Systems Study on Partitioning and Transmutation at JAERI

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Under the framework of Japanese OMEGA program, the Japan Atomic Energy Research Institute (JAERI) has studied P-T technologies aiming at a goal to provide a different HLW management from geological disposal. Technology of the proposed P-T system is based on the double stratum fuel cycle concept. The partitioning process has a potential capability to separate long-lived nuclides from HLW. The dedicated transmutation systems have a potential capability to burn minor actinides efficiently. Technology results so far obtained are sufficiently encouraging. P-T system requiments are discussed in view of risks due to P-T. The reduction of the risks demands a high transmutation rate, a high burnup and a low leakage factor.

1. INTRODUCTION

One of the most important problems with nuclear energy is the management of high-level radioactive waste (HLW) arising from the reprocessing of spent nuclear fuel. The hazard potential of actinides and fission products in the HLW is high due to their radioactivity. Of particular concern are the nuclides with very long half-life whose hazard remains high for millions of years. The major candidate scheme for the long-term waste management in most nuclear countries is the permanent disposal of unpartitioned HLW, or unreprocessed spent fuel, into a stable geological formation to isolate them from the human environment. There is, however, concern about the uncertainties in the long-term performance of an underground repository.

To mitigate the issues in the present waste management scheme, partitioning and transmutation (P-T) technology can play various roles according to the stages of advancement of the technology, such as a supporting technology by reduction of waste volume and heat generation, a complementary technology by mitigation of natural barrier uncertainty, and a new technology different from the geological disposal.

Under the framework of the long-term research and development program on P-T (OMEGA program) in Japan, the Japan Atomic Energy Research Institute (JAERI) has studied P-T technologies aiming at an ambitious goal to provide a different HLW management from geological disposal. The technologies include a partitioning process to separate HLW into four element groups together with minor-actinides group, and two different kinds of dedicated transmutation system; actinide burner fast reactor and proton accelerator-based transmutation system, both of which use fast neutrons and have comparable transmutation capabilities.

The proposed P-T system is based on the concept of double stratum fuel cycle, where the fuel cycle for partitioning and transmutation (P-T cycle) can be separated completely from the conventional commercial fuel cycle for power reactors. Technologies of the proposed P-T system are presented. The leakage of target nuclides in separation process and fabrication process has a very negative impact on the effectiveness of the P-T. The reduction of the overall leakage demands both a high burnup and a low leakage factor. Data needs and R&D issues to achieve the goal are discussed.

2. JAERI R&D ON PARTITIONING AND TRANSMUTATION UNDER THE OMEGA PROGRAM

JAERI is carrying out R&Ds for advanced partitioning technology, transmutation with burner fast reactor, and proton accelerator-based transmutation under the OMEGA program[1]. Aims of the program are to widen options of future waste management and to explore the possibility to utilize HLW as useful resources. The program is conceived as a research effort to pursue benefits for future generations through the long-term basic R&D, and is not to seek a short-term alternative for established or planned fuel cycle back-end policies.

An advanced partitioning process has been developed to separate elements in HLW into four groups; transuranium elements (TRU), Sr-Cs, Tc-platinum group metals and the other elements.

Conceptual design studies have been carried out for actinide burner fast reactors and accelerator-based transmutation systems. To support the design studies of these transmutation systems, several basic researches are in progress or planned. These include the nuclear data measurements of minor actinides, thermodynamic and thermophysical studies on minor-actinide compounds, spallation integral experiment, and thermal-hydraulic experiment.

Construction of a high-intensity proton linear accelerator with an energy of 1.5 GeV and an average beam current of 10 mA, named the Engineering Test Accelerator (ETA), has been proposed to perform various engineering experiments and demonstration tests for accelerator-based transmutation system. R&D work for the full-scale mockup of ETA front-end, called the Basic Technology Accelerator (BTA, 10 MeV-10 mA), is in progress.

3. DESCRIPTION OF TECHNOLOGY

3.1 Concept of Double Stratum Fuel Cycle

JAERI is aiming to develop an advanced partitioning process of TRUs and long-lived fission products from HLW and dedicated systems for their subsequent transmutation. The dedicated transmutation system is specially designed to burn minor actinides efficiently in a very hard neutron energy spectrum and high neutron flux. In this context, JAERI has been pursuing the concepts of accelerator-driven system and actinide burner reactor as dedicated transmuter, rather than the transmutation scenarios using commercial power reactor.

With the dedicated transmuter, the troublesome MA from the waste management view point could be confined in a P-T fuel cycle for transmutation, which forms the second stratum separated from the first one of conventional commercial fuel cycle for power generation. The concept of double-stratum fuel cycle is illustrated in Fig. 1. It could offer several advantages over the recycling of MA to the commercial power reactor. These are higher transmutation rate, effective confinement of MAs, and no impact on the power reactor operation. There will be no additional shielding and cooling requirements to the existing commercial fuel cycle facilities.

3.2 Four-Group Partitioning Process

An advanced partitioning process has been developed to separate elements in HLW from reprocessing of spent fuel into four groups (TRU, Tc-platinum group metals, Sr-Cs, and the others)[2]. The flow sheet of the four-group partitioning process is shown in Fig. 2.

In this process, Am and Cm are extracted with the solvent diisodecylphosphric acid (DIDPA), and Np is extracted with addition of hydrogen peroxide. The DIDPA solvent is also be applied to the separation of Am and Cm from rare earths. The separation of Tc is made by adsorption with an active carbon column. Tc is adsorbed from HLW adjusted to 0.5 M nitric acid concentration and adsorbed Tc is eluted from the column by using alkaline potassium thiocyanate solution (2M KSCN-4M NaOH) as eluant. Sr and Cs are separated by adsorption with the inorganic ion exchangers of zeolite and titanic acid. Iodine will be recovered from the reprocessing offgas by adequate sorption methods.

3.3 Transmutation Systems

(1) Accelerator-based Transmutation System

Two types of accelerator-based transmutation system concept have been proposed; solid system and molten-salt system. In either system, a minor-actinide loaded subcritical core is driven by a high-intensity proton linear accelerator and uses fast neutrons to burn actinides efficiently.

The conceptual design of the solid target/core system [5] is shown in Fig. 3. The design of the solid system is based on the status of Na-cooled fast reactor technology. The fuel is actinide alloy or nitride clad in ODS steel. A high-energy proton beam is injected through beam window into the spallation target at the center of the core. The target consists of multi-layers of solid tungsten, which is designed to maximize the number of emitted neutrons and to flatten the axial neutron flux distribution. The heat generated in the target and core is removed by Na flow, and is recovered by a steam turbine plant into electricity. The solid system, having an actinide inventory of 3160 kg and an effective neutron multiplication factor of 0.89, produces 820-MWt thermal power with a 1.5 GeV-39 mA proton beam.

Another innovative option is the molten-salt target/core system [4]. Chloride salt ($64NaCl\text{-}5PuCl_3\text{-}31MACl_3$) is used both for fuel and for target material, and at the same time it also serves as primary coolant. This significantly simplifies the target/core configuration, as schematically shown in Fig. 4. A proton beam is injected into the central target/core region through the beam window. Intermediate heat exchangers and salt pumps are installed in the annular region around the internal reflector that surrounds the target/core region. This in-vessel heat exchanger design minimizes the total actinide inventory in the system. The molten state of the fuel salt offers the possibility of continuous on-line processing of actinides and reaction products.

The molten-salt system has an actinide inventory of 5430 kg and an effective neutron multiplication factor of 0.92, and produces 800-MWt thermal power with a 1.5 GeV-25 mA proton beam.

(2) Actinide Burner Reactor

The guidelines for designing an actinide burner reactor (ABR) as a dedicated transmuter are; minor actinide as the major fuel constituent, very hard neutron spectrum, very high neutron flux, and dry reprocessing of actinide fuel.

Two types of ABR concept were previously proposed [5], namely Na-cooled metallic fuel ABR and He-cooled particle-bed ABR. Design modification has been attempted to improve the safety characteristics [6]. To increase the effective delayed neutron fraction, Pu in the fuel is replaced with enriched U (90% enrichment). To avoid the large positive void coefficient for Na cooling, liquid Pb is used as coolant instead of Na. Also, metallic fuel is replaced with nitride fuel because of relatively low melting point and low thermal conductivity of metallic minor-actinide fuel.

The Pb-cooled ABR (L-ABR) has ductless, pin-bundle type fuel assemblies (Fig. 5). The plant will be consist of six reactor modules, each having a thermal power of 180 MWt and a minor-actinide inventory of 573 kg.

The He-cooled particle-bed ABR (P-ABR) has fuel elements of particle bed formed in the annular space of concentric porous frits (Fig. 6). Fuel particles are directly cooled with He gas. Very high power density is obtained since a large heat transfer surface per volume is very effective for heat removal. A fuel particle consists of actinide nitride microsphere and thin TiN coating layers. P-ABR has a thermal power of 1200 MWt and a minor-actinide inventory of 1865 kg.

3.4 Actinide Fuel Fabrication and Reprocessing

For a dedicated actinide transmuter, a fuel form with a high heavy-metal atom density is desirable in view of the neutron spectrum and the fuel cycle efficiency. One of the promising candidate fuels is the mixed mononitride: (U, Np, Pu, Am, Cm)N. The mutual solubility of the actinide mononitrides is expected to be sufficiently high since they have the same NaCl-type structure with lattice parameters which are close to each other. Fabrication process of the nitrides may follow that of UN and PuN. Figure 7 shows a proposed fuel cycle scheme of the TRU nitride fuel.

The nitrates of the minor actinides (MA) recovered in the partitioning of HLW could be readily converted to solid micorspheres consisting of the actinide oxides and carbon with a sol-gel process. In a sol-gel process being studied at JAERI, an ammonia donor, hexamethylenetetramine (HMTA), is added to the nitrate solution. By heating the liquid droplets, HMTA decomposes to form ammonia which causes gelling of the droplets. The solid microsphere is then converted to the nitride by the carbothermic reduction. The technique to fabricate the nitrides of transplutonium elements by the carbothermic reduction would be similar to those for UN and PuN, since the Gibbs free energy of formation is estimated to be roughly the same [7].

For reprocessing the irradiated MA nitride fuel, a pyrochemical process with the molten-salt electrorefining could be applied [8]. The procedure would be very similar to that of the molten-salt electrorefining

of alloy fuels, which has been developed at Argonne National Laboratory[9]: the fuel is anodically dissolved into a molten LiCl-KCl salt, and the actinide metals are recovered on either solid cathode or liquid-Cd cathode. The liquid-Cd cathode will be used for recovering the TRU elements.

4. TECHNOLOGY RESULTS

4.1 Partitioning

The four-group partitioning process have been developed through laboratory-scaled experiments since 1985. In the mixer-settler experiments with the actual HLW, it was demonstrated that more than 99.99% of Am and Cm were recovered with the extractant DIDPA. It was also verified that more than 99.95% of Np was extracted in a series of experiments with the synthesized HLW. The separation of Tc was demonstrated with a high recovery over 99% in the tests with synthesized HLW.

These experiments with actual or synthesized HLW indicate that the proposed partitioning process has great promise of realizing the target separation efficiencies for the important elements in HLW without undue difficulty. The partitioning process will be tested with actual HLW at the Nuclear Fuel Cycle Safety Engineering Research Facility (NUCEF) that was constructed at JAERI Tokai, and will come into hot operation in 1995. The chemical engineering test mainly with a simulated HLW is also planed to start in 1996. Fundamental data for designing a partitioning pilot plant will be accumulated consistently until about 2000.

4.2 Transmutation

The proposed accelerator-based transmutation systems have hard neutron spectra with core averaged neutron energies around 700 keV. The core averaged neutron flux is 4×10^{15} n/cm^2/s for the solid system and 5.9×10^{15} n/cm^2/s for the molten-salt system. The actinide burnups per 1 GWt per year in the solid system and molten-salt system are 360 kg (10 %/y) and 370 kg (6 %/y), respectively. The solid and molten-salt systems produce 246-MWe and 360-MWe electricity, respectively. The system can provide enough electricity to drive its own accelerator.

As the first step toward the intense proton accelerator development, the four main accelerator components, ion source, radio-frequency quadrupole (RFQ), drift-tube linac (DTL) and radio-frequency (RF) source, have been developed[10]. The beam acceleration test with the ion source and RFQ was made successfully at a beam current of 52 mA (peak) and 5% duty. High power tests of the DTL hot-test model began in 1994. As the next development step, the design work for the BTA is in progress.

Significantly hard neutron spectra are achieved for the proposed ABRs, core averaged mean neutron energies being around 700 keV. The core averaged neutron flux is 3.1×10^{15} n cm^2/s for the lead-cooled ABR (L-ABR) and 5.9×10^{15} n/cm^2/s for the particle-bed ABR (P-ABR). The minor-actinide burnups per 1 GWt per year in the L-ABR and P-ABR are 190 kg and 200 kg, respectively. These values are decreased by 30 to 40% from those of the original ABR designs because of the contribution of U-235 fission. The minor-actinide burnup ratio is 11 %/cycle for the L-ABR with a cycle length of 550 days and 13 %/cycle for the P-ABR with a cycle length of 300 days.

4.3 Actinide Fuel Fabrication and Reprocessing

Studies on actinide fuel fabrication and reprocessing technology have been made. PuN and NpN have been successfully fabricated with a carbothermic reduction process, where the mixture of the oxide and carbon is heat-treated in flowing $N_2 + H_2$[11,12]. The study of the chemical vapor deposition of low-density TiN (buffer) coating for the nitride particle fuel is underway; initial attempts to deposit the low-density TiN on stationary substrates have been successfully made. The study on the sol-gel processing of the nitride fuel is also being made.

5. GOAL OF PARTITIONING AND TRANSMUTATION

Partitioning and transmutation technology can play various roles in HLW management depending on the stages of technology development. So, the goal of P-T will vary with P-T introduction timeframes of near term, mid-term, and long term. At present, technical feasibility of P-T is already established to reduce the volume and heat generation of HLW to some extent. In the near term, P-T technology could support the HLW

management in improving the safety of geological disposal through the reduction of the HLW volume and heat generation. In the mid-term, P-T can be a complementary technology by mitigation of concerns about natural barrier uncertaity, leading to further improvement in the long-term radiological safety assurance. The long-term goal of P-T is the most ambitios and challenging. The P-T technology can be a new waste management technology alternative to the geological disposal.

In the preliminary strategic study [13], priority of nuclides to be separated for transmutation was determined and target separation efficiencies were preliminarily defined for minor actinides and fission products in HLW.

Priority of nuclides, determined based on the half-lives and radioactive toxicity of nuclides in HLW, is as follows:

1; TRU nuclides including residual Pu
2; Tc-99 and I-129
3; Sr-90 and Cs-137
4; Zr-93, Cs-135 and Sm-151
5; long-lived activation products (C-14, Ni-59 etc.)

If neutron reaction is applied to transmute long-lived nuclides into shorter-lived or stable nuclides, TRU can be effectively transmuted to fission products by fission reaction, and Tc-99 and I-129 can be transmuted to stable nuclides by neutron capture reaction. However, it is rather difficult to transmute the other nuclides with lower priority by applying neutron reaction.

If potential radioactive toxicity should be balanced before and after reactor operation, the potential radioactive toxicity allowed for residual waste including long-lived nuclides should be equivalent to that of uranium ore. Target separation efficiencies were preliminarily defined for TRUs and fission products in HLW, comparing their radioactive toxicities with that of uranium ore. The target separation efficiencies defined for important elements from HLW are as follows;

Pu:	99.9%,	Np:	99.5%,	Am:	99.99%,
Cm:	99.9%,	Tc & I:	99.0%,	Sr &Cs:	99.9%.

The laboratory-scaled experiments at JAERI shows that the proposed partitioning process has high possibility to realize these target separation efficiencies.

6. P-T SYSTEM REQUIREMENTS

Performance of P-T systems should meet several requirements to achieve a goal of P-T. These requirements will be quantified through the systems and strategy studies including cost and benefit evaluation of P-T systems. Here, the P-T system requirements are discussed in a qualitative manner.

First, the system should has the sufficient capability of reducing the overall risks including both long-term and short-term risks caused by radiological toxicity of waste, and at the same time it should be economically feasible. This requires large transmutation capacity and rate together with reasonably good energy balance of the transmutation plant.

The transmutation rate should be large so as to make the time period required for transmutation (effective half-life) much shorter than the half-life of natural decay of the target nuclides, and also than the plant lifetime. Thus, the largest possible transmutation rate is desirable for the effective reduction of hazard. The transmutation capacity should be as large as or larger than the production of target nuclides. The number of power reactors supported by a transmutation plant is proportional to its transmutation capacity.

In case of accelerator-based transmutation, the accelerator consumes considerably large electric power to deliver the beam to the plant. The accelerator electricity input to be required for transmutation should be sufficiently small than the total electricity output of power reactors that are supported by the transmutation plant. The positive energy balance may be preferred for the transmutation plant, that is, it is to be desired that power output from the transmutation plant is larger than the power required to operate the plant including the accelerator.

It is impossible to achieve a complete transmutation in a single irradiation, target nuclides should be recycled many times to burn them up sufficiently. Each time the target nuclides pass through one cycle, it is also impossible to recover untransmuted nuclides completely in separation process. There will be some unavoidable leakage of untransmuted nuclides to various secondary waste streams. This leakage have a very negative impact on the effectiveness of P-T. The reduction of the overall leakage demands both a high burnup and a low leakage. The higher burnup in a single cycle needs the fewer cycles to burn up a given amount, and thus the less untransmuted nuclides will be lost.

.These requirements may be explained to some extent in terms of the radiological risks associated with the P-T system. The long-term risks can be assumed to be proportional to the leakage of target nuclides and the short-term risks, to the target nuclide inventory and resident time in transmuters and fuel cycle facilities. Here, the discussion is limited to TRU nuclides and they are dealt with collectively.

Risk due to waste leakage R_W is proportional to the total leakage factor. For batch processes repeated infinitely in a P-T fuel cycle shown in Fig. 8, R_W is approximately given as

$$R_W \propto \alpha_P + (1 - \alpha_P)[(\alpha_F + \alpha_S(1 - \varepsilon)]/[\varepsilon + (\alpha_F + \alpha_S)(1 - \varepsilon)] \quad (1)$$

where, ε is the burnup per cycle, α_P, α_F, and α_S are the leakage factor in partitioning of HLW, the leakage factor in fuel fabrication, and the leakage factor in separation, respectively. Assuming $\alpha_P = 0.1\%$, $\alpha_F = 0.15\%$, $\alpha_S = 0.1\%$, and $\varepsilon = 18\%$, the total leakage factor becomes about 1.4%. These assumed values represent the target loss factors of current process technology development. To achieve the most challenging goal of P-T, it is necessary to develop the technology to further reduce the loss and to recover the loss so that the eventual leakage to secondary waste streams can be minimized.

For continuous process for a liquid fuel system shown in Fig. 9, R_W becomes

$$R_W \propto \alpha_P + (1 - \alpha_P)\alpha_S/(\varepsilon + \alpha_S) \quad (2)$$

where, constant fuel flow rate through processing is assumed and the cycle length is defined as the ratio of the fuel inventory in the system to the fuel flow rate through processing. The liquid fuel system has an advantage of complete avoidance of fuel fabrication process that is rather laborious and responsible for a larger fraction of leakage. Since the liquid fuel system is free from the radiation damage of cladding material, a very high burnup can be expected. In such a case, however, the system in equilibrium has to be operated at a very high fission product concentration of the magnitude of ε.

The transmuter inventory risk R_T can be assumed to be proportional to the fuel inventory and resident time in the transmuter, and is expressed as

$$R_T \propto t_T(1 - \varepsilon/2)/\varepsilon \quad (3)$$

where, t_T is the cycle time. The transmuter inventory risk is nearly in inversely proportion to the burnup per unit time, or the transmutation rate (the ratio of the transmuted mass per unit time to the fuel inventory at the begining of cycle). This means that a higher power density (higher neutron flux) is desirable to reduce the risk. The proportional coefficient is dependent on the types of transmuter and its fuel.

In the early ATW concept[14] proposed by Los Alamos, efficient transmutation was expected at a very high thermal neutron flux of the order of 10^{16} n/cm^2/s in a liquid fuel with a very small inventory. This approach is attractive to reduce the transmuter inventory risk significantly, but may involve many severe technical problems.

In the liquid fuel system, the power density is generally not a limiting factor for the core design, because its core can be designed to contain no solid components. Although a very high power density is achievable in the core, the liquid fuel system can not entirely circumvent the heat removal problem that determines the transmutation rate. The heat removal problem usually appears instead in intermediate heat exchangers, and it can become still more difficult. The fuel contained in the primary fuel loops other than the core region occupies a considerably large fraction of the total inventory. If the design had followed a conventional design approach with external shell-and-tube type heat exchangers, it would be practically impossible to achieve a sufficiently high transmutation rate.

The fuel cycle risk R_F can be assumed to be proportional to the fuel inventory and processing time in the fuel cycle facilities, and is expressed as

$$R_F \propto t_P + t_P/\varepsilon + t_S(1 - \varepsilon)/\varepsilon \quad (4)$$

where, t_P, t_F and t_S are time lengths per cycle required for partitioning, fuel fabrication and separation, respectively. A high burnup and short processing times are desirable to reduce the fuel cycle risk. In case of liquid fuel system, there is no risks due to fuel fabrication, that is, $t_F = 0$ in Eq. (4).

Another major contributor to the short-term risks is transportation of radioactive materials. Collocation of dedicated transmuters and P-T fuel cycle facilities in the proposed double stratum fuel cycle concept could substantially reduce the risk due to transportation.

7. UNCERTAINTIES AND DATA NEEDS

One of the most important problems in the P-T systems study is that the data and methods are insufficient. Their uncertainty affects the predicted system performance.

The accuracy of present nuclear data is considered to be satisfactory for actinide transmutation in LMFBRs where relatively small amount of actinide is added to the ordinary fuel. However, it is not satisfactory yet in actinide burner reactors loaded with minor-actinide enriched fuel [15]. The JENDL Actinide File [16] is being compiled for the use in the transmutation study and contains neutron induced reaction data for about 90 nuclides from Tl-208 to Fm-255.

In the accelerator-based transmutation system, the data and methods for high-energy nuclear reaction are essential. In our design study, the nuclear reaction in the energy range above 15 MeV is calculated with a Monte Carlo simulation code NMTC/JAERI [17,18]. The proton-induced spallation process in a target is the primary source of neutrons. The most important quantity is the neutron yield of spallation reaction from the designer's standpoint. The yield of spallation products is also important for the estimation of their toxicity. The neutron yield from the minor-actinide target can be estimated in the error range of ±20% [19]. With this level of confidence, it is possible to make approximate evaluation of the concept of an accelerator-based system. To make more accurate evaluation, further experiments and developments of code with more accurate nuclear data are required.

As well as the nuclear data, physical property data for minor actinide fuel are absolutely lacking. The uncertainty in fuel data also affects significantly to the transmutation rate of the system. Data of thermal conductivity and melting point of fuel are most influential. High-temperature thermal conductivity data are totally missing for Np, Am, Cm, AmN and CmN. In the case of fluid fuel, specific heat also has a major influence.

There are also little data of damage in structural materials irradiated by high energy particles. Although they do not have direct effects on the transmutation rate, they are essential in the design of accelerator-based systems.

Uncertainties and data needs are large in fuel fabrication and reprocessing in the P-T fuel cycle. Thermodynamic and thermophysical databases of the TRU alloys, nitrides and chlorides are still limited. Compounds of Am have the problem of evaporative loss or vapor-phase transport of Am during fabrication and irradiation. Thermodynamic data of the molten salts containing actinide chlorides, particularly $AmCl_3$ and $CmCl_3$, have to be better defined.

As discussed in Sec. 6, technology development aiming toward higher-burnup transmutation and lower-leakage partitioning is the most important to reduce the risks associated with the P-T system. Scientific and engineering data concerning to the high burnup and low leakage should be of top priority.

To fulfill a wide spectrum of data needs for P-T, it is necessary to follow a systematic approach. The approach may consist of a series of processes: sensitivity analysis of system performance to the uncertainties, identification of technical priority issues due to their impact on system design, examination of existing database, assessment of critical data needs, review experimental and testing capability, estimation of schedule and cost, and formulation of experimental and testing plan. These processes will be iterative through design study and systems study.

8. ECONOMICS

It is premature to estimate the cost of the P-T system. Here, some qualitative discussions are made on economics of the P-T system.

The mass flow within the P-T fuel cycle in the double stratum fuel cycle concept is much smaller compared to that in the conventional fuel cycle. The amount of mass flow determines the scale of the fuel cycle facilities, and hence their construction and operation costs. HLW is about 3% of spent fuel by mass; TRUs correspond about 0.1%. Compared to a reprocessing plant with a throughput of 4000 kg/day, the construction and operation costs of a corresponding partitioning facility are estimated to be only about 1% and 2.5%, respectively [20]. Fuel flow through the P-T cycle is 0.2 - 1% depending on the fuel burnup. Cost of actinide particle fuel fabrication and partitioning facilities in the P-T fuel cycle is estimated approximately $970M for an annual throughput of 4130 kg.

Cost of the actinide burner reactor will be roughly the same as that of a commercial fast reactor with equivalent thermal power. The thermal power of the actinide burner reactor corresponds to about 2.5 - 5% of the total thermal power of the supported commercial reactors. Cost of transmuter could be covered by electric power generation. For the accelerator-based transmutation system, cost of the target/core system will be comparable to that of the equivalent actinide burner reactor. Cost of the accelerator is not yet estimated, but it may increase the total cost by 50 - 100%. Detailing the design of the target/core would assure the operation at a higher neutron multiplication factor; this could considerably reduce the cost of the accelerator. Design, construction and operation of the proposed ETA will provide more detailed information for the accelerator cost estimation.

Implementation of P-T will significantly decrease the volume, heat generation and toxicity of radioactive waste, resulting in a reduction of the cost of geological disposal. This could compensate for a substantial portion of the extra cost due to introduction of P-T.

9. CONCLUDING REMARKS

Technology of the proposed P-T system based on the double stratum fuel cycle concept was presented. The partitioning process has a potential capability to separate long-lived nuclides from HLW, leaving final solution virtually free of both ultra-long-lived nuclides and high-decay-heat nuclides. The dedicated transmutation systems have a potential capability to burn minor actinides efficiently. Technology results so far obtained are sufficiently encouraging. Although technical feasibility of P-T is regarded as established, challenge still remain. Further R&D should be needed for other long-lived fission products than minor actinides. To achieve the ultimate goal of providing a different HLW management from geological disposal, technology development aiming toward higher-burnup transmutation and lower-leakage partitioning is of prime importance. R&D on P-T should be steadily carried out on a long time scale.

Systems studies should be needed to show its effective contribution to HLW management, not only in one specific country but also in more broad area. In this context, the P-T systems study under the framework of the OECD/NEA collaboration program will play a central role in finding out our common understandings on incentives for introducing P-T and technical issues to be developed further.

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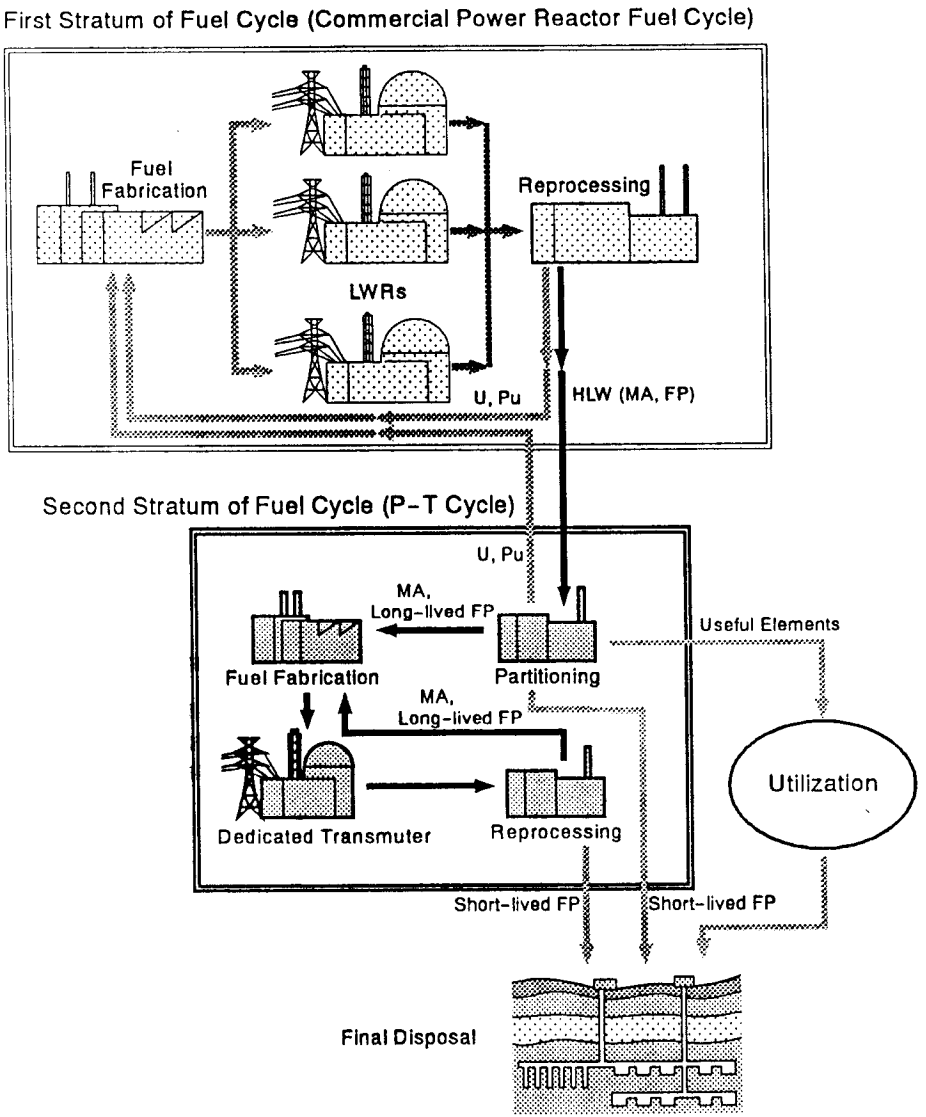

Fig. 1 Concept of Double Stratum Fuel Cycle

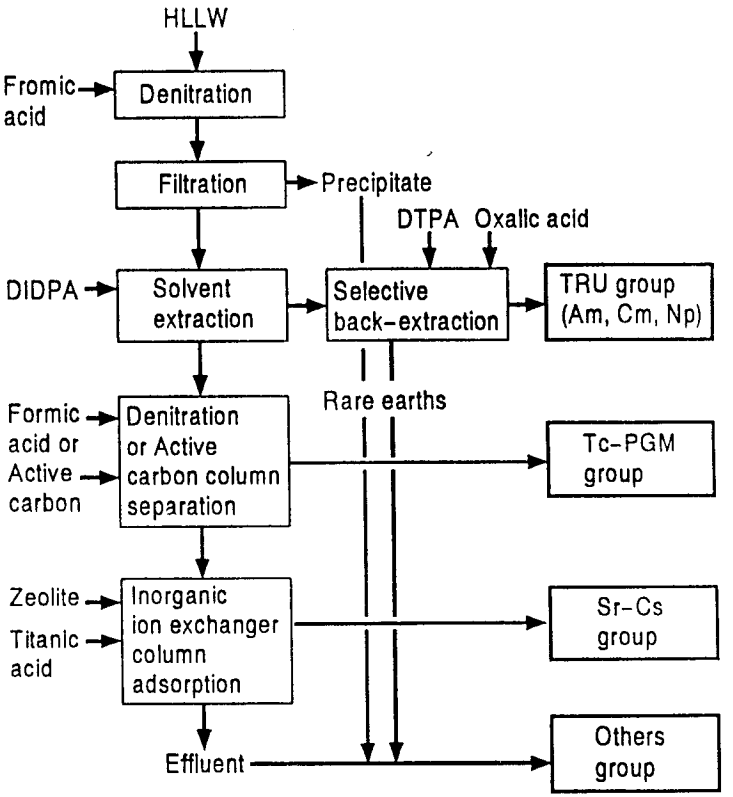

Fig. 2 Four Group Partitioning Process

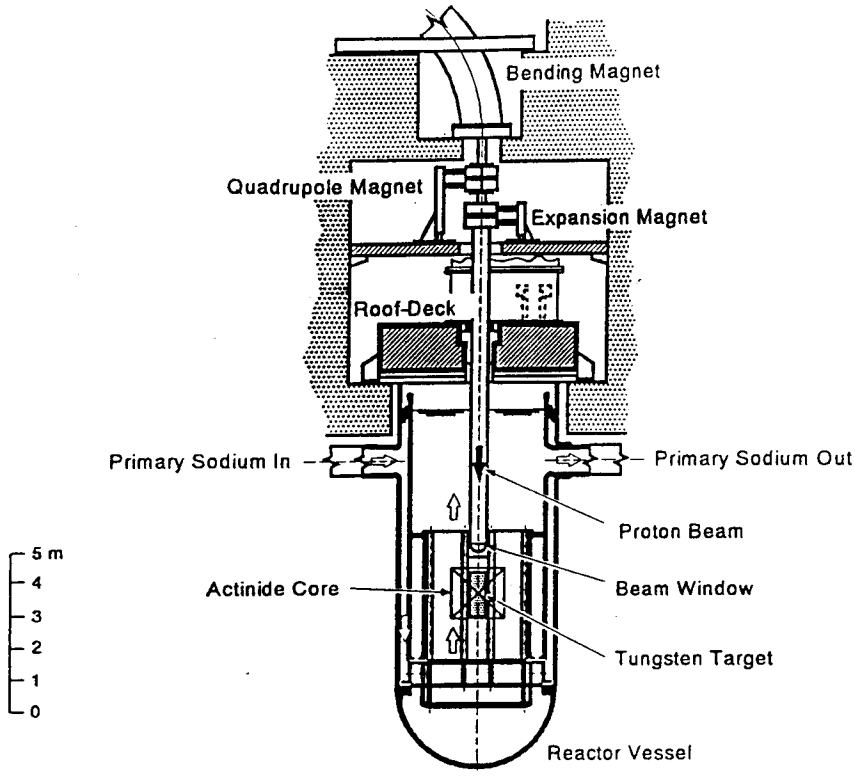

Fig. 3 Solid Target/Core System

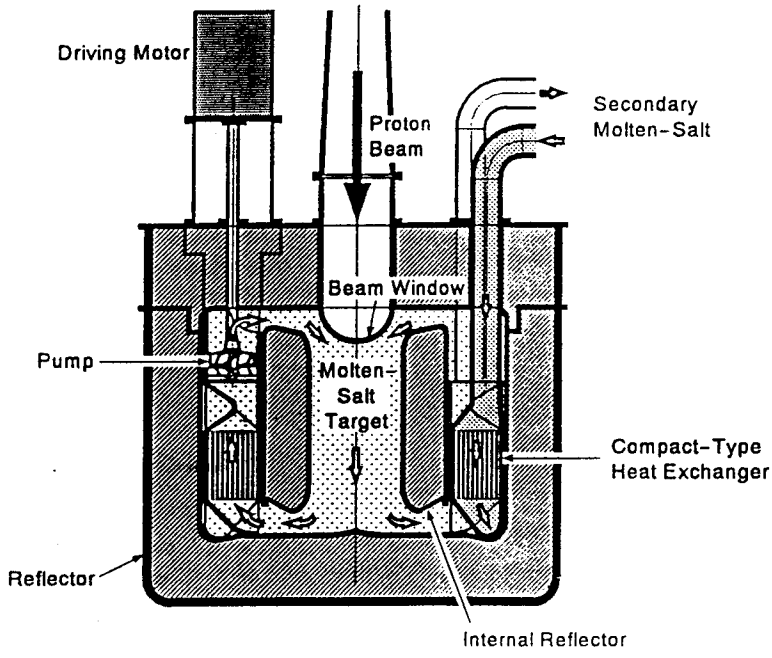

Fig. 4 Concept of Molten-Salt Target/Core System

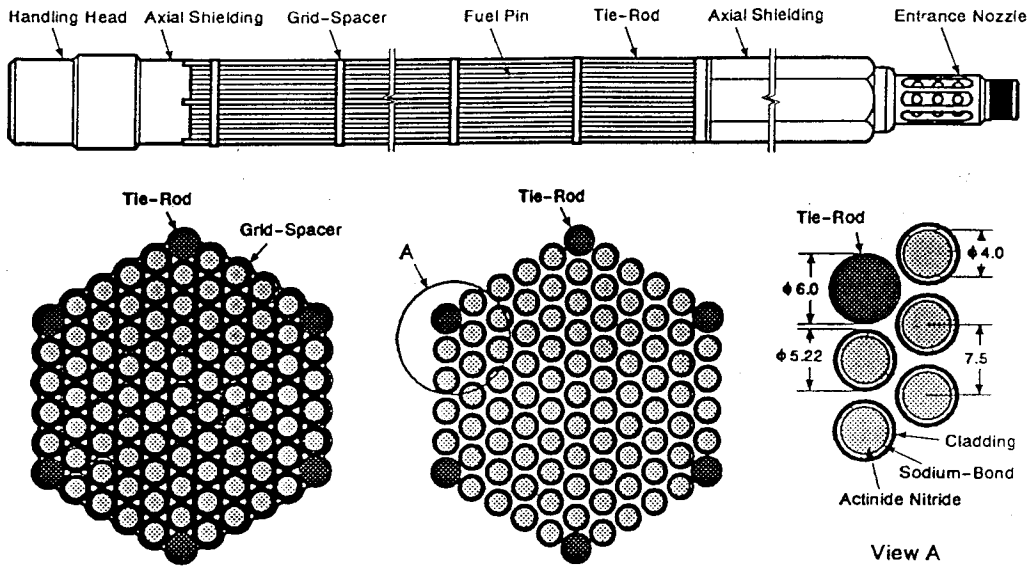

Fig. 5 Actinide Fuel Subassembly of L-ABR

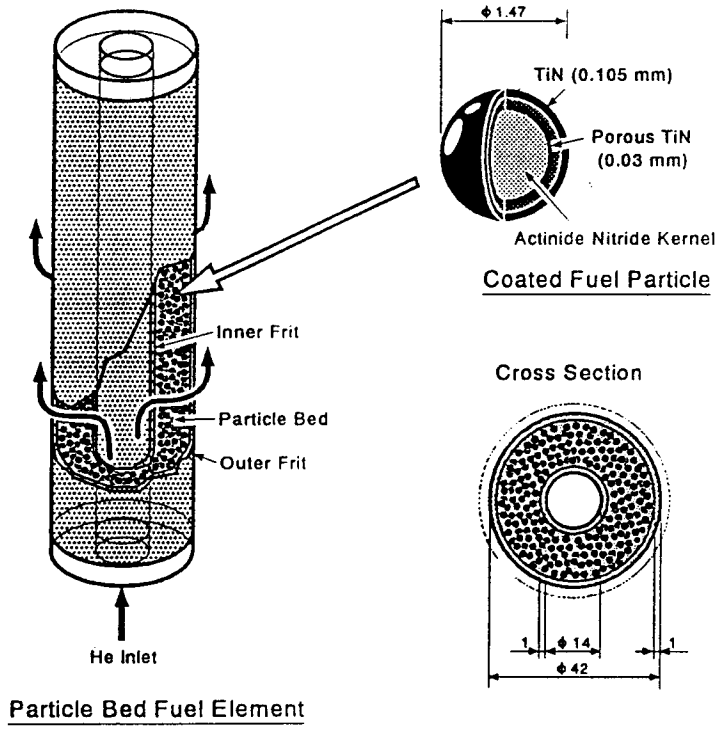

Fig. 6 Coated Fuel Particle and Particle-Bed Fuel Element for P-ABR

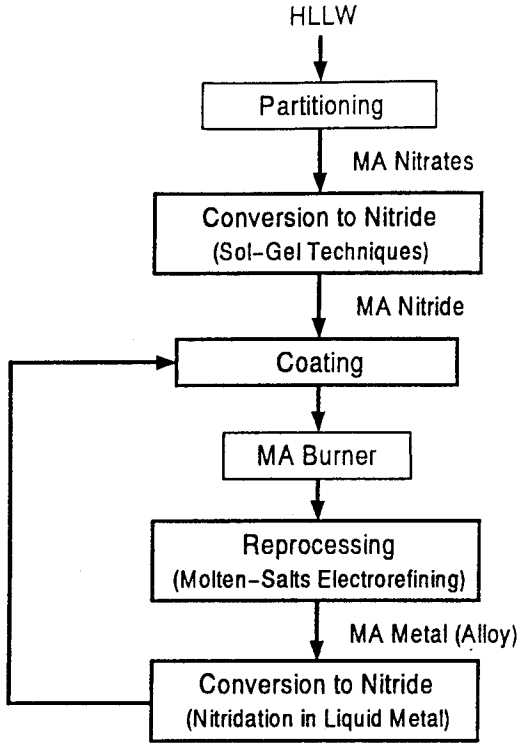

Fig. 7 MA Nitride Fuel Cycle

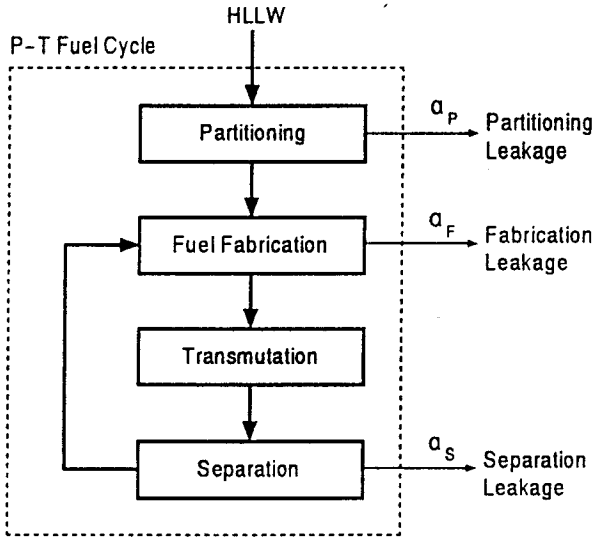

Fig. 8 P-T Fuel Cycle with Batch Processing

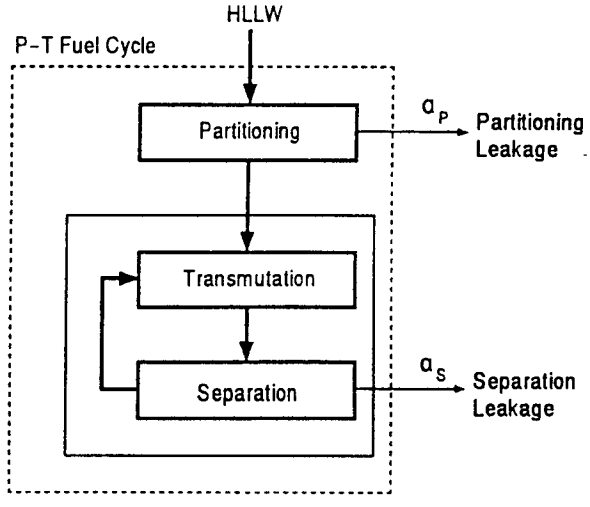

Fig. 9 P-T Fuel Cycle with Continuous Processing