SPENT FUEL REPROCESSING: AN OVERVIEW

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ABSTRACT

India has entered in the field of spent fuel reprocessing as early as sixties by way of R&D studies and finalising the process flow sheet. India's first spent fuel reprocessing plant was commissioned in the year 1965 at Trombay to reprocess spent fuel arising from research reactors. The recovered plutonium is being utilised to feed various programmes of the department. With the passage of time, the country has mastered the technology of spent fuel reprocessing in terms of percentage receovery, reduction in generation of waste volume and improvement in safety culture.

In seventies, the country has entered in the field of reprocessing of spent fuel arising from power reactor by way of design, erection and commissioning of a reprocessing plant at Tarapur (PREFRE) and subsequently one more reprocessing plant has been commissioned at Kalpakkam (KARP).

Presently, spent fuel from KAPS and MAPS are being reprocessed at PREFRE Tarapur and KARP Kalpakkam respectively and fuel from Dhruva & CIRUS is being reprocessed at Plutonium Plant, Trombay.

Recently, the country has also developed the process flow sheet for separation of uranium from thorium rod irradiated in a research reactor and this has been demonstrated by successful commissioning of a plant at BARC, Trombay (UTSF) and recovered uranium is being used for various programmes of the department. Design work is also in progress for separation of uranium from thorium rod irradiated in power reactor. R&D activities are also going on for development of process flow sheet for reprocessing of spent fuel which will be arising from AHWR in near future.

INTRODUCTION

Energy security is the key to the success of a nation in its forward stride and the per capita energy consumed is an index of civilization. Means of achieving this goal depends on the resources at hand and its efficient deployment. Over the years nuclear energy has evolved as a viable alternative to conventional routes of energy production.

For long-term nuclear power production, there are two fuel cycle options that are of relevance and under consideration at the present juncture, viz. the once through cycle with permanent disposal of spent fuel and the closed fuel cycle with reprocessing and recycle of uranium and plutonium. Both options require efficient and safe waste management strategies and are being practiced by different countries as per their priorities.

The proven resources of low priced uranium are insufficient to support a long-term and meaningful contribution to India’s energy demand by way of nuclear energy. Closing the nuclear fuel cycle by reprocessing the spent fuel and recycle of uranium and plutonium back into reactor systems helps in exploiting the full potential of nuclear power and maximizes the resource

utilization. The Indian nuclear resources have been estimated to be around 60000 tonnes of uranium and around 360000 tonnes of thorium. In terms of fossil fuel, this is equal to around 1.2 billion tonnes of coal equivalent through pressurized heavy water reactor (PHWR), around 800 billion tonnes of coal equivalent through fast breeder reactor (FBR) and other reactor systems using thorium. The three stage Indian nuclear energy programme designed in the second half of the last century by the late Homi J. Bhabha is based on the optimum use of the available resources.

The first stage of the nuclear power programme, comprising setting up of Pressurised Heavy Water Reactors(PHWRs) and associated fuel cycle facilities is already in place. Twelve PHWRs are operating and six PHWRs comprising a mix of 540 and 220 MWe rating are under construction. The second stage envisages the setting up of Fast Breeder Reactors(FBRs) backed up by reprocessing plants and plutonium based fuel fabrication plants. In order to multiply the fissile inventory, fast breeder reactors are necessary for our programme. A 40 MWt Fast Breeder Test reactor has been operating at the Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam, since attaining first criticality on 18 October 1985. Project activities of a 500 MWe Prototype Fast Breeder Reactor(PFBR) is in progress at Kalpakkam. The third stage will be based on thorium-^{233}Uranium cycle. ^{233}U is obtained by irradiation of thorium in PHWRs and FBRs. An Advanced Heavy Water Reactor(AHWR) is being developed at Bhabha Atomic Research Centre (BARC) to expedite transition to thorium based systems. Reprocessing forms the vital link between the three stages and the success of the closed fuel cycle would depend on the efficient utilization of plutonium for power generation as it can increase the quantum of energy derived from a given amount of uranium which varies depending on the reactor systems used.

In comparison to the waste from reprocessing and recycle, the disposal of spent fuel on once through basis does not eliminate the plutonium inventory that would keep escalating with the increased nuclear power generation and spent fuel storage sites. It can be reduced only by its sustained irradiation in reactors.

The aim of reprocessing is to recover uranium and plutonium which form the bulk of the spent fuel for recycle in reactors and to compact the fission products wastes in a form suitable for long term storage. The reprocessing waste would contain mainly fission products and small amounts of transuranium elements immobilized in specially formulated glass matrix, sealed in metal canisters designed for long-term storage.

The choice of the Reprocessing and Plutonium Recycle option can endow the nuclear power program with a variety of midcourse options in both uranium and thorium fuel cycle with plutonium forming the vital link between the two. As plutonium is an energy source with a long half life, its utilization for power generation can be in `reprocess to recycle' mode at any given point of time. With a good inventory of spent fuel, this `reprocess to recycle' approach after extended periods of fuel storage, to meet the plutonium demand when it occurs has several advantages which renders reprocessing and nuclear waste management a more viable and safer technology along with reduced man-rem expenditures. Further, with the depletion of the natural uranium and fossil resources, the recycle of reprocessed uranium with altered fissile content would become economically viable.

From the safety point of view, the reprocessing technology has made vast improvements by complying with the national and international regulatory requirements and its annual radioactivity releases through various forms of effluents have steadily decreased over the years. As of today these releases are very small in comparison to the present environmental burden of plutonium and other radioactive elements released through atmospheric testing of nuclear weapons and nuclear accidents.

Reprocessing started in India in the early days of the nuclear energy programme based on indigenous efforts. At present, India has three reprocessing plants to extract plutonium from spent fuel, the first at Trombay, the second at Tarapur and the third at Kalpakkam. The reprocessing capacity is augmented in a phased manner to cater to the needs of the different reactor systems as per the transition of the stages.

PUREX PROCESS

The importance of Reprocessing was evident right at the beginning and was given due attention. By the time India entered into the domain of reprocessing, a certain level of understanding and maturity had already been achieved in this domain and the natural technology choice was PUREX, a solvent extraction process using 30% TBP in an inert diluent mixture of paraffins with 12-14 carbon atoms or pure n-dodecane, totally amenable for automation and remote handling. The basic steps involved in the process are

1. Head-end treatment involving chemical or mechanical decladding followed by dissolution of fuel in nitric acid, feed clarification and adjustment of chemical composition of the solution for solvent extraction.
2. Co-decontamination involving extraction of uranium (as U(VI)) and of plutonium (as Pu(IV)) leaving bulk of the fission products in aqueous phase which goes as high active waste.
3. Washing/scrubbing of organic stream with nitric acid, some times using two nitric acid scrubs of different HNO_3 concentratin to backwash fission products co-extracted with uranium and plutonium
4. Partitioning of uranium and plutonium by selective reduction of Pu(IV) to Pu(III) which goes to the aqueous phase, and back extraction of U(VI) with dilute nitric acid.
5. Further purification of uranium and plutonium streams to obtain U and Pu of desired purity.
6. Treating the used solvent for its recycle
7. Waste management.

PUREX process has been the workhorse of fuel reprocessing for the last few decades and no other process developed before or after can claim its versatility. Today the word "PUREX" is a generic term. The process has undergone many modifications since its introduction and the flow sheets employed vary depending on the practitioners. Fig.1. shows the typical flow sheet employed for the processing of spent fuels discharged from PHWRs with an average burnup between 6000-8000 MWD/t. cooled for 3-5 years The radioactive source term of spent fuel for a typical burnup of 6600 MWD/T discharged from a 220 MWe PHWR after a cooling of 3 and 5 years is given in Table 1.

Evolution of Reprocessing in India

The reprocessing programme was launched with the design, construction and commissioning of the demonstration plant at Trombay. Preliminary design work was started in

January 1959 and completed by January 1961. During this period experiments with pulsed perforated columns were carried out to confirm design data. This was followed by finalization of the process and equipment design, and fabrication and installation of equipment and piping in the process cells and associated systems. The plant was commissioned in 1964 to reprocess the spent fuel from 40 MW_{Th} research reactor CIRUS. The metallic fuel elements 3.4 m long, were of natural uranium clad in aluminium. For the head end treatment, chemical dejacketting was followed by dissolution of the fuel in concentrated nitric acid under reflux conditions. The PUREX process comprised a decontamination cycle, a partition cycle and two separate parallel cycles for the purification of uranium and plutonium. The reductant used in the partitioning stage was ferrous sulphamate solution in nitric acid medium. The final purification of plutonium nitrate solution was by ion exchange. The Trombay plant had a nominal capacity of 30 tonnes HM/year. Being first of its kind, the design philosophy was completely based on direct maintenance concept. The Trombay plant was preceded by a very limited amount of laboratory experiments. The experience in operating the plant and in assessing future requirements in reprocessing served as the basis for R&D programme in the field.. The successful operation of the plant also helped in providing plutonium for pursuing various programmes of nuclear research and development.

The Trombay plant gave sufficient impetus to continue R&D in the domain of reprocessing. In particular, these included solvent degradation studies, development of equipment and systems for higher plant throughput and bringing about improvement in performance, representative sampling and analysis, on-line instrumentation and data acquisition system for process control and operation safety. The results of these efforts were integrated into the design of the second reprocessing plant constructed at Tarapur (commissioned in 1975)for reprocessing of zircaloy cladded spent oxide fuel from Tarapur and Rajasthan Atomic Power Stations. This plant uses a chop-leach technique for the head end and uranous nitrate stabilised by hydrazine as the reductant for partitioning. Instead of the separate co-decontamination and partitioning cycle a combined co-decontamination cum partitioning cycle was introduced. The ion exchange purification of plutonium was replaced with a 20% TBP solvent extraction/stripping cycle to cater to the needs of higher Pu throughput. Several innovations such as pneumatic pulsers in place of mechanical pulsing, air lift as a metering device for radioactive process solutions, thermosyphon evaporators, solvent wash systems for aqueous streams emanating from solvent extraction etc were introduced in the plant. The experience gained from the earlier plant gave enough insight into the material of construction used for critical equipment fabrication and qualification. Austinitic stainless steel variety 304 L was the choice available at that point of time. Except for the head-end, which had provision for remote maintenance of in-cell equipment, the concept used for the rest of the plant was that of direct maintenance. The plant had a nominal capacity of 0.5 tonnes HM/d. Several campaigns of reprocessing were carried out under international safeguards at this facility. This plant has provided valuable experience in material accounting practices to meet the international standards.

This plant also provided experience in the design of appropriate packages and safe in-land transportation of spent fuels which is a vital input for locating the reprocessing facilities. All transport of radioactive materials in India is governed by guidelines issued by the statutory regulatory authority, the Atomic energy Regulatory Board(AERB). These materials can be

transported only in packages, which are designed in accordance with standards and guide lines prescribed by the AERB. These guide lines are based on the International Atomic Energy Agency (IAEA) advisory regulations for the safe transport of radioactive materials. Spent fuel assemblies from power reactors are shipped in special casks known as "Type B" packages (Fig.2). These casks have two functions: the containment of the nuclear materials, and protection of people and the environment from radiation. They are shielded with steel or a combination of steel and lead. These casks are tested to with stand the most severe accidents without breaking or leaking. Standards set by the AERB include dropping the cask, heating it in an intense fire, and immersing it in water. Since 1975 there have been several shipments (Fig. 3) of spent fuel involving several kilometers with no property damage or personal injury, no breach of containment, and very low dose rate to the personnel involved.

The Trombay plant, being the first one built in India for acquisition of skills required in the vital area of reprocessing, had to be subjected from time to time to decontamination inorder to permit access into the process cells for trying out different concepts to optimise the process conditions. In view of the inherently corrosive environment to which process and piping were constantly exposed during the years of operation, it was considered desirable to decommission the plant for effecting the necessary replacements to extend its life. This opportunity was also utilized to increase the capacity to meet additional reprocessing requirements to treat the spent fuel from another research reactor Dhruva built at Trombay. The entire decommissioning programme was meticulously planned to keep the personnel radiation exposures as low as possible, by training personnel in the type of operations involved and devising proper tools and equipment. Attention was paid to control and manage the wastes generated.

The decommissioning procedure specific to this plant comprised several sequential steps. The campaign of internal decontamination of equipment and piping followed multiple decontamination routes using various types of decontaminants. The maximum number of pieces of equipment possible was covered in a single route to minimize the quantity of decontaminants used, so as to restrict the generation of radioactive waste. The range of equipment decontaminated included pulsed perforated plate columns, evaporators, condensers, ion-exchange columns, storage vessels with the associated piping etc. Following the internal decontamination of the equipment, the task of decontaminating interior surfaces of the cells and exterior surfaces of equipment and piping was undertaken deploying various types of tools and gadgets. The success of the decommissioning operations could be gauged from the insignificantly low background levels of radiation fields (<5mR/hr) ultimately achieved, the absence of transferable contamination on cell surfaces, and the fact that personnel exposures were well with in ICRP limits. This resulted in salvaging of most of the cells and permitted almost unrestricted access into them for carrying out fresh installation work. The feed back information and experience obtained during the execution of the above mentioned jobs once again emphasised the importance of making provisions for decommissioning to be incorporated at the design stage of reprocessing plants.

After the successful operation of the power reactor reprocessing facility at Tarapur and the experience gained during the decommissioning operation of Trombay plant, the need arose to augment the reprocessing capacity to treat the spent fuel from the increased nuclear power generation. To cater to the needs of reprocessing zircaloy clad natural uranium oxide spent fuel

from Madras atomic power station, a new plant was designed near the power station location, Kalpakkam, with a 0.5 tonne HM/d capacity. The execution of this plant was carried out with the involvement of industry in the fabrication of equipment, their installation and piping work. With the acceleration of power programme and the increased spent fuel arisings, the need for fissile and fertile material recycling has to be augmented. It is essential that the projects in future are cost effective and the gestation periods will have to be shortened. Even though the engineering design of a reprocessing plant has many complex requirements with respect to equipment, piping, ventilation, exhaust, remote handling etc. (Figs. 4-6), by involving the industry in the detailed design, procurement and construction with the basic design support from the experts, the execution time can be reduced. The Kalpakkam plant design is to serve as a standard design for future plants. The design aims at availability of the plant capacity throughout the operation of the power station. The reprocessing capacity is augmented in a phased manner to cater to the fuel requirements of the reactor systems being introduced into the nuclear energy programme in a "reprocess to recycle" mode. The existing capacity to reprocess 150 tonnes power reactor spent fuel will go up to 550 tonnes by the year 2010 to meet the fuel requirements of PFBR. This will be further enhanced to 850 tonnes by 2014 to cater to the needs of additional FBRs and AHWR.

Around 40 years of experience in the spent fuel reprocessing based on PUREX process has given the confidence that this technology can be successfully employed for the recovery of both U and Pu with an yield exceeding 99.5%. It is reported that by fine tuning of the parameters, this can be improved to 99.8-99.9%. Even though Np inventory in the spent fuel discharged from the PHWR is low, Np recovery can also be achieved by minor changes in the flow-sheet. Feed clarification is one of the important step to obviate the interfacial activity accumulation and crud formation during solvent extraction. Substantial reduction in waste volume was achieved over the years by resorting to salt free reagents. Replacement of ferrous sulphamate with hydrazine stabilised uranous in the partitioning cycle brought a major change in this field which reduced the corrosion problems to great extent and a much cleaner waste is being generated in this cycle. Evaporation followed by acid reduction by formaldehyde is used to reduce the high level waste volume. By resorting to these procedures the high level waste volume could be restricted to 600 liters per tonnes of HM processing. The overall decontamination factors for the Pu and U products from fission products exceed 10^6 and the products are refabricated with minimum radiation protection.

With the present state of the art, reprocessing plants can be built with a high degree of remotisation and automation. The safety features that can be built into the system is very high and adequate steps have been taken to avoid criticality incidents and minimise radiation exposures to O&M staff. Even though the exposure limits have been brought down by ICRP, there is still a margin and the ALARA principle is in practice. The gaseous and liquid effluents undergo thorough processing prior to the discharge to the environment. Over the years, improved practices has brought down the discharge levels to much lower levels than the stipulated values. This has resulted in a renewed interest in the nuclear power all over the world and it is inevitable that one day nuclear power will have its re-emergence.

In the technological domain much changes have taken place. The uranous production by electrolysis has been standardised to optimum current efficiency and conversion by resorting to

new electrode material like titanium substrate insoluble anode and titanium cathode. Catalytic reduction of uranium(VI) to uranium(IV) over finely divided platinum dust is also being developed as another effective method of U(IV) production.

The in-situ reduction of U(VI) to U(IV) for the partitioning of Pu using specially designed mixer settlers and pulsed columns was also demonstrated on a pilot plant scale using titanium cathode and titanium substrate insoluble anode. The operating experience gained from these pilot studies will be used for firming up the design of such systems for future reprocessing plants.

Homogeneous sampling of key measurement points is vital to the nuclear material management strategy and needs careful engineering design to achieve the target value. Vacuum assisted airlift operated sampling design has been developed in house to meet the sampling requirement of the PUREX process with in built safety features to control the vacuum and the flooding of the sample. This system was thoroughly tested during the IAEA safeguard campaigns at Tarapur. This has validated the design aspects of the sampling system. The analytical values matched closely with those reported by the safeguard inspector. Further efforts are on to automate the sampling system to minimize the exposure of the personnel. Schematic diagram of a typical sampling circuit is given in Fig. 7.

Major engineering developments have taken place in the head-end systems and has direct bearing on the throughput of the reprocessing plant. The shearing machines used at Tarapur plant was an imported commercial system. An indigenous shearing machine has been developed and installed at KARP incorporating many design improvement over the imported machine, is working well. Changes has also been incorporated in the clapper door assembly to improve reliability and plant throughput. The design of shearing machine and clapper assembly is being standardised for the subsequent reprocessing plants. Laser assisted dismantling of the fuel bundle followed by single pin chopping is also being developed. Developments are under way to design and fabricate indexing casks and automated charging of the fuel bundles into the shearing machine magazine in an effort to increase the throughput with minimum radiation exposure to operator.

Another area which essentially determines the operating life of a reprocessing plant is the corrosion resistance of the material of construction. Some recent developments in corrosion and radiation resistant materials have resulted in reliable performance with reduced maintenance. The materials for nuclear reprocessing have to ensure resistance against intergranular corrosion in nitric acid at different concentrations and temperatures. Earlier plants had worked on low carbon grade 304L stainless steel. Factors other than sensitization that can cause intergranular corrosion in oxidising nitric acid environments are the presence of active inclusions and segregation of Si and P to grain boundaries. With this understanding of the corrosion of austenitic stainless steel in nitric acid environments, tighter specifications have been formulated. These challenges have led to the development of nitric acid grade(NAG) type 304 L SS. The NAG stainless steel produced in India for reprocessing applications has already achieved a corrosion resistance rate as low as a value as 10 mpy.

Irradiated thorium Processing

For India, the building up of fissile material inventory at a fast pace is a prerequisite for the early introduction of thorium in the fuel cycle as natural thorium does not contain any fissile component. As the fissile inventory increased with the advancement of the nuclear

energy program, the various steps towards implementation of thorium fuel cycle were also initiated. To meet the challenges of thorium based fuel cycle, the R & D efforts are directed towards extractive metallurgy of thorium, fuel fabrication and utilization in reactors, reprocessing of irradiated thorium for ^{233}U recovery and studies on ^{233}U based reactor system. Irradiation studies with thoria started in the blanket region of CIRUS. Reactor Physics studies led the use of thoria in the flux flattening during the initial startup of PHWR. With the introduction of AHWR into the power programme, where a Th-Pu MOX is used as fuel, an altogether new dimension will be added to reprocessing requiring a three components separation In addition to this the well known radiological aspects of thorium fuel cycle also need to be tackled as most of the problems of this cycle are associated with reprocessing, fuel fabrication and the waste management.

When BARC started working on THOREX process, acronym for the process used for the separation of ^{233}U and Th from irradiated thoria, the basic laboratory data were scarce and most of the batch and counter-current extraction and stripping data were generated by in-house studies. Different flow-sheets were developed for the recovery of ^{233}U alone or for both ^{233}U and thorium. As the recovery of ^{233}U alone was contemplated during the initial phase of the DAE program, more stress was given to the process using 5% TBP-Shell Sol-T (SST) solvent.

The chemical decladding and the acid dissolution of the decladded fuel rods are carried out. The presence of fluoride ion helps in the dissolution of thorium oxide by nitric acid. The use of fluoride ion enhances the corrosion of stainless steel equipments. This problem is controlled by the addition of appropriate amounts of aluminium to complex the excess fluoride ion. However, if the fluoride ions remain uncomplexed in any of the process streams, it could enhance corrosion problems. The method of preparation of ThO_2 has a role to play in the dissolution pattern of the final oxide. Oxides prepared by sol gel route are reported to show better dissolution characteristics. If the thoria is clad in zirconium based alloys or in SS as expected in PHWRs and FBRs, then mechanical chop-leach process is used for dissolution.

The versatile extractant TBP in hydrocarbon diluent still remains the best choice for the extraction of both ^{233}U and thorium or for the selective extraction of ^{233}U alone. Depending on the requirement whether both thorium and ^{233}U are to be recovered or only ^{233}U is to be recovered, the TBP content in the diluent (usually Shell Sol-T, dodecane or n-paraffin) to be used as extractant varies. Generally, 3 to 7.5% TBP (at BARC, 5% TBP) has been used as extractant when ^{233}U alone is to be recovered. In this technique, ^{233}U is extracted preferentially with 5% TBP leaving bulk of the thorium in the raffinate. A maximum of 8 g/l thorium is co-extracted along with ^{233}U in this step, when 5% TBP is used. The organic phase is scrubbed with 1-2 M nitric acid to remove the co-extracted thorium. Thus the organic phase finally contains only ^{233}U, and its final thorium contamination depends on the number of scrub stages provided and their efficiency in scrubbing out thorium. The ^{233}U from the organic phase is finally stripped with strip acid of 0.01 M HNO_3 to recover the extracted uranium.

An engineering scale Facility for ^{233}U Separation (FUS) has been designed and commissioned at Trombay for the processing and recovery of ^{233}U from CIRUS and DHRUVA irradiated thorium fuel rods on a regular basis. The modifications felt necessary from the pilot

plant studies was incorporated in the design of equipment and in the choice of process flowsheets. Specially designed CALMIX mixer settlers have been chosen as contactor equipment. The scrub section has been extended sufficiently to provide for adequate scrubbing of thorium from the uranium loaded organic. The loaded organic stripped with 0.01 M HNO_3 and the ^{233}U product solution is purified using a cation exchange resin (Dowex 50X4). The loading effluent containing ^{233}U is concentrated and precipitated as ammonium diuranate and finally calcined to oxide. A schematic diagram of the THOREX flow sheet is given in Fig. 8.

In the Fast reactor fuel reprocessing domain, it appears that the PUREX process will be the choice in the immediate future if adequate measures are taken to tackle the solvent degradation due to increased radiolysis resulting from higher burnup. Use of fast contactors to reduce the residence time coupled with a more efficient solvent clean up can take care of the problem to a certain extent. Currently, the evaluation of the flow sheet developed for FBTR spent fuel reprocessing is in progress on a laboratory scale. However the pyrochemical methods will be the ultimate process due to process compactness, absence of solvent degradation, reduced criticality problems, total recycling efficiency of actinides and low waste volumes. Basic research on the molten salt electrorefining process for advanced fuels, such as alloy, carbide and nitride, is in progress in India.

DEVELOPMENTS IN REPROCESSING

Even though PUREX process is well entrenched to meet the present and near future challenges, it is being constantly improved to achieve higher and higher goals. Development activities are being pursued in the areas mentioned below to enhance the process performance.
Chemical aspects of various process steps are continuously under refinement to

1. make the process cheaper and more reliable
2. improve the recoveries of uranium and plutonium and the decontamination factors
3. Development of efficient partitioning techniques
4. Co-processing and co-conversion for direct production of U-Pu MOX
5. reduce the waste volume generation and to eliminate inter mediate level waste streams
6. simplify the process eg. reduce number of cycles
7. remove the long-lived actinides and fission products from high level waste to minimise hazards of its long term storage
8. develop alternate processes

Side by side with changes in the chemical aspects, developments taking place elsewhere in the science and technology frontier had also its impact on the PUREX process. Equipment design, on-line measurement of process parameters, computerised data logging and control, robotics and automation, material development etc. will taken this technology to further heights by reducing direct maintenance, providing automatic built-in safety features against accidents which in turn reduced the radiation exposure to the working personnel

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REFERENCES

1. Anil Kakodkar, "Nuclear Power in India: An Inevitable Option for Sustainable Development of a sixth Humanity", World Nuclear Association Annual Symposium, London (2002).
2. Sethna H.N., Srinivasan N., "Fuel reprocessing Plant Trombay", Peaceful Uses of Atomic energy (Proc. 3rd Int. Conf., Geneve, 1964),10 Un, New York (1965),272
3. Sethna H.N., Srinivasan N., Chem. Engng. Prog. (symp. Ser.), 65, (1969)95
4. Sethna H.N., Srinivasan N., Nucl. Met. Symposium on Reprocessing of Irradiated Fuels, Ames 1969
5. Prasad A.N., Kumar S.V. "Indian Experience in Fuel Reprocessing", Nuclear Power and Its Fuel Cycle (Proc. Conf. Salzburg, 1977)3,IAEA, Vienna(1977),571
6. Rao M.K. "Decommissioning Aspects of Nuclear Chemical Plant", Decommissioning of Nuclear Facilities (Proc. Symp. Vienna, 1978), IAEA, Vienna(1979),597
7. Prasad A.N., Kumar S.V. " Fuel Reprocessing Experience in India ", (Int. Conf. On Nuclear Power Experience, Vienna,1982),Vienna(1983)831.

Table 1: Radioactive source term of the Spent fuel discharged from a 220 MWe PHWR

Nuclide	3Year cooling	5 Year Cooling	Nuclide	3Year cooling	5 Year Cooling
Actinides g/t HM			Fission Products Ci/t HM		
U234	4.40E+01	4.40E+01	Sr 90	1.38E+04	1.32E+04
U235	2.53E+03	2.53E+03	Y 90	1.38E+04	1.32E+04
U236	6.91E+02	6.91E+02	Zr 95	5.99E+00	2.19E-03
U238	9.86E+05	9.86E+05	Nb 95	1.38E+01	5.04E-03
Np237	2.36E+01	2.37E+01	Tc 99	2.84E+00	2.84E+00
Pu238	2.88E+00	2.84E+00	Ru106	2.07E+04	5.24E+03
Pu239	2.67E+03	2.67E+03	Rh106	2.07E+04	5.24E+03
Pu240	8.92E+02	8.91E+02	Sb125	1.46E+03	8.86E+02
Pu241	1.50E+02	1.36E+02	Cs134	5.73E+03	2.92E+03
Pu242	3.64E+01	3.64E+01	Cs137	2.00E+04	1.91E+04
Am241	2.52E+01	3.88E+01	Ce144	2.92E+04	4.92E+03
Am243	1.09E+00	1.09E+00	Pr144	2.92E+04	4.92E+03
Cm242	3.54E-03	1.84E-04	Pm147	2.39E+04	1.41E+04
Cm243	3.50E-03	3.34E-03	Eu154	8.80E+02	7.49E+02
Cm244	6.91E-02	6.40E-02	Eu155	5.07E+02	3.83E+02

Basis: Average burnup of 6600 MWD_t/ton
computed using Origen 2.

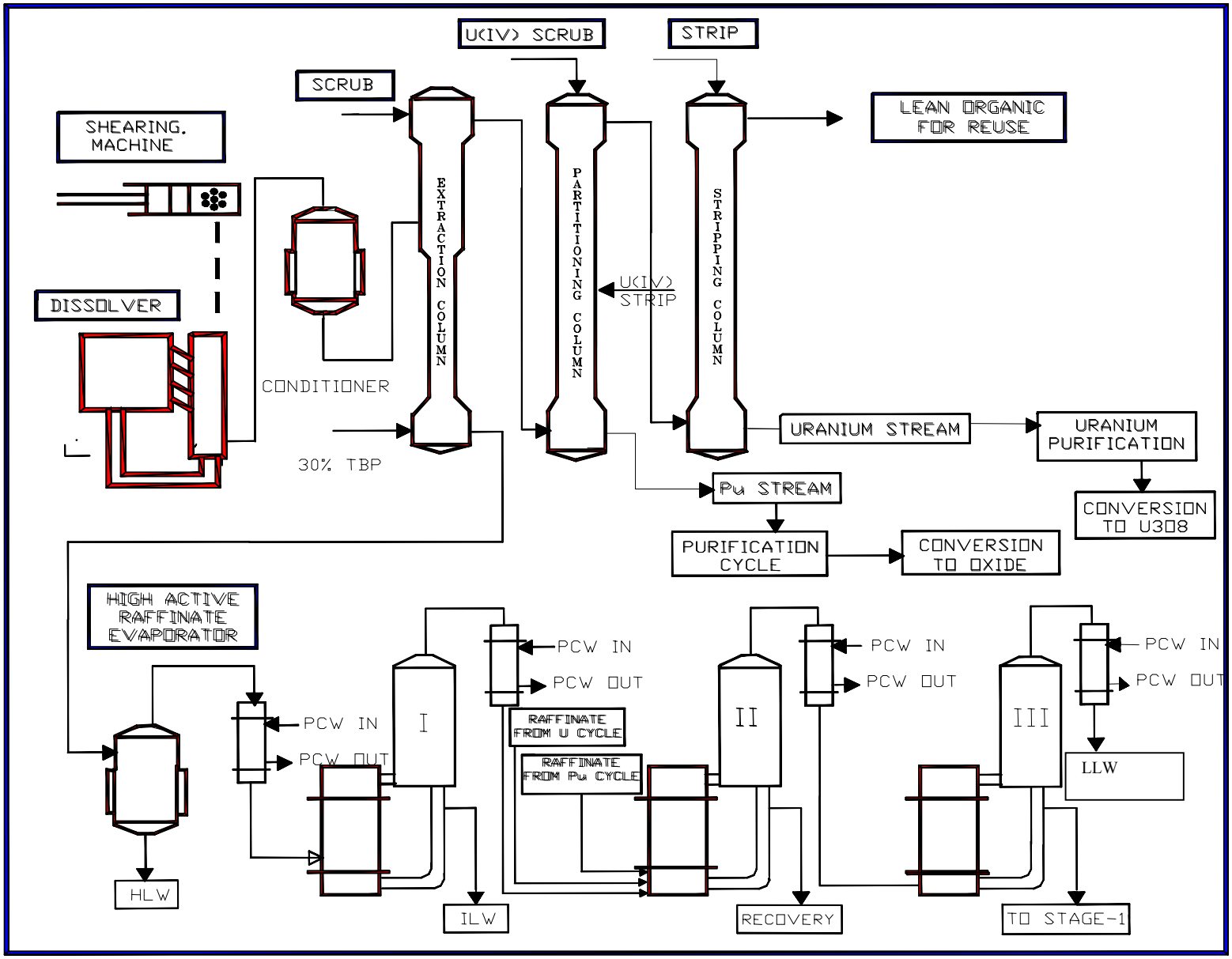

Fig.1. PUREX Process Flow Sheet

Fig.2. Spent Fuel Transportation Cask

Fig.3. Spent Fuel Shipment on Trailer

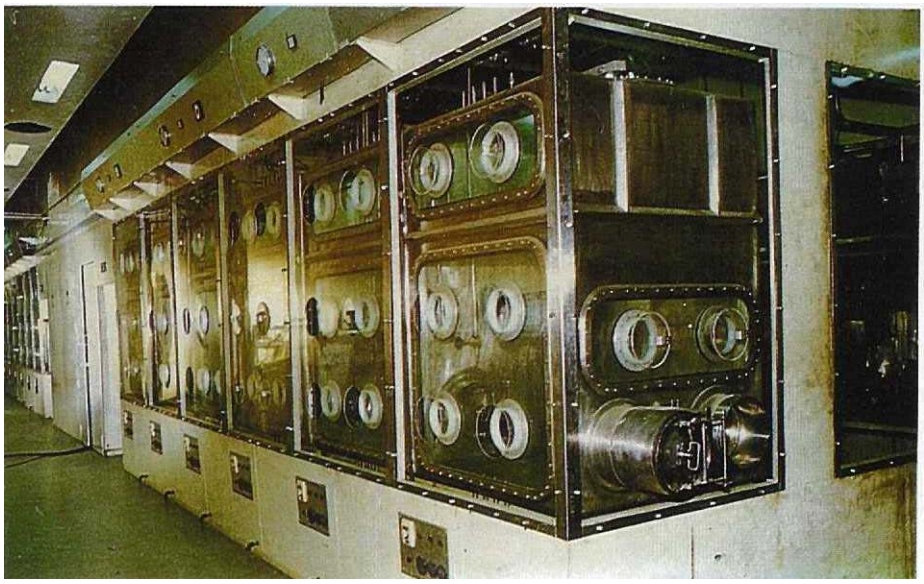

Fig. 4. Glove Box Train for Plutonium Reconversion

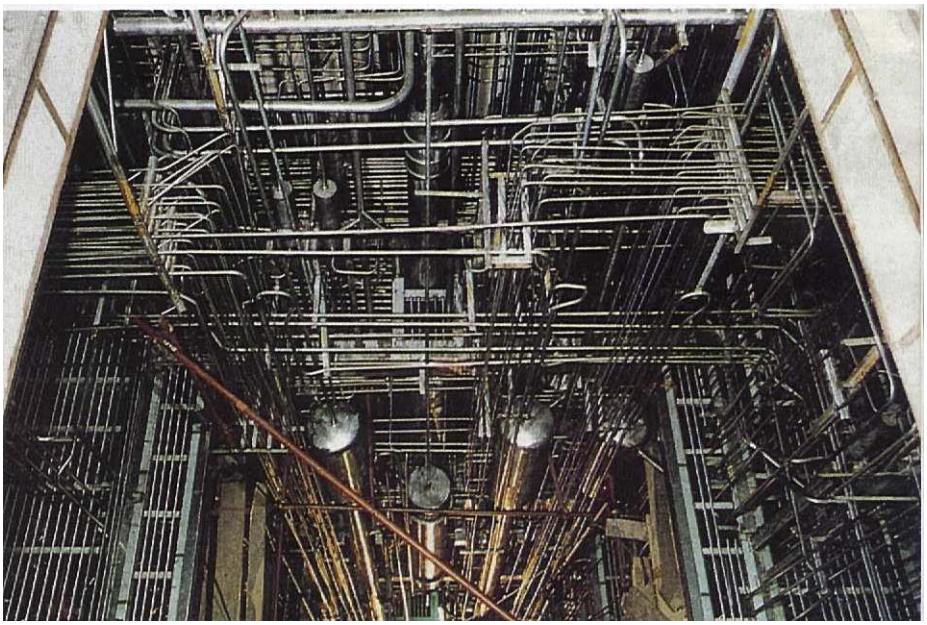

Fig. 5 Process Piping Inside the Cell of a Reprocessing Plant

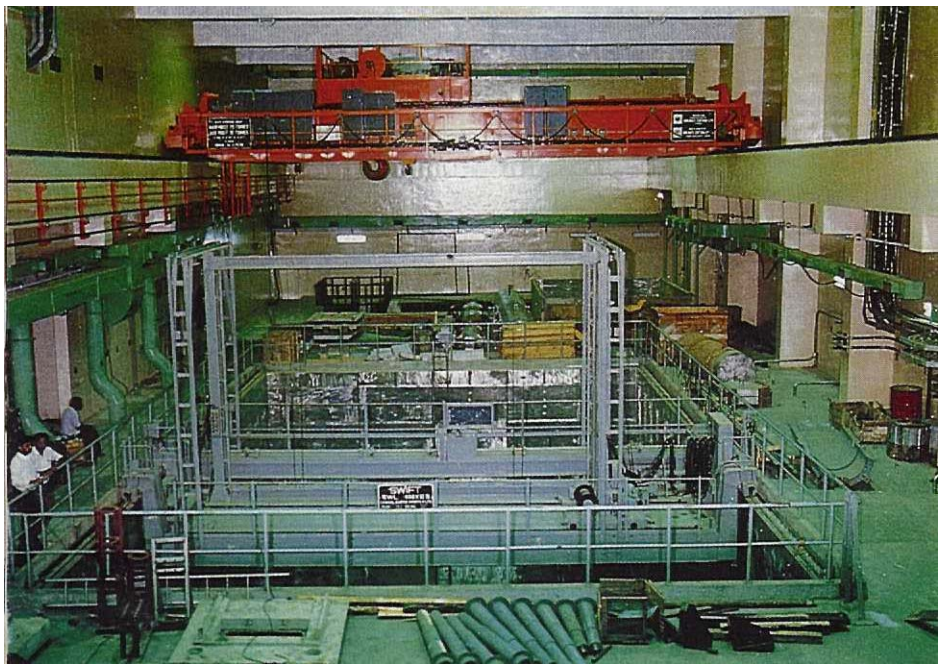

Fig.6. Fuel Handling Area of Kalpakkam Reprocessing Plant

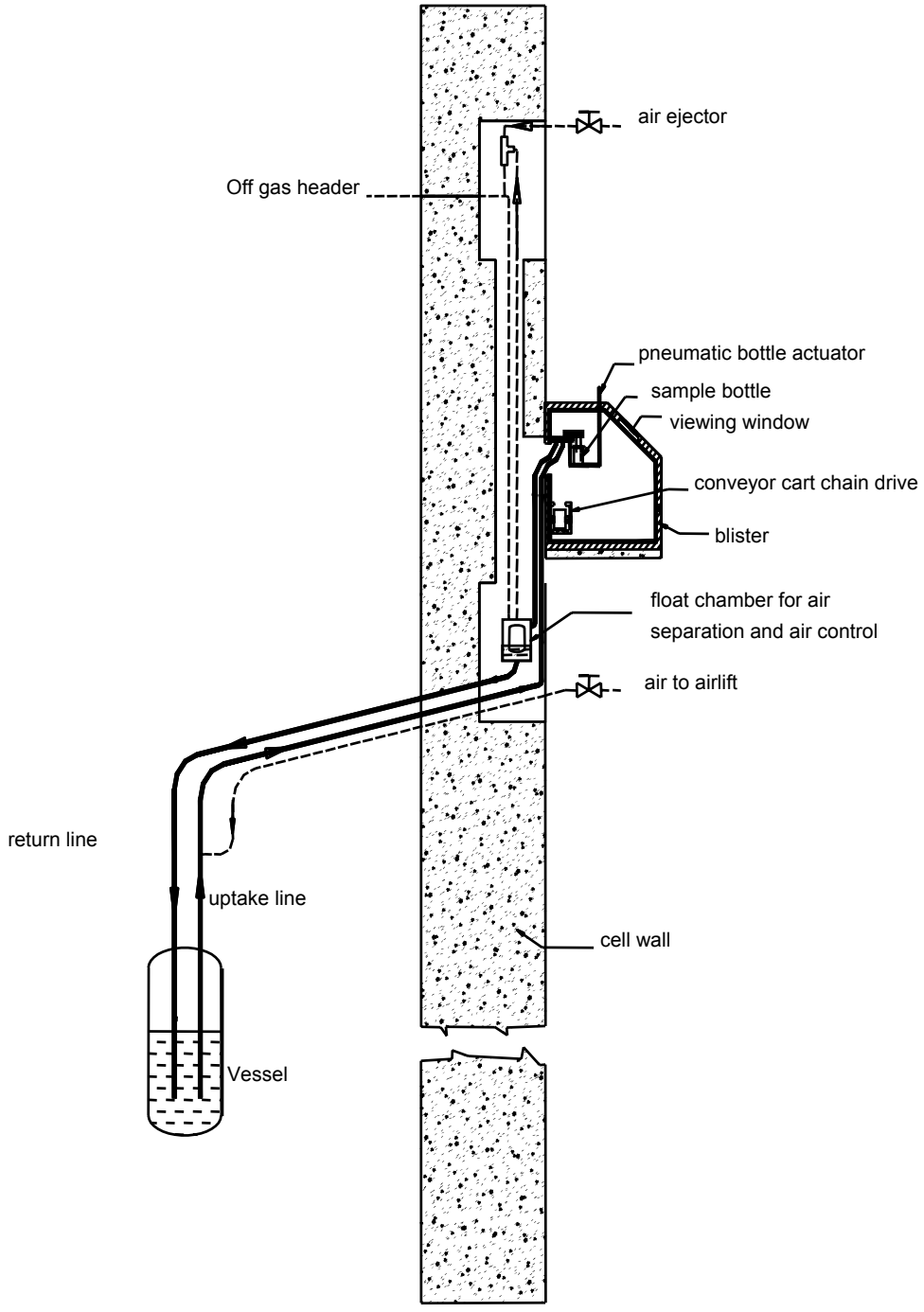

Fig. 7. Schematic Diagram of a Typical Sampling Circuit

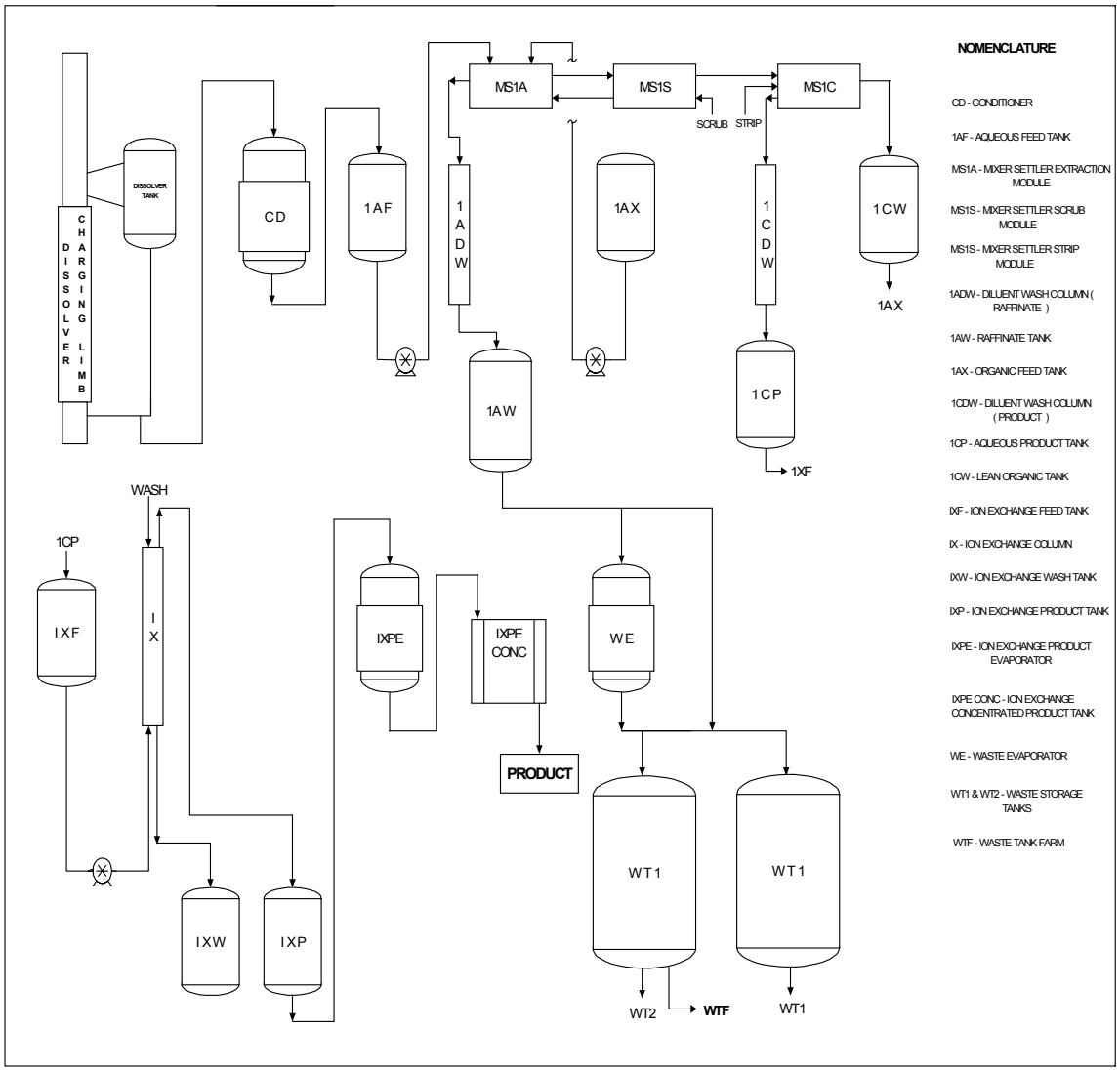

Fig.8. THOREX Process Flow Sheet