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Technology readiness assessment of partitioning and transmutation in Japan and issues toward closed fuel cycle

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ABSTRACT

This paper treats a technology readiness assessment of partitioning and transmutation in Japan and issues toward closed fuel cycles. The generic technology readiness level in this study is based on the definition in the Global Nuclear Energy Partnership: TRL 3 shows the status that critical function are proved and elemental technologies are identified; TRL 4 represents the level that the related technologies are validated at bench-scale in laboratory environment; and TRL 5 indicates the completion of the development related to the subsystem and elemental technologies. The reviewed technological area includes the partitioning and transmutation technologies for minor actinide cycle: fast breeder reactor, and accelerator driven system for minor actinide transmutation; partitioning processes; and minor actinide bearing fuels. The assessments reveal that the TRLs stay around the final step of concept development (TRL 3) and the first half step of elemental technology development (TRL 4) because each system requires more development of its elemental technologies. The fast breeder reactor is assessed to be at TRL 4 because critical experiments with americium and neptunium would be additionally required, and the technology for the accelerator driven system reaches TRL 3 due to several researches. Consequently, a common key issue is how nuclear calculation methodology will be validated for the MA-bearing-fuelled core; however, critical experiments with several kilogrammes of americium or more are difficult in the existing experimental facilities. On the other hand, engineering scale tests of the MA partitioning processes using actual spent fuel, and engineering scale of fabrication and irradiation tests with the separated materials are required to achieve the second half step of elemental technology development (TRL 5); however, they could be a massive investment. Therefore, laboratory-scale tests using actual material are proposed. The tests simulate a nuclear fuel cycle: partitioning actual spent fuels; and fabricating MA bearing fuels from the extracted materials; and then irradiating them. It should be that the tests advance technological readiness from TRL 4 to TRL 4+, which is a reasonable and feasible pathway.

1. Introduction

The purpose of this study is providing clarified information related to the current maturity of the partitioning and transmutation (P-T) technologies by applying the methodology of technology readiness level (TRL). That is to say, this study deals with the materialization of specific TRLs for the P-T technologies, the maturity assessment of Japan by the TRLs, and the overview of issues in the development toward closed fuel cycles. The last two decades of research succeeded in a significant progress but a long way to goal is still left. That is, many difficulties associated with the technology development, which is called "Valley of Death", lies before us in that the P-T system has a broad research area and it needs a long term and a huge resource up to practical use. Naturally the related technologies should be developed proficiently so that any delay of subsystem development does not prevent the whole progress deadly. Smart resource allocation requires the high transparency of technological advance in various fields. That is, it is vital that specialists of different areas communicate and mutually understand their issues in progress: from basic research to technology development, and then to a project for practical realization; and the targets and their priorities are shared among specialists

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and management. This work is the first attempt to deploy the TRL methodology in the atomic energy community of Japan.

How have maturity assessments been treated in the P-T technology? The project of Options Making Extra Gains from Actinides and fission products (OMEGA) was launched in Japan for the purpose of reducing minor actinide (MA) and long lived fission products (LLFP) in 1988. The Japan Atomic Energy Commission (JAEC) made the second comparative review of the technologies related to this project including their maturities from 2008 to 2009 (JAEC, 2009).

In USA, the Clean Use of Reactor Energy (CURE) was developed by Westinghouse Hanford Company and Battle's Pacific Northwest Laboratory, supported by the Department of Energy (DOE); the CURE is a concept of partitioning and transmutation with the purpose of reducing long-lived radioactive nuclides; and they studied the feasibility of P-T technology and examined the process (Westinghouse Hanford Company, 1990). Moreover, Committee on separations technology and transmutation systems, Board on radioactive waste management, and Commission on geosciences, environment and resources of National Research Council released a comprehensive assessment of strategies related to technologies for separations and transmutation (National research council, 1996). Recently, the Global Nuclear Energy Partnership initiative (GNEP) by the DOE applied the TRL methodology to the transuranic uranium combustion technology, advanced recycling reactor, and recycling facility (DOE, 2007). Additionally, an indicator to quantitatively measure the development of fuel cycle was proposed (Carmack and Pasamehmetoglu, 2008b; McCarthy and Pasamehmetoglu, 2009). Finally, DOE's Office of Nuclear Energy prepared a programmatic environmental impact statement (PEIS) to assess the potential environmental impacts of expanding nuclear power in the US using either the existing fuel cycle or various alternative closed and open fuel cycles (DOE, 2008).

In France, the CEA set up an international peer review board with foreign specialists, focussing on the current maturity and future development of the P-T technology, and the recommendations of research and development (R&D) plan (OECD-NEA, 2006). These activities will contribute to the international cooperation for the P-T technology development and the improvement of technology management by enhancing objectivity and transparency without doubt.

This study assesses the maturity of P-T technologies: fast reactor (FR), and accelerator driven subcritical transmutation system; aqueous reprocessing, and molten salt electro-refining partitioning technologies; and oxide, metal, and nitride fuels. This paper also assesses four concepts of nuclear fuel cycle: sodium-cooled fast reactors with oxide, and metal fuels; reactor with high MA-concentration oxide target; and Accelerator Driven System (ADS). But it does not include the innovative technologies for Japan Sodium-cooled Fast Reactor (JSFR). Naturally the assessment is in accordance with the reported technological facts that are utilizable in Japan. Therefore these published articles and technical reports are referred in this paper as many as practicable.

This paper includes a part of achievement by a task force in the Research Committee on P-T and MA Cycle under the Atomic Energy Society of Japan (AESJ) (AESJ, 2010; Minato et al., 2012; Ikeda et al., 2011c). The task force spontaneously evaluated the maturity of P-T technologies in order to help the second review of P-T technology of the Japan Atomic Energy Commission (JAEC). This TRL evaluation was made in cooperation with the experts of each technology field. This activity is independent of the Fast Reactor Cycle System Technology Development Project in Japan. In addition, the expressed opinions do not necessarily reflect the official views of the authors' organizations.

2. Technology readiness approach and the assessed partitioning and transmutation technologies

This session describes a typical process of technology evolution, and classification by the TRL approach, and then specifies the technologies to be assessed.

2.1. Generic definition of technology readiness level

Technology developments have their own story, but invariably any technology begins to burgeon in the earth of "science", and in most cases it evolves from applied science to technology. Finally demonstration, practical use, and commercialization follow after the accomplishment of the technology development.

National Aeronautics and Space Administration (NASA) established the TRL methodology for maturity measurement in the above technology development process (Mankins, 1995). In this paper, the TRLs have nine levels of classification as shown in Fig. 1. Each level is basically defined in the same manners as in GNEP (DOE, 2007), and so as to be equivalent among different areas as follows:

TRL 1–3: concept development phase. An idea is invented and reported (TRL 1), and then is put into shape and the applications are formulated (TRL 2), and the critical function of the concept is proved by analyses and/or experiments (TRL 3).

TRL 4–6: proof of principle phase. The concept is technologically concretized and specified. That is, the degree of similarity (fidelity) of experiments betters from bench-scale tests using simple models in laboratory environment (TRL 4) to engineering scale tests using prototype models in relevant environment (TRL 5). At first, at component-level elemental technologies are tested (TRL 4) and next at subsystem-level it is proved (TRL 5). Finally the technology is proved as a system (TRL 6).

TRL 7–9: proof of performance phase. At first, a prototype model demonstrates it as a system (TRL 7), next a first actual system demonstrates it (TRL 8), and finally actual achievements accumulate in practical use (TRL 9).

2.2. Scope of the assessed technologies

Table 1 provides the assessed four concepts which are being developed in Japan. They consist of several kinds of technologies as follows:

- Systems of energy production and transmutation: single strata schemes with fast reactors and "Double Strata scheme" that has accelerator driven systems (ADSs) for transmutation and energy production reactors.
- Transmutation systems: sodium-cooled fast reactors with oxide or metal fuel, and a Pb-Bi cooled subcritical reactor with nitride fuel for the ADS.
- Technologies of partitioning and recovery: five types of wet-processes for oxide and two types of dry pyro processes. The assessed wet-processes are crystallization and co-extraction, extraction chromatography, solvent extraction for trivalent-f-elements intra-group separation in CMPO-complexant System (SETFICS), diisodecylphosphoric acid (DIDPA), and tridentate diglycolamide (DGA) methods. Molten salt electro-refining method is examined as dry pyro processes for metal and nitride fuels.
- Fuel cycle: homogeneous, heterogeneous, and ADS-Double Strata fuel cycles shown in Fig. 2. In the homogeneous fuel cycle, active core fuels contain MA. The heterogeneous fuel cycle is defined that target subassemblies load MA and fuels do not contain MA. The type of the target subassembly is chosen to be mixed oxide in this assessment.