

Chapter 7

Contribution of the European Commission to a European Strategy for HLW Management Through Partitioning & Transmutation

Presentation of MYRRHA and Its Role in the European P&T Strategy

Hamid Ait Abderrahim

Abstract MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) is an experimental accelerator-driven system (ADS) currently being developed at SCK•CEN for replacement of material testing reactor BR2. The MYRRHA facility is conceived as a flexible fast-spectrum irradiation facility that is able to run in both subcritical and critical modes. The applications catalogue of MYRRHA includes fuel developments for innovative reactor systems, material developments for GEN IV systems and fusion reactors, doped silicon production, radioisotope production, and fundamental science applications, thanks to the high-power proton accelerator. Next to these applications, MYRRHA will demonstrate the ADS full concept by coupling a high-power proton accelerator, a multi-megawatts spallation target, and a subcritical reactor at reasonable power level to allow operational feedback, scalable to an industrial demonstrator, and to allow the study of efficient transmutation of high-level nuclear waste. Because MYRRHA is based on the heavy liquid metal technology, namely lead–bismuth eutectic (LBE), it will be able to significantly contribute to the development of Lead Fast Reactor (LFR) technology and will have the role of European Technology Pilot Plant in the roadmap for LFR. The current design of the MYRRHA ADS and its ability to contribute to the European Commission strategy for high-level waste management through Partitioning and Transmutation (P&T) are discussed in this chapter.

Keywords ADS • HLW Management • MYRRHA • P&T

H.A. Abderrahim (✉)
SCK•CEN, Boeretang 200, 2400 Mol, Belgium
e-mail: haitabde@sckcen.be; myrrha@sckcen.be

7.1 Introduction

When concerned with energy, one cannot avoid considering geostrategic questions and the international political situation. Indeed, major armed conflicts in the world in past decades are taking place in major fossil energy production countries or on the major roads connecting places of great production with those of large consumption. Therefore, Europe is very concerned about the security of its supply in terms of energy, especially when considering the limited energy fossil resources in the European Union (EU). As such, nuclear power remains a major energy source in the EU.

Presently, the EU relies, for 30 % of its electric power production, on generation II–III fission nuclear reactors, leading to the annual production of 2,500 t/year of used fuel, containing 25 t plutonium, and high-level wastes (HLW) such as 3.5 t of minor actinides (MA), namely, neptunium (Np), americium (Am), and curium (Cm), and 3 t of long-lived fission products (LLFPs). These MA and LLFP stocks need to be managed in an appropriate way. The reprocessing of used fuel (closed fuel cycle) followed by geological disposal, or direct geological disposal (open fuel cycle), are today the envisaged solutions in Europe, depending on national fuel cycle options and waste management policies. The required time scale for geological disposal exceeds our accumulated technological knowledge, and this remains the main concern of the public. Partitioning and Transmutation (P&T) has been pointed out in numerous studies as the strategy that can relax constraints on geological disposal and reduce the monitoring period to technological and manageable time scales. Therefore, a special effort is ongoing in Europe and beyond to integrate P&T in advanced fuel cycles and advanced options for HLW management. Transmutation based on critical or subcritical fast-spectrum transmuters should be evaluated to assess the technical and economic feasibility of this waste management option, which could ease the development of a deep geological storage.

Despite diverse strategies and policies pursued by European Member States concerning nuclear power and the envisaged fuel cycle policy ranging from the once-through without reprocessing to the double-strata fuel cycle ending with ADS as the ultimate burner or generation IV (Gen-IV) fast critical reactors multi-recycling all transuranic (TRUs), P&T requires an integrated effort at the European and even worldwide level. Even when considering the phase-out of nuclear energy, the combination of P&T and a dedicated burner such as ADS technologies, at a European scale, would allow meeting the objectives of both types of countries, those phasing out nuclear energy as well as countries favoring the continuation of nuclear energy development toward the deployment of new fast-spectrum systems.

The concept of partitioning and transmutation has three main goals: reduction of the radiological hazard associated with spent fuel by reducing the inventory of minor actinides, reduction of the time interval required to reach the radiotoxicity of

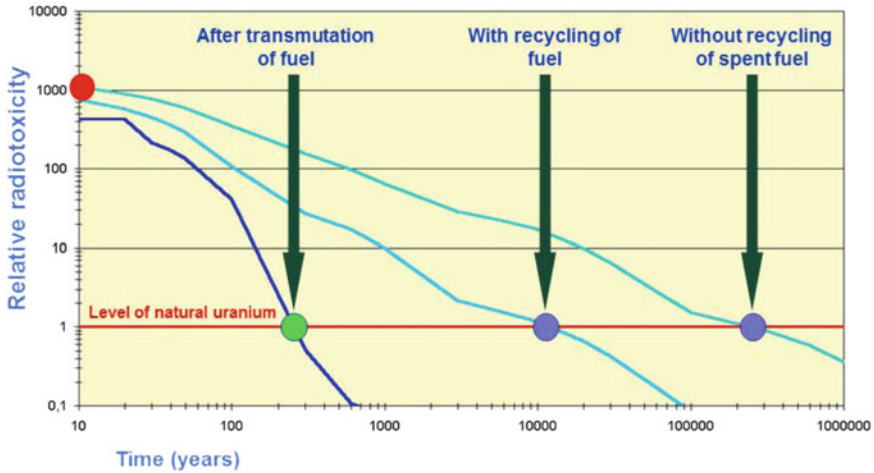


Fig. 7.1 Radiotoxicity of radioactive waste [4]

natural uranium, and reduction of the heat load of the HLW packages to be stored in geological disposal, leading to its efficient use.

Transmutation of high-level radioactive elements with a long half-life present in the nuclear waste reduces the radiological impact of the actinides (such as americium, curium, and neptunium) and fission products. The time scale (Fig. 7.1) needed for the radiotoxicity of the waste to drop to the level of natural uranium will be reduced from a ‘geological’ value (500,000 to 1 million years) to a value that is comparable to that of human activities (several hundreds of years) [1–3]. During transmutation, the nuclei of the actinides are fissioned into shorter-lived fission products.

To transmute the minor actinides in an efficient way, high intensity and high energy neutron fluences are necessary. Therefore, only nuclear fast fission reactors, being critical or subcritical, can be utilized.

If the aim is to transmute large amounts of minor actinides in the dedicated transmuter then it is necessary to use an accelerator-driven system. The subcriticality is mandatory because of the smaller delayed neutron fraction within the minor actinides (0.01–0.1 %) compared to uranium-235 (0.7 %) to allow the criticality variation control.

After nearly 20 years of basic research funded by national programs and EURATOM framework programs, the research community needs to be able to quantify indicators for decision makers, such as the proportion of waste to be channeled to this mode of management, but also issues related to safety, radiation protection, transport, secondary wastes, costs, and scheduling.

From 2005, the research community on P&T within the EU started structuring its research toward a more integrated approach. This effort resulted, during the FP6, into two large integrated projects, namely, EUROPART dealing with partitioning, and EUROTRANS dealing with accelerator driven system (ADS), design for

transmutation, development of advanced fuel for transmutation, R&D activities related to the heavy liquid metal technology, innovative structural materials, and nuclear data measurement. This approach resulted in a European strategy, the so-called four building blocks at engineering level for P&T, as given next. The implementation of P&T of a large part of the high-level nuclear wastes in Europe needs the demonstration of its feasibility at an “engineering” level. The respective R&D activities could be arranged in these four “building blocks,” as listed next:

1. Demonstration of the capability to process a sizable amount of spent fuel from commercial LWRs to separate plutonium (Pu), uranium (U), and minor actinides (MA),
2. Demonstration of the capability to fabricate, at a semi-industrial level, the dedicated fuel needed to load in a dedicated transmuted (JRC-ITU)
3. Design and construction of one or more dedicated transmuted
4. Provision of a specific installation for processing of the dedicated fuel unloaded from the transmuted, which can be of a different type than that used to process the original spent fuel unloaded from commercial power plants, together with the fabrication of new dedicated fuel

These “blocks will” result in identification of the costs and benefits of partitioning and transmutation for European society.

7.2 MYRRHA: A Flexible Fast-Spectrum Irradiation Facility

MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) is the flexible experimental accelerator-driven system (ADS) in development at SCK•CEN. MYRRHA is able to work both in subcritical (ADS) and in critical mode. In this way, MYRRHA targets the following applications catalogue:

- To demonstrate the ADS full concept by coupling the three components (accelerator, spallation target, and subcritical reactor) at reasonable power level (50–100 MW_{th}) to allow operation feedback, scalable to an industrial demonstrator;
- To allow the study of the efficient technological transmutation of high-level nuclear waste, in particular, minor actinides that would require high fast flux intensity ($\Phi_{>0.75\text{MeV}} = 10^{15} \text{ n/cm}^2 \text{ s}$);
- To be operated as a flexible fast-spectrum irradiation facility allowing for
 - Fuel developments for innovative reactor systems, which need irradiation rigs with a representative flux spectrum, a representative irradiation temperature, and high total flux levels ($\Phi_{\text{tot}} = 5 \cdot 10^{14} \text{ to } 10^{15} \text{ n/cm}^2 \text{ s}$); the main target will be fast-spectrum GEN IV systems, which require fast-spectrum conditions;
 - Material developments for GEN IV systems, which need large irradiation volumes with high uniform fast flux level ($\Phi_{>1 \text{ MeV}} = 1 \sim 5 \cdot 10^{14} \text{ n/cm}^2 \text{ s}$) in

various irradiation positions, representative irradiation temperature, and representative neutron spectrum conditions; the main target will be fast-spectrum GEN IV systems;

- Material developments for fusion reactors, which need also large irradiation volumes with high constant fast flux level ($\Phi_{>1 \text{ MeV}} = 1 \sim 5 \cdot 10^{14} \text{ n/cm}^2 \text{ s}$), a representative irradiation temperature, and a representative ratio $\text{appm He/dpa(Fe)} = 10$;
- Radioisotope production for medical and industrial applications by
 - Holding a backup role for classical medical radioisotopes;
 - Focusing on R&D and production of radioisotopes requiring very high thermal flux levels ($\Phi_{\text{thermal}} = 2 \text{ to } 3 \cdot 10^{15} \text{ n/cm}^2 \text{ s}$) because of double-capture reactions;
- Industrial applications, such as Si-doping, need a thermal flux level depending on the desired irradiation time: for a flux level $\Phi_{\text{thermal}} = 10^{13} \text{ n/cm}^2 \text{ s}$, an irradiation time in the order of days is needed, and for a flux level of $\Phi_{\text{thermal}} = 10^{14} \text{ n/cm}^2 \text{ s}$, an irradiation time in the order of hours is needed to obtain the required specifications.

Further in this section, we discuss some basic characteristics of the accelerator and of the core and primary system design.

7.3 The MYRRHA Accelerator

The accelerator is the driver of MYRRHA because it provides the high-energy protons that are used in the spallation target to create neutrons, which in turn feed the core. In the current design of MYRRHA, the machine must be able to provide a proton beam with energy of 600 MeV and an average beam current of 3.2 mA. The beam is delivered to the core in continuous wave (CW) mode. Once per second, the beam is shut off for 200 μs so that accurate on-line measurements and monitoring of the subcriticality of the reactor can take place. The beam is delivered to the core from above through a beam window.

Accelerator availability is a crucial issue for the operation of the ADS. A high availability is expressed by a long mean time between failure (MTBF), which is commonly obtained by a combination of overdesign and redundancy. In addition to these two strategies, fault tolerance must be implemented to obtain the required MTBF. Fault tolerance will allow the accelerator to recover the beam within a beam trip duration tolerance after failure of a single component. In the MYRRHA case, the beam trip duration tolerance is 3 s. Within an operational period of MYRRHA, the number of allowed beam trips exceeding 3 s must remain under 10. Shorter beam trips are allowed without limitations. The combination of redundancy and fault tolerance should allow obtaining a MTBF value in excess of 250 h.

At present, proton accelerators with megawatt-level beam power in CW mode only exist in two basic concepts: sector-focused cyclotrons and linear accelerators (linacs). Cyclotrons are an attractive option with respect to construction costs, but they do not have any modularity, which means that a fault tolerance scheme cannot be implemented. Also, an upgrade of its beam energy and intensity for industrial application presently is not a realistic option. A linear accelerator, especially if made superconducting, has the potential for implementing a fault tolerance scheme and offers a high modularity, resulting in the possibility to recover the beam within a short time and increasing the beam energy and intensity toward industrial application of ADS technology.

7.4 Design of the Core and Primary System

Because MYRRHA is a pool-type ADS, the reactor vessel houses all the primary systems. In previous designs of MYRRHA, an outer vessel served as secondary containment in case the reactor vessel leaks or breaks. In the current design, the reactor pit fulfills this function, improving the capabilities of the reactor vault air cooling system. The vessel is closed by the reactor cover, which supports all the in-vessel components. A diaphragm, inside the vessel, acts to separate the hot and cold LBE plenums; it supports the in-vessel fuel storage (IVFS) and provides a pressure separation. The core is held in place by the core support structure consisting of a core barrel and a core support plate. Figure 7.2 shows vertical cut sections of the MYRRHA reactor showing its main internal components.

At the present state of the design, the reactor core (Fig. 7.3) consists of mixed oxide (MOX) fuel pins, typical for fast reactors. In subcritical mode, the central hexagon houses a window beam tube-type spallation target. Thirty-seven positions can be occupied by in-pile test sections (IPS) or by the spallation target (the central one of the core in subcritical configuration) or by control and shutdown rods (in the core critical configuration). This design gives a large flexibility in the choice of the more suitable position (neutron flux) for each experiment.

The requested high fast flux intensity has been obtained by optimizing the core configuration geometry (fuel rod diameter and pitch) and maximizing the power density. We will be using, for the first core loadings, 15-15Ti stabilized stainless steel as cladding material instead of T91 ferritic-martensitic steel that will be qualified progressively further on during MYRRHA operation for a later use. The use of lead–bismuth eutectic (LBE) as coolant permits lowering the core inlet operating temperature (down to 270 °C), decreasing the risk of corrosion and allowing increasing the core ΔT . This design, together with the adoption of reliable and passive shutdown systems, will allow meeting the high fast flux intensity target.

In subcritical mode, the accelerator (as described in the previous section) is the driver of the system. It provides the high-energy protons that are used in the spallation target to create neutrons which in their turn feed the subcritical core. In subcritical mode the spallation target assembly, located in the central position of the

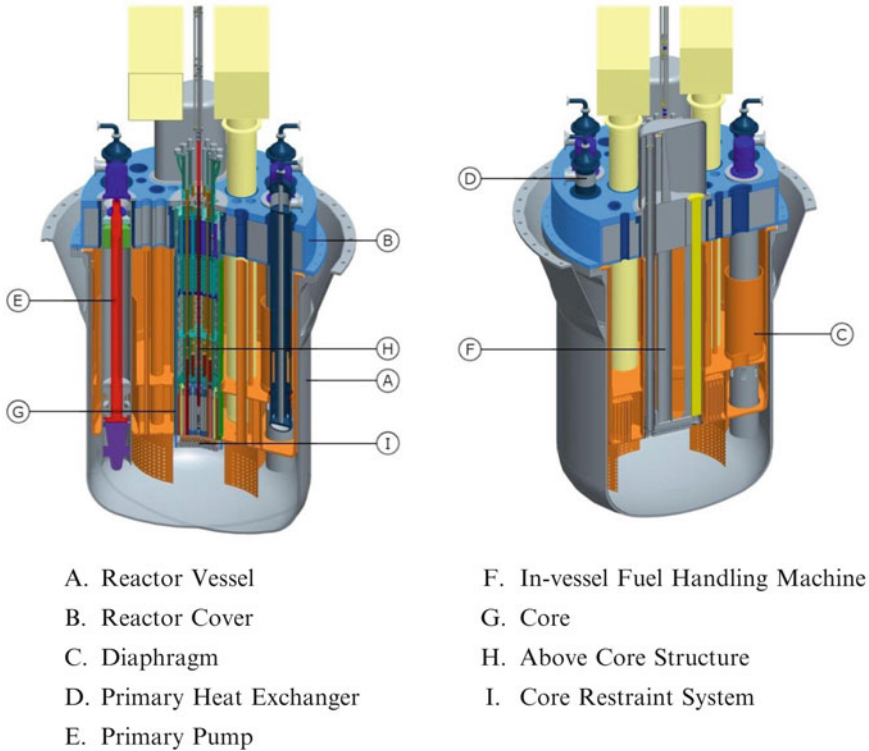


Fig. 7.2 Section of the MYRRHA-FASTEF reactor

core, brings the proton beam via the beam tube into the central core region. The spallation heat deposit is dissipated to the reactor primary circuit. The spallation module guarantees the barrier between the reactor LBE and the reactor hall and ensures optimal conditions for the spallation reaction. The spallation module assembly is conceived as an IPS and is easily removable or replaceable.

The primary, secondary, and tertiary cooling systems have been designed to evacuate a maximum thermal core power of 110 MW. The 10 MW more than the nominal core power account for the power deposited by the protons, for the power of in-vessel fuel, and for the power deposited in the structures by γ -heating. The average coolant temperature increase in the core in nominal conditions is 140 °C with a coolant velocity of 2 m/s. The primary cooling system consists of two pumps and four primary heat exchangers (PHX).

The interference of the core with the proton beam, the fact that the room located directly above the core will be occupied by much instrumentation and IPS penetrations, and core compactness result in insufficient space for fuel handling to (un)load the core from above. Since the very first design of MYRRHA, fuel handling has been performed from underneath the core. Fuel assemblies are kept by buoyancy under the core support plate.

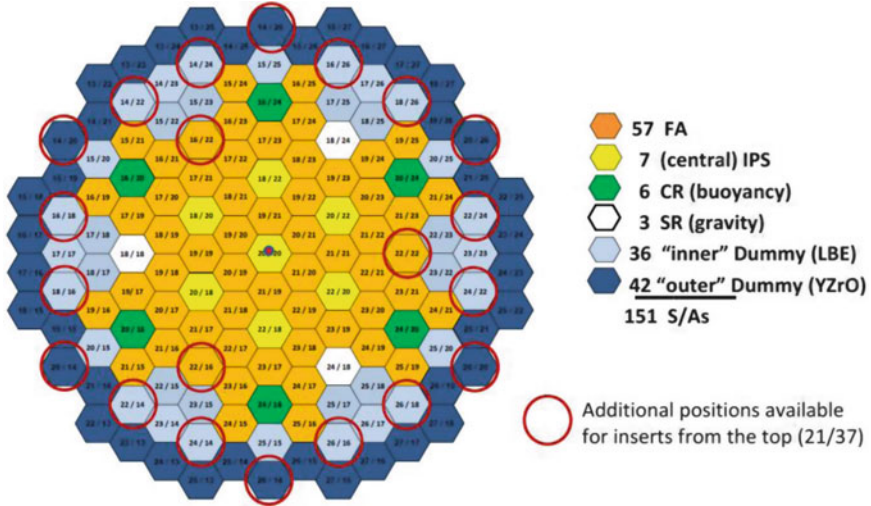


Fig. 7.3 Cut of the MYRRHA-FASTEF core, showing the central target, the different types of fuel assemblies, and dummy components

Two fuel-handling machines are used, located at opposite sides of the core (Fig. 7.4). Each machine covers one side of the core. The use of two machines provides sufficient range to cover the necessary fuel storage positions without the need of an increase for the reactor vessel when only one fuel-handling machine is used. Each machine is based on the well-known fast reactor technology of the ‘rotating plug’ concept using SCARA (Selective Compliant Assembly Robot Arm) robots. To extract or insert the fuel assemblies, the robot arm can move up or down for about 2 m. A gripper and guide arm is used to handle the FAs: the gripper locks the FA, and the guide has two functions, namely to hold the FA in the vertical orientation and to ensure neighboring FAs are not disturbed when a FA is extracted from the core. An ultrasonic (US) sensor is used to uniquely identify the FAs.

The in-vessel fuel-handling machine will also perform in-vessel inspection and recovery of an unconstrained FA. Incremental single-point scanning of the diaphragm can be performed by an US sensor mounted at the gripper of the IVFHM. The baffle under the diaphragm is crucial for the strategy as it limits the work area where inspection and recovery are needed. It eliminates also the need of additional recovery and inspection manipulators, prevents items from migrating into the space between the diaphragm and the reactor cover, and permits side scanning.

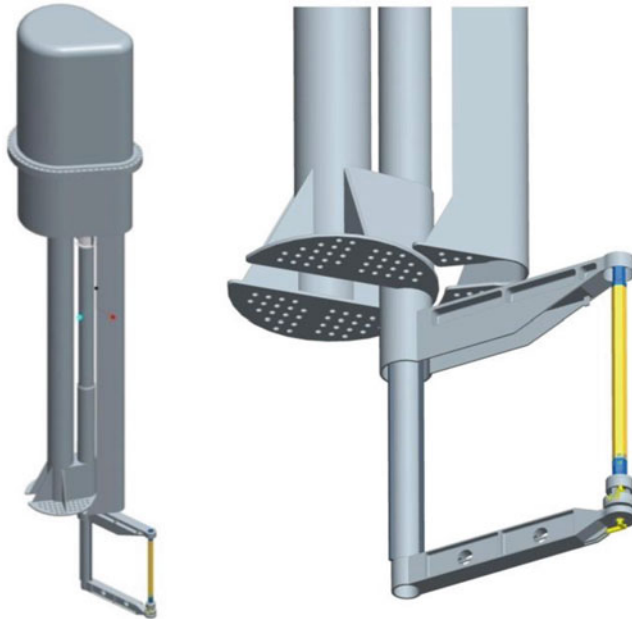


Fig. 7.4 The in-vessel fuel-handling machine

7.5 MYRRHA, A Research Tool in Support of the European Roadmap for P&T

Spent nuclear fuel from light water reactors (LWR) contains a mixture of uranium and plutonium (up to 95 % of the initial uranium mass), fission products, and minor actinides such as neptunium, americium, and curium. In the shorter term, the highly active but short-lived fission products will dominate the activity of this spent fuel. However, the transuranics including plutonium and the minor actinides (together with a few long-lived fission products) are largely responsible for the long-term radiotoxicity and heat production of LWR spent fuel.

The principle behind Partitioning and Transmutation (P&T) is to isolate the minor actinides from this LWR spent fuel and transmute them. As for these isotopes the fission to capture ratio increases with increasing neutron energy, a fast neutron spectrum facility is required. By burning the minor actinides, the long-lived, heat-producing component of spent fuel can be strongly reduced, which decreases the radiotoxicity of the spent fuel and its heat load. Both conditions will ease the design and construction of a long-term storage solution (geological disposal) from the engineering point of view.

Partitioning & Transmutation requires the development of an advanced fuel cycle. Currently, two major options for P&T are being studied worldwide: the single-stratum approach wherein the minor actinides are burned in fast reactors that are deployed for electricity production and the double-strata approach where the Pu

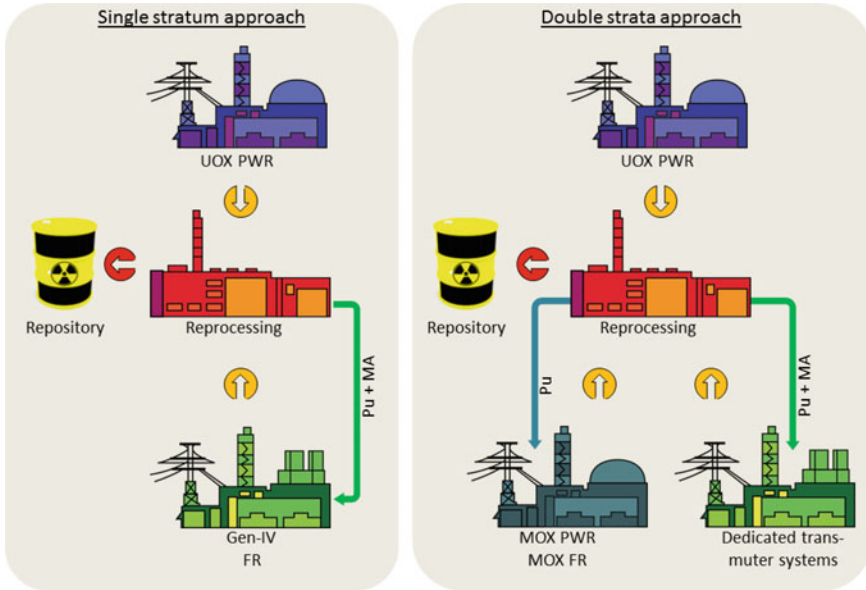


Fig. 7.5 Single-stratum vs. double-strata approach

is burned for electricity production in LWRs and FRs whereas the minor actinides are burned in a dedicated facility (Fig. 7.5).

In the single-stratum approach, the minor actinides can be mixed homogeneously in the fast reactor fuel or can be loaded in dedicated targets. In the homogeneous option, care must be taken in the analysis of the change in the core safety parameters such as delayed neutron fraction, Doppler constant, and void coefficient. By increasing the concentration of minor actinides in the fuel mixture, these safety parameters typically go in the wrong direction and hence pose a threat to the reactor safety. Because of this, one expects a maximum of 4–5 % minor actinide loading in the fuel.

Also, the fabrication and reprocessing of this “spiked” fast reactor fuel or the dedicated minor actinide target requires extra care because the presence of the minor actinides increases heat production during these fabrication processes. The presence of Cm-244 will pose a shielding problem because of its spontaneous fission and hence neutron emission.

Given the fact that only small amounts of minor actinides can be loaded per reactor, limited by a maximum concentration in case of the homogeneous option or limited by the number of target positions in the heterogeneous option, a large number of reactors will be required to use this minor actinide-spiked fuel or house these dedicated targets; this will certainly be the case when nations decide to also treat their legacy LWR waste and not only the minor actinides produced in this future advanced fuel cycle. Implied are a large number of transports of these

fuels and targets from reprocessing site to fuel fabrication site and to transmutation sites and back.

In the double-strata approach, a dedicated transmutation facility is foreseen in the form of an accelerator-driven system. Because of the reactor physics properties of such an ADS (one does not rely on a subtle equilibrium such as the chain reaction, but the ADS subcritical core acts merely as a multiplier of a primary neutron source), one can devise fuels that have a very high minor actinide content. The EC-FP6 program IP-EUROTRANS delivered the conceptual design of such an industrial transmuter (EFIT). In EFIT, 400 MWth core designs were made with uranium-free inert matrix fuels having a mixture of plutonium and minor actinides. In EFIT, the so-called 42–0 approach core was developed, meaning a core design that would be as plutonium neutral as possible (no burning nor breeding of plutonium) and which could in optimal conditions burn 42 kg minor actinides per TWh power produced. This system was used in the EC-FP6 program PATEROS, which produced a roadmap for the development of Partitioning and Transmutation at the European level. The deployment of such an industrial transmuter as EFIT would be very difficult for small nuclear countries and hence this scheme is optimal in a regional approach.

Because the burning of the minor actinides is done in a very concentrated manner, these industrial transmuters can be located near a fuel reprocessing and transmuter fuel fabrication facility, limiting the transportation of hazardous materials. Calculations have indicated that the support ratio, that is, the ratio of the total power of industrial transmuters to the total power of electricity-generating systems, is about 6 %. Also with this “concentrated” approach, one can much easier envisage the burning of the LWR legacy waste in a reasonable amount of time without impacting the regular electricity production installations.

Within the PATEROS project, a number of nuclear fuel cycle scenarios have been studied. Different regions have been identified: a group of countries that are stagnant with respect to nuclear energy production or in phase-out (“Group A,” typically Belgium, Czech Republic, Germany, Spain, Sweden, Switzerland) and a group of countries which are developing an advanced fuel cycling with the deployment of fast reactors (“Group B,” typically France). Different objectives were set concerning the burning of the minor actinides. Within the EC-F7 ARCAS project, which continues on the work done in PATEROS, it was estimated that to burn the minor actinides present in Group A in a reasonable time frame (less than 100 years), the group would need to deploy 7 EFIT-like facilities. If also Group B wants to stabilize their minor actinide inventory, 15 EFIT-like installations would be needed, and if total minor actinide elimination is required in Groups A and B, 20 EFIT-like installations are to be built.

At the European level, four building block strategies for partitioning and transmutation have been identified. Each block poses a serious challenge in research and development to reach an industrial-scale deployment. These blocks are as follows.

- Demonstration of advanced reprocessing of spent nuclear fuel from LWRs, separating uranium, plutonium, and minor actinides;

- Demonstrate the capability to fabricate at semi-industrial level dedicated transmuter fuel heavily loaded in minor actinides;
- Design and construct one or more dedicated transmuters;
- Demonstration of advanced reprocessing of transmuter fuel together with the fabrication of new transmuter fuel.

MYRRHA will support this roadmap by playing the role of an accelerator-driven system prototype (at reasonable power level) and as a flexible irradiation facility providing fast neutrons for the qualification of materials and fuel for an industrial transmuter. MYRRHA will be capable of irradiating samples of this inert matrix fuels, but it is also foreseen to house fuel pins or even a limited number of fuel assemblies heavily loaded with MAs for irradiation and qualification purposes.

7.6 Conclusions

SCK•CEN is proposing to replace its aging flagship facility, the Material Testing Reactor BR2, by a new flexible irradiation facility, MYRRHA. Considering international and European needs, MYRRHA is conceived as a flexible fast spectrum irradiation facility able to work in both subcritical and critical mode. Despite several nonobvious design challenges, such as the use of LBE, the increased level of seismic loading (consequence of Fukushima), or the choice of passive mode for decay heat removal in emergency conditions, we found no significant showstopper in the design. The R&D program that is running in parallel has taken into account international recommendations from experts concerning the remaining technological challenges as mentioned in Section VI (above).

MYRRHA is now foreseen to be in full operation by 2025, and it will be able to be operated in both operation modes, subcritical and critical. In subcritical mode, it will demonstrate the ADS technology and the efficient demonstration of MA in subcritical mode. As a fast spectrum irradiation facility, it will address fuel research for innovative reactor systems, material research for GEN IV systems and for fusion reactors, radioisotope production for medical and industrial applications, and industrial applications, such as Si-doping.

The MYRRHA design has now entered into the Front End Engineering Phase, covering the period 2012–2015. The engineering company that handles this phase has currently started the work. At the end of this phase, the purpose is to have

- Progressed in such a way in the design of the facility that the specifications for the different procurement packages of the facility can be written,
- Adequately addressed the remaining outstanding R&D issues,
- obtained the construction and exploitation permits, and
- Formed the international members' consortium for MYRRHA.

Belgium and SCK•CEN have opened participation in the MYRRHA to EU member states and to the European Commission but also to worldwide participation, as the

issue of safe and efficient management of high-level nuclear waste is a worldwide issue, whatever the policy adopted or to be adopted by the countries that have industrialized nuclear power generation and want to phase it out, those willing to continue its use, and those willing to start nuclear power generation.

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