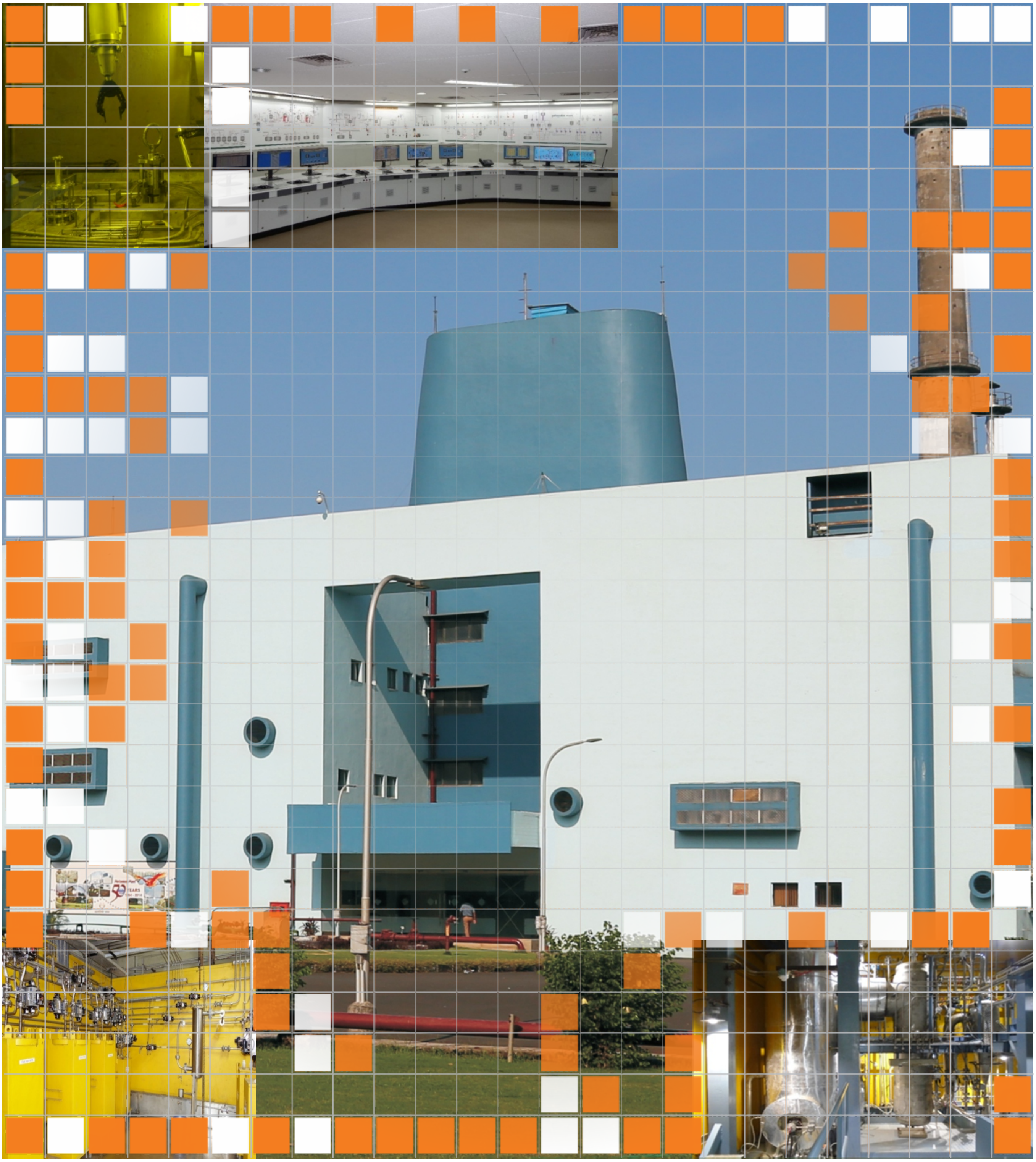
NUCLEAR FUEL CYCLE

V2



THE NUCLEAR FUEL CYCLE vertical of the DAE Vision Programme focuses on the exploration and enhancement of uranium, thorium, and rare earth (RE) material reserves in the front end. In the back end, construction and commissioning of integrated fuel reprocessing plants for PHWRs and advanced reactor systems are critical for efficient fuel recycling. These efforts are complemented by the adoption of waste management technologies to ensure safe and sustainable disposal of nuclear waste.

In BARC, comprehensive initiatives are underway to ensure the sustained safe and reliable operation of nuclear facilities, enhance overall plant performance, optimize resource utilization, and maintain environmental releases to minimum.

Research and development efforts are being intensified to develop advanced, future-ready technologies and to recover valuable radioisotopes from nuclear waste, supporting societal applications and promoting the sustainable management of the back-end fuel cycle.

Front end of Fuel Cycle

Recovery and Extraction of Atomic Minerals: The recovery of uranium and by-products from low-grade Kudada ore of the Singhbhum Shear Zone, containing 0.035% U_3O_8 and 0.2% total rare earth elements (REE), has been successfully achieved. A process flow-sheet for uranium recovery through acid leaching–ion exchange–precipitation route was developed, demonstrating the feasibility of producing yellow cake assaying 82.5% U_3O_8 with an overall uranium recovery efficiency of 92%.

Experimental separation studies further confirmed that uranium can be effectively adsorbed from leach liquor using a strong-base anion exchange resin. The resin's breakthrough and saturation capacities were optimized, and subsequent elution and precipitation yielded uranium peroxide as the final product.

A comprehensive extraction process for the recovery of rare earth elements (REEs) and valuable by-products from Dantala ore of the Siwana Ring Complex (SRC), Rajasthan, has also been developed. The integrated flowsheet comprising flotation, leaching, solvent extraction, and precipitation enabled recovery of approximately 85% of REE values as mixed oxalates. Concurrently, recoveries of around 75% were achieved for niobium (Nb), zirconium (Zr), and hafnium (Hf) in the form of mixed hydroxides.

Chemical analysis of the Ramaniya ore sample from the SRC showed 0.36% total REE content (with 37% heavy rare earth elements), in addition to 0.68% Zr, 0.034% Nb, 0.015% Hf, and trace quantities of thorium and uranium.

Rare Earths Recovery: Preparation of samarium metal has been successfully demonstrated at a batch scale of 120g through the lanthano-thermic reduction of samarium oxide. Calcio-thermic reduction technology for large-scale production of neodymium–praseodymium (Nd-Pr) metals has been validated at kilogram scale. Additionally, pilot-scale production trials of lamp and LED phosphors at a 5kg scale were successfully demonstrated at IREL's RETTP facility in Bhopal.

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BARC provided comprehensive technical guidance, including standard operating procedures, for the demonstration followed by commissioning of plants for the preparation of samarium metal and lamp and LED phosphors at IREL's RETTP facility in Bhopal.

A new cathode material, lanthanum hexaboride (LaB_6), has been successfully synthesized as an import substitute for use in electron beam accelerators. By optimizing the processing parameters, fully dense LaB_6 pellets (10mm in diameter) were produced in batches of up to 1kg, marking a significant milestone in indigenous advanced material development.

Back end of Fuel Cycle

Spent Fuel Reprocessing: The Plutonium Plant at Trombay has successfully completed over six decades of spent fuel reprocessing, marking a significant milestone in India's nuclear fuel cycle program. As the country's first reprocessing facility, it played a pivotal role in developing the technology base and operational expertise for recycling Heavy Water Reactor spent fuel.

The Effluent polishing system at WIP Trombay.

The operations at several radioactive waste management facilities in Trombay focused on recovering valuable radioisotopes for societal applications, minimizing environmental discharges, and reducing secondary waste generation.

Reprocessing of thoria bundles irradiated in Pressurized Heavy Water Reactors (PHWRs) was successfully demonstrated at the WPRTRF facility in Trombay.

To improve process efficiency and product morphology, equipment for converting uranyl nitrate solution to uranium oxide via the ammonium di-uranate route was upgraded. These upgrades include precise pH and temperature control during precipitation, improved filtration through a Nutsche filter system, reduced moisture content using a conical dryer, and enhanced automation.

Radioactive Waste Management: The radioactive waste management facilities at Trombay, including the Waste Immobilization Plant (WIP), Effluent Treatment Plant (ETP), Decontamination Centre (DC), and Radioactive Solid-Waste Management Site (RSMS) - were operated to ensure the safe and effective management of radioactive wastes arising from fuel cycle facilities and radiological laboratories of BARC. These operations focused on recovering valuable radioisotopes for societal applications, minimizing environmental discharges, and reducing secondary waste generation.

Low-level effluents received at the ETP were decontaminated prior to discharge using chemical precipitation and ion exchange methods to minimize environmental impact.

The Decontamination Centre processed protective gear and cut-end rods for reuse, while solid radioactive wastes were compacted or incinerated via a plasma-assisted incinerator to achieve significant volume reduction before disposal in the Near Surface Disposal Facility (NSDF).

Ageing Management of Backend Fuel Cycle Facilities: Effective ageing management is essential for ensuring the long-term safety and reliability of nuclear fuel cycle facilities.

A comprehensive ageing management program has been implemented to sustain backend operations by identifying, evaluating, and mitigating risks associated with the degradation of equipment, systems, and structures.

The strategy combines preventive and corrective measures. Preventive actions include routine inspections, testing, and maintenance to detect early signs of wear or malfunction, while corrective measures involve repair, replacement, or modification of components at the end of their service life.

Continuous ageing management activities are being implemented across reprocessing and waste management facilities at Trombay, extending their operational longevity and maintaining high safety standards.

Upgraded PLC-SCADA System of WIP Trombay.

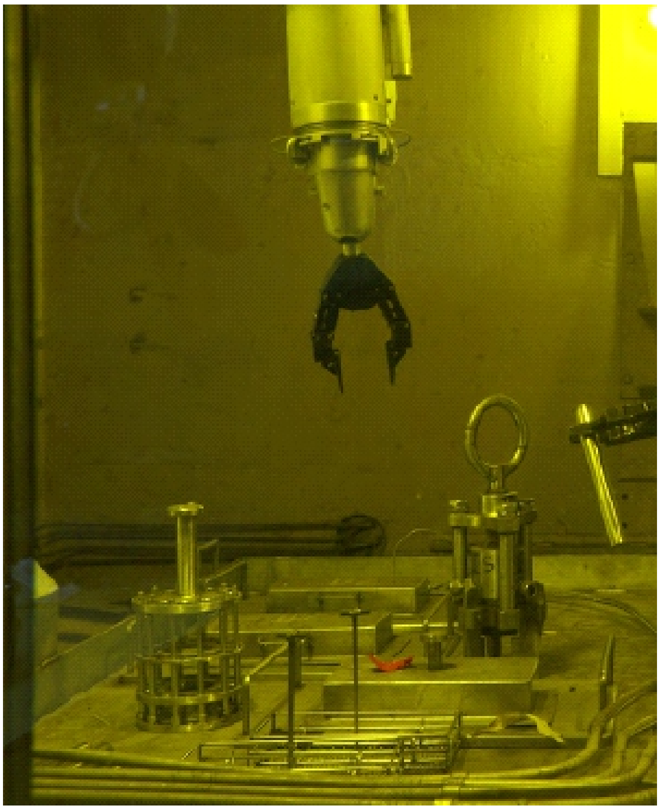
Recovery of Valuable Radionuclides for Societal Applications: India has developed and deployed advanced technologies for the recovery of valuable radionuclides such as Cs-137, Sr-90, and Ru-106 from high-level liquid waste (HLLW) for beneficial use in healthcare and industry.

Cesium-137 is converted into a non-dispersive cesium-glass matrix for use in blood irradiation devices that prevent transfusion-associated graft-versus-host disease. To date, over 450 kCi of Cs-137 have been recovered, yielding about 250 Cs-glass pencils. A re-designed production system with single-step pouring and an indexing arrangement has improved annual capacity from 40 to 100 pencils.

Strontium-90 is purified for the generation of Yttrium-90 (Y-90), a key isotope in targeted internal radiotherapy, particularly for neuroendocrine tumors.

A di-glycol amide (DGA)-impregnated resin column was developed to enhance Y-90 extraction efficiency. Process validation is underway for regulatory clearance from the Radiation Protection Committee (RPC).

Ruthenium-106 recovered from waste streams is utilized to fabricate RuBy plaques — an indigenous product for ocular cancer therapy. Currently, fifteen hospitals in India employ RuBy plaques in medical treatments.



Cesium glass pencil making in progress.

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Research and Development for Back end of Fuel Cycle: Research and development activities are underway on the reprocessing of various nuclear fuels envisaged under the departmental programme. A comprehensive roadmap for fuel reprocessing in molten salt reactors (MSRs) and molten salt breeder reactors (MSBRs) has been formulated and is being actively implemented. India's IMSBR initiative aims to utilize thorium resources to enhance long-term energy security, with the commissioning of a 5 MWth demonstration reactor representing an initial milestone.

Ongoing MSR reprocessing research focuses on protactinium recovery, uranium recycling, and efficient removal of fission products to sustain optimal reactor performance. Emphasis is placed on pyrochemical technologies, including fluoride volatility, reductive extraction, vacuum distillation, and electro-refining.

Engineering-scale development of these processes will strengthen the objectives of Aatmanirbhar Bharat by advancing indigenous fuel cycle capabilities and promoting sustainable nuclear energy generation.

A pyrolysis–incineration-based process has been developed for the treatment of alpha-bearing solid wastes comprising cellulose, plastic, and rubber.

A plant-scale system, housed within a series of glove boxes, was operated continuously on an inactive-campaign basis to demonstrate throughput capacity. Parallel research on zircaloy hull management involves developing a chemical dissolution process using sulfur monochloride and thionyl chloride.

Laboratory-scale tests involving 250 g of zircaloy-4 cladding successfully demonstrated complete dissolution and zirconium recovery. Performance

Incinerator (left) & Quencher (right) of Organic Liquid Waste Incineration System (OLWIS).

evaluation of CA-BTPhen, developed for single-step minor actinide partitioning, is currently in progress.

A Cold Crucible Induction Melter (CCIM), developed by BARC, to address operational and design challenges in high-level liquid waste (HLLW) vitrification, has been installed at WIP, Trombay.

The installation included a high-frequency induction heating power supply, induction coils, and busbar assemblies, which were successfully integrated with the melter.

Given that the current generation of Thermosyphon Evaporators (TSEs) in back end facilities has shown vulnerability to failure due to severe intergranular corrosion (IGC) of SS304L heat exchanger tubes, next-generation heat exchangers have been fabricated using titanium alloy tubes and titanium-clad stainless steel tube sheets.

Fabrication was accompanied by rigorous inspections and stringent acceptance criteria. Five such units were successfully fabricated, comprehensively tested, and are now ready for deployment in back end fuel cycle facilities.

Computational Method for Prediction of Chemical Durability of Nuclear Glass: A computational scheme has been developed to predict the chemical durability of sodium borosilicate (NBS) glass by performing large scale molecular dynamics (MD) simulations.

Cascade evolution profiles for irradiated glass captured the depolymerization of glass and first-time leach rate in irradiated glass was predicted.

Simulations showed that structural damage scaled with total deposited energy rather than recoil energy. Overlapping of structural profiles for PKA energies below 10 keV, suggest that structural recovery is feasible at lower recoil energies. The findings suggest that while NBS glass may undergo moderate structural and chemical degradation, it will retain long-term stability under repository conditions.

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Plutonium Plant in BARC Trombay.

Front end of Fuel Cycle

Recoveries of around 75% were achieved for the atomic minerals niobium (Nb), zirconium (Zr), and hafnium (Hf) in the form of mixed hydroxides.

Uranium recovery through acid leaching–ion exchange–precipitation route was developed, demonstrating the feasibility of producing yellow cake with an overall uranium recovery efficiency of 92%.

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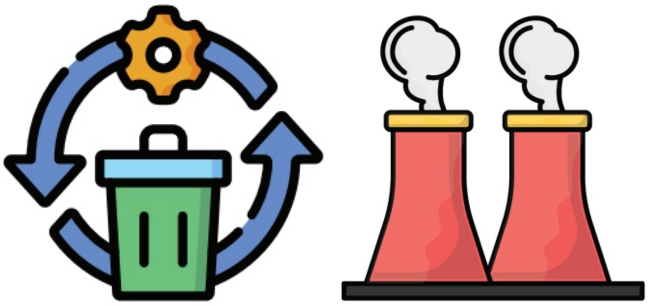

Back end of Fuel Cycle

Reprocessing of thoria bundles irradiated in PHWRs was successfully demonstrated at Trombay.

Radionuclides Cs-137, Sr-90, and Ru-106 are obtained from high-level liquid waste with key applications in healthcare and industry.