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Reprocessing of spent nuclear fuel in India: Present challenges and future programme

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A R T I C L E I N F O

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A B S T R A C T

Adoption of the closed nuclear fuel cycle is an imperative option for the Indian nuclear power programme in view of the limited resources of natural uranium and abundance of thorium. The issues associated with the long-term radiotoxicity of spent fuel can also be addressed in the closed fuel cycle with this option. The present paper focusses on the scientific and technological challenges associated with reprocessing of spent fuel from both the thermal and fast reactors. The experience gained in the operation of reprocessing plants in the separation of spent fuel of thermal reactors into uranium, plutonium and high level waste is described in this paper. Challenges resolved during the reprocessing of spent mixed carbide fuel from Fast Breeder Test Reactor (FBTR) in CORAL plant are described in detail. This experience enabled the design of a commercial scale reprocessing plant which is under construction to handle the spent fuel from 500 MWe Prototype Fast Breeder Reactor (PFBR). Recent developments in the separation of minor actinides from high level waste is also briefly discussed. The experience gained in the thorium fuel cycle with the reprocessing of spent thorium fuel is also covered.

1. Introduction

For sustainable energy contribution, Indian nuclear power programme is formulated with closed fuel cycle. The fuel cycle (Fig. 1) is said to be closed if the unburnt and the bred fissile materials are recovered and reused in the reactor as fuel. The fissile material is recovered from the spent nuclear fuel by reprocessing and the wastes consisting primarily the fission products are vitrified and stored in repositories. With additional nuclear power generation capacities getting added in many countries and closed fuel cycle being an attractive option both in terms of sustainability as well as economics, the spent fuel reprocessing is predicted to take a centre stage of activity of the nuclear industry in the coming years. It is also not uncommon in some countries, such as India, where reprocessing plants are designed to recover and recycle plutonium from the spent fuel as early as possible after discharge from the reactor, not only due to the lack of large uranium reserves but also because of the large energy demands in coming decades.

1.1. Need for reprocessing

Irradiated fuel is discharged from the nuclear reactor before the fissile material is completely burnt. This is due to the accumulation of fission products which consume neutrons rendering the nuclear chain reaction unsustainable as well as the potential failure of the fuel at higher burnup[1] (which is the measure of energy extracted from the fuel) due to clad rupture. In the case of thermal neutron spectrum reactors, commonly called thermal reactors, the burnup varies from 6 to 50 GWd/Te (that is, approximately 0.6–5% of the fissile material only is burnt). In fast neutron spectrum reactors, commonly called fast reactors, the fissile material can be burnt up to even 20 atom %, that is with the energy extraction of as high as 200 GWd/Te. In these reactors, the limitation is mostly due to the loss of integrity of the structural material (clad and wrapper) that provides the containment and the loss of neutron due to absorption by fission products is less than that of thermal reactors.

It is prudent to recover the fissile material left in the spent fuel

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[1] burnup is the term used in the nuclear industry which is the measure of the amount of energy extracted from the fuel; 1 GWd = 8.64×10^{13} J.

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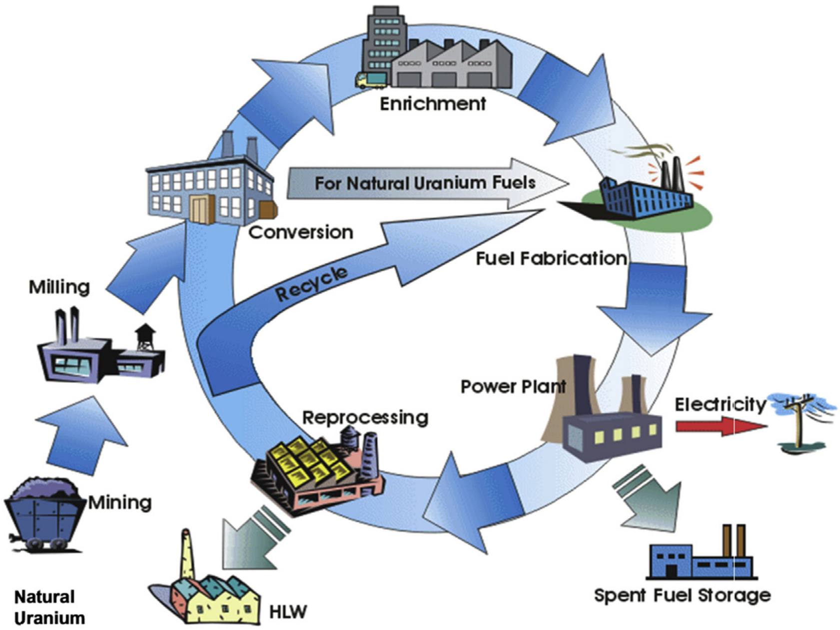

Fig. 1. A schematic of nuclear fuel cycle.

for reuse by reprocessing, as it reduces the requirement of fresh materials. Also, this reduces the volume of the radioactive waste to be disposed off for the same amount of power production. The design of the reprocessing process flow sheet depends not only on the chemical form of the spent fuel (whether metal or oxide or carbide etc.) but also on the burn-up and cooling period given for the spent fuel after discharge prior to its processing. This cooling reduces the radioactivity associated with the fuel since the fission products undergo decay to lesser radioactive species.

Reprocessing of the spent nuclear fuel aims primarily at the recovery of unburnt fuel (uranium) and plutonium (which is bred from the fertile ^{238}U) and ^{233}U (bred from the fertile Th) from the fission products and minor actinides (refer appendix). These fission products should be removed to meet the fuel specification for reuse in the reactors and to reduce the shielding requirement for the downstream fuel cycle activities such as fuel fabrication.

1.2. History of reprocessing and present international scenario

Though reprocessing is primarily required for sustainability of fissile material resources for energy production, it was first deployed for recovering plutonium for weapon production during the Second World War by USA in mid 1940s.The first quantities of plutonium were recovered from irradiated uranium by the bismuth phosphate co-precipitation process (Lawroski and Levenson, 1957). However, only Plutonium–Uranium EXtraction (PUREX) process (Lanham and Runion, 1949) based on Tributyl phosphate (TBP) as solvent, is the one which was deployed world-wide. PUREX process was developed at the Knolls Atomic Power Laboratory in 1950 and demonstrated in a pilot plant at Oak Ridge, USA in 1952. Since its first deployment in large scale at Hanford, USA in 1956, other countries such as the Soviet Union, India, Germany, France and Japan have used this process (Sheldon, 1977; Naylor and Eccles, 1988; Ebert, 1988; Fournier et al., 1992; Anderson et al., 1994). Though originally developed for low plutonium bearing thermal reactor fuel, it is found to be adaptable for plutonium based mixed oxide (MOX) fuels used in thermal reactors as well as plutonium rich fast reactor fuels. The experience with reprocessing, both in terms of performance and safety has been highly satisfactory. Substantial processing of the spent fuels discharged from thermal reactors has been done in the reprocessing plants in France, Russia, Japan, UK, USA and India with a total installed annual capacity of approximately 6000 Te of heavy metal (uranium and plutonium). Over 94,000 Te of spent fuels have been reprocessed (IAEA-TECDOC, 2006) (till 2006). Major civilian reprocessing capacities exist is in France, UK, Japan, Russia and India. Only France and UK have demonstrated the feasibility of commercial-scale fuel reprocessing. Though reprocessing technology exists, for reasons of non-proliferation, presently the technology is not being pursed in USA. China, India and Russia are expected to add additional annual capacities of 2600 Te in the next 6–10 years. As of 2004, about 10,500 Te of spent fuel was being discharged every year, adding to the 1,78,000 Te that accumulated till 2004.

Presently no other country other than India has interest in Thorium fuel cycle. Experience has been gained on application of THOREX process on the recovery of ^{233}U from irradiated thorium and the process has been demonstrated in pilot plant scale both at BARC, Mumbai as well as at IGCAR, Kalpakkam. Comprehensive efforts continue for developing a mature reprocessing technology for spent fuel from thorium based reactors.

Because of the potential use of these fissile materials in nuclear weapons, the technology remains closely guarded and only a few countries have the operating plants in civilian regime, such as Russia, UK, France, Japan and India.

1.3. Nature and contents of spent nuclear fuel

Spent fuel contains almost the entire quantity of radioactivity encountered in the nuclear fuel cycle. The radioactivity is mainly due to the fission products whose quantity in the spent fuel increases with the burn-up. The composition of the spent fuel discharged from a typical thermal reactor with a burnup of about 33 GWd/Te and five years of cooling is given in Table 1 (Bell, 1973) along with the disposition of its constituents. The concentration of fission products, which are typically around 0.6–5% in thermal reactor spent fuels, generally increases with burnup. Though, the

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