Nuclear Fuel Cycle and Materials Technologies

Objective

To enhance and further strengthen the capabilities of interested Member States for policy making, strategic planning, technology development and implementation of safe, reliable, economically efficient, proliferation resistant, environmentally sound and secure nuclear fuel cycle programmes.

Uranium Production Cycle and the Environment

The projected growth in nuclear power is expected to increase uranium requirements for power reactors from 68 640 tonnes of uranium per year (t U/a) in 2010 to between 107 600 and 136 900 t U/a in 2030, based respectively on the reference and high nuclear growth scenarios of the World Nuclear Association.

The 2010 edition of the joint IAEA–OECD/NEA publication *Uranium 2009: Resources, Production and Demand*, the next edition of which will be published in 2012, divides conventional uranium resources into 'identified resources' and 'undiscovered resources'. According to the report, most current exploration is focused on new areas with estimated undiscovered resources, and much of the effort is in countries with no recent history of uranium exploration.

To address challenges in identifying uranium resources in 'greenfield' areas, i.e. areas that have not been previously investigated, the Agency organized a technical meeting on uranium provinces and mineral potential modeling. At the meeting, held in Vienna in June, some 80 experts from 35 Member States discussed the occurrence, nature and control of economic uranium mineralization in current and potential 'uranium provinces'. Uranium provinces are regions of the Earth's crust with rocks having uranium concentrations above normal abundance, generally as distinct deposits. The participants agreed that the critical application of mineral potential modelling techniques would be essential in locating new uranium deposits. They stressed the relative importance of different mantle and crustal processes and geological cycles in the formation of 'mega-uranium' provinces, for example the Central Asia uranium province and the Middle East–North Africa–Latin America phosphate uranium province. They concluded that further research is needed to globally consolidate the present understanding of the formation of uranium provinces, and that greater attention should be given to mineral potential modelling in mega-uranium provinces that cross national borders.

Unconventional uranium resources and thorium further expand the resource base. These resources include uranium in seawater and resources from which uranium is only recoverable as a minor by-product. Past estimates of potentially recoverable uranium associated with phosphates, non-ferrous ores, carbonatite, black schist and lignite are of the order of 10 Mt U.

In response to rising interest, the Agency organized a technical meeting on uranium extraction from phosphates. The meeting, which was held in Vienna in September and attended by 40 experts from 27 Member States, introduced the concept of 'comprehensive extraction' to optimize the return from any mining and processing operation. The objective is to extract all elements of current and potential value, not just a single target commodity. The meeting also discussed technology, operational efficiency, environmental impacts and sustainability in the context of past experience, as well as current research and priority areas in the phosphoric acid pre-treatment and solvent extraction stages, where further attention could improve overall economics. The meeting strongly endorsed training and professional development in the 'triple bottom line method', comprising economic, social and environmental criteria for measuring and evaluating returns from enterprise performance.

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The Agency also organized an international training meeting/workshop course on uranium extraction from phosphates and phosphoric acid, in Marrakech, Morocco, in association with the Moroccan Association of Nuclear Engineers (AIGAM) and with the support of the Moroccan Ministry of Energy, Mines, Water and Environment. The 50 participants from over 30 Member States received training in starting uranium extraction plants in phosphoric acid production facilities (Fig. 1).

World thorium resources are estimated to be about 6 Mt. Although thorium has been used as a nuclear fuel on a demonstration basis, its broader use would depend on the commercial deployment of thorium fuelled reactors, which is currently a gradual process. In 2011, India started the site selection process for an experimental thorium fuelled 300 MW(e) advanced heavy water reactor that is expected to be operational by 2020.

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The Agency held a technical meeting on world thorium resources, in October in Thiruvananthapuram, India (Fig. 2). Organized in cooperation with Indian Rare Earths Limited (IREL) and with support from the Atomic Minerals Directorate for Exploration and Research, Hyderabad, and the University of Kerala, Thiruvananthapuram, and with over 50 experts attending from 20 Member States, the meeting focused on resource estimates, exploration, production and the use of thorium in the nuclear fuel cycle, with an emphasis on environmental, health, safety, economic and social licensing aspects. The participants noted thorium's promise in extending the global deployment of nuclear power and concluded that the technology is sufficiently mature for initial commercial deployment, although no one has yet taken that step. It also addressed the co-production of thorium and rare earth elements, and the importance of conserving thorium and defining good practices to store co-produced thorium for future use.

FIG. 1. Uranium extraction workshop in Marrakech, Morocco.

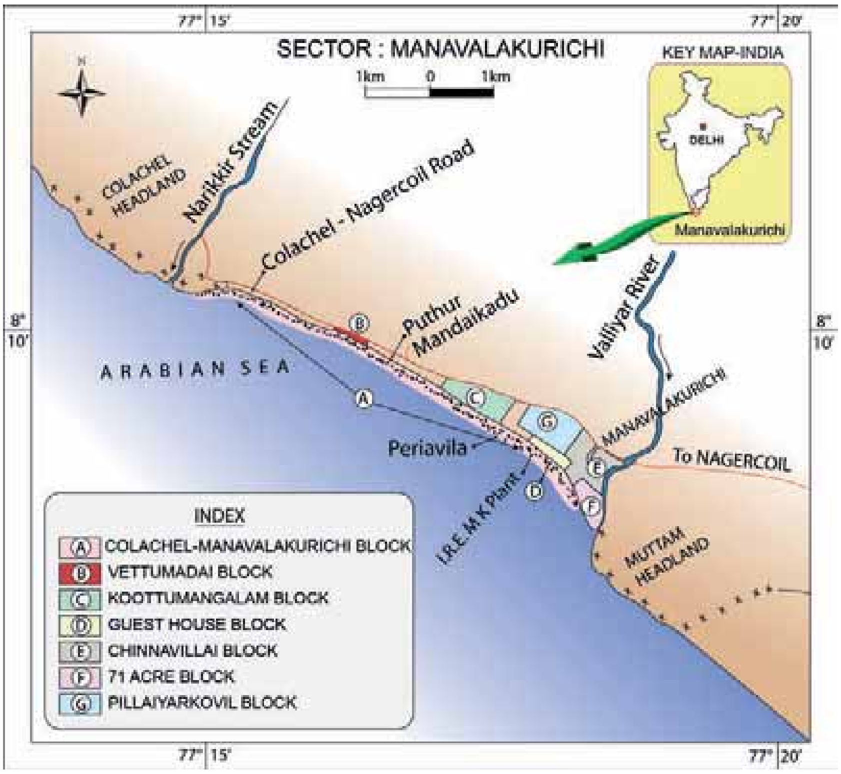

FIG. 2. Map of the Manavalakurichi beach sand thorium deposit, India.

Nuclear Power Reactor Fuel Engineering

The Agency assists Member States in pooling information and undertakes cooperative research on the development, design, manufacture, use in reactors, and performance analysis of nuclear fuel. In 2011, the annual demand for LWR fuel fabrication services remained at about 7000 tonnes of enriched uranium in fuel assemblies, but it is expected to increase to about 9500 t U/a by 2020. For PHWRs, requirements accounted for 3000 t U/a.

The Agency published the results of a CRP in a report entitled *Optimization of Water Chemistry to Ensure Reliable Water Reactor Fuel Performance at High Burnup and in Ageing Plants (FUWAC)* (IAEA-TECDOC-1666). The CRP built on improvements from earlier research on data processing technologies and diagnostics for water chemistry and corrosion control in nuclear power plants. These improvements made it possible to better control and monitor water chemistry. The CRP that ended in 2011 reviewed the principles of managing water chemistry, taking into account improvements in control and monitoring, new materials, the impact of more onerous operating conditions, crud induced power shifts and ageing. The final report (IAEA-TECDOC-1666) compiles the principal insights in five areas: corrosion of primary circuit materials, the composition and thickness of deposits on fuel, crud induced power shift, fuel oxide growth and thickness, and radioactivity buildup in the reactor coolant system.

A CRP on 'Fuel Behaviour Modelling: FUMEX-3' was completed in 2011. More than 20 Member States contributed to the CRP and to the joint IAEA–OECD/NEA International Fuel Performance Experiments (IFPE) Database that was created within the FUMEX series of CRPs. The CRP improved fuel modelling codes to better predict the behaviour of fuel at high burnups, in particular the mechanical interactions that occur during transients. And a new CRP on fuel cladding cracking, entitled 'Evaluation of Conditions for Hydrogen-induced Degradation of Zirconium Alloys during Fuel Operation and Storage', was initiated in 2011 in response to the accident at TEPCO's Fukushima Daiichi nuclear power plant.

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The Agency organized a technical meeting in Japan on the behaviour and modelling of fuel for water cooled reactors under severe transient and loss of coolant accident conditions. The specialists, from 19 Member States, identified deficiencies in experimental data and differences in safety criteria, and recommended improved international coordination in testing fuel and comparing different codes used to model fuel behaviour.

Spent Fuel Management

In 2011, about 10 500 tonnes of heavy metal (t HM) were discharged as spent fuel from all nuclear power reactors. The total cumulative amount of spent fuel that has been discharged globally up to December 2011 is approximately 350 500 t HM. Currently, less

FIG. 3. The Central Interim Storage Facility for Spent Nuclear Fuel (CLAB) at Oskarshamn, Sweden, an away from the reactor underground wet storage pool facility.

than 25% of discharged fuel is reprocessed, and the implementation of disposal facilities for spent fuel or high level waste has been delayed in most Member States. Consequently, there are growing inventories of spent nuclear fuel. This fuel will have to be stored for longer periods than initially intended, with storage times possibly extending beyond 100 years (Figs 3 and 4).

In 2011, the Agency initiated a new CRP on demonstrating performance of spent fuel and related storage system components during very long term storage. Its objectives are to: create a network of experts; assemble the necessary models and experimental data; develop a method to demonstrate long term spent fuel performance; develop the capability to assess the impact of high burnup and mixed oxide fuel on long term spent fuel storage, transport and disposal; and document the technical basis for demonstrating long term spent fuel performance to help transfer the knowledge to countries introducing nuclear power programmes.

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Topical Advanced Fuel Cycle Issues

The chemical separation of various constituents of spent nuclear fuel (called 'partitioning') could facilitate the reuse of separated fissile material to obtain extra energy and reduce the radiotoxicity of nuclear waste, and thus the size of geological repositories. The Agency held a technical meeting on 'Advanced Partitioning Processes', in Vienna in June, to review the status and prospects of partitioning and its possible contribution to advanced and proliferation resistant nuclear fuel cycles. The meeting concluded that although hydro- and pyro-metallurgical separation technologies were at advanced stages at the pilot scale, more work was needed for engineering scale development. The meeting identified specific scale-up challenges such as equipment and facility design.

In the area of fuels and fuel cycles for sodium cooled fast reactors, the Agency published *Status and Trends of Nuclear Fuels Technology for Sodium Cooled Fast Reactors* (IAEA Nuclear Energy Series No. NF-T-4.1) and *Status of Developments in the Back End of the Fast Reactor Fuel Cycle* (IAEA Nuclear Energy Series No. NFT4.2). The first publication describes manufacturing processes, out of pile properties, and the irradiation behaviour of mixed uranium plutonium oxide, carbide, nitride and metallic fuels. It also covers minor actinide bearing fuels. The second publication is a comprehensive presentation of partitioning technologies and related issues concerning the back end of the sodium cooled fast reactor fuel cycle.

There is continuing interest in the deployment of small and medium reactors (SMRs), given their

FIG. 4. The Independent Spent Fuel Storage Installation at the Surry Nuclear Power Plant in Virginia, USA, an at-reactor dry storage cask facility.

potential suitability for small electricity grids, remote locations and non-electric applications, and their potentially lower capital costs and simplified infrastructure requirements. Research and development of innovative fuels and fuel cycle options for SMRs are under way in several Member States. In response, the Agency organized a technical meeting on fuel and fuel cycles for SMRs for Member States to exchange information and experience on nuclear fuel and fuel cycle technologies related to SMRs for electricity generation, process heat and marine propulsion, and breeding and/or burning transuranic elements. The meeting concluded that fuel discharge burnup and fuel residence in the reactor core needed to be optimized to ensure that SMR fuel cycles were in fact economical.

Integrated Nuclear Fuel Cycle Information System

Comprehensive information on worldwide nuclear fuel cycle activities is available through the Agency's Integrated Nuclear Fuel Cycle Information System (iNFCIS) (*http://infcis.iaea.org/*). iNFCIS attracts more than 600 000 visits annually from researchers, professionals, policy makers and the general public. The on-line information system includes the Nuclear Fuel Cycle Information System (NFCIS), World Distribution of Uranium Deposits (UDEPO), Post-Irradiation Examination Facilities Database (PIE) and Minor Actinide Property Database (MADB). In 2011, a new database on the World Distribution of Thorium Deposits and Resources (ThDEPO) was added to the system, and iNFCIS was migrated to the NUCLEUS platform, the Agency's common access point for its scientific, technical and regulatory information resources.

iNFCIS makes it possible to analyse the different stages, facilities, capacities, interlinkages and synergies related to various fuel cycle options and approaches. Using the data in iNFCIS, the Agency projects that fuel services such as uranium conversion, enrichment, fuel fabrication and reprocessing, and recycling will experience growth similar to the projected growth in uranium requirements for power reactors noted above (Fig. 5). Currently, most of these service capacities are slightly underutilized, but facility replacements will be required in the near future. iNFCIS enables the early identification of potential bottlenecks in the fuel cycle supply chain for a variety of scenarios, for example the Agency's high and low projections as reported in the next chapter on 'Capacity Building and Nuclear Knowledge Maintenance for Sustainable Energy Development'.

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FIG. 5. Uranium ore processing at the Key Lake operation in Canada.