CLOSED FUEL CYCLE

For Sustainable Growth of Nuclear Power Program in India

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ABSTRACT

Energy availability is an enabler for growth, progress and prosperity. Indeed, energy availability and progress feedback positively to each other. The Indian growth story means higher energy demand, which will further fuel growth in a virtuous cycle. However, India has not been blessed with an abundance of fossil fuel reserves, which in turn places an emphasis on the judicious management of available energy resources to allow sustainable growth. While renewable energy is the new rage and is growing increasingly popular, harnessing the power of the atom was the original "low pollution energy" idea dating back to the 1960s in India.

Recognizing with acute foresight that India would have to tap her abundant Thorium reserves and not depend upon imported Uranium, Dr. Homi J. Bhabha, the founder of the Indian Atomic Energy Programme conceptualized a three stage nuclear power programme. Indeed, the three stage nuclear fuel programme necessitates a closed fuel cycle with reprocessing of spent fuel. In addition to long-term energy security, and optimum utilization of Uranium resources, reprocessing promises reduced radio-toxicity and a smaller waste volume for final disposal in a repository. Additionally, reprocessing opens new avenues for the recovery of valuable radionuclides from radioactive wastes for various societal applications, reinforcing our view that nuclear waste is an abundant resource for national wealth.

The status and recent advancements of back end fuel cycle activities to realize the closed fuel cycle for each stage of the Indian nuclear power program along with achievements in the field of radioactive waste management in India are presented in this article.

KEYWORDS: Fuel cycle options, Closed fuel cycle, Reprocessing, spent nuclear fuel, High level waste, Radioactive waste management, Wealth from waste, Geological disposal facility.

THE INDIAN economy is growing fast leading to an increase in prosperity, quality of life, purchasing power and an insatiable appetite for energy. By 2036–37, electricity utilization is expected to double [1]. Meeting this demand by the conventional fossil fuelled route is unsustainable economically and especially environmentally. Various sources of energy including renewable sources such as solar, wind, hydroelectricity, geothermal, tidal etc. have emerged as promising alternates for fossil fuels. However, these energy sources are not reliably available at all time, necessitating a base driver. This role can be appreciably filled by nuclear energy thereby permitting an energy mix with an optimal utilization of available energy resources to ensure growth of the country.

The vision of nuclear energy utilization in India was first nurtured and brought to realization by Dr. Homi J. Bhabha in the early 1960s. He was acutely aware that India possessed only limited resources of Uranium but abundant reserves of Thorium. Therefore, Dr. Bhabha advocated the three stage nuclear fuel programme intended to bring long-term energy security to India and minimize dependence on imported Uranium. As part of this programme, natural uranium fuelled pressurized heavy water reactors (PHWRs) would be used to generate electricity and plutonium. The latter would be utilized in preparation of mixed oxide (MOX) fuel for Fast Breeder Reactor (FBR) in the second stage to generate electricity and enable breeding uranium-233 (^{233}U) from thorium. In the third stage, ^{232}Th - ^{233}U will be used as fuel in advanced reactors for energy extraction from abundant thorium reserves and thereby achieve long-term energy security [2,3,4].

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Indeed, the vision of a three stage Indian nuclear power program (INPP), cannot be fructified without adoption of a closed fuel cycle considering spent nuclear fuel (SNF) as a resource. For all the stages of INPP, reprocessing of SNF is essential for extracting the fuel and to recycle them in next generation reactors.

Fuel Cycle Options

The fuel cycle can be open or closed depending upon the management philosophy for SNF. In case of the former, the SNF is classified as a waste, slated for direct disposal in a geological disposal facility (GDF). The latter entails chemical treatment of the SNF to recover fissile and fertile materials for reuse. The merits and limitations of each philosophy have been widely debated and both have their proponents and opponents. Of course, there is no one-size-fits-all in terms of selection of a suitable fuel cycle option. This must be selected based upon a variety of factors including the demand for energy, size of the nuclear power program, availability of resources, technology knowhow, public perception, long term strategy etc. Countries adopting the open fuel cycle generally utilize thermal neutron reactors for extraction of energy from the fission of enriched uranium-235 (^{235}U). Such a scheme obviates the need for complex reprocessing and waste management strategies. In contrast, the adoption of a closed fuel cycle is technologically more challenging requiring the chemical treatment of SNF for reprocessing and deployment of an FBR for breeding fertile material. Despite this, the closed fuel cycle significantly reduces decay heat load in the waste, reduces waste volume and mitigates radio-toxicity.

India's closed fuel cycle option is based on multi recycling of plutonium in FBRs with recovery of plutonium from SNF of MOX fuel of each cycle for its use in the next reactor for energy production. This results in maximum utilization of fertile uranium by converting it into fissile plutonium.

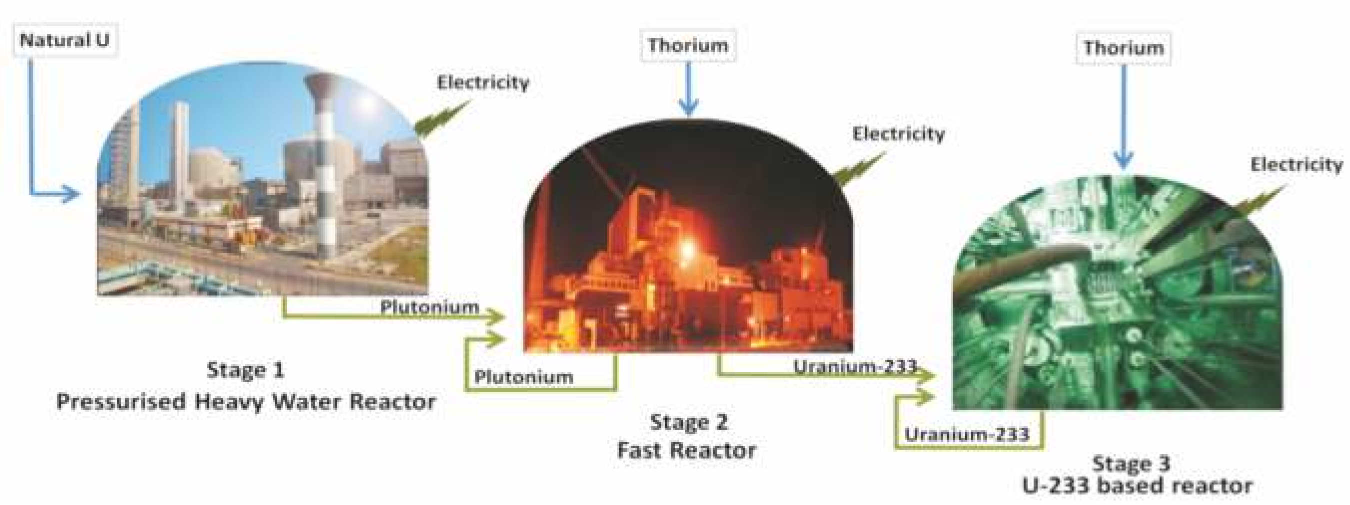

Fig.1: Closed fuel cycle based three stage nuclear power program.

Another area where the two approaches differ is in terms of economics. The largest cost associated with an open fuel cycle is the cost of construction and supervision of a GDF. Since the open cycle is technologically modest, upfront costs for disposal are lower. However, delays in GDF construction and operation can lead to rapid cost increases driven by the need for extending long term storage of SNF, augmentation of additional storage capacities, repacking of SNF etc. Available information estimates the cost of a GDF at hundreds of billions of dollars over a period of 100–150 years.

The closed fuel cycle entails higher upfront costs for investments associated with cost of recycling facilities and fast reactors. However, significant cost saving can be realized in the GDF due to reduction in decay heat, waste volume and radio-toxicity. Hence, the open-cycle has lower short-term costs but uncertainties around long term costs and waste hazards increase with time. In comparison, closed cycle options having higher short- to mid-term costs but the characteristics of the waste limit the long-term hazard, thus reducing future uncertainties [5].

Unlike open fuel cycle, the closed fuel cycle largely depends on back end facilities including reprocessing plants, high level waste management plants among others for achieving its goals.

Closed fuel cycle offers different options such as mono recycling of plutonium or multi recycling of plutonium. For example, France follows the mono recycling option based on the two stage cycle. In this scheme, SNF discharged from the first stage of uranium fuelled reactors is reprocessed to recover plutonium and uranium. MOX fuel consisting of recovered plutonium along with depleted uranium is fuelled to a reactor in the next stage. SNF of MOX fuel of second stage reactor is not reprocessed but considered a waste for disposal. This option helps in saving of 75% fresh fuel as well as reducing the waste volume requiring disposal in the repository [5]. Besides this, it also bypasses the need for Fast Breeder Reactor technology. In contrast, India's closed fuel cycle option is based on multi recycling of plutonium in FBRs with recovery of plutonium from SNF of MOX fuel of each cycle for its use in the next reactor for energy production. This results in maximum utilization of fertile uranium by converting it into fissile plutonium. This leads to a significant reduction in overall requirement of fresh uranium fuel for a given electricity generated as compared to an open fuel cycle as well or a closed fuel cycle with mono recycling of plutonium.

Closed Fuel Cycle - India's Option

India has adopted the closed fuel cycle to meet the goals of the three stage INPP, to allow optimum utilization of available uranium resources, while extracting maximum utility from abundant deposits of thorium. Multi recycling of plutonium is envisaged for maximum utilization of fertile uranium by placing MOX (mixed oxides of plutonium and depleted uranium) in Fast Breeder reactors to breed the fissile plutonium from fertile uranium, for its utilization in similar reactors. There also are plans to place thorium in Fast Breeder reactors as a blanket material at a later stage to breed ^{233}U for fuelling advanced reactors of the third stage (Fig.1).

In addition to ensuring optimal utilization of fuel, the closed fuel cycle also helps in reducing long term radio-toxicity associated with high level waste. For example, the radio-toxicity of SNF, disposed directly from an open fuel cycle, will decay to that of natural uranium in about 200,000 years. On the contrary, SNF discharged from a closed cycle scheme will have its radio-toxicity decay to that of natural uranium is about 10,000 years [6]. Besides this, close fuel cycle option recovers and, hence, removes almost all of the uranium and plutonium in SNF, which would end up in GDF in case of an open fuel cycle. Most advantageously, the final waste volume needing disposal in GDF will be reduced significantly in case of a closed cycle. This is emphasized by the fact that the volume of resulting vitrified waste after reprocessing of SNF generated from Indian PHWR is about five times lesser than volume of SNF if disposed directly. Besides this, it opens up new ways of partitioning of high level waste for transmutation of long lived minor actinides and also for recovery of valuable radionuclide for societal applications. Separation of heat generating fission products from long lived minor actinides further reduces the volume and decay heat associated with the final waste volume needed to be disposed in GDF.

A closed fuel cycle utilizing multi-recycle option helps in minimization of waste volume, thereby reducing concerns of long term radio-toxicity, while a reduction in the decay heat load helps reduction in space and time for geological isolation with beneficial impact on GDF cost.

Back end facilities including reprocessing of SNF plays a vital role in the power program conceptualized on the basis of a closed fuel cycle by providing fuel for same as well as next stage reactors. Unlike open fuel cycle, the closed fuel cycle largely depends on back end facilities including reprocessing plants, high level waste management plants etc. for achieving its goals.

Fig.2: Reprocessing Plant, Trombay.

Fig.3: PREFRE-I, Tarapur.

Fig.4: KARP, Kalpakkam.

Reprocessing of Spent Nuclear Fuel

By the time reprocessing was taken up by India, it was a relatively mature process and the best technological choice was the PUREX process, which is a solvent extraction process using 30% TBP in pure n-dodecane, for reprocessing of spent nuclear fuel (SNF). It may be mentioned here that the PUREX process is the workhorse of reprocessing and no process before or since can match its versatility.

Based on same, India has a wealth of experience in the reprocessing of SNF spanning more than five decades. The first reprocessing plant, i.e. Plutonium Plant, was commissioned in the year 1965 at Trombay and the same is still under operation, reprocessing the SNF from Trombay reactors (Fig.2). Based on experience obtained from the plant, reprocessing of Power Reactor (PHWR) fuel was initiated in the early seventies by building and operating the Power Reactor Fuel Reprocessing Plant (PREFRE-I) at Tarapur (Fig.3). Subsequently, one reprocessing plant at Kalpakkam, KARP, and one more reprocessing plant at Tarapur, PREFRE-II, were constructed and are presently under operation for reprocessing of PHWR Fuel (Fig.4). Recently, an additional plant KARP-II has been commissioned for PHWR Fuel reprocessing at Kalpakkam. Out of these, PREFRE-I has been shut down after successfully completing its operating life while the rest of the plants are in operation. India has mastered the technology of reprocessing of SNF of thermal neutron based research as well as power reactors such as PHWRs. The plutonium thus recovered has been utilized for fabrication of MOX fuel for upcoming Prototype Fast Breeder Reactor (PFBR), thus closing the fuel cycle of first stage of INPP. The management of high level waste generated from reprocessing is carried out safely and effectively as described in the subsequent section.

Concerted R&D efforts are underway in the field of HLLW portioning, which will enable a reduction in waste volume and mitigate the necessity for a GDF in the near future.

Over the period, indigenous developments resulted in various improvisations in the process flow sheet to improve recovery, separation efficiency and thus product quality of U and Pu. Recent developments have been carried out in the field of head end systems along with a desired state of automation to provide better availability of system, enhanced throughput and minimize personnel exposure. As a result, some of the reprocessing facilities have delivered better than rated capacity. As the nuclear energy based power capacity is likely to be increased multi-fold, the need for reprocessing SNF will also increase concomitantly. Utilising the vast experience in the field of spent fuel reprocessing, large capacity Integrated Nuclear Recycle Plant (INRP) is under construction at Tarapur to increase multifold the reprocessing capacity of the country.

Reprocessing of spent fuel generated from Fast Breeder Test Reactor has also been demonstrated in the CORAL facility at Kalpakkam. Similarly, capability in reprocessing of Thoria fuel has also been shown successfully at BARC, Trombay demonstrating the technology needed for third stage of INPP. Thoria fuels irradiated at CIRUS and at PHWR were successfully reprocessed for recovery of ^{233}U as well as thorium at UTSF and PRTRF of Trombay respectively [7,8,9,10].

Radioactive Waste Management

The management of radioactive waste is an important aspect for the widespread acceptability of nuclear power while ensuring sustainability of the programme. Consequently, the safe management of radioactive waste has been an important consideration since the inception of our nuclear power program. Waste volume minimization and near zero discharge of radioactivity have always been the central principles of radioactive waste management. The implementation of the nuclear waste management plan hinges on the following broad concepts: delay and decay; dilute and disperse; recycle and reuse and concentrate and contain.

As mentioned earlier, an important advantage of the closed cycle is the reduction in the volume and radio-toxicity of the waste requiring internment in the GDF. However, safe and effective management of High Level Liquid Waste (HLLW), generated during the reprocessing of SNF, is an important and decisive aspect motivating the selection of the closed fuel cycle. HLLW contains more than 99% of radioactivity present in SNF. Conventionally, HLLW is immobilized in an inert glass matrix by vitrification process to reduce the waste volume and to isolate the radionuclides from the environment. Vitrified HLLW is stored in a passive air cooled vault for removal of decay heat for a few decades followed by planned disposal in a GDF sited in stable granitic host rock about a few hundred meters below the surface.

The first vitrification facility for HLLW, Waste Immoblisation Plant (WIP), was built in the early 1990's at Tarapur based on an Induction Heated Metallic Melter (IHMM) for converting HLLW, generated from PREFRE-I, into a vitreous waste product (VWP). Based on the experience gained from WIP, Tarapur, another IHMM based vitrification plant was commissioned at Trombay in 2002, which remains under operation to treat HLLW generated from reprocessing research reactor SNF (Fig.5). The Joule Heated Ceramic Melter (JHCM) was developed to overcome the throughput limitation of IHMM thereby catering to a higher capacity of HLLW immobilization. This melter was successfully deployed at the Advanced Vitrification System (AVS), Tarapur (Fig.6). WIP, Kalpakkam has been commissioned for management of HLLW using JHCM in the year 2017 (Fig.7). Combining all these

Fig.5: WIP, Trombay.

Fig.6: AVS, Tarapur.

Fig.7: WIP, Kalpakkam.

plants, more than 500 vitrification operations were carried out safely showcasing the capabilities of the country in the field of vitrification of HLLW. India is among very few countries of the world, which have gained proficiency in the vitrification technology at an industrial scale.

The first facility for the interim storage of vitrified HLLW in an air cooled vault, Solid Storage Surveillance Facility (SSSF), Tarapur was commissioned and remains in operation. More recently, the Vitrified Waste Storage Facility (VWSF), Kalpakkam was also commissioned in 2020 for the interim storage of vitrified HLLW.

For GDF, R&D with respect to finalization of the site selection criteria, characterization of backfill materials, modeling of radionuclide migration in the geosphere, thermal-hydraulic studies, conceptualization of design etc. are underway. National as well as international collaborative works with various academic and other research institutes of the country and across the globe are being pursued for converging expeditiously on an optimal solution for such the complex problem of a GDF. At present, there are no operational GDFs anywhere in the world.

Concerted R&D efforts are underway in the field of HLLW portioning, which will enable a reduction in waste volume and mitigate the necessity for a GDF in the near future. Further, consistent efforts directed towards novel extractants has led to the successful commissioning of solvent extraction based Actinide Separation Demonstration Facility (ASDF), Tarapur in year 2014 aiming to partition of minor actinides from HLLW. ASDF, Tarapur has been the first and only engineering scale facility in the world for partitioning of minor actinides from HLLW treating few tens of thousands of liters of HLLW. Based on successful operation of ASDF, Tarapur, another engineering scale solvent extraction based partitioning system at WIP; Trombay was built and commissioned in the year 2015 for the separation of radioactive components from inactive components.

Utilising this solvent extraction system, recovery of many valuable fission products such as ^{137}Cs, ^{90}Sr, ^{106}Ru etc. could be demonstrated on a bulk scale from HLLW at WIP, Trombay for various societal applications. Besides recovery of useful radionuclides, partitioning process could also demonstrate multifold reduction in final vitrified waste volume greatly reducing space demand in the GDF. Considering the advantages of partitioning of HLLW prior to vitrification and the technological knowhow accrued, the same is being implemented at High Level Waste Management plant engaged in management of HLLW from reprocessing of power reactor spent nuclear fuel.

Besides management of HLLW, Intermediate Level Liquid Waste (ILLW) generated from reprocessing facilities is also treated effectively using radionuclide specific ion exchange resins at waste management facilities of Trombay, Tarapur and Kalpakkam. Low Level Liquid Waste (LLLW), generated from all the fuel cycle facilities, are treated intensely prior to discharge to the environment. Chemical treatment is the oldest process under operation at various radioactive waste management sites for getting good decontamination factors for bulk removal of radioactivity prior to discharge of effluent to the environment. R&D is ongoing for the development of membrane based novel technologies for treatment of large volume of LLLW to achieve superior decontamination factors and to discharge minimal radioactivity, thereby realizing the concept of 'near zero discharge of radioactivity'.

Low and intermediate level radioactive solid waste are generated from all the fuel cycle facilities. Various treatment methodologies such as compaction, incineration and melt-densification have been deployed based on the nature of radioactive solid waste to reduce the volume prior to their disposal in Near Surface Disposal Facility (NSDF). Recently, plasma based incineration system has been developed at Trombay to treat large quantities of polymeric waste for achieving augmented volume reduction factor without generation of toxic gases. This radioactive solid waste is finally disposed in a suitable engineered barrier, based on their nature and category of waste, in NSDF, which have been designed based on a multi-barrier concept to retard the migration of radionuclide to the environment. Presently, about eight NSDFs are under operation in the country for disposal of low and intermediate level radioactive solid waste after suitable treatment, if required. The NSDFs will have surveillance for 300 years after closure to monitor the migration of radionuclides, if any. More than 60 years of experience of disposal of solid waste in NSDF enhances the confidence on its design and construction for safe disposal of radioactive solid waste. For example, the NSDF site of BARC, Trombay commenced operations for the disposal of wastes since the 1960's and no noteworthy migration of radionuclides from the disposal site has been observed till date.

Wealth from Waste

HLLW contains many valuable radionuclide such as ^{137}Cs, ^{90}Sr, ^{106}Ru etc. which are potentially useful in many societal applications. Solvent extraction system of WIP, Trombay could demonstrate the recovery of ^{137}Cs, ^{90}Sr and ^{106}Ru for their societal applications. Recovered ^{137}Cs is converted into non-dispersive sealed source of Cs glass pencil for application in blood irradiation. India is the first country to

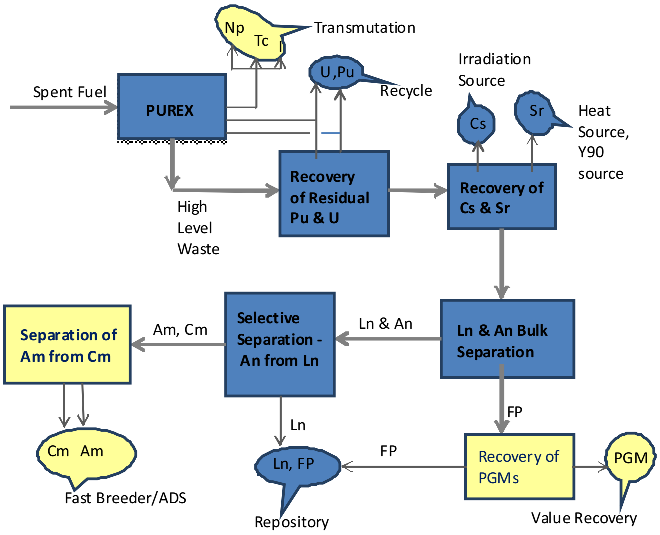

Fig.8: Evolving fuel cycle.

deploy ^{137}Cs in non-dispersive glass form for irradiation application. ^{90}Sr is recovered and purified for milking of clinical grade ^{90}Y for radiopharmaceutical applications. ^{106}Ru based eye plaques, RuBy, has been indigenously developed of different configurations from recovered ^{106}Ru from radioactive waste for affordable eye cancer treatment. Thus recovery of valuable radio-nuclide for deployment in social applications is an important contribution of the reprocessing scheme.

Evolving Fuel Cycle

Development of technologies for novel extractants and partitioning processes have paved new avenues at the back end of the fuel cycle. Closed fuel cycle can be further evolved to separate various radionuclide at different stages of the fuel cycle for their optimum management, as well as societal applications, if needed. A glimpse of the evolving fuel cycle is illustrated in Fig.8.

Future Activities

To reduce the fuel cycle costs, continued R&D efforts are required in the PHWR reprocessing program to further optimize consumption of chemicals, water, energy, manpower, dose etc. Further improvements in processes are needed to reduce the generation of secondary wastes as well as further volume reduction of solid wastes like hull, Coolant tubes etc. Process intensification (larger columns, compact layout, automation, etc.) also need to be evolved to achieve larger throughput in plants with smaller footprints.

As the Indian Nuclear Power program also has BWRs, PWRs, FBRs and it is also planned to establish AHWR, MSR and Research reactors with different types of fuels, continued R&D on back end technologies required for each type of fuel needs to be pursued with vigor to be prepared for future programs which are promising. Keeping in view the reactors operated using imported fuel, robust technological solutions are required for addressing the safe guard aspects. Methodology for disposal of decommissioned wastes from power plants also needs to be evolved.

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