Following the first Information Exchange Meeting, the NEA helped organize two specialist meetings. The first meeting was held in November 1991on the topics of partitioning technology. A

wide range of processes for the separation of actinides and fission products,both wet and dry,were presented. The second was in March 1992,on the topics of accelerator-based transmutation. A wide variety of concepts to discuss were presented together with presentations on data acquired,data needs and applicable models.

3) 2nd International Information Exchange Meeting
(ANL,US,November 1992)

The presented papers indicated that there was a common concern about the need of guidance on research needs. A number of emerging important issues were identified during the meeting, including the legal background, the incentives and the implications for the whole fuel cycle in different countries.

(2) On-Going Programs

1) 3rd International Information Exchange Meeting
(Cadarache,France,12-14 December 1994)

At the 2nd International Information Exchange Meeting,it was concluded that a comparison of systems studies, or proto-system studies, already in progress should form a significant part of the 3rd meeting in December 1994. This is regarded as a first phase in the approach to a more co-ordinated systems study that would seek to identify advantages and disadvantages of introducing the P-T to the nuclear fuel cycle. Other areas of interest will be the effects of progress made in various national P-T

activities,technical advances,economic assessments, objectives of the P-T and environmental impact considerations. It is currently interested to invite participants from the Russian Federation to this meeting.

2) Preliminary Systems Study on Partitioning and Transmutation of Long-lived Nuclides

In order to improve understanding of the merits and drawbacks of introducing the P-T technology into the nuclear fuel cycle, analytic and presentational tools will be developed for comparing the many different technical approaches in relation to a variety of measures of cost and benefit. This activity will be intended to run for 5 years. In 1998, a state of the art report will be submitted, which will identify advantages and disadvantages, key technologies, target capabilities of the P-T technologies.

4. PROPOSED TRANSMUTATION CONCEPTS

Although many different types of nuclear particles are available to transmute waste isotopes, neutron reactions are most effective to transmute them from the energy balance point of view. Therefore, there have been many studies of transmutation in neutron fields generated by a variety of devices, including thermal reactors, fast reactors, accelerators, and fusion reactors.

4.1 Thermal Reactors

Thermal neutrons have high reaction cross-sections with the actinide isotopes than fast neutrons. In thermal reactors, transmutation by neutron capture is the dominant process for the long lived actinide isotopes, such as Np-237, Am-241 and Am-243. These isotopes are incinerated in an indirect way by formation of a heavier decay product with very high fission cross-section, such as Pu-238, Pu-239, Am-242m, Cm-243 and Cm-245.

Introduction of minor actinides with high neutron capture cross-section into reactor core will decease the reactivity and require higher fissile enrichment. During the life of the reactor core, the reactivity may increase with the formation of fissile nuclides. This means that most of the minor actinides play a role as burnable poison. The presence of non-negligeable rare earths co-extracted with Am and Cm in the separation process reduces the reactivity. Separation of rare earths from Am and Cm should be needed from the neutron economy point of view.

Two types of minor actinide recycling modes can be consid-

ered: homogeneous and heterogeneous recycling. The latter could transmute roughly the same amount of minor actinides as the homogeneous recycling from reactor physics point of, and minimize the number of fuel pin and assembly containing minor actinides. However, the thermal characteristics of fuel assemblies loaded with high concentration of minor actinides require the use of specially designed fuel pins and assemblies. In this case, strong neutron self-shielding may lead to significant reduction of transmutation.

The long-lived fission products of interest, such as Tc-99 and I-129,can be transmuted to stable isotopes by neutron capture reaction. The thermal neutron cross-sections of these nuclides are bigger than the fast ones,but are not big enough to transmute them effectively. This leads to need of high-flux thermal reactor for effective transmutation of Tc-99 and I-129.

(1) PWR based transmutation concept proposed by the CEA [14]

Two types of transmutation concepts based on PWR are proposed by the CEA. They are MOX felled PWRs with homogeneous and heterogeneous loading of minor actinides. In the latter, volume ratio of fuels with transmutation materials to all fuels is 30%. Nuclides to be transmuted in the reactors are Np-237,Am-241,Am-242 and Am-243.

The principal design considerations are paid for followings:

- highest transmutation rate and radiotoxicity reduction,
- Use of well known current reactor technology with little development,and

- Same safety and performance levels as current reactors.

The reactor design and physics parameters are given in Table 4.1 and 4.2 for homogeneous loading, and Table 4.3 and 4.4 for heterogeneous loading, respectively.

(2) PWR based transmutation concept proposed by JAERI [15]

JAERI proposes a concept to transmute Np-237, which is based on the existing PWR with much higher enriched uranium (8.2 w/o) fuel. The transmutation target nuclide Np-237 is homogeneously mixed with uranium fuel.

The principal design considerations are paid for followings:
- The transmutation target is limited only to Np-237 which is the most important nuclide with long half-life and high radiotoxicity generated in uranium-oxide fuel, and
- The Np transmutation should be made by the existing PWR without any significant modification.

The reactor design and physics parameters is given in Table 4.4 and 4.5.

(3) PBR based burner concept proposed by BNL [6]

A high flux particle bed reactor concept (PBR) for rapid transmutation of actinides and long-lived fission products is proposed by BNL. This concept is based on the PBR nuclear rocket system currently under development by the Air Force Space Nuclear Thermal Propulsion (SNTP) Program and draws on much of the technology that has been developed by the SNTP program.

The basic building of the PBR are the fuel particles which are similar to the proven HTGR BISO. Two types of particles would be employed: one containing plutonium for the "driver" fuel elements,and one containing minor actinides for the "target". The fuel elements consist of a bed made up of the appropriate particles, and constrained between two porous, co-axial cylindrical "frits"(see Fig.4.1).

Several potential core designs were evaluated, falling into two general categories: heavy water moderated,and solid moderator systems. The major constraints for the core design are the desire to minimize the Pu/minor-actinides inventory in the reactor. and the overall reactor size; therefore the total number of elements, the particle fissile and minor actinide loading ,and the radial reflector are minimized.

The selected characteristics of heavy water moderated PBR burner concept are given in Table 4.7.

4.2 Fast Reactors

Fast neutrons will fission all of the actinides, but the reaction cross-sections are much smaller than for thermal neutrons. This effect will be compensated by the neutron flux in the fast reactors, which is 100 to 1000 times higher than in the thermal reactors. The build-up of higher actinides by neutron capture is much smaller with fast neutrons than thermal neutrons. The fission to capture ratio of minor actinides increases with the mean neutron energy. If a fast reactor concept with very hard

neutron spectrum is established, the minor actinides are additional fissionable resources instead of waste materials as in the thermal reactor. However, loading amount of minor actinides may be seriously limited, because of their unfavorable characteristics to safety physics parameters, such as coolant-void coefficient, Doppler coefficient, effective delayed neutron fraction and prompt neutron life time.

There are two types of minor actinide recycling modes also for fast reactors: homogeneous and heterogeneous recycling. The feature is similar to that of the thermal reactors, except lower neutron self-shielding in the fast reactors.

The long-lived fission products such as Tc-99 and I-129 can also be transmuted in the fast reactors, using neutrons with appropriate energy.

(1) LMFBR based transmutation concept proposed by CEA [14]

Two types of 1450 MWe LMFBR based transmutation concepts are proposed by CEA: one with homogeneous loading of minor, and one with heterogeneous loading of separate Np and Am targets. The nuclides to be transmuted are Np-237 and Am-241 for the first concept, and Np-237 and Am isotopes.

The Principal design considerations are paid for followings:

- Highest transmutation rate and radiotoxicity reduction,
- Use of well known current LMFBR technology with little development, and
- Same safety and performance levels as conventional LMFBRs.

The principal design and physics parameters are listed in

Table 4.8 and 4.9 for homogeneous loading of minor actinides, and Table 4.10 and 4.11 for heterogeneous loading, respectively.

(2) LMFBR based transmutation concept proposed by PNC [16]

PNC has investigated various kinds of LMFBR based transmutation concepts. The present proposal is one of these concepts with homogeneous loading of minor actinides. The nuclides to be transmuted are Np-237, Am-241 and Am-243.

The design principle is to develop a LMFBR core concept loaded with minor actinides which brings no serious issue to core performances in consideration of fuel cycle technology.

The principal design and physics parameters are given in Table 4.12 and 4.13.

(3) ALMR based transmutation concept proposed by GE and ANL [17]

The ALMR plant utilizes six reactor modules. The thermal rating of each module is 840 MWt. Conventional ALMR core designs utilize a radially heterogeneous configuration; the inclusion of internal blanket zones allows fuel cycle operation in a 'breakeven' mode where the fissile material (transuranics, primarily Pu-239 and Pu-241) is consumed and destroyed at roughly equal rates. The 840 MWt breakeven core has a total of 192 fueled assemblies (108 drivers and 84 blankets). The driver fuel form is metal fuel alloy (U-TRU-10%Zr). Minor actinides are included in the source LWR spent fuel (10.7% MA/TRU).

Two burner configurations are presented. A primary goal in

developing the burner core configurations is to maintain compatibility with the breakeven reactor design; design changes to the conventional reactor are to be minimized. Net consumption of transuranics in the burner designs is achieved by removing fertile material from the breakeven configuration.

The Core layouts of the burner designs are shown in Fig.4.2 and the neutronics parameters are given in Table 4.14.

(4) LMFBR based transmutation concept proposed by CRIEPI [18]

CRIEPI proposes a 1000 MWe LMFBR based transmutation concept of minor actinides. The fuel is metallic alloy type with minor actinides (Np,Am,Cm) of 5 w/o. The design principle is to deveop 600-1000 MWe commercial FBR with U-Pu-MA-Zr fuel, which is produced from dry process with pyrochemical partitioning. The proposed 1000 MWe FBR is expected to transmute minor actinides generated from 6 plants of 1000 MWe LWR.

The principal design and physics parameters are listed in Table 4.15 and 4.16.

(5) LMFBR based transmutation concept proposed by Toshiba Corporation [9]

The transmutation concept based on 600 MWe LMFBR with flat core is proposed by Toshiba Corporation. The fuel is metallic alloy type of 3 w/o minor actinides. In the core, the minor actinides mixed fuels are homogeneously arranged, and in the blanket,the fuels are heterogeneously arranged. This arrangement

is effective to reduce Na void reactivity effect.

The principal design considerations are paid for followings:

- Homogeneous TRU-recycling called "actinide recycling" without separation of minor actinides from Pu in LWR and FBR spent fuel
- Safety consideration, and
- Excess neutron utilization for balancing breeding capacity, storaged minor actinides transmutation and long-lived fission products incineration.

The principal design and physics parameters are listed in Table 4.17 and 4.18.

(6) Fast burner reactors proposed by JAERI

Three types of fast burner reactors with nitride fuel for TRU transmutation are proposed by JAERI.

The first is a helium-cooled fast reactor with coated particle fuel (P-ABR:see Fig.4.3) and the second is a lead-cooled modular type fast reactor with pin type fuel (L-ABR) [19]. The both reactors have the core with very hard neutron energy spectrum, in which much of the minor actinide transmutation occurs by fission reaction, not by neutron capture.

The principal design considerations for these two reactors are paid for followings:

- Minor actinides burner reactor specially designed for efficient fissioning of minor actinides,
- Primary fuel material of minor actinides, and enriched uranium or plutonium,
- A fast reactor with very hard neutron spectrum and high neutron

flux.

Use of enriched uranium instead of plutonium increases effective delayed neutron fraction of the reactor.

The principal design and physics parameters are given in Table 4.19 and 4.20 for the P-ABR,and Table 4.21 and 4.22 for the L-ABR.

The third concept is a lead-cooled fast reactor with nitride fuel of Th-Pu-10w/oMA [15]. In this reactor, minor actinides can be incinerated simultaneously by burning excess plutonium in a closed fast reactor fuel cycle.

The principal design and physics parameters are given in Table 4.23 and 4.24.

4.3 Accelerator Driven Transmutation Systems

These systems use spallation reaction to produce,high energy particles (e.g.1 GeV protons), a large amount of neutrons that in a second moment are introduced in a multiplying medium.

Spallation, a reaction in which a high-energy primary particle interacts with a target nucleus, is thought to take place in two stages. In the first stage (the intranuclear cascade phase), the incident proton creates a high energy particle cascade inside the nucleus. During the intranuclear cascade,high-energy (>20MeV) "secondary" particles and low-energy(<20 MeV) "cascade" particles escape the nucleus; at the end the nucleus is typically left in a highly excited state. In the second stage (the evaporation phase) ,the excited nucleus relaxes, primarily by emitting low-energy

(<20 MeV) " evaporation" neutrons. It is defined low-energy "spallation" neutron the sum of the low-energy cascade and evaporation neutrons.

For thick targets, the high-energy secondary particles (plus their progeny) can undergo further spallation reactions. For some target materials, low-energy spallation neutrons can enhance neutron production through low-energy (n,xn) reactions. The total low-energy neutron production from a target is the sum of low-energy spallation neutron production plus the net production from low-energy (n,xn) reactions.

Using a calculation code as a model which is approximately correct, about 90% of the neutrons coming from a cylindrical target bombarded by 1 GeV protons, have less than 20 MeV with an average energy of only 4.8 MeV; remainder, 10% of the total, have energies below 400 MeV with an average of 105 MeV.

(1) Accelerator-driven system proposed by JAERI [20]

Three types of accelerator-driven system are proposed by JAERI, each of which uses a large linear proton accelerator to drive and control its specific subcritical core containing minor actinides and other long-lived nuclides.

The first concept called "Alloy fueled core system" is shown in Fig.4.4. In this concept, the accelerator injects 1.5 GeV proton beam of 39 mA into the tungsten target located at the center of the sodium-cooled fast reactor core, which is loaded with alloy fuel containing minor actinides. The principal design parameters are given in Table 4.25.

The second is called "Molten salt core" concept. The accelerator injects 1.5 GeV proton beam of 25 mA in the core with hard neutron spectrum, which is loaded with chloride molten salt fuel containing minor actinides. This concept would be a continuous processing system,in which the reaction products are removed from the fuel on line. The principal design parameters are listed in Table 4.26.

The third is called "Eutectic target-core" concept. The accelerator injects 1.5 GeV proton beam of 30 mA into the eutectic alloy (Np-Pu-Co-Ce-Tc) target-core with graphite blanket, which is cooled by molten fluoride salt. This system intends simultaneous transmutation of Np-237 and Tc-99. The design parameters are given in Table 4.27.

(2) Accelerator-driven systems proposed by BNL

Three types of transmutation concepts are proposed by BNL: one with a large linear proton accelerator [5], and two with a small power accelerator [21].

The first is the PHOENIX concept using a large linear proton accelerator which can produce a 104 mA beam of 1.6 GeV protons. A modular concept is developed for the PHOENIX subcritical lattice. Each module resembles the core of the Fast Flux Test Facility (FFTF), with the minor actinides,formed into oxide fuel rods replacing the uranium and plutonium in the FFTF fuel. The concept is shown in Fig.4.5.

The second is the "MOX fueled core" concept,in which a multi segmented cyclotron injects 2.5-5 mA beam of 1.5 GeV protons into

the lead target located at the center of MOX fueled fast reactor core which operates at slightly subcritical condition. Minor actinides are incinerated by fast neutron fission reaction, and long-lived fission products such as Tc-99 and I-129 are transmuted in yttrium-hydride moderator surrounding the core. The design parameters are given in Table 4.28.

The third is the "Particle fueled core" concepts. This uses a multi-segmented cyclotron to inject 4-8 mA beam of 1.5 GeV protons into the lead spallation target located at the center of the core with fast neutron spectrum, which is loaded with nitride coated particle fuel. The core operates at slightly subcritical condition. The long-lived fission products can also be transmuted as in the second concept. The principal design parameters are given in Table 4.29.

(3) Accelerator-driven systems proposed by CEA [14]

Three types of transmutation systems are under investigation at the CEA to mainly incinerate Tc-99. Each system use the accelerator with the proton beam of 1.5 GeV and 70-100 mA to strike the lead chloride molten salt target containing Th, Th-Pu or Pu. The design parameters and mass balances of the systems are given in Table 4.30.

(4) Los Alamos ATW concepts

Contrary to the above mentioned accelerator-driven transmutation concepts in which the transmutation occurs mainly by fast neutron, the ATW concepts uses the thermal neutrons to transmute minor actinides and long-lived fission products.

In the ATW concept,the linear proton accelerator operates at 1.6 GeV at a continuous-wave current of 250 mA. The primary proton beam is then split into four beams, each having a current of 62.5 mA. Each of the four beams directed into four separated target/blanket modules. The high-energy proton beam strikes a centrally located spallation target to produce an intense source of neutrons.

The base-case design is comprised of heavy-water-cooled tungsten rods, and its blanket region and balance-of-plant design is based on existing heavy-water reactor technology employed in the CANDU reactor system [22]. Another option is the use of a flowing lead target. The use of such a target adds complexity to the design but has the potential to increase the neutron utilization efficiency. The layout for the target/blanket of the ATW is shown in Fig.4.6, and the key design parameters are compared with those of the CANDU in Table 4.31.

An advanced ATW concept is also proposed,which has a target-blanket with slowly circulating higher actinide liquid fuel and heat removal by a larger, thorium-bearing molten salt loop [23]. This concept is shown in Fig.4.7.

(4) Other proposed systems

There are some ATW type concepts proposed by the ENEA [8], the Royal Institute of Technology [10] and the ITEP [12]. In the ENEA concept, a subcritical core with lead spallation target is driven by a proton accelerator with the beam of 1.6 GeV and 200 mA. The core is loaded with minor actinides and long-lived fission products. In the concept of the Royal Institute of Technology, a subcritical core with lithium fluoride salt (liquid Pb, solid Th) spallation target is driven by a proton (deutron) linear accelerator or a cyclotron with the beam of 1 GeV and 5-100 mA. The core is cooled by helium and is loaded with minor actinide molten salt fuel or graphite pebble bed particle fuel.

The design parameters of the concepts proposed by 3 organizations are given in Table 4.32,4.33 and 4.34, respectively.

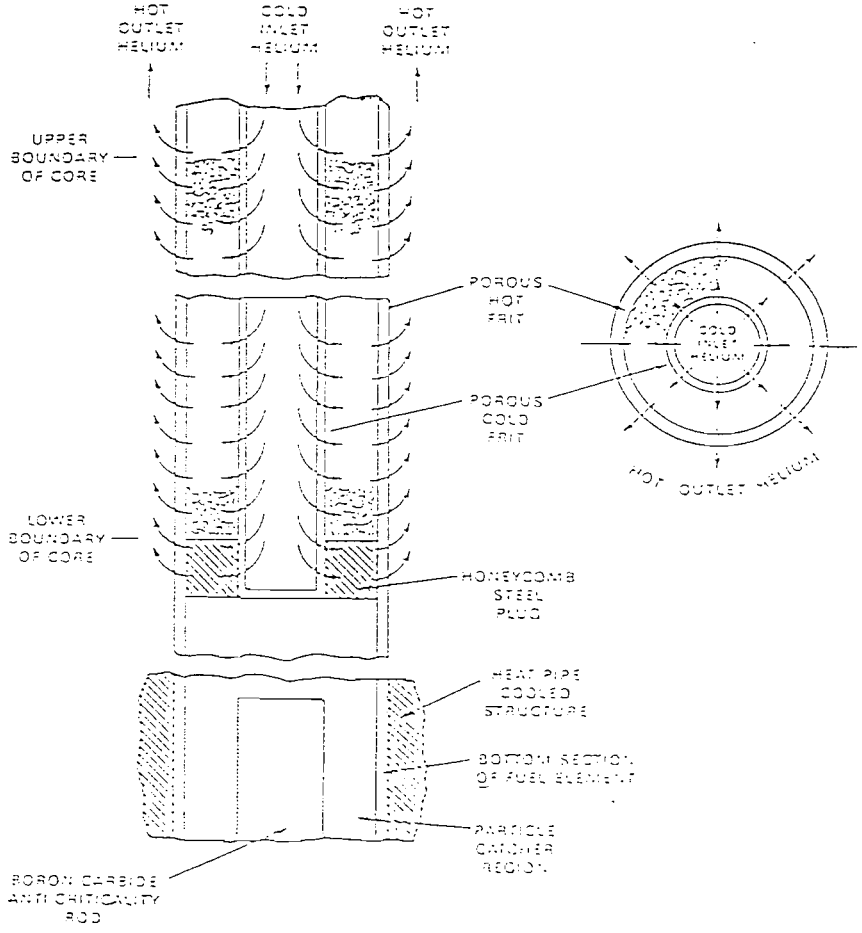

Fig. 4.1 A Fuel Element for Pressure Vessel Configuration of PBR

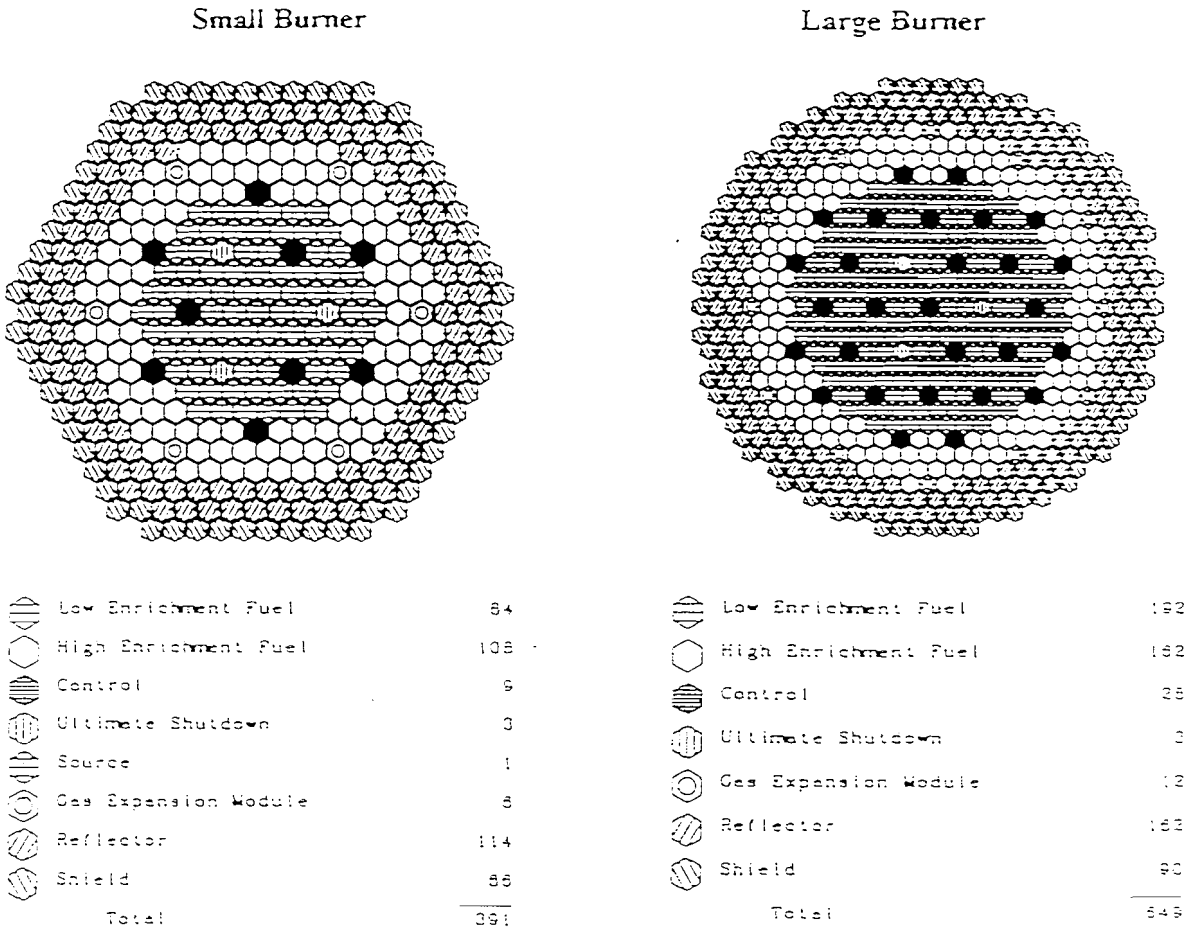

Fig. 4.2 Core Configuration of ALMR for Actindes Burning

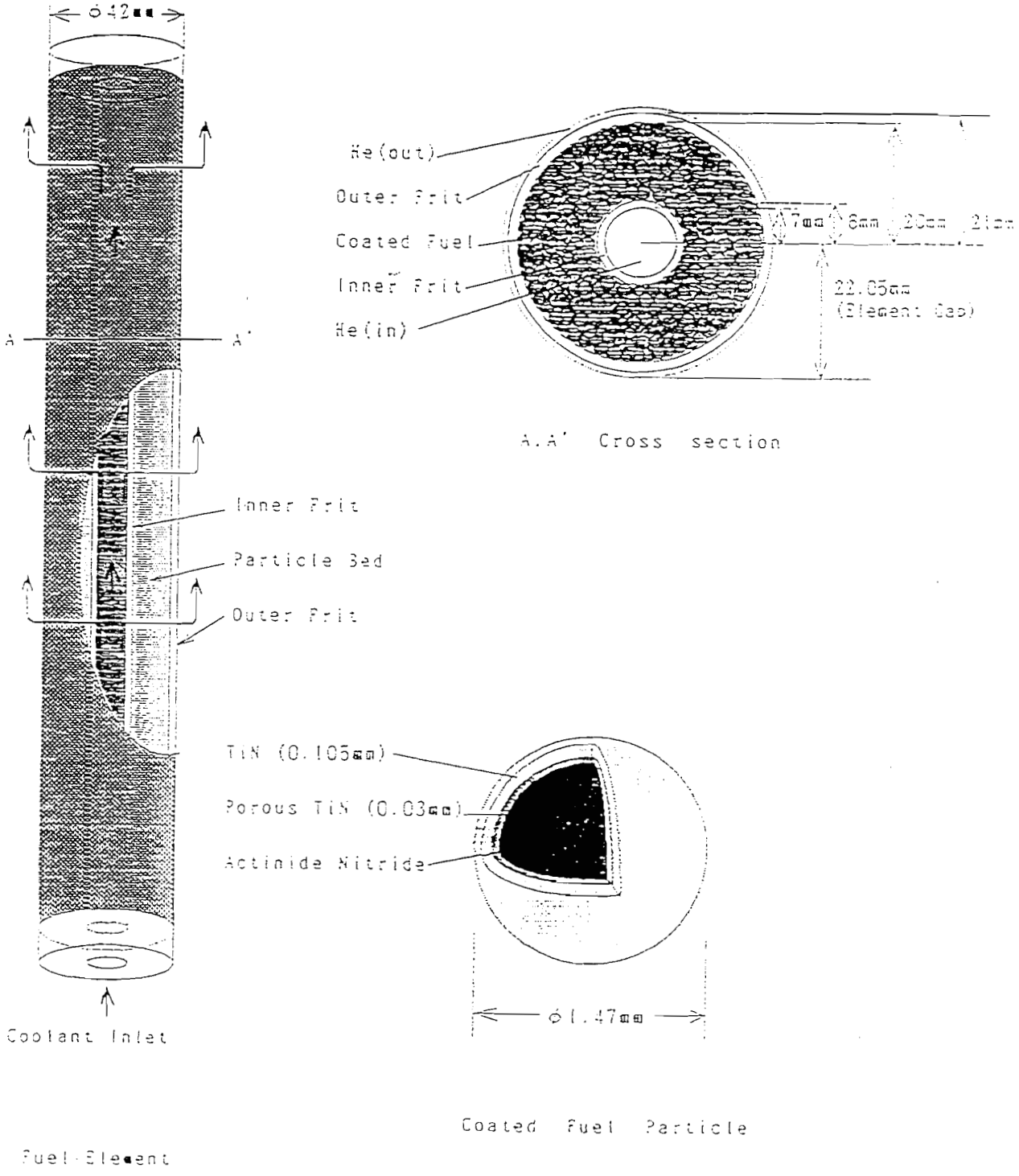

Fig. 4.3 Fuel Concept of Helium-Cooled Actinides Burner (P-ABR)

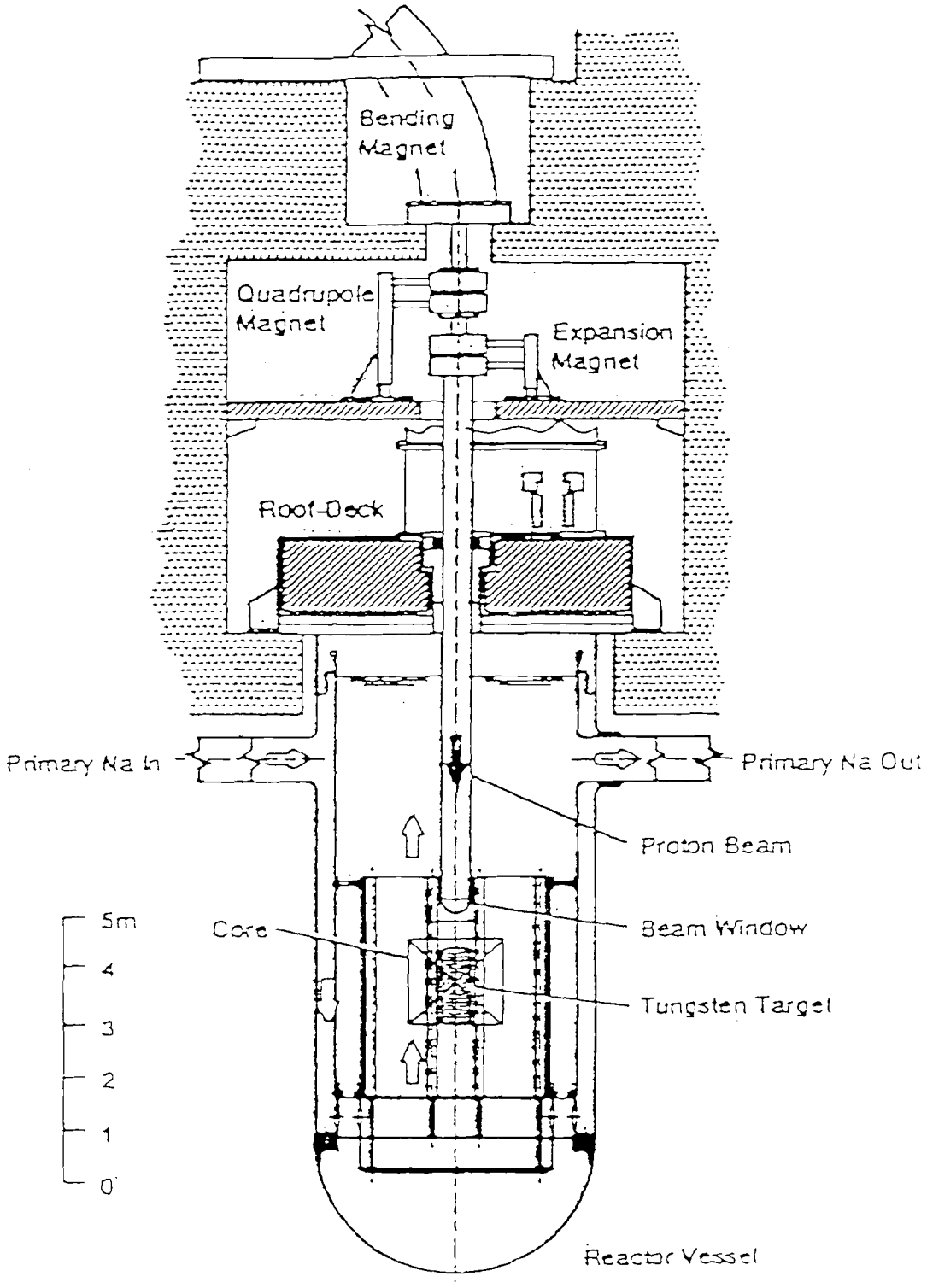

Fig. 4.4 Schematic Figure of Accelerator-Driven Transmutation Concept - Alloy Fuel Core System -

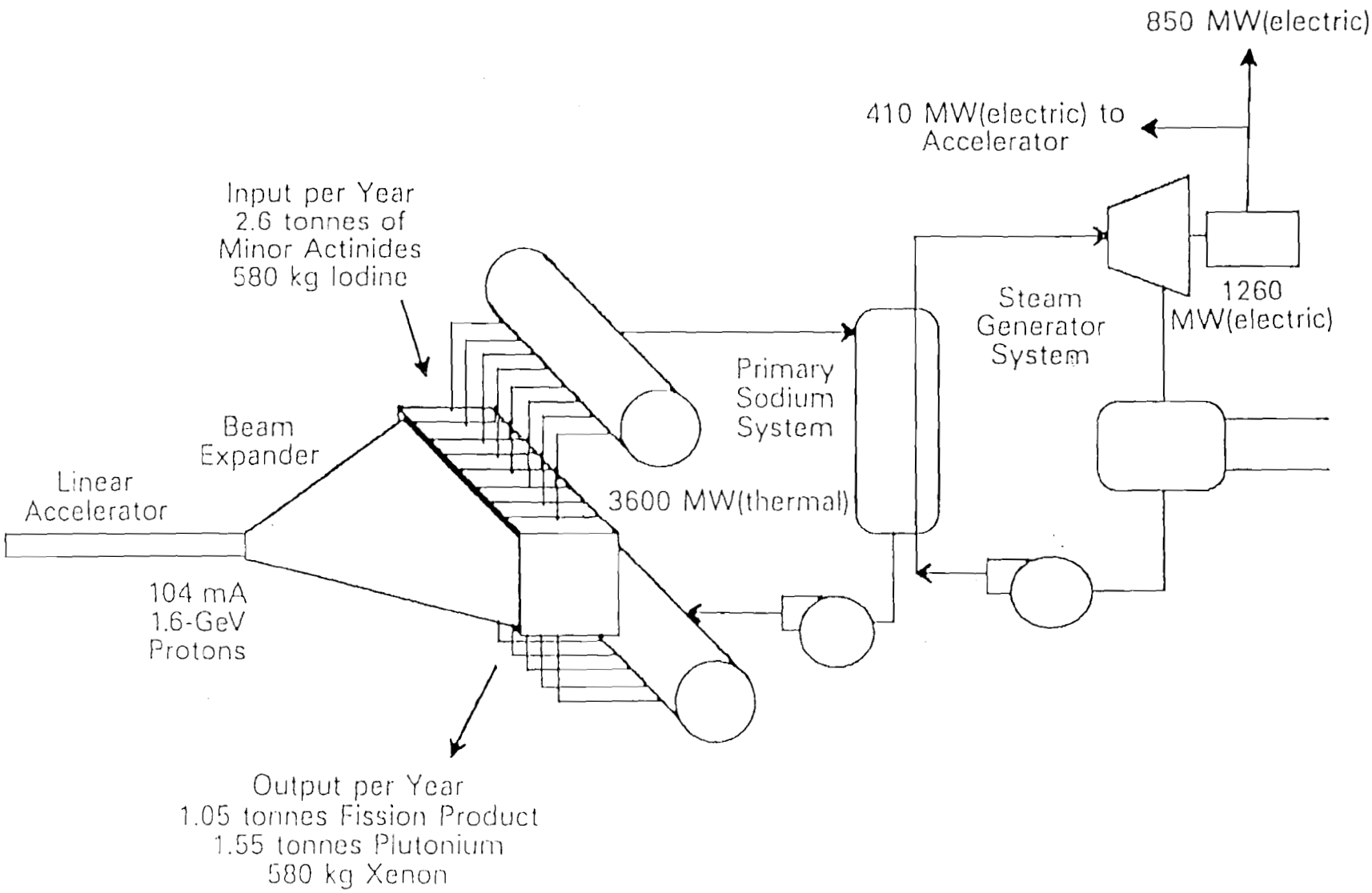

Fig. 4.5 The PHOENIX Concept (intermediate Na system not shown)

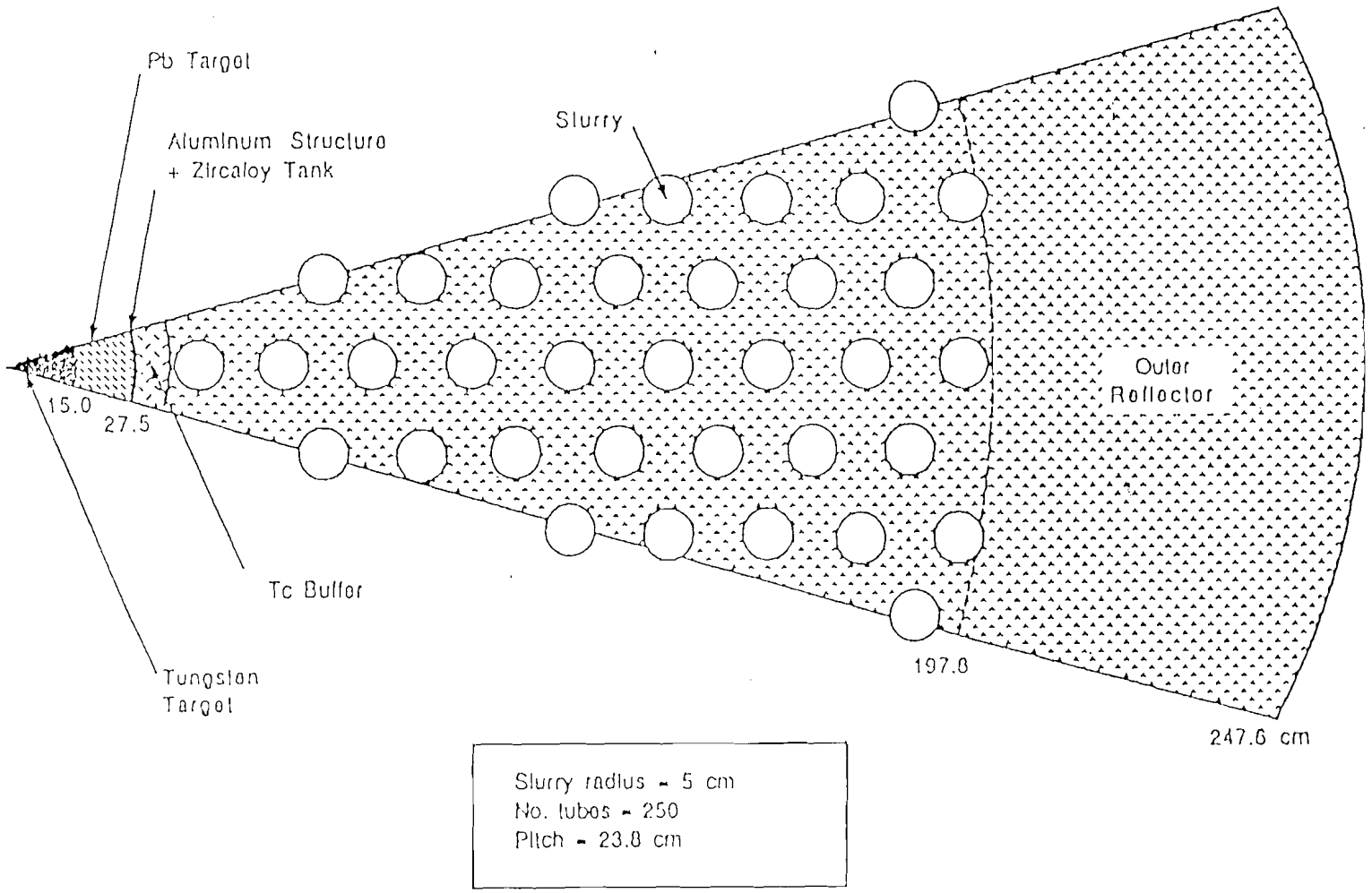

Fig. 4.6 Layout of Core/Target of the Los Alamos ATW

A Schematic layout of the ATW target–blanket. The blanket is divided radially into four parts: (1) a central molten salt column which is the target for the proton beam; (2) a uranium multiplier where most of the source neutrons are generated; (3) a fission product and actinide transmutation region, which also prevents thermal neutrons from the multiplying blanket from being parasitically absorbed in the target region; and (4) the outer thorium–uranium multiplying breeding region of the blanket, which improves the neutron economy of the system and generates most of the electric power

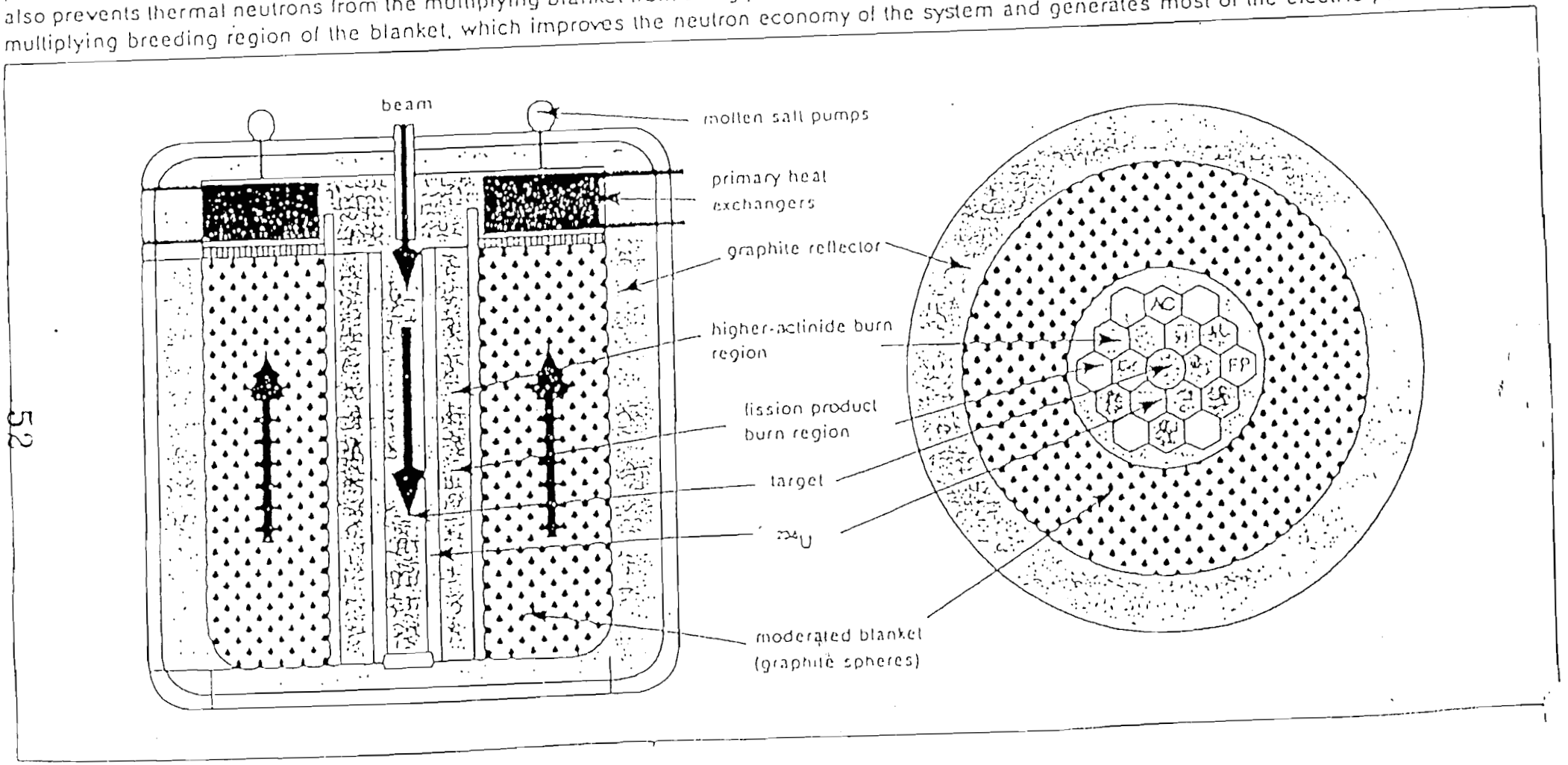

Fig. 4.7 Advanced Los Alamos ATW Concept

Table 4.1 Principal Design Parameters of PWR Based Transmutation Concept Proposed by CEA - Homogeneous Loading of Minor Actinides - [14]

Items	
Thermal power (MWt)	4250
Electric power (MWe)	1450
Equivalent core diameter (cm)	376
Equivalent core height (cm)	420
Averaged core composition (v/o)	
fuel/clad+structure/coolant	23.2/7.45/69.35
Type of fuel	oxide
Core averaged fresh fuel composition (w/o)	
U/Pu/Np, Am and Cm	91/ 8/ 1
Isotopic composition of Pu in fresh fuel (w/o)	
$^{238}Pu/^{239}Pu/^{240}Pu/^{241}Pu/^{242}Pu$	1.8/58.0/22.5/12.0/5.7
Isotopic composision of minor actinides (w/o)	
$^{237}Np/^{241}Am/^{242}Am/^{243}Am/^{243}Cm/^{244}Cm$	55.7/27.8/0.07/16.4/0/0

Table 4.2 Generic and Safety-Related Physics Parametes of the Proposed Concept Given in Table 4.1

Items	BOL[1]	BOEC[2]
- Power density: average in core (w/cm^3)		
maximum in core		
- Linear heat rate: average (w/cm)		
maximum		
- Neutron flux averaged in core (n/cm^2 sec)	2.5×10^{14}	
- Neutron energy averaged in core (KeV)	-	-
- Fuel dwelling time in core (EFPD)[3]	1220	-
- Burnup reactivity swing (%δk/k/365EFPD)	4.1	
- Coolant void reactivity effect (%δk/k)		
All reactor region voided	-0.24	-
Core and axial blanket voided	-	-
Only core voided	-	-
- Doppler reactivity coefficient (Tdk/dt)	-2.6×10^{-2}	-
- Effective delayed neutron fraction	-	-
- Control rod material		-
- Central control rod worth (%δk/k/kg)		-

1) Begining of Life, 2) Begining of Equilibrium Cycle,
3) Equivalent full power days

Table 5.2 Material inventory and mass balance of Np Target in PWR Based Transmutation Concept Proposed by CEA - Heterogeneous Loading -

Nuclides	Initial inventory (kg)	Mass balance in EOC[1] (unit:kg)		
		BOEC[2]	EOEC[3]	EOEC-BOEC
Fuel				
Uranium				
U-235				
U-236				
U-238				
Plutonium				
Pu-238			58	
Pu-239			7.5	
Pu-240			1.2	
Pu-241			0.7	
Pu-242			0.1	
Minor actinides				
Neptunium				
Np-237		232	153	- 79
Americium				
Am-241			0.04	+ 0.04
Am-242m				
Am-243				
Curium				
Cm-242				
Cm-243				
Cm-244				
Cm-245				
Tc-99, I-129			0.10, 0.03	
Transmutation capability (kg/GWt EFPY)			37.2 (Np)	

1) Equilibrium Cycle, 2) Begining of Equilibrium Cycle,
3) End of Equilibrium Cycle.

Table 4.3 Principal Design Parameters of PWR Based Transmutation Concept Proposed by CEA - Heterogeneous Loading of Np and Am Target - [14]

Items		
Thermal power	(MWt)	2785
Electric power	(MWe)	960
Equivalent core diameter	(cm)	304
Equivalent core height	(cm)	366
Averaged core composition	(v/o)	
fuel/clad+structure/coolant		30.0/10.8/59.2
Type of fuel		oxide
Np target composition	(w/o)	
U/Pu/^{237}Np		0/ 0/100
Am target composition	(w/o)	
U/Pu/Am		0/ 0/100
Isotopic composision of Am	(w/o)	
^{241}Am/^{242}Am/^{243}Am		72.4/ 0.2/27.4

Table 4.4 Generic and Safety-Related Physics Parametes of the Proposed Concept Given in Table 4.3

Items		BOL[1]	BOEC[2]
- Power density: average in core	(w/cm^3)	105	
maximum in core		245	
- Linear heat rate: average	(w/cm)	178	
maximum		419	
- Neutron flux averaged in core	(n/cm^2 sec)	3.0 x 10^{14}	
- Neutron energy averaged in core	(KeV)	-	-
- Fuel dwelling time in core	(EFPD)[3]	1120	-
- Burnup reactivity swing	(%δk/k/365EFPD)	11	
- Coolant void reactivity effect	(%δk/k)		
All reactor region voided			-
Core and axial blanket voided		-	-
Only core voided		-	-
- Doppler reactivity coefficient	(Tdk/dt)	-	-
- Effective delayed neutron fraction		-	-
- Control rod material		Ag, In, Cd	-
- Central control rod worth	(%δk/k/kg)		-

1) Begining of Life, 2) Begining of Equilibrium Cycle,
3) Equivalent full power days

Table 4.5 Principal Design Parameters of PWR Based Transmutation Concept Proposed by JAERI [15]

Items	
Thermal power (MWt)	3410
Electric power (MWe)	1146
Equivalent core diameter (cm)	337
Equivalent core height (cm)	366
Averaged core composition (v/o)	
fuel/clad+structure/coolant	31/11/58
Type of fuel	oxide
Core averaged fresh fuel composition (w/o)	
U/Pu/Np,Am and Cm	97/ 0/ 3
Isotopic composition of Pu in fresh fuel (w/o)	
$^{238}Pu/^{239}Pu/^{240}Pu/^{241}Pu/^{242}Pu$	-
Isotopic composision of minor actinides (w/o)	
$^{237}Np/^{241}Am/^{242}Am/^{243}Am/^{243}Cm/^{244}Cm$	100/0/0/0/0/0

Table 4.6 Generic and Safety-Related Physics Parametes of the Proposed Concept Given in Table 4.5

Items	BOL[1]	BOEC[2]
- Power density: average in core (w/cm^3)	91	
maximum in core		
- Linear heat rate: average (w/cm)	183	
maximum		
- Neutron flux averaged in core (n/cm^2 sec)	1.2×10^{14}	
- Neutron energy averaged in core (KeV)	-	-
- Fuel dwelling time in core (EFPD)[3]	1500	-
- Burnup reactivity swing (%δk/k/365EFPD)		
- Coolant void reactivity effect (%δk/k)		-
All reactor region voided	-50	-
Core and axial blanket voided	-	-
Only core voided	-	-
- Doppler reactivity coefficient (Tdk/dt)		-
- Effective delayed neutron fraction	-	-
- Control rod material	Ag-In-Cd	-
- Central control rod worth (%δk/k/kg)		-

1) Begining of Life, 2) Begining of Equilibrium Cycle,
3) Equivalent full power days

Table 4.7 Selected Characteristics of Heavy Water Moderated PBR Burner

Moderator	D_2O	
Number of Pu Driver Elements	72	
Number of MA Target Elements	42	
Power Level with Driver Elements @ 5 MW/t	1080	
K_∞ (Clean)	1.040±0.005	
(Average Flux)$_{target}$/(Average Flux)$_{core}$	0.86	
Target (Flux E > 5.5KeV/Total Flux)	0.59	
Initial Loadings, Kg.		
Plutonium	30.0	
Neptunium	7.5	
Americium	9.9	
Curium	0.3	
Total Minor Actinides	17.5	
Final Loadings after 30 days @ Φ(driver) = Φ(target), Kg.		
Plutonium	8.77[1]	9.56[2]
Neptunium	2.46	1.64
Americium	1.34	2.10
Curium	6.89	3.45
Total Minor Actinides	11.19	7.19

(1) Pu/LWR Spectrum in ORIGEN2
(2) FFTF Spectrum in ORIGEN2

Table 4.8 Principal Design Parameters of MOX-LMFBR Based Transmutation Concept Proposed by CEA - Homogeneous Loading of Minor Actinides - [14]

Items		
Thermal power	(MWt)	3600
Electric power	(MWe)	1450
Equivalent core diameter	(cm)	390
Equivalent core height	(cm)	140
Averaged core composition	(v/o)	
fuel/clad+structure/coolant(Na)		31/25/38
Type of fuel		oxide
Core averaged fresh fuel composition	(w/o)	
U/Pu/Np, Am and Cm		76/19/ 5
Isotopic composition of Pu in fresh fuel	(w/o)	
$^{238}Pu/^{239}Pu/^{240}Pu/^{241}Pu/^{242}Pu$		1.9/57.3/23.5/11.8/5.5
Isotopic composision of minor actinides	(w/o)	
$^{237}Np/^{241}Am/^{242}Am/^{243}Am/^{243}Cm/^{244}Cm$		50/50/0/0/0/0

Table 4.9 Generic and Safety-Related Physics Parametes of the Proposed Concept Given in Table 4.8

Items		BOL[1]	BOEC[2]
- Power density: average in core	(w/cm^3)	215	
maximum in core		320	
- Linear heat rate: average	(w/cm)	320	
maximum		480	
- Neutron flux averaged in core	(n/cm^2 sec)	3.0×10^{15}	
- Neutron energy averaged in core	(KeV)	530	
- Fuel dwelling time in core	(EFPD)[3]	1500	
- Burnup reactivity swing	(%δ k/k/365EFPD)	1.5	
- Coolant void reactivity effect	(%δ k/k)		
All reactor region voided			-
Core and axial blanket voided			-
Only core voided		2.5	-
- Doppler reactivity coefficient	(Tdk/dt)	-6.03×10^{-3}	-
- Effective delayed neutron fraction		0.00340	-
- Control rod material			-
- Central control rod worth	(%δ k/k/kg)		-
- Prompt neutron life time	(sec)		-

1) Begining of Life, 2) Begining of Equilibrium Cycle,
3) Equivalent full power days

Table 4.10 Principal Design Parameters of MOX-LMFBR Based Transmutation Concept Proposed by CEA - Heterogeneous Loading of Np and Am Targets - [14]

Items		
Thermal power	(MWt)	3600
Electric power	(MWe)	1450
Equivalent core diameter	(cm)	390
Equivalent core height	(cm)	140
Averaged core composition	(v/o)	
fuel/clad+structure/coolant(Na)		31/25/38
Type of fuel		
Core averaged fresh fuel composition	(w/o)	
U/Pu/Np, Am and Cm		80/20/ 0
Isotopic composition of Pu in fresh fuel	(w/o)	
$^{238}Pu/^{239}Pu/^{240}Pu/^{241}Pu/^{242}Pu$		1.9/57.3/23.5/11.8/ 5.5
Isotopic composision of Np and Am targets	(w/o)	
^{237}Np and $^{241}Am/^{242}Am/^{243}Am$		100 63.4/0.2/36.4

Table 4.11 Generic and Safety-Related Physics Parametes of the Proposed Concept Given in Table 4.10

Items		BOL[1]	BOEC[2]
- Power density: average in core	(w/cm^3)	215	
maximum in core		320	
- Linear heat rate: average	(w/cm)	320	
maximum		480	
- Neutron flux averaged in core	(n/cm^2 sec)	3.1 x 10^{15}	
- Neutron energy averaged in core	(KeV)	505	
- Fuel dwelling time in core	(EFPD)[3]	1500	-
- Burnup reactivity swing	(%δ k/k/365EFPD)	2.6	
- Coolant void reactivity effect	(%δ k/k)		
All reactor region voided		1.5	-
Core and axial blanket voided			-
Only core voided		1.4	-
- Doppler reactivity coefficient	(Tdk/dt)	1.06 x 10^{-2}	-
- Effective delayed neutron fraction		0.00365	-
- Control rod material			-
- Central control rod worth	(%δ k/k/kg)		-
- Prompt neutron life time	(sec)		

1) Begining of Life, 2) Begining of Equilibrium Cycle,
3) Equivalent full power days

Table 4.12 Principal Design Parameters of MOX-LMFBR Based Transmutation Concept Proposed by PNC [16]

Items	
Thermal power (MWt)	2517
Electric power (MWe)	1000
Equivalent core diameter (cm)	368
Equivalent core height (cm)	100
Averaged core composition (v/o)	
fuel/clad+structure/coolant(Na)	41.6/20.9/37.5
Type of fuel	oxide
Core averaged fresh fuel composition (w/o)	
U/Pu/Np, Am and Cm	76.6/18.4/ 5.0
Isotopic composition of Pu in fresh fuel (w/o)	
$^{238}Pu/^{239}Pu/^{240}Pu/^{241}Pu/^{242}Pu$	- /58/24/14/ 4
Isotopic composision of minor actinides (w/o)	
$^{237}Np/^{241}Am/^{242}Am/^{243}Am/^{243}Cm/^{244}Cm/^{245}Cm$	49.1/30.0/0.08/15.5/0.05/ /5.0/0.26

Table 4.13 Generic and Safety-Related Physics Parametes of the Proposed Concept Given in Table 4.12

Items	BOL[1]	BOEC[2]
- Power density: average in core (w/cm^3)		224
maximum in core		400
- Linear heat rate: average (w/cm)		231
maximum		413
- Neutron flux averaged in core (n/cm^2 sec)		2.3 x 10^{15}
- Neutron energy averaged in core (KeV)		
- Fuel dwelling time in core (EFPD)[3]		456
- Burnup reactivity swing (%δk/k/365EFPD)		1.52
- Coolant void reactivity effect (%δk/k)		
All reactor region voided		-
Core and axial blanket voided	2.78	-
Only core voided		-
- Doppler reactivity coefficient (Tdk/dt)	-7.1 x 10^{-3}	-
- Effective delayed neutron fraction	0.0035	-
- Control rod material	B4C(^{10}B:33.3%)	-
- Central control rod worth (%δk/k)	1.46	-
- Prompt neutron life time (sec)	3.4 x 10^{-7}	-

1) Begining of Life, 2) Begining of Equilibrium Cycle,
3) Equivalent full power days

Table 4.14 Neutronics Results of ALMR Actinide Recycling

	Breakeven	Small Burner	Large Burner
Core Height (in.)	42	26	18
Core Diameter (in)	141	141	175
# of Fuel Assy	108	192	354
# of Blanket Assy	84	-	-
Conversion Ratio	1.06	0.72	0.59
Cycle Length (months)	23	12	12
Burnup Reactivity Swing (S)	0.57	8.99	8.45
Peak Linear Power	9.5	10.4	8.2
Sodium Void Worth	6.2	-2.50	< 0
TRU Enr. (wt% in U-TRU-Zr)	21	19/23	24/29
TRU Inventory (kg/core)	2681	2554	3890
TRU Consumption Rate			
kg/year /core	-28.2	83.2	121.0
% inventory/year	-1.1	3.3	3.1

Table 4.15 Principal Design Parameters of Metal-Fuel-LMFBR Based Transmutation Concept Proposed by CRIEPI [18]

Items		
Thermal power	(MWt)	2632
Electric power	(MWe)	1000
Equivalent core diameter	(cm)	290
Equivalent core height	(cm)	100
Averaged core composition	(v/o)	
fuel/clad+structure/coolant(Na)		35.8/24.8/39.4
Type of fuel		Pu-U-MA-Zr
Core averaged fresh fuel composition	(w/o)	
U/Pu/Np, Am and Cm/rare earths		72/18/5/5
Isotopic composition of Pu in fresh fuel	(w/o)	
$^{238}Pu/^{239}Pu/^{240}Pu/^{241}Pu/^{242}Pu$		0/58/24/14/4
Isotopic composision of minor actinides	(w/o)	
$^{237}Np/^{241}Am/^{242}Am/^{243}Am/^{243}Cm/^{244}Cm$		54/23/0/17/0/6

Table 4.16 Generic and Safety-Related Physics Parametes of the Proposed Concept Given in Table 4.15

Items	BOL[1]	BOEC[2]
- Power density: average in core (w/cm^3)		379
maximum in core		587
- Linear heat rate: average (w/cm)		320
maximum		500
- Neutron flux averaged in core (n/cm^2 sec)		5.15×10^{15}
- Neutron energy averaged in core (KeV)		423
- Fuel dwelling time in core (EFPD)[3]		1095
- Burnup reactivity swing (%δ k/k/365EFPD)		3.75
- Coolant void reactivity effect (%δ k/k)		
All reactor region voided	3.74	-
Core and axial blanket voided		-
Only core voided		-
- Doppler reactivity coefficient (Tdk/dt)	-3.2×10^{-3}	-
- Effective delayed neutron fraction	0.0031	-
- Control rod material	B_4C	-
- Central control rod worth (%δ k/k/^{10}B kg)	0.054	-
- Prompt neutron life time (sec)		-
- Axial thermal expansion (δ k/k)/(δ L/L)	-0.586	-

1) Begining of Life, 2) Begining of Equilibrium Cycle,
3) Equivalent full power days

Table 4.17 Principal Design Parameters of Metal-Fuel-LMFBR Based Transmutation Concept Proposed by Toshiba Corporation [9]

Items	
Thermal power (MWt)	1575
Electric power (MWe)	600
Equivalent core diameter (cm)	358
Equivalent core height (cm)	45
Averaged core composition (v/o)	
fuel/clad+structure/coolant(Na)	38.5/35.9/25.6
Type of fuel	metallic
Core averaged fresh fuel composition (w/o)	
U/Pu/Np, Am and Cm	71/26/3
Isotopic composition of Pu in fresh fuel (w/o)	
$^{238}Pu/^{239}Pu/^{240}Pu/^{241}Pu/^{242}Pu$	1.0/57.1/22.4/15.1/4.4
Isotopic composision of minor actinides (w/o)	
$^{237}Np/^{241}Am/^{242}Am/^{243}Am/^{243}Cm/^{244}Cm$	50.9/23.6/0.9/23.6/0.4/0.6

Table 4.18 Generic and Safety-Related Physics Parametes of the Proposed Concept Given in Table 4.17

Items	BOL[1]	EOC[2]
- Power density: average in core (w/cm^3)		350
maximum in core		
- Linear heat rate: average (w/cm)		
maximum		495
- Neutron flux averaged in core (n/cm^2 sec)		
- Neutron energy averaged in core (KeV)		
- Fuel dwelling time in core (EFPD)[3]		1095
- Burnup reactivity swing (%δk/k/365EFPD)		4.6
- Coolant void reactivity effect (%δk/k)		
All reactor region voided		
Core and axial blanket voided		-0.35 - 0.00
Only core voided		0.25 - 0.60
- Doppler reactivity coefficient (Tdk/dt)		-1.7×10^{-3}
- Effective delayed neutron fraction		0.0035
- Control rod material		B_4C
- Central control rod worth (%δk/k/kg)		-
- Prompt neutron life time (sec)		2.4×10^{-7}

1) Begining of Life, 2) Equilibrium Cycle、
3) Equivalent full power days

Table 4.19 Principal Reactor Design Parameters of Helium-Cooled Actinide Burner Concept (P-ABR) Proposed by JAERI [19]

Items		
Thermal power	(MWt)	1200
Electric power	(MWe)	185
Equivalent core diameter	(cm)	124
Equivalent core height	(cm)	124
Averaged core composition	(v/o)	
fuel/clad+structure/coolant(He)		22.1/25.9/52.0
Type of fuel		nitride
Core averaged fresh fuel composition	(w/o)	
U/Pu/Np, Am and Cm		35/ 0/65
Isotopic composition of U in fresh fuel	(w/o)	
$^{235}U/^{236}U/^{238}U$		90.0/ 0/10.0
Isotopic composision of minor actinides	(w/o)	
$^{237}Np/^{241}Am/^{242}Am/^{243}Am/^{243}Cm/^{244}Cm$		56.2/26.4/0/12.0/0.03/5.1

Table 4.20 Generic and Safety-Related Physics Parametes of the Proposed Concept Given in Table 4.19

Items		BOL[1]	BOEC[2]
- Power density: average in core	(w/cm^3)	801	801
maximum in core		1090	1090
- Linear heat rate: average	(w/cm)		
maximum			
- Neutron flux averaged in core	(n/cm^2 sec)	5.9×10^{15}	5.9×10^{15}
- Neutron energy averaged in core	(KeV)	722	700
- Fuel dwelling time in core	(EFPD)[3]	300	300
- Burnup reactivity swing	(%δ k/k/365EFPD)	6.11	7.96
- Coolant void reactivity effect	(%δ k/k)		
All reactor region voided		-	-
Core and axial blanket voided		-	-
Only core voided		-	-
- Doppler reactivity coefficient	(Tdk/dt)	-1.7×10^{-4}	-
- Effective delayed neutron fraction		0.0026	-
- Control rod material		B_4C	-
- Central control rod worth	(%δ k/k)	-1.01	-
- Prompt neutron life time	(sec)	1.5×10^{-7}	-

1) Begining of Life. 2) Begining of Equilibrium Cycle.
3) Equivalent full power days

Table 4.21 Principal Design Parameters of Lead-Cooled Actinide Burner Concept Proposed by JAERI [19]

Items		
Thermal power	(MWt)	180 x 6
Electric power	(MWe)	370
Equivalent core diameter	(cm)	98
Equivalent core height	(cm)	47
Averaged core composition	(v/o)	
fuel/clad+structure/coolant(Pb)		28.9/10.3/60.8
Type of fuel		nitride
Core averaged fresh fuel composition	(w/o)	
U/Pu/Np, Am and Cm		36/ 0/64
Isotopic composition of U in fresh fuel	(w/o)	
$^{235}U/^{236}U/^{238}U$		90/ 0/10
Isotopic composision of minor actinides	(w/o)	
$^{237}Np/^{241}Am/^{242}Am/^{243}Am/^{243}Cm/^{244}Cm$		56.2/26.4/0/12.0/0.3/5.1

Table 4.22 Generic and Safety-Related Physics Parametes of the Proposed Concept Given in Table 4.21

Items	BOL[1]	BOEC[2]
- Power density: average in core (w/cm^3)	580	580
maximum in core	754	754
- Linear heat rate: average (w/cm)		
maximum		
- Neutron flux averaged in core (n/cm^2 sec)	2.8×10^{15}	3.0×10^{15}
- Neutron energy averaged in core (KeV)	720	700
- Fuel dwelling time in core (EFPD)[3]	550	550
- Burnup reactivity swing (%δ k/k/365EFPD)	3.09	4.46
- Coolant void reactivity effect (%δ k/k)		
All reactor region voided	-1.3	-
Core and axial blanket voided		-
Only core voided	-1.3	-
- Doppler reactivity coefficient (Tdk/dt)	-1.3×10^{-4}	-
- Effective delayed neutron fraction	0.0026	-
- Control rod material	B_4C	-
- Central control rod worth (%δ k/k/kg)	-0.511	-
- Prompt neutron life time (sec)	1.3×10^{-7}	-

1) Begining of Life, 2) Begining of Equilibrium Cycle,
3) Equivalent full power days

Table 4.23 Principal Design Parameters of Th-Loaded Lead-Cooled Fast Reactor Based Transmutation Concept Proposed by JAERI [15]

Items	
Thermal power (MWt)	1500
Electric power (MWe)	600
Equivalent core diameter (cm)	355
Equivalent core height (cm)	100
Averaged core composition (v/o)	
fuel/clad+structure/coolant(Pb)	30/10/60
Type of fuel	nitride
Core averaged fresh fuel composition (w/o)	
Th/Pu/Np, Am and Cm	63/17/10
Isotopic composition of Pu in fresh fuel (w/o)	
$^{238}Pu/^{239}Pu/^{240}Pu/^{241}Pu/^{242}Pu$	0/58/24/14/4
Isotopic composision of minor actinides (w/o)	
$^{237}Np/^{241}Am/^{242}Am/^{243}Am/^{243}Cm/^{244}Cm/^{245}Cm$	59/28/0.1/10/0.2/2.6/0.1

Table 4.24 Generic and Safety-Related Physics Parametes of the Proposed Concept Given in Table 4.23

Items	BOL[1]	BOEC[2]
- Power density: average in core (w/cm^3)		
maximum in core	230	300
- Linear heat rate: average (w/cm)		
maximum	470	600
- Neutron flux averaged in core (n/cm^2 sec)		
- Neutron energy averaged in core (KeV)		
- Fuel dwelling time in core (EFPD)[3]	3000	-
- Burnup reactivity swing (%δ k/k/365EFPD)	-0.61 - 0.57	
- Coolant void reactivity effect (%δ k/k)		
All reactor region voided		-
Core and axial blanket voided	-3.8	-
Only core voided		-
- Doppler reactivity coefficient (Tdk/dt)		-
- Effective delayed neutron fraction		-
- Control rod material		-
- Central control rod worth (%δ k/k/kg)		-
- Prompt neutron life time (sec)		-

1) Begining of Life, 2) Begining of Equilibrium Cycle,
3) Equivalent full power days

Table 4.25 System Design Parameters of Accelerator-Driven Transmutation Concept Proposed by JAERI - Alloy Fuel Core System - [20]

Items		
Accelerator		
-Type		Proton LINAC
-Particle		Proton
-Energy	(MeV)	1500
-Current	(mA)	39
Target		
-Equivalent diameter	(cm)	40
-Equivarent height	(cm)	140
-Target material		W
-Cooling material		Na
Subcritical core		
-Equivalent diameter	(cm)	140
-Equivalent height	(cm)	140
-Material composition	(v/o)	
Fuel/Target/Clad+Structure/Coolant		3.6/1.7/80.7/14.0/0
-Chemical form of fuel		metallic
-Materials of coolant and moderator		Na / -
-Averaged fresh fuel composition	(w/o)	
U/Pu/Np, Am, Cm/LLFP		0/25.8/74.2/0
-Isotopic composition of Pu	(w/o)	
$^{238}Pu/^{239}Pu/^{240}Pu/^{241}Pu/^{242}Pu$		1.6/49.5/35.8/8.5/4.7
-Isotopic composition of MA	(w/o)	
$^{237}Np/^{241}Am/^{243}Am/^{243}Cm/^{244}Cm/^{245}Cm$		56.2/26.4/12.0/0.0/5.1/0.3
-Averaged composition of Long-lived FP	(w/o)	
$^{99}Tc/^{129}I$		-
System Characteristics		
-Effective multiplication factor: k_{eff}		0.89
-Thermal Power in core	(MWt)	820 (246 MWe)
-Power density: average	(W/cm^3)	400
maximum	(W/cm^3)	930
-Linear heat rate: average	(W/cm)	260
maximum	(W/cm)	610
-Neutron flux averaged in core	(n/cm^2 s)	4×10^{15}
-Neutron energy averaged in core	(KeV)	690
-Fuel dwelling time	(EFPD)[1]	
-Target dwelling time	(EFPD)	
-Burnup reactivity swing	(%δ k/k/365EFPD)	

1) Equivalent Full Power Day

Table 4.26 System Design Parameters of Accelerator-Driven Transmutation Concept Proposed by JAERI - Molten Salt Core System - [20]

Items		
Accelerator		
-Type		Proton LINAC
-Particle		Proton
-Energy	(MeV)	1500
-Current	(mA)	25
Target		
-Equivalent diameter	(cm)	-
-Equivarent height	(cm)	-
-Target material		-
-Cooling material		-
Subcritical core		
-Equivalent diameter	(cm)	210
-Equivalent height	(cm)	170
-Material composition	(v/o)	
Fuel/Clad+Structure/Coolant/Moderator		14.7/85.3/0/0
-Chemical form of fuel		molten salt
-Materials of coolant and moderator		-
-Averaged fresh fuel composition	(w/o)	
U/Pu/Np, Am, Cm/LLFP		0/15/85/0
-Isotopic composition of Pu	(w/o)	
$^{238}Pu/^{239}Pu/^{240}Pu/^{241}Pu/^{242}Pu$		1.6/49.5/8.5/4.7
-Isotopic composition of MA	(w/o)	
$^{237}Np/^{241}Am/^{243}Am/^{243}Cm/^{244}Cm/^{245}Cm$		56.2/26.4/12.0/0.0/5.1/0.3
-Averaged composition of Long-lived FP	(w/o)	
$^{99}Tc/^{129}I$		-
System Characteristics		
-Effective multiplication factor: k_{eff}		0.92
-Thermal Power in core	(MWt)	800 (240 MWe)
-Power density: average	(W/cm^3)	310
maximum	(W/cm^3)	1660
-Linear heat rate: average	(W/cm)	
maximum	(W/cm)	
-Neutron flux averaged in core	(n/cm^2 s)	
-Neutron energy averaged in core	(KeV)	
-Fuel dwelling time	(EFPD)[1]	
-Target dwelling time	(EFPD)	
-Burnup reactivity swing	(%δ k/k/365EFPD)	

1) Equivalent Full Power Day

Table 4.27 System Design Parameters of Accelerator-Driven Transmutation Concept Proposed by JAERI - Eutectic Metal Target-Core System - [20]

Items		
Accelerator		
-Type		Proton LINAC
-Particle		Proton
-Energy	(MeV)	1500
-Current	(mA)	30
Target		
-Equivalent diameter	(cm)	40
-Equivarent height	(cm)	100
-Target material		(Np-Pu-Co-Ce-Tc) liquid fuel
-Cooling material		-
Subcritical core		
-Equivalent diameter	(cm)	160
-Equivalent height	(cm)	160
-Material composition	(v/o)	
Fuel/Clad+Structure/Coolant/Moderator		10/0/5/85
-Chemical form of fuel		(Np-Pu-Co-Ce-Tc) liquid fuel
-Materials of coolant and moderator		$LiF-BeF_2$ / Graphite
-Averaged fresh fuel composition	(w/o)	
U/Pu/Np, Am, Cm/LLFP		0/26.2/68.3/5.5
-Isotopic composition of Pu	(w/o)	
$^{238}Pu/^{239}Pu/^{240}Pu/^{241}Pu/^{242}Pu$		1.6/49.7/35.7/8.4/4.6
-Isotopic composition of MA	(w/o)	
$^{237}Np/^{241}Am/^{242}Am/^{243}Am/^{243}Cm/^{244}Cm$		100/0/0/0/0/0
-Averaged composition of Long-lived FP	(w/o)	
$^{99}Tc/^{129}I$		100/0
System Characteristics		
-Effective multiplication factor: k_{eff}		0.93
-Thermal Power in core	(MWt)	455 (150 MWe)
-Power density: average	(W/cm^3)	
maximum	(W/cm^3)	
-Linear heat rate: average	(W/cm)	
maximum	(W/cm)	
-Neutron flux averaged in core	(n/cm^2 s)	
-Neutron energy averaged in core	(KeV)	
-Fuel dwelling time	(EFPD)[1]	
-Target dwelling time	(EFPD)	
-Burnup reactivity swing	(%δ k/k/365EFPD)	

1) Equivalent Full Power Day

Table 4.28 System Design Parameters of Accelerator-Driven Transmutation Concept PProposed by BNL - MOX Fuel Core System - [21]

Items		
Accelerator		
-Type		Multi-Segmented Cyclotron
-Particle		Proton
-Energy	(MeV)	1500
-Current	(mA)	2.0 - 5.0
Target		
-Equivalent diameter	(cm)	10
-Equivarent height	(cm)	75
-Target material		Pb
-Cooling material		He
Subcritical core		
-Equivalent diameter	(cm)	180
-Equivalent height	(cm)	93
-Material composition	(v/o)	
Fuel/Clad÷Structure/Coolant/Moderator		35/24/41/0
-Chemical form of fuel		oxide
-Materials of coolant and moderator		Na / -
-Averaged fresh fuel composition	(w/o)	
U/Pu/Np.Am.Cm/LLFP		73/22/5/0
-Isotopic composition of Pu	(w/o)	
$^{238}Pu/^{239}Pu/^{240}Pu/^{241}Pu/^{242}Pu$		0/58/24/14/4
-Isotopic composition of MA	(w/o)	
$^{237}Np/^{241}Am/^{242}Am/^{243}Am/^{243}Cm/^{244}Cm$		53.6/23.1/0/17.4/0/5.9
-Averaged composition of Long-lived FP	(w/o)	
$^{99}Tc/^{129}I$		94/6
System Characteristics		
-Effective multiplication factor: k_{eff}		0.98 - 0.99
-Thermal Power in core	(MWt)	700 (280 MWe)
-Power density: average	(W/cm^3)	930
maximum	(W/cm^3)	
-Linear heat rate: average	(W/cm)	
maximum	(W/cm)	
-Neutron flux averaged in core	(n/cm^2 s)	
-Neutron energy averaged in core	(KeV)	
-Fuel dwelling time	(EFPD)[1]	
-Target dwelling time	(EFPD)	
-Burnup reactivity swing	(%δ k/k/365EFPD)	

1) Equivalent Full Power Day

Table 4.29 System Design Parameters of Accelerator-Driven Transmutation Concept Proposed by BNL - Particle Fuel Core System - [21]

Items		
Accelerator		
-Type		Multi-Segmented Cyclotron
-Particle		Proton
-Energy	(MeV)	1500
-Current	(mA)	4 - 8
Target		
-Equivalent diameter	(cm)	10
-Equivarent height	(cm)	60
-Target material		-
-Cooling material		-
Subcritical core		
-Equivalent diameter	(cm)	150
-Equivalent height	(cm)	60
-Material composition	(v/o)	
Fuel/Clad+Structure/Coolant/Moderator		
-Chemical form of fuel		nitride coated particle
-Materials of coolant and moderator		He / $YH_{1.7}$
-Averaged fresh fuel composition	(w/o)	
U/Pu/Np, Am, Cm/LLFP		0/34/66/0
-Isotopic composition of Pu	(w/o)	
$^{238}Pu/^{239}Pu/^{240}Pu/^{241}Pu/^{242}Pu$		15.8/49.6/35.7/8.4/4.6
-Isotopic composition of MA	(w/o)	
$^{237}Np/^{241}Am/^{242}Am/^{243}Am/^{243}Cm/^{244}Cm$		56.7/26.2/0/11.8/0.3/5.0
-Averaged composition of Long-lived FP	(w/o)	
$^{99}Tc/^{129}I$		93/7
System Characteristics		
-Effective multiplication factor: k_{eff}		0.98 - 0.99
-Thermal Power in core	(MWt)	1000 (370 MWe)
-Power density: average	(W/cm^3)	3400
maximum	(W/cm^3)	
-Linear heat rate: average	(W/cm)	
maximum	(W/cm)	
-Neutron flux averaged in core	(n/cm^2 s)	8.4×10^{15}
-Neutron energy averaged in core	(KeV)	740
-Fuel dwelling time	(EFPD)[1]	
-Target dwelling time	(EFPD)	
-Burnup reactivity swing	(%δ k/k/365EFPD)	2.0

1) Equivalent Full Power Day

Table 4.30 System Design Parameters of Accelerator-Driven Concepts Proposed by CEA [14]

		HYBRID TYPES		
		1	2	3
1	General GOAL's	Min FUEL CYCLE TOXICITY Min Reproc. Mass BREEDING Tc-99-BURNOUT	Low FUEL CYCLE TOXICITY BREEDING Pu^3-BURNOUT Tc-99-BURNOUT	Low FUEL CYCLE TOXICITY Pu^3-high rate BURNOUT Tc-99-BURNOUT
2	Closed Fuel Cycle Type's	3 REEDER Th-cycle	BREEDER-BURNER Th-Pu^3 cycle	BURNER Pu^3-cycle
3	Subcriticality(averaged) level:$(1-K_{eff})$	0.15	0.10	0.12
4	CURRENT(MA) { Particles-protons Energy-1500Mev	100	70	35
5	Initial FUEL composition-SALT (mols)	$ThCl_4$: $PbCl_2$ = 60 : 40	$ThCl_4$: Pu^3Cl_3 : $PbCl_2$ = 57: 3: 40	Pu^3Cl_3 : $PbCl_2$ = 15 : 85
6	Fuel LIFE (years)	50	50	30
7	Fuel BURNUP (%H.a.)	50	~ 50	35
8	Principal CORE+TARGET characteristics			
	Power (th) in CORE (MWt)	2500	2500	2500
	Power DENSITY (averaged) wt/cm³	40	40	50
	(maximum) wt/cm³	100	100	100
	CORE SIZE (D x H) (cm)	360 x 600	360 x 600	350 x 600
	TARGET SIZE (D x H) (cm)	160 x 200	160 x 200	150 x 200
	TERGET MATERIAL	FUEL	FUEL	FUEL
	neutron flux (averaged) in CORE	$2 \cdot 10^{15}$	$2 \cdot 10^{15}$	10^{15}
	Burnup swing ($\Delta K/K\%$ per year)	<0.2	<0.2	~3
	Time INTERVAL between Discharges (y)	10	10	1
9	CHARGE—DISCHARGE MASS (Kg/year)			
	Thorium 232	1800 — 735	1750 — 750	—
	URANIUM 233	— 90	— 92	—
	234	— 31	— 30	—
	235	— 6.5	— 6.2	1 — 3.05
	236	— 3.0	— 2.8	— 0.25
	PLUTONIUM 238	— 3.0	53 — 0.4	— 0.9
	239	— 0.036	— 0.22	1240 — 60
	240	— 0.0	— 1.7	— 110
	241	— 0.0	— 0.24	— 10
	242	— 0.0	— 0.14	— 20
	Americium 241	— 0.0	— 0.14	— 1.7
	242m	— 0.0	— 0.01	— 0.12
	243	— 0.0	— 0.04	— 0.32
	Curium 242	— 0.0	— 0.0	— 0.23
	243	— 0.0	— 0.0	— 0.02
	244	— 0.0	— 0.03	— 0.12
	245	— 0.0	— 0.0	— 0.01
	99	100 — 32	100 — 30	540 — 30
	237	— 6.4	— 5.0	— 0.05
10	TRANSMUTATION POTENTIAL: TRANSMUTATION RATE(av.) Kg/Mwt(t)year			
	for Tc-99	0.024	0.023	0.13
	for Pu-239	—	0.021	0.37
11	WASTE TOXICITY WASTE TOXICITY-REFERENCE [ ] for time interval 10^3 ÷ 10^4 years after discharge	$\frac{1}{1000}$ (stand.FR) $\frac{1}{15000}$ (stand.FR)	$\frac{1}{500}$ (stand.FR) $\frac{1}{3000}$ (stand.FR)	$\frac{1}{10}$ (CAPRA-type)

Table 4.31 Key Design Parameter Comparison Between ATW and CANDU

PARAMETER	CANDU-3	ATW
1. Blanket Arrangement		
Type	horizontal pressure tube	same
Coolant	pressurized heavy water	same
Moderator	heavy water	same
Number of Fuel Assemblies	232	250
Fuel Assembly Material	Zirconium-Niobium	same
Total mass of Fuel	53174 kg	1550 kg
		(total primary loop)
k_{eff}	1.0	0.95
2. Fuel		
Fuel	compacted/sintered	aqueous actinide
	natural UO_2 pellets	solution (75 gm/l);
		(Pu, Np, Am, Cm)
Form	fuel bundle assembly;	flowing fuel solution
	37 elements/assembly	
Bundle Length	0.495 m	-
Bundle Outer Diameter	0.1024 m	0.10 m
Bundles/Fuel Assembly	12	-
3. Heat Transport System		
Number of Steam Generators	2	same
Steam Generator Type	vertical U-tube	same
Number of Heat-Transport Pumps	2	same
Pump Type	vertical, centrifugal, single	same
	suction, double discharge	
Number of Intermediate Heat Exchangers (IHX)	-	2
IHX Type	-	vertical once-through
Number of IHX Pumps	-	2

Table 4.31 (Continuation)

PARAMETER	CANDU-3	ATW
IHX Pump Type	-	vertical, centrifugal,
		single suction, double
		discharge
Blanket Outlet Pressure	9.9 MPa	13.1 MPa
Blanket Outlet Temp.	310 C	325 C
Blanket Inlet Temp.	258 C	273 C
Total Flowrate	5300 kg/s	5240 kg/s
Steam Outlet Temp.	260 C	same
Feedwater Inlet Temp.	187 C	same
Steam Quality	99.75%	same
Steam Pressure	4.6 MPa	same
IHX Outlet Temp.	-	310 C
IHX Outlet Pressure	-	13.2 MPa
IHX Inlet Temp.	-	258 C
IHX Flowrate	-	5744 kg/s
4. Power		
Total Fission Heat	1440.3 MW_t	1542 MW_t
Net Electrical Output	450 MWe	487 MWe

Table 4.32 System Design Parameters of Accelerator-Driven Transmutation Concept Proposed by ENEA - ATW Type - [8]

Items		
Accelerator		
-Type		Proton LINAC
-Particle		Proton
-Energy	(MeV)	1600
-Current	(mA)	200
Target		
-Equivalent diameter	(cm)	27
-Equivarent height	(cm)	200
-Target material		Liquid Lead
-Cooling material		-
Subcritical core		
-Equivalent diameter	(cm)	
-Equivalent height	(cm)	
-Material composition	(v/o)	
Fuel/Clad+Structure/Coolant/Moderator		
-Chemical form of fuel		Molten salt or slurry
-Materials of coolant and moderator		
-Averaged fresh fuel composition	(w/o)	
U/Pu/Np, Am, Cm/LLFP		0/94/6/0
-Isotopic composition of Pu	(w/o)	
$^{238}Pu/^{239}Pu/^{240}Pu/^{241}Pu/^{242}Pu$		1.4/55.0/25.5/13.3/4.8
-Isotopic composition of MA	(w/o)	
$^{237}Np/^{241}Am/^{242}Am/^{243}Am/^{245}Cm/^{244}Cm$		74.1/6.0/0.1/13.7/0.1/6.0
-Averaged composition of Long-lived FP	(w/o)	
$^{99}Tc/^{129}I$		100/0
System Characteristics		
-Effective multiplication factor: k_{eff}		
-Thermal Power in core	(MWt)	
-Power density: average	(W/cm^3)	
maximum	(W/cm^3)	
-Linear heat rate: average	(W/cm)	
maximum	(W/cm)	
-Neutron flux averaged in core	(n/cm^2 s)	
-Neutron energy averaged in core	(KeV)	
-Fuel dwelling time	(EFPD)[1]	
-Target dwelling time	(EFPD)	
-Burnup reactivity swing	(%δ k/k/365EFPD)	

1) Equivalent Full Power Day

Table 4.33 System Design Parameters of Accelerator-Driven Transmutation Concept Proposed by Royal Institute of Technology -ATW Type - [10]

Items		
Accelerator		
-Type		Proton LINIAC or Cyclotron
-Particle		Proton or Deutron
-Energy	(MeV)	~1000
-Current	(mA)	5 - 100
Target		
-Equivalent diameter	(cm)	40
-Equivarent height	(cm)	400
-Target material		Solid Th or Liquid Pb or ^{7}Li
-Cooling material		-
Subcritical core		
-Equivalent diameter	(cm)	~400
-Equivalent height	(cm)	~400
-Material composition Fuel/Clad+Structure/Coolant/Moderator	(v/o)	
-Chemical form of fuel		Molten salt or Slurry
-Materials of coolant and moderator		
-Averaged fresh fuel composition U/Pu/Np, Am, Cm/LLFP	(w/o)	
-Isotopic composition of Pu $^{238}Pu/^{239}Pu/^{240}Pu/^{241}Pu/^{242}Pu$	(w/o)	
-Isotopic composition of MA $^{237}Np/^{241}Am/^{242}Am/^{243}Am/^{243}Cm/^{244}Cm$	(w/o)	
-Averaged composition of Long-lived FP $^{99}Tc/^{129}I$	(w/o)	
System Characteristics		
-Effective multiplication factor: k_{eff}		
-Thermal Power in core	(MWt)	
-Power density: average	(W/cm^3)	
maximum	(W/cm^3)	
-Linear heat rate: average	(W/cm)	
maximum	(W/cm)	
-Neutron flux averaged in core	(n/cm^2 s)	
-Neutron energy averaged in core	(KeV)	
-Fuel dwelling time	(EFPD)[1]	
-Target dwelling time	(EFPD)	
-Burnup reactivity swing	(%δ k/k/365EFPD)	

1) Equivalent Full Power Day

Table 4.34 System Design Parameters of Accelerator-Driven Transmutation Concept Proposed by Institute of Theoretical and Experimental Physics (ITEP) [12]

Items		
Accelerator		
-Type		Proton LINIAC
-Particle		Proton
-Energy	(MeV)	1000
-Current	(mA)	100
Target		
-Equivalent diameter	(cm)	50
-Equivarent height	(cm)	400
-Target material		W, Pb-Bi eutectic alloy
-Cooling material		H_2O
Subcritical core		
-Equivalent diameter	(cm)	600
-Equivalent height	(cm)	600
-Material composition	(v/o)	
Fuel/Clad+Structure/Coolant/Moderator		4.7/4.5/3.5/84.6
-Chemical form of fuel		molten salt
-Materials of coolant and moderator		
-Averaged fresh fuel composition	(w/o)	
U/Pu/Np, Am, Cm/LLFP		
-Isotopic composition of Pu	(w/o)	
$^{238}Pu/^{239}Pu/^{240}Pu/^{241}Pu/^{242}Pu/241Am$		2/60/22/10/4/2
-Isotopic composition of MA	(w/o)	
$^{237}Np/^{241}Am/^{242}Am/^{243}Am/^{243}Cm/^{244}Cm$		
-Averaged composition of Long-lived FP	(w/o)	
$^{99}Tc/^{129}I$		
System Characteristics		
-Effective multiplication factor: k_{eff}		0.97
-Thermal Power in core	(MWt)	1100 (380 MWe)
-Power density: average	(W/cm^3)	5.3
maximum	(W/cm^3)	10.6
-Linear heat rate: average	(W/cm)	81.4
maximum	(W/cm)	162.8
-Neutron flux averaged in core	(n/cm^2 s)	10^{14}
-Neutron energy averaged in core	(KeV)	
-Fuel dwelling time	(EFPD)[1]	
-Target dwelling time	(EFPD)	
-Burnup reactivity swing	(%δ k/k/365EFPD)	

1) Equivalent Full Power Day

5. TRANSMUTATION CAPABILITY OF PROPOSED CONCEPTS

The transmutation capability has been usually discussed using the transmutation rate defined as a ratio of weight of minor actinides which is transmuted by fission and capture to that of initial loading of minor actinides per unit time. There is another definition, so-called burnup rate, which is a ratio of weight of minor actinides incinerated by fission reaction to that of initial loading of minor actinides per unit time [15]. This is because the aim of transmutation is the conversion of long-lived nuclides to shorter-lived or stable nuclides and fission, not capture,is a real transmutation reaction for minor actinides.

Since it is difficult to separate transmutation by fission from by capture in the burnup calculation, the transmutation capability of the proposed concepts is discussed based on the classical definition.

$$\text{Transmutation capability} = \frac{MA(BOEC) - MA(EOEC)}{(\text{cycle time}) \times (\text{thermal power})}$$

$$\text{Transmutation rate} = \frac{MA(BOEC) - MA(EOEC)}{MA(BOEC) \times (\text{cycle time})}$$

where, MA(BOEC) and MA(EOEC): minor actinides quantities at the beginning and end of equilibrium cycle (kg), cycle time: equivalent full power year (EFPY) between BOEC and EOEC, and thermal power:(GWt).

5.1 Thermal Reactors

Materials inventory and mass balance of PWR based transmutation concepts proposed by the CEA is given in Table 5.1 for the homogeneous arrangement of minor actinides, and in Table 5.2 and 5.3 for the heterogeneous arrangement with Np and Am targets. In the first concept with the homogeneous arrangement,the transmutation capability is 11.3 kg/GWt/EFPY and then the corresponding transmutation rate is 5.0%/EFPY. This substantially low transmutation capability is due to significant buildup of Cm-244. In the second concepts, the transmutation capability is 37.2 kg/GWt/EFPY (11.1%/EFPY) and 17.3 kg/GWt/EFPY (16.8%/EFPY) for the Np and Am targets themselves,respectively.

Materials inventory and mass balance of UO2 fueled PWR based transmutation concept proposed by JAERI is given in Table 5.4. The transmutation capability is 11.3 kg/GWt/EFPY (6.8%/GWt/EFPY). The JAERI concept has the equivalent transmutation rate of Np-237 with that of the CEA first concept (5.7%/EFPY).

5.2 Fast Reactors

Materials inventory and mass balance are given in Table 5.5 to 5.12 for fast reactor based transmutation concepts proposed by the organizations.

The transmutation capabilities are 57.9 kg/GWt/EFPY for the CEA first MOX-LMFBR, 58.2 for the PNC-MOX-LMFBR, 53.6 for the CRIEPI-metal fuel LMFBR, 256.4 for the JAERI P-ABR, 290.3 for the JAERI L-ABR and 112.6 for the JAERI-Th loaded LMR, respectively.

The corresponding transmutation rates are 9.0%/EFPY, 7.0, 12.4, 20.6, 10.4 and 5.5,respectively. As for the LMFBR based concepts loaded heterogeneously with minor actinides targets, the transmutation capability is 48.2 kg/GWt/EFPY (4.9%/EFPY) for Np-target and 39.0 kg/GWt/EFPY (3.9%/EFPY),respectively.

The fast reactor based transmutation concepts has higher transmutation capability than LWR based ones, because of their higher minor actinides inventory and higher neutron flux than LWR concepts.

5.3 Accelerator Based Transmutation Concepts

Exact burnup calculation is very much troublesome for the accelerator-driven systems, since various kinds of high energy particle reactions include in the calculation. Therefore, there is a few calculation results related to the material mass balance as shown above for reactor based transmutation systems.

Table 5.13 and 5.14 show simple transmutation rates of transmutation nuclides, without treating their burnup and decay chains, for the "MOX fueled core" and "Particle fueled core" concepts proposed by the BNL. In these tables,transmutation rate of Tc-99 and I-129 is straight forward. The transmutation capability of the first concept is 84 kg/GWt/EFPY (10.7%/EFPY) for Tc-99 and 13 kg/GWt/EFPY (23.1%/EFPY) for I-129, and the transmutation capability is 44.3 kg/GWt/EFPY (6.1%/EFPY) for Tc-99 and 6.4 kg/GWt/EFPY (13.6%/EFPY) for I-129.

Table 5.15 shows materials mass balance of the "Alloy fueled core" concept proposed by the JAERI, using preliminary but more

rigorous approach as shown in Fig.5.1. In this concept, the transmutation capability of minor actinides is 306 kg/GWt/EFPY (10.7%/EFPY).

Table 5.16 summarizes the data existing in literature concerning the transmutation capability. In the case of the PHOENIX concept, the comparison was performed between the waste inventory and the release limits for 10000 years after disposal (see Fig.5.2).

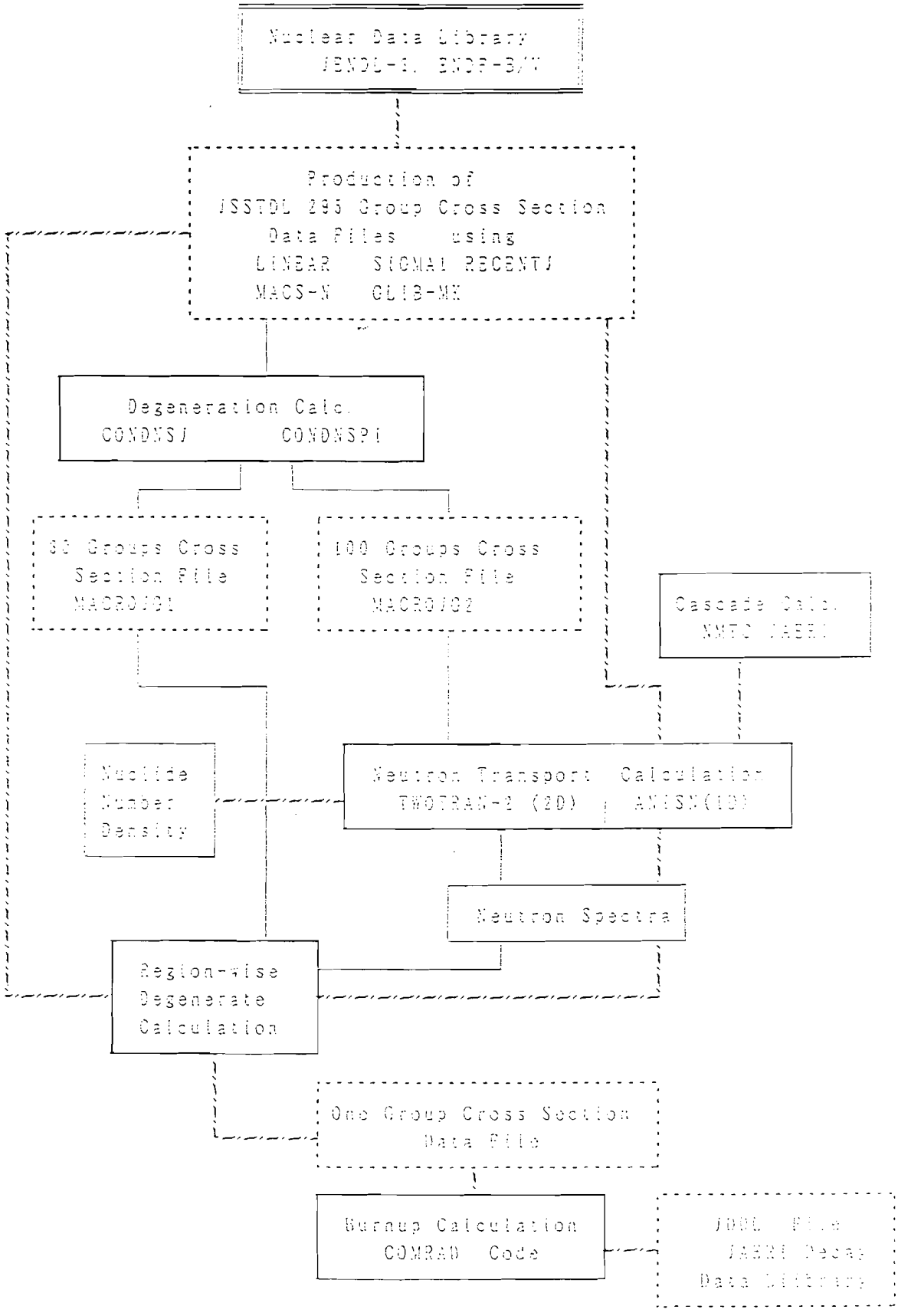

Fig. 5.1 Flow Chart for Burnup Calculation in Accelerator Transmutation System at JAERI

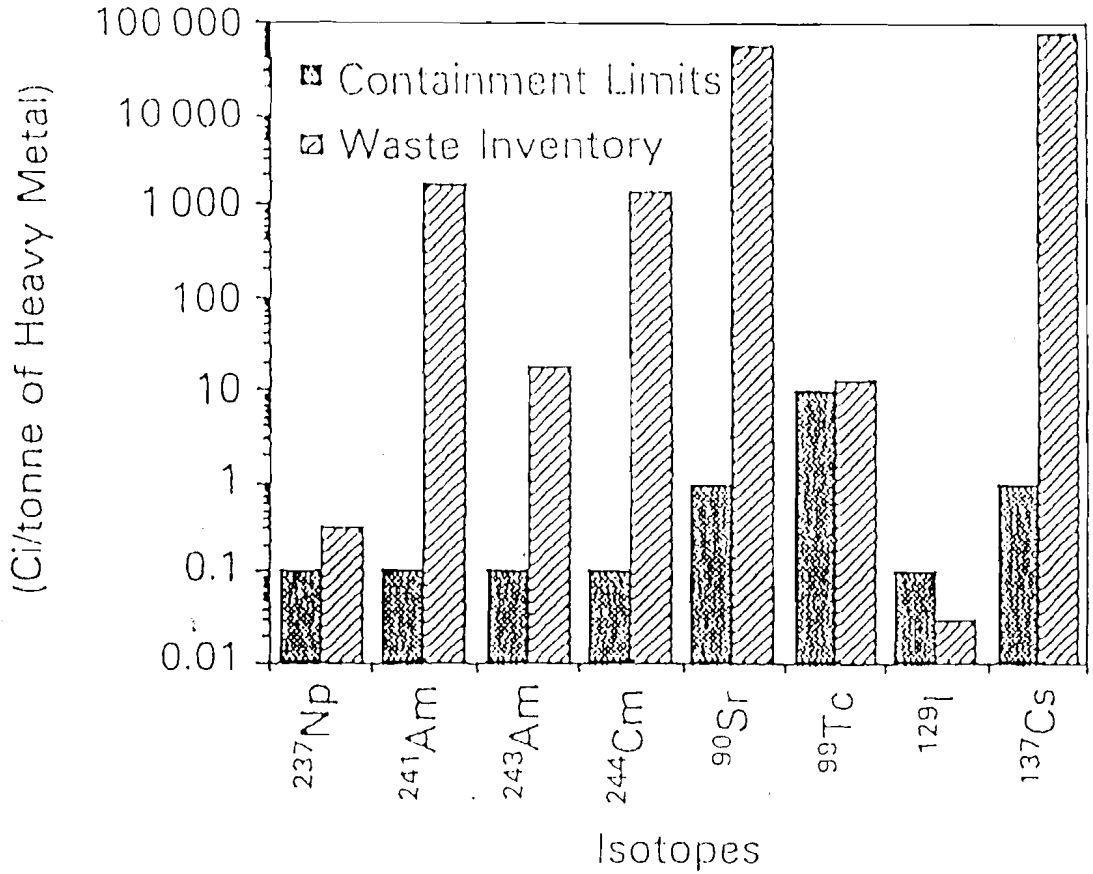

Fig. 5.2 Waste inventory compared with release limits for 10 000 yr after disposal (limits specified in 40CFR191 and were in proposed 109CFR60). Conclusion: Partitioning at 10^{-5} or better should meet these containment requirements.

Table 5.1 Material inventory and mass balance of PWR Based Transmutation Concept Proposed by CEA - Homogeneous Loading of Minor Actinides -

Nuclides	Initial inventory (kg)	Mass balance in EOC[1] (unit:kg)		
		BOEC[2]	EOEC[3]	EOEC-BOEC
Fuel				
Uranium				
U-235	209	165	144	- 21
U-236	-	10	14	+ 4
U-238	84392	83564	83126	-438
Plutonium				
Pu-238	133	268	335	+ 67
Pu-239	4299	3073	2562	-511
Pu-240	1674	1765	1759	- 6
Pu-241	887	873	882	+ 9
Pu-242	427	484	520	+ 36
Minor actinides				
Neptunium				
Np-237	510	411	365	- 46
Americium				
Am-241	262	254	215	- 39
Am-242m	0.7	5.4	4.7	- 0.7
Am-243	154	175	187	+ 12
Curium				
Cm-242	-	44	45	+ 1
Cm-243	-	1.2	1.9	+ 0.7
Cm-244	-	56	84	+ 28
Cm-245	-	3.7	7.6	+ 3.9
Other actinides				
Transmutation capability (kg/GWt EFPY)			11.3	

1) Equilibrium Cycle, 2) Begining of Equilibrium Cycle,
3) End of Equilibrium Cycle. T(EOEC)-T(BOEC)=ΔT=0.8 EFPY

Table 5.3 Material inventory and mass balance of Am Target in PWR Based Transmutation Concept Proposed by CEA - Heterogeneous Loading -

Nuclides	Initial inventory (kg)	Mass balance in EOC[1] (unit:kg)		
		BOEC[2]	EOEC[3]	EOEC-BOEC
Fuel				
Uranium				
U-235				
U-236				
U-238				
Plutonium				
Pu-238			19	
Pu-239			3.2	
Pu-240			0.9	
Pu-241			0.6	
Pu-242			4.1	
Minor actinides				
Neptunium				
Np-237				
Americium				
Am-241		52	8.8	- 43
Am-242m		0.14	0.16	+ 0.02
Am-243		20	11	- 9.1
Curium				
Cm-242			4.3	+ 4.3
Cm-243			0.5	+ 0.5
Cm-244			10	+ 10
Cm-245				
Tc-99, I-1298			0.13, 0.04	
Transmutation capability (kg/GWt EFPY)			17.3 (Am)	

1) Equilibrium Cycle, 2) Begining of Equilibrium Cycle,
3) End of Equilibrium Cycle.

Table 5.4 Material inventory and mass balance of PWR Based Transmutation Concept Proposed by JAERI

Nuclides	Initial inventory (kg)	Mass balance in EOC[1] (unit:kg)		
		BOEC[2]	EOEC[3]	EOEC-BOEC
Fuel				
Uranium				
U-235	6475	1295	683	- 612
U-236	0	0	0	
U-238	72981	14596	14162	- 434
Plutonium				
Pu-238		585	585	0
Pu-239		318	318	0
Pu-240		153	153	0
Pu-241		102	102	0
Pu-242		114	114	0
Minor actinides				
Neptunium				
Np-237	2700	540	310	- 230
Americium				
Am-241			11	+ 11
Am-242m			0.4	+ 0.4
Am-243			28	+ 28
Curium				
Cm-242			16	+ 16
Cm-243				
Cm-244			14	+ 14
Cm-245			1.8	+ 1.8
Other actinides				
Transmutation capability (kg/GWt EFPY)			11.3	

1) Equilibrium Cycle, 2) Begining of Equilibrium Cycle,
3) End of Equilibrium Cycle. T(EOEC)-T(BOEC)=ΔT= 4 EFPY

Table 5.5 Material inventory and mass balance of MOX-LMFBR Based Transmutation Concept Proposed by CEA - Homogeneous Loading of MA -

Nuclides	Initial inventory (kg)	Mass balance in EOC[1] (unit:kg)		
		BOEC[2]	EOEC[3]	EOEC-BOEC
Fuel				
Uranium				
U-235	86	86	37	- 47
U-236	0	0	10	+ 10
U-238	34206	34206	30215	-3991
Plutonium				
Pu-238	161	161	673	+ 512
Pu-239	4970	4970	4450	- 520
Pu-240	2036	2036	2227	- 191
Pu-241	1022	1027	535	- 492
Pu-242	479	479	449	- 30
Minor actinides				
Neptunium				
Np-237	1128	1128	607	- 521
Americium				
Am-241	1128	1193	653	- 540
Am-242m			41	+ 41
Am-243			75	+ 75
Curium				
Cm-242			55	+ 55
Cm-243			7	+ 7
Cm-244			24	+ 24
Cm-245			2	+ 2
Other actinides				
Transmutation capability (kg/GWt EFPY)			57.9	

1) Equilibrium Cycle, 2) Begining of Equilibrium Cycle,
3) End of Equilibrium Cycle. T(EOEC)-T(BOEC)=ΔT= 4 EFPY

Table 5.6 Material inventory and mass balance of Np target in MOX-FBR Based Transmutation Concept Proposed by CEA - Heterogeneous Loading -

Nuclides	Initial inventory (kg)	Mass balance in EOC[1] (unit:kg)		
		BOEC[2]	EOEC[3]	EOEC-BOEC
Fuel				
Uranium				
U-235				
U-236				
U-238				
Plutonium				
Pu-238			1108	+1108
Pu-239			151	+ 151
Pu-240			20	+ 20
Pu-241			1	+ 1
Pu-242			0.1	+ 0.1
Minor actinides				
Neptunium				
Np-237		3574	1440	-2134
Americium				
Am-241				
Am-242m				
Am-243				
Curium				
Cm-242				
Cm-243				
Cm-244				
Cm-245				
Other actinides				
Transmutation capability (kg/GWt EFPY)			48.2 (Np)	

1) Equilibrium Cycle, 2) Begining of Equilibrium Cycle,
3) End of Equilibrium Cycle. T(EOEC)-T(BOEC)=ΔT= 12.3 EFPY

Table 5.7 Material inventory and mass balance of Am target in MOX-LMFBR Based Transmutation Concept Proposed by CEA - Heterogeneous Loading -

Nuclides	Initial inventory (kg)	Mass balance in EOC[1] (unit:kg)		
		BOEC[2]	EOEC[3]	EOEC-BOEC
Fuel				
Uranium				
U-235				
U-236				
U-238				
Plutonium				
Pu-238			675	+ 675
Pu-239			97	+ 97
Pu-240			126	+ 126
Pu-241				
Pu-242				
Minor actinides				
Neptunium				
Np-237				
Americium				
Am-241		2234	734	-1500
Am-242m		7	70	+ 63
Am-243		1282	498	- 784
Curium				
Cm-242			440	+ 440
Cm-243			59	+ 59
Cm-244				
Cm-245				
Other actinides				
Transmutation capability (kg/GWt EFPY)			39.0 (Am)	

1) Equilibrium Cycle, 2) Begining of Equilibrium Cycle,
3) End of Equilibrium Cycle. T(EOEC)-T(BOEC)=ΔT= 12.3 EFPY

Table 5.8 Material inventory and mass balance of MOX-LMFBR Based Transmutation Concept Proposed by PNC

Nuclides	Initial inventory (kg)	Mass balance in EOC[1] (unit:kg)		
		BOEC[2]	EOEC[3]	EOEC-BOEC
Fuel				
Uranium				
U-235		139	116	- 22
U-236		6.2	11	- 4.8
U-238		53870	52590	-1280
Plutonium				
Pu-238		145	259	+ 115
Pu-239		3781	3997	+ 216
Pu-240		1493	1547	+ 54
Pu-241		666	529	- 136
Pu-242		267	288	+ 20
Minor actinides				
Neptunium				
Np-237		719	590	- 129
Americium				
Am-241		459	395	- 64
Am-242m		12	19	+ 7.1
Am-243		240	210	- 29
Curium				
Cm-242		19	27	+ 8.0
Cm-243		1.7	2.4	+ 0.7
Cm-244		113	131	+ 19
Cm-245		8.8	13	+ 4.0
Other actinides				
Transmutation capability (kg/GWt EFPY)			58.2	

1) Equilibrium Cycle, 2) Begining of Equilibrium Cycle,
3) End of Equilibrium Cycle. T(EOEC)-T(BOEC)=ΔT= 3 EFPY

Table 5.9 Material inventory and mass balance of Metal Fuel LMFBR Based Transmutation Concept Proposed by CRIEPI

Nuclides	Initial inventory (kg)	Mass balance in EOC[1] (unit:kg)		
		BOEC[2]	EOEC[3]	EOEC-BOEC
Fuel				
Uranium				
U-235		5.7	2.5	- 3.2
U-236		1.1	1.7	+ 0.6
U-238		5635	4978	- 658
Plutonium				
Pu-238		338	204	- 133
Pu-239		598	634	+ 36
Pu-240		330	328	- 1.5
Pu-241		46	49	+ 2.5
Pu-242		85	75	- 9.8
Minor actinides				
Neptunium				
Np-237		175	90	- 85
Americium				
Am-241		66	32	- 34
Am-242m		2.0	1.7	- 0.2
Am-243		62	41	- 21
Curium				
Cm-242		3.5	4.3	+ 0.8
Cm-243		0.4	0.3	+ 0.0
Cm-244		59	55	- 3.8
Cm-245		12	13	+ 1.6
Other actinides				
Transmutation capability (kg/GWt EFPY)			53.6	

1) Equilibrium Cycle, 2) Begining of Equilibrium Cycle,
3) End of Equilibrium Cycle.

Table 5.10 Material inventory and mass balance of Helium-Cooled Actinide Burner (P-ABR) Proposed by JAERI

Nuclides	Initial inventory (kg)	Mass balance in EOC[1] (unit:kg)		
		BOEC[2]	EOEC[3]	EOEC-BOEC
Fuel				
Uranium				
U-235	904	575	425	- 150
U-236	0	125	142	+ 18
U-238	101	131	125	- 5.7
Plutonium				
Pu-238		379	391	+ 12
Pu-239		62	79	+ 18
Pu-240		49	49	+ 0.0
Pu-241		2.1	3.7	+ 1.6
Pu-242		32	37	+ 4.7
Minor actinides				
Neptunium				
Np-237	1049	808	645	- 163
Americium				
Am-241	493	356	277	- 78
Am-242m	0	6.8	6.8	+ 0.0
Am-243	224	180	147	- 33
Curium				
Cm-242	0	0.53	21	+ 20
Cm-243	0.53	1.6	1.6	+ 0.0
Cm-244	95	122	123	+ 0.53
Cm-245	5.3	16	16	+ 0.53
Other actinides		27	27	+ 0.33
Transmutation capability (kg/GWt EFPY)			256.4	

1) Equilibrium Cycle. 2) Begining of Equilibrium Cycle.
3) End of Equilibrium Cycle.

Table 5.11 Material inventory and mass balance of LLead-Cooled Actinide Burner (L-ABR) Proposed by JAERI

Nuclides	Initial inventory (kg)	Mass balance in EOC[1] (unit:kg)		
		BOEC[2]	EOEC[3]	EOEC-BOEC
Fuel				
Uranium				
U-235	290	177	138	- 40
U-236	0	33	38	+ 4.6
U-238	32	39	37	- 1.3
Plutonium				
Pu-238		96	104	+ 8.6
Pu-239		13	17	+ 4.0
Pu-240		16	17	+ 0.36
Pu-241		0.61	0.97	+ 0.36
Pu-242		8.2	9.7	+ 1.6
Minor actinides				
Neptunium				
Np-237	321	280	230	- 23
Americium				
Am-241	151	122	99	- 23
Am-242m	0	2.2	2.3	+ 0.12
Am-243	69	58	48	- 10
Curium				
Cm-242	0	0.12	4.0	+ 3.9
Cm-243	0.12	0.24	0.24	+ 0.0
Cm-244	29	35	35	+ 0.0
Cm-245	1.6	4.1	4.3	+ 0.25
Other actinides		7	7	+ 0.0
Transmutation capability (kg/GWt EFPY)			290.3	

1) Equilibrium Cycle, 2) Begining of Equilibrium Cycle,
3) End of Equilibrium Cycle.

Table 5.12 Material inventory and mass balance of Th-Loaded Lead-Cooled Fast Reactor Based Transmutation Concept Proposed by JAERI

Nuclides	Initial inventory (kg)	Mass balance in EOC[1] (unit:kg)		
		BOEC[2]	EOEC[3]	EOEC-BOEC
Fuel				
Uranium				
U-235			10	+ 10
U-236				
U-238				
Plutonium				
Pu-238		-	599	+ 599
Pu-239		2791	1137	-1654
Pu-240		1160	963	- 197
Pu-241		679	256	- 423
Pu-242		195	196	+ 1.0
Minor actinides				
Neptunium				
Np-237		1796	829	- 967
Americium				
Am-241		870	482	- 388
Am-242m		2.8	20	+ 17
Am-243		308	182	- 126
Curium				
Cm-242		0	22	+ 22
Cm-243		0	0	0
Cm-244		78	120	+ 42
Cm-245		4.4	17	+ 12
Other actinides				
Transmutation capability (kg/GWt EFPY)			112.6	

1) Equilibrium Cycle, 2) Begining of Equilibrium Cycle,
3) End of Equilibrium Cycle.

Table 5.13 Material Inventory and Transmutation Rate of "MOX Fuel Core" Concept Proposed by BNL

Nuclides	Initial inventory (kg)	Transmutation rate (kg/year)		
		by caputure	by fission	total
Fuel				
Uranium				
U-235	9.1			
U-236	-			
U-238	4494			
Plutonium				
Pu-238	-			
Pu-239	646			
Pu-240	268			
Pu-241	156			
Pu-242	446			
Minor actinides				
Neptunium				
Np-237	179	24	8.0	32
Americium				
Am-241	77	11	3.5	15
Am-242m	-			
Am-243	58	4.7	1.7	6.4
Curium				
Cm-242	-			
Cm-243	-			
Cm-244	20	1.4	1.3	2.7
Cm-245	-			
Other actinides				
Long-lived FP				
Tc-99	507	31		31
I-129	33	4.5		4.5
(I-127)				
Transutation capability (kg/GWt EFPY)			---	

Table 5.14 Material inventory and transmutation rate of "Particle Fuel Core" Concept Proposed by BNL

Nuclides	Initial inventory (kg)	Transmutation rate (kg/year)		
		by capture	by fission	total
Fuel				
Uranium				
U-235				
U-236				
U-238				
Plutonium				
Pu-238	108			
Pu-239	338			
Pu-240	243			
Pu-241	57			
Pu-242	31			
Minor actinides				
Neptunium				
Np-237	764	121	85	206
Americium				
Am-241	360	69	37	107
Am-242m	-			
Am-243	163	18	13	31
Curium				
Cm-242	-			
Cm-243	74	6.8	10	17
Cm-244	-			
Cm-245	-			
Other actinides				
Long-lived FP				
Tc-99	550	59		59
I-129	39	9		9
(I-127)	13			
Transmutation capability (kg/GWt EFPY)			---	

Table 5.15 Materials Inventory and Mass Balance of Accelerator-Driven Transmutation Cncept Proposed by JAERI - Alloy Fuel Core System -

Nuclides	Initial inventory (kg)	Mass balance in EOC[1] (unit:kg)		
		BOEC[2]	EOEC[3]	EOEC-BOEC
Fuel				
Uranium				
U-235			0.9	+ 0.9
U-236			0.2	+ 0.2
U-238			0.0	+ 0.0
Plutonium				
Pu-238	13	13	470	+ 457
Pu-239	401	401	156	- 246
Pu-240	292	292	193	- 99
Pu-241	69	69	34	- 35
Pu-242	38	38	47	+ 8.9
Minor actinides				
Neptunium				
Np-237	1861	1861	593	-1268
Americium				
Am-241	292	292	95	- 197
Am-242m	0	0	9.5	+ 9.5
Am-243	133	133	57	- 77
Curium				
Cm-242	0	0	7.2	+ 7.2
Cm-243	0.3	0.3	1.0	+ 0.7
Cm-244	57	57	61	+ 4.8
Cm-245	3.1	3.1	10	+ 7.2
Other actinides				
Transmutation capability (kg/GWt EFPY)			307	

1) Equilibrium Cycle, 2) Begining of Equilibrium Cycle,
3) End of Equilibrium Cycle.
T(EOEC)-T(BOEC)=ΔT= 6 EFPY

Table 5.16 Transmutation Capability, Survey of Data

Concept	Proton beam energy (MeV)	Proton beam current (mA)	Actinide burnup (kg/yr.)	Actinide composition	Actinide Inventory (kg)	Number of LWR of 3000-3600 MW served	Fission Product burnup (kg/yr.)	Fission Product Inventory (kg)
PHOENIX /1/	1600	104		MA		75		
Plant with Sodium-cooled Solid Target/Core /2/	1500	39	250	MA	3160	10		
Molten-Salt Target System /3/	1500	25	250	15 mol % Pu 85 mol % MA		10		
Fission Product Transmutation System /3/	1500	250				10		
ATW /4/	1600	250	1200	90% Pu, 10% MA	1300	8	132 Tc, 28 I	Tc between (328 - 397)

6. CALCULATIONAL METHODS

6.1 Thermal and Fast Reactors

In the case of thermal and fast reactors, the presence of actinides does not change the calculational methods presently applied provided the nuclear data, in particular cross-sections are available in the required group structure. Self shielding effect and Doppler broadening are calculated in the usual manner.

Multigroup cross-section libraries are generated by retrieval and processing codes (such as NJOY) which depart directly from ENDFB/4, ENDFB/5, ENDFB/6, JEF or JEF2 and JENDL3. In the case of continuous cross-section libraries as used by some Monte Carlo codes, in particular MCNP, the ACER module of NJOY is applied.

Reactivity and flux calculations are carried out for thermal reactors by code systems like WIMS or APOLLO-KAFKA. Fast reactors are calculated by similar systems based on nodal methods or different SN codes. Burnup and fission product decay is determined by ORIGEN, ORIGINS, FISBIN or PEPIN.

6.2 Accelerator Driven Systems

In accelerator-driven systems, the neutron energy extends to several hundred MeV. In classical reactor codes the upper energy limit lies between 15 and 20 MeV. In accelerator driven systems, between 10% and 20% of the spallation neutrons are above this limit and therefore require to be considered in the calculations. Usually a classical Monte Carlo code like MCNP or MORSE is

extended to higher energies by codes like HETEC (High Energy Transport Code,ORNL) or NMTC (Neutron Meson Transport Code).

Several research institutes upgraded two of the above mentioned codes and tailored the combination to their own requirements. Brookhaven National Laboratory is for example using BNLF,a modified combination of NMTC and MORSE. A similar combination is used by JAERI and the KFA Julich. In the Rutherford Laboratory Atchison used experimentally adjusted parameters for the fission process and put this fission model into HETC. At LANL Prael developed a code system by combining an upgraded HETC with MCNP and called it LAHET. In LAHET the geometry transport capability is that of the Monte Carlo Neutron and Photon transport code MCNP. LAHET includes two models for fission induced by high energy interactions : the ORNL model and Rutherford Appleton Laboratory model. HETC treats all interactions by protons, pions and muons, but neutron interactions only above the cut-off energy of 20 MeV.

F. Atchison reviewed in detail "Data and Methods for the Design of Accelerator Based Transmutation Systems" [24].

6.3 Used Calculational Methods for Proposed Concepts

At the CEA, in the case of LWRs, nuclear data used is JEF. Neutronic calculation is made by two dimensional transport code APOLLO with 99 group cross-sections generated from JEF. The code is a modular one which solves the multigroup transport equation by the collision probability method,and a multicell approximation is available for 2D geometries. Burnup calculation is made by the

three dimensional diffusion code CRONOS which allows pin by pin core calculations.

In the case of fast reactor,standard isotopes cross sections are provided from CARNAVAL. Minor actinides data are provided from JEF and added to the standard isotopes cross-sections. Neutronic calculations are made by two dimensional diffusion code ERANOS with 25 group cross sections mentioned above. Burnup is calculated also by ERANOS.

AT the JAERI, nuclear data library JENDL-3 is commonly used for transmutation studies. In the case of LWR, neutronic calculation is made by the two dimensional diffusion option of the modular code system SRAC with 107 group cross-sections generated from JENDL-3. However ,resonance absorptions are calculated accurately by the ultra-fine group method. Burnup calculation is carried out by zero-dimensional burnup option of SRAC, where FP chain treats explicitly important 65 fission product nuclides.

In the case of fast reactors including burner reactors, neutronic calculations are carried out by the two dimensional diffusion option of the code system ABC-S or SRAC/COREBN, with 70 group cross-sections generated from JENDL-3. Burnup is calculated with burnup option of the above mentioned code systems.

In the case of accelerator-driven system,nuclear data source comes from JENDL-3 or ENDFB/5. High and medium energy reaction calculations are performed by NMTC/JAERI. Neutronic calculations are made by TWOTRAN-2 with 30 group cross-sections. Burnup is calculated by COMRAD of which flow chart is given in Fig.5.1.

The three Japanese organizations described below propose their LMFBR based transmutation systems.

At the PNC, neutronic and burnup calculations are carried out by the two dimensional diffusion code CITATION-FBR (a modified version of original CITATION) with 18 group cross sections generated from JENDL-2.

At the CRIEPI, standard isotopes cross-sections are provided from JFS 70 group cross-sections set and minor actinides cross sections are generated from JENDL-2 or ENDFB/5. Neutronic and burnup calculations are carried out by two dimensional diffusion code CITATION-TRU with 70 or 18 group cross-sections. The code is a modified version of CITATION which can easily calculate complex minor actinide nuclides burnup/decay chain.

At the Toshiba Corporation, JFS 70 group cross-sections set is used for standard isotopes and minor actinides cross-sections are generated from JENDL-3. Neutronics are calculated with 70 group two dimensional or 7 group three dimensional diffusion code. Burnup calculations are based on two dimensional code.

The research organizations described below propose their accelerator-driven transmutation systems.

At the BNL, Nuclear data source is ENDFB/4. High and medium energy reaction calculations are carried out by LAHET and NMTC/BNL. In the latter, a fission model based on the Fong's statisti-

cal model is adopted into the NMTC code. Neutronic calculations are performed by the continuous energy Monte Carlo code MCNPH. Burnup calculations are based on the ORIGEN-2 code with associated cross-sections.

At the ENEA, nuclear data source is JEF or ENDFB/5. High and medium energy reactions are performed by NMTC/JAERI and HETC/KFA2 codes. Neutronics are calculated with the Monte Carlo code MCNP-4 and burnup is calculated by the ORIGEN-1 and 2 codes.

At the Royal Institute of Technology, nuclear data source is ENDFB/5 or 6. High and medium energy reaction calculations are made by the LAHET code. Neutronic and burnup calculations are carried out by MCNP-4 and ORIGEN-2,respectively.

At the ITEP, nuclear data is ENDFB/6. Neutronic and burnup calculations are performed by a two dimensional transport code with 26 group cross-sections and the three dimensional TRIFOB code,respectively.

7. INTEGRAL EXPERIMENTS

7.1 Thermal Reactors

Extensive integral experiments on minor actinides have been carried out and are planned especially in France. As for LWR,as a part of the SHERWOOD program,irradiation experiments were carried out by irradiating UO2 pins doped with minor actinides at center the material testing reactor MELUSINE. The capture reaction rates were measured for Am-241,Am-243, and Cm-244. During R&D on high conversion light water reactor, the ICARE program and the ERASME program were performed. In the ICARE program,two experimental UO2 pins doped with minor actinides were irradiated at the center of 261 pin lattice of MOX fuel in the MELUCINE. The ERASME program was performed in the critical facility EOLE at Cadarache.

In the framework of the SPIN program, the ACINEAU experiment is planned to take place in the OSIRIS at Saclay at the end of 1994. The purpose is to assess the feasibility of transmutation of Np and Am in water reactors, to study the metallurgical behaviour of fuels and targets and the thermomechanical behaviour of the rods with a view of their subsequent optimization, and to compare the efficiency of actinide burning in a thermal flux with that in a fast flux.

7.2 Fast Reactors

Many integral experiments at fast reactors on minor actinides were carried out in several countries.

In the united state of America, irradiation experiment was performed at the experimental fast reactor EBR-II to measure the capture and fission rates of Np-237 together with major actinides. In the Fast Flux Test Facility (FFTF), transmutation of Tc-99 was measured using moderated assemblies at the periphery of the FFTF. Under the collaboration with the UKAEA, extensive irradiation experiments were carried out at the UK prototype fast reactor PFR. Irradiated minor actinides are Np-237,Pu-238,Pu-242, Pu-244,Am-241,Am-243,Cm-243,Cm-244 and higher Cm.

In France,PROFIL,TRAPU and SUPERFACT programs were performed in the French prototype fast reactor PHENIX. In the PROFIL program, separate isotope samples were irradiated,which included Np-237,Am-241,Am-243, Cm-244. In the TRAPU experiment, special fuel pins were irradiated and analyzed to identify the detailed isotope composition in the irradiated pins. The SUPERFACT program has allowed to conclude on the feasibility of transmutation of Np homogeneous fuels (in the range of 2% to 45%) and its extension to higher burnup (> 10 a%) is under way. In the fast critical assembly MASURUCA,physics experiments have been carried out, such as fission chamber measurement and reactivity measurement. The BALZAC experiment measured the reactivity/atom of minor Pu and Am-241. Basing on the experiences of the SUPERFACT,a irradiation experiment of many pins with 2 % Np is planned to start in 1994 in the SUPERPHENIX.

In Japan,at the JAERI, a series of integral experiments were performed at the critical assembly FCA, to measure fission rate and sample reactivity of minor actinides, such as Np-237, Pu-238, Am-241 and Am-243. The measurements were made in the wide range

of neutron spectrum fields. Under the collaboration with the ORNL in the USA, the minor actinide samples irradiated at the PFR mentioned above were sent to the JAERI and are being analysed to verify the JENDL cross sections. At the PNC, reaction rate measurement of Np has been made at the pulse reactor YAYOI,and transmutation rate measurement and irradiation test of minor actinide containing pins are planned at the experimental fast reactor JOYO. The CRIEPI has proceeded nuclear data verification test at the KNK-II reactor under the collaboration with the TUI and KfK.

7.3 Accelerator-Driven Systems

S.Cierjacks overviewed the present status of integral validation experiments related to neutron and proton production ,and spallation and fission products [25].

(1) Experiments planned in the United State of America

An apparatus is built to generate the nuclides under conditions simulating a spallation neutron production,which is used at one of the beam lines of the Brookhaven National Laboratory's Alternate Gradient Synchrotron. Target material used is lead or tungsten and proton fluence is determined by an aluminum foil. The lead or tungsten foils are irradiated to energies in the range of interest,about 1 GeV, and assayed for their gamma spectra, using germanium diode gamma detectors. The spectra are then analyzed for the quantities presence of the respective nuclides as a function of time after the end of irradiation.

The afterheat develops in target material due to formation of radionuclides during proton-bombardment spallation process. It is experimentally determined by directly evaluating the heat produced by the spallation-induced radioactivity using a novel type of calorimeter. The first experiments made use of the BNL Linac Isotope Producer with 0.2 GeV proton energy impinging on lead target.

An experimental study has been conducted at Texas A & M University to compare measured and calculated spallation product yields from a lead target. A special spallation product, decay gamma library.was constructed and incorporated into the standard GENIE gamma-ray peak and nuclide identification software. A total of 11 different nuclides in nine mass chains were identified from the multichannel counting spectra. Additional experiments employing copper,gold and thorium targets are planned.

In order to resolve the difference between the code prediction and existing experimental data relating to the n/p parameter ,a related experiment is made by creating a configuration that is simple enough from a material and geometric standpoint.

The experiment uses the BNL's Alternate Gradient Syncrotron. Momentum-analyzed protons in the giga-electron-volt range will pass through two "paddle" detectors,further defining their energy by time of flight and arranged to produce a coincidence for each proton of the correct energy passing through to a lead or tungsten target located within a neutron detector. This detector is a cylindrical (CH2) moderator pierced by He-3 proportional counters arranged concentrically with the cylinder axis.

(2) Experiments planned in Japan

Spallation integral experiments are underway in order to obtain data on nuclide production ,to estimate the yield of neutrons and spallation products, and to investigate the validity of the spallation simulation code NMTC/JAERI. The 500 MeV booster proton syncrotron facility at the National Laboratory of High Energy Physics (KEK) is used for the experiments. Target materials used so far are lead and tungsten. Experiment with a target of depleted uranium is also planned. The number of induced reactions in the activation samples were measured. The measured results agree fairly well with the prediction by NMTC/JAERI.

(3) Experiments planned in Switzerland

The experiment ATHENA is in progress at the Paul Scherrer Institute, which is aimed at solving some specific data and methods problems relating to the accelerator-based transmutation of actinides. In a first phase,thin samples of actinides are irradiated with 590 MeV protons from the PSI ring accelerator. The generated spallation and fission products are analyzed and are compared with theoretical predictions. The principal motivation is to confirm the high potential of the high-energy fission reactions for transmutation. In a second phase, it is proposed to study relating to multiplying target-blanket assemblies.

8. CONCLUSIONS AND RECOMMENDATIONS

The main purpose of phase-I of this program is to have common understandings in the member countries for the announced transmutation devices,their physics performances and their related fuel cycle consideration. To this end the task force has examine more than 20 different concepts of transmutation and has collected the results of the calculation of transmutation rate of each concept.

The transmutation concepts which the task force has examined are listed below;

1) Thermal Reactor based concepts
   - PWR based systems with homogeneous and heterogeneous arrangements of minor actinides,contributed from the CEA,
   - PWR based system,contributed from the JAERI,and
   - High flux PBR based system proposed by the BNL,taken from the open literature.

2) Fast Reactor based concepts
   - MOX fueled systems with homogeneous and heterogeneous arrangements of minor actinides,contributed from the CEA,
   - MOX fueled system,contributed from the PNC,
   - Metal fueled system,contributed from the CRIEPI,
   - Metal fueled system with flat core,contributed from the Toshiba Corporation,
   - Two types of minor actinides burner system,contributed

from the JAERI,

- Th loaded system,contributed from the JAERI,and
- ALMR actinide recycling system proposed by the GE and ANL, taken from the open literature.

3) Accelerator based concepts

- Two types of system consisting of fast subcritical core and small accelerator,contributed from the BNL,
- Three types of system consisting of fast subcritical core and relatively large accelerator,contributed from JAERI,
- Los Alamos ATW system,taken from the open literature,
- PHOENIX system proposed by the BNL,taken from the open literature,
- Three types of Tc-99 incineration system,contributed from the CEA,and
- ATW-type systems,contributed from the ENEA,Royal Institute of Technology and ITEP.

Based on the comparison of the results of the calculation of transmutation rate of each concept, there seem to be significant discrepancies between the concepts. As for reactor based system, for example, there is a significant difference of Cm-244 burnup characteristics among fast reactor based systems, although it might depends not only cross-section itself,but also neutron flux and initial isotopic vector of minor actinides. And there is only one calculated result of mass balance of minor actinides between BOEC and EOEC of accelerator based systems, this might be partly due to some difficulties of taking account of high energy neutron

above 20 MeV into burnup calculation. Therefore, it is felt that further investigation by benchmarks for a set of common system on calculation methods of transmutation rate should be beneficial in order to understand and assess their physics performances precisely.

In addition to that, the task force members have suggested that the following fundamental issues should be resolved in terms of scientific aspects of transmutation concepts,such as:

- radiotoxicity after transmutation
- safety features of transmutation system
- nuclear data of transuranium nuclides

A further discussion should be held to analyze discrepancies and uncertainties lying in the above scientific issues. Also it has been suggested that the above issues are too broad to be reviewed thoroughly within the present small task force. Therefore,as a starting point of phase II of the program, a specialist meeting is proposed with a view to identifying subjects to be handled by the NSC with respect to the above issues.

PREFERENCES

[1] J.Y.Barre,J.Bouchard: French R&D Strategy for the Bach End of the Fuel Cycle, Proceedings of International Conference and Technology Exhibition on Future Nuclear System;Emerging Fuel Cycles & Waste Disposal Options,GLOBAL'93,P27-32, Seattle,Washington, September 12-17,1993.

[2] Japan's Atomic Energy Commission; Long-term Research and Development on Partitioning and Transmutation Technology in Japan,October,1988.

[3] M.L.Thompson,J.E.Quinn: The ALMR System's Missions for Transmuting Waste into Energy,Proceedings of International Conference and Technology Exhibition on Future Nuclear System;Emerging Fuel Cycles & Waste Disposal Options GLOBAL'93,P110-117,Seattle,Washington,September 12-17,1993.

[4] E.D.Arthur,H.J.Dewey: The Los Alamos Accelerator Transmutation of Nuclear Waste (ATW) Concept,LANL-USA,Presented at the Symposium on Separation Technology and Transmutation Systems (STATS),Washington D.C.,January 13-14,1992.

[5] G.J.Van Tuyle et al.: Accelerator-Driven Subcritical Target Concept for Transmutation of Nuclear Wastes,Nuclear Tech nology,Vol.101,P1-17,January 1993.

[6] J.Powell et al.: High Flux Particle Bed Reactor Systems for Rapid Transmutation of Actinides and Long Lived Fission Products,Proceedings of International Conference and Technology Exhibition on Future Nuclear System;Emerging Fuel Cycles & Waste Disposal Options,GLOBAL'93,P1300-1305,Seattle,Washington,September12-17,1993.

[7] H.Takahashi: The Use of Minor Actinides and a Small Proton Accelerator for Fast Reactor with a High Breeding Gain, Proceedings of the Specialists' Meeting on Accelerator-Based Transmutation,P65-82,PSI Villigen,March 24-26,1992.

[8] P.A.Landeyro: Contribution from the ENEA in Italy to the Task Force Request.

[9] M.Kawashima: Contribution from the Toshiba Corporation in Japan to the Task Force Request.

[10] W.Gudowski: Contribution from the Royal Institute of Technology in Sweden to the Task Force Request.

[11] V.S.Kagramanian: Contribution from the Institute of Physics and Power Engineering (IPPE) in Russia to the Task Force Request.

[12] G.V.Kiselev: Contribution from the Institute of Theoretical and Experimental Physics (ITEP) to the Task Force Request.

[13] J.A.Rawlins et al.: CURE: Clean Use of Reactor Energy, WHC-EP-0268,May 1990.

[14] A.Zaetta: Contribution from the CEA in France to the Task Force Request.

[15] H.Takano: Contribution from the JAERI in Japan to the Task Force Request.

[16] T.Wakabayashi: Contribution from the PNC in Japan to the Task Force Request.

[17] C.L.Cockey et al.: Higher Actinide Transmutation in the ALMR Proceedings of International Conference and Technology Exhibition on Future Nuclear Systems;Emerging Fuel Cycles & Waste Disposal Option,GLOBAL'93,P123-135,Seattle,Washington, September 12-17,1993.

[18] T.Matsumura: Contribution from the CRIEPI in Japan to the Task Force Request.

[19] T.Mukaiyama: Contribution from the JAERI in Japan to the Task Force Request.

[20] T.Takizuka,T,Nishida,T.Sasa: Contribution from the JAERI in Japan to the Task Force Request.

[21] H.Takahashi: Contribution from the BNL in the US to the Task Force Request.

[22] M.Cappiello et al.: Target/Blanket Conceptual Design for the Los Alamos ATW Concept,Proceedings of the Specialists' Meeting on Accelerator-Based Transmutation,PSI Villigen,March 24-26,1992.

[23] C.Bowman et al.: Nuclear Energy Generation and Waste Transmutation Using an Accelerator-Driven Intense Thermal Neutron Source,LA-UR-91-91-2601,LANL,(1991).

[24] F.Atchison: Data and Methods for the Design of Accelerator-Based Transmutation Systems,Proceedings of the Specialists' Meeting on Accelerator-Based Transmutation,P440-498,PSI Villigen,March 24-26,1992.

[25] S.Cierjacks: Cross Section Measurements,Integral Validation Experiments and Nuclear-Model Code Developments of Importance to Accelerator-Based Transmutation,Proceedings of the Specialists' Meeting on Accelerator-Based Transmutation, P556-567,Villigen,March 24-26,1992.

APPENDIX

FORM-A

INFORMATION ON TRANSMUTATION DEVICES AND THEIR PHYSICS PARAMETERS

Name :

Affiliation :

Address :

Tel : Fax ::

I. General

(1) Selected nuclides to be transmuted in your transmutation device:

(2) Principal design consideration in your design work, such as transmutation capability, conservative design, small change from original core performance, safety consideration and so on:

(3) Type of transmutation devices, reactor or accelerator-driven device:

☐ reactor ☐ accelerator-driven device

If you give x for reactor, go to Section II in page 2, and if you give x for accelerator driven device, go to Section III in page 8.

II. Nuclear Reactor used for transmutation

We provide the information form for uraium-plutonium cycle based nuclear reactor here. Then,if you work for thorium-uranium based reactor,please kindly provide similar form.

(1) Description of nuclear reactor:

1) Type of reactor:

☐ PWR ☐ BWR ☐ Gas-cooled reactor ☐ Heavy water-moderated reactor
☐ LMFBR ☐ Liquid metal-cooled reactor ☐ Others

If you select Others or there is fairly large difference between your proposing reactor and its original reactor listed above,please give its brief description or illustration here or another white sheet.

2) Thermal and electric powers:

· Thermal power :_____MWt
· Electric power:_____MWe

3) Core dimension:

· Equivalent core diameter:_____cm
· Equivalent core hight :_____cm

4) Fuel arrangement regarding transmutation materials:

☐ Homogeneous arrangement ☐ Heterogeneous arrangement

In the case of Heterogeneous arrangement,

· Volume ratio of fuels with trannsmutation materials to all fuels:_____%

5) Type of fuels:

☐ Oxide fuel ☐ Nitride fuel ☐ Carbide fuel ☐ Metallic fuel

6) Core averaged fresh fuel composition (wt%):

· U : Pu : Np,Am,Cm : long-lived FP =_____:_____:_____:_____

7) Isotopic composition (wt%) of Pu,Minor Actinide(Np,Am.Cm) and long-lived FP:

· Pu

Pu-238	Pu-239	Pu-240	Pu-241	Pu-242

· Minor Actinide (Np,Am,Cm)

Np-237	Am-241	Am-242	Am-243	Cm-243	Cm-244

Long-lived fission products (ex.Tc,I etc.)

Please add isotopes of long-lived FP,if necessary.

8) Averaged core composition (vol%):

Fuel	Clad+Structure	Coolant	Moderator*

*:for gas-cooled reactor,heavy water-moderated reactor,etc.

(2) General physics parameters and transmutation capability:

1) Principal core characteristics:

Items	BOL[1]	BOEC[2]
Thermal power in core (MWt)		
Power density : averaged in core (w/cm^3)		
maximum in core (w/cm^3)		
Linear heat rate : avaraged (w/cm)		
maximum (w/cm)		
Neutron flux averaged in core ($n/cm^2 \cdot sec$)		
Neutron energy averaged in core (KeV)		
Fuel dwelling time in core (EFPD)*		
Burnup reactivity swing (%δk/k/365EFPD)		

*:Equivalent Full Power Days, 1) Beginning of life, 2) Beginning of Equilibrium cycle

2) Inventory and transmutation capability:

· Fuel and transmutation material inventory and their mass balance:

Nuclides	Initial inventory (kg)	Mass balance in EOC (unit:kg)		
		BOEC[1] mass	EOEC[2] mass	EOEC-BOEC
Uranium				
U-235				
U-236				
U-238				
Plutonium				
Pu-238				
Pu-239				
Pu-240				
Pu-241				
Pu-242				
Neptunium				
Np-237				
Amerisium				
Am-241				
Am-242m				
Am-243				
Curium				
Cm-242				
Cm-243				
Cm-244				
Cm-245				
Higher actinides				
Long-lived FP				

1):Beginning Of Equilibrium Cycle, 2):End Of Equilibrium Cycle.
Please add isotopes of long-lived FP for transmutation,if necessary.

· Transmutation capability

$$\text{Transmutation capability} = \frac{\text{Difference of minor actinides between EOEC and BOEC}}{\text{(EFPY*between EOEC and BOEC) x thermal power(MWt)}}$$

$$= \underline{\qquad\qquad} \text{ kg/MWt·EFPY}$$

*:Equivalent Full Power Year.

(3) Safety-related physics parameters:

Please fill the table with the values at BOL.

Parameters	Values
Coolant void reactivity effect (%δk/k)	
- All reactor region voided	
- Core and axial blanket voided*	
- Only core voided*	
Doppler reactivity coefficient* (Tdk/dT)	
Effective delayed neutron fraction*	
Prompt neutron life time* (sec)	
Contol rod material	
Central control rod worth (%δk/k/kg)	

*:only for fast reactors.

(4) Data and method used in reactor design work:

1) Nuclear data:

· Nuclear data source library or group cross-section library:

☐ ENDF/B- ☐ JEF ☐ JENDL- ☐ Others

☐ ORIGEN- ☐ WIMS ☐ JFS ☐ CARNAVAL- ☐ Others

If you select Others or there are any significant modefications for the original library on minor actinides and long-lived FP isotopes, please give their brief description.

2) Calculation method:

· Neutronic calculation code:

Name of code : ☐ Diffusion ☐ Transport
☐ 2D ☐ 3D

Number of energy group used for calculation:

If there are any significant differences between your code and usually used code,please give their brief description.

· Burnup calculation code:

Name of code: ☐ 0D ☐ 1D ☐ 2D ☐ 3D

If there are any significant differences in calculation model and/or burnup chain model of minor actinide and long-lived FP isotopes, please give their brief description.

(5) Integral experiment related to transmutation:

1) Irradiation experiments in power reactor:

· Name of facility:

☐ Fast reactor
☐ Thermal reactor

· Irradiated minor actinide and long-lived FP isotopes:

· Purpose of experiment:

☐ Nuclear data verification
☐ Transmutation rate measurement
☐ Others

If you select Others, please give a brief description.

2) Experiment in critical assembly and research reactor:

· Name of facility:

☐ Fast neutron field
☐ Thermal neutron field

· Measured minor actinide and long-lived FP isotopes:

· Kind of measurements:

☐ Reaction rate ratio
☐ Sample reactivity worth
☐ Others

If you select Others, please give a brief description.

3) Future programme, if you have:

Thank you for your hearty cooperation !!

Ⅲ. Accelerator-driven Devices used for transmutation

We provide the information form for uranium-plutonium cycle based nuclear rectors here. Then,if you work for thorium-uranium based reactors,please kindly provide similar form.

(1) Description of Accelerator driven devices:

1) Type of Accelerator:

☐ Proton LINAC ☐ Electron LINAC ☐ Others

If you select Others,please give its brief description or illustration here or another white sheet.

2) Particle's energy and current:

· Particle :_____
· Energy :_____ MeV
· Current :_____ mA

3) Type of device:

☐ Subcritical core ☐ Sucritical core wtih target* ☐ Others
*: specific spallation target,such as Pb and W.

If you select Others,please give its brief description or ilustration here or another white sheet

4) Neutron spectrum in device:

☐ Fast ☐ Thermal ☐ Others

5) Thermal and electric powers :

· Thermal power :_____ MWt
· Electric power :_____ MWe

6) Target and/or subcritical core dimension, and subcriticality:

· Equivalent target
diameter : _____ cm and height : _____ cm

· Equivalent subcritical core
diameter : _____ cm and height : _____ cm

· Effective neutron multiplication factor : _____

7) Fuel arrangement in subcritical core:

☐ Homogeneous arrangemnet ☐ Heterogeneous arrangement

In the case of Heterogeneous arrangement,

· Volume ratio of fuels with transmutation materials to all fuels: _____ %

8) Type of fuels :

☐ Metallic fuel ☐ Molten salt or slurry fuel ☐ Oxide fuel
☐ Nitride fuel ☐ Carbide fuel ☐ Others

If you select Others,please give brief description.

9) Core avearged fresh fuel composition (wt%) :

· U : Pu : Np,Am,Cm : long-lived FP = _____ : _____ : _____ : _____

10) Isotopic composition (wt%) of Pu, minor actinide(Np,Am,Cm) and long-lived FP:

· Pu

Pu-238	Pu-239	Pu-240	Pu-241	Pu-242

· Minor actinide (Np,Am,Cm)

Np-237	Am-241	Am-242	Am-243	Cm-243	Cm-244

· long-lived fission products (ex.Tc,I etc.)

Tc-99	I-129	Sr-90	Cs-137		

11) Materials and Averged composition in subcritical core:

	Fuel	Clad+Structure	Coolant	Moderator
Materials	---	---		
Ave.composition (vol%)				

12) Type of target

· Target materials and its cooling materials

(2) General physics parameters and transmutation capability

1) Principal core & target characteristics :

Items	BOL[1)]	BOEC[2)]
Thermal power in core (MWt) Power density : averaged in core (w/cm^3) maximum in core (w/cm^3) Linear heat rate : averaged (w/cm) maximum (w/cm) Neutron flux averaged in core ($n/cm^2 \cdot sec$) Neutron energy averaged in core (keV) Fuel dwelling time in core (EFPD)* Target dwelling time in core (EFPD)* Burnup reactivity swing (%δk/k/365EFPD)		

*:Equivalent Full Power Day, 1) Beginning of life, 2) Beginning of equilibrium cycle

2) Inventory and transmutation capability:

· Fuel and transmutation material inventory and their mass balance:

Nucides	Initial inventory (kg)	Mass balance in BOC (unit : kg)		
		BOEC[1] mass	EOEC[2] mass	EOEC-BOEC
Uranium				
U-235				
U-236				
U-238				
Plutonium				
Pu-238				
Pu-239				
Pu-240				
Pu-241				
Pu-242				
Neptunium				
Np-237				
Amerisium				
Am-241				
Am-242m				
Am-243				
Curium				
Cm-242				
Cm-243				
Cm-244				
Cm-245				
Higher Actinides				
Long-lived FPs				

1) Beginning Of Equilibrium Cycle, 2) End Of Equilibrium Cycle.
Please add isotopes of long-lived FP for transmutation, if necessary.

· Transmutation capability :

$$\text{Transmutation capability} = \frac{\text{Difference of minor actinides between EOEC and BOEC}}{(\text{EFPY*between EOEC and BOEC}) \times \text{thermal power(MWt)}}$$

$$= \underline{\qquad\qquad} \text{ kg/MWt·EFPY}$$

*:Equivalent Full Power Year.

(3) Safety-related physics parameters:

Please fill the table with the values at BOL.

Parameters	Values
Coolant void reactivity effect (%δk/k)	
- All device region voided	
- Core and target voided	
- Only core voided	
Doppler reactivity coefficient (%Tdk/dT)	
Effective delayed neutron fraction	
Beam switching off time (sec)	
Beam equivalent worth (%δk/k/MW)	
Particle beam alignement	

(4) Data and method used in the device design work:

1) Nuclear data:

· Nuclear data source library or group cross-section library :

☐ ENDF/B-____ ☐ JEF ☐ JENDL-____ ☐ HILO ☐ Others

☐ ORIGEN-____ ☐ WINS ☐ JFS ☐ CARNAVAL-____ ☐ Others

If you select Others or there are any significant modifications for the original library on minor actinides and long-lived FP isotopes, please give their brief description.

2) Calculation method:

· Neutronic calculation code:

Name of code: _____ ☐ Diffusion ☐ Transport
☐ 2D ☐ 3D

Number of energy group used for calculation: _____

· High and medium energy reactions calculation code:

☐ NMTC/JAERI ☐ LAHET ☐ HETC/KFA2 ☐ Others

If there are any significant differences between your code and usually used code, please give their brief description.

· Burnup calculation code :

Name of code: _____ ☐ 0D ☐ 1D ☐ 2D ☐ 3D

If there are any significant differences in calculational model and/or burnup chain model of minor actinides and long-lived FP isotopes, please give their brief description.

(5) Integral experiments related to transmutation:

1) Spallation integral experiment:

· Name of accelerator facility: _____

- Irradiated minor actinide and target material isotopes:

- Purpose of experiments:
  - ☐ Measurement of nuclear data in the high energy region
  - ☐ Verification of spallation codes
  - ☐ Reaction rate, reaction products, particle energy spectrum, energy deposition
  - ☐ Others

If you select Others, please give their brief description.

2) Experiment using subcritical assembly:

- Name of facility: _____
  - ☐ Fast neutron field
  - ☐ Thermal neutron field

- Measured minor actinide and long-lived FP isotopes:

- Kind of measurements:
  - ☐ Reaction rate ratio
  - ☐ Others

If you select Others, please give their brief description.

3) Future programme, if you have:

Thank you for your hearty cooperation !!

FORM-B

INFORMATION ON TRANSMUTATION STRATEGIES

Name :

Affiliation :

Address :

Tel : Fax :

I. Objectives of your transmutation strategies,such as radiotoxicity reduction in the deep storage (source-term reduction),radiotoxicity reduction at the outcome in the biological sphere (long-term risk reduction), mass reduction in a straight forward way,and others.

☐ in your national programme ☐ in your organisation programme
☐ your own opinion

II. Your fuel cycle concept with transmutation and associated partitioning, including an illastration if possible.

III. Your opinion on overall effect of introducing partitioning and transmutation into the nuclear fuel cycle:

Thank you for your hearty cooperation !!

SUMMARY

The proposed nuclear reactor-based and accelerator-based transmutation concepts are summarized in this report, based on reply to the request of information on proposed concept to about 30 specialist working for transmutation in the United State of America, European countries, Russia and Japan. The task force reviews the concepts,and recommends followings;

(1) Benchmarks for a set of common transmutation system model on calculation methods,

(2) Effect of trasmutation rate on radiotoxicity reduction,

(3) Safety features of transmutation systems, and

(4) Nuclear data of transmutation nuclides.

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