



# MYRRHA: A multipurpose accelerator driven system for research & development

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## Abstract

SCK·CEN, the Belgian Nuclear Research Centre, in partnership with IBA s.a., Ion Beam Applications, is designing an ADS prototype, MYRRHA, and is conducting an associated R&D programme. The project focuses primarily on research on structural materials, nuclear fuel, liquid metals and associated aspects, on subcritical reactor physics and subsequently on applications such as nuclear waste transmutation, radioisotope production and safety research on subcritical systems. The MYRRHA system is intended to be a multipurpose R&D facility and is expected to become a new major research infrastructure for the European partners presently involved in the ADS Demo development. Ion Beam Applications is performing the accelerator development. Currently the preliminary conceptual design of the MYRRHA system is under way and an intensive R&D programme is assessing the points of greatest risk in the present design. This work will define the final choice of characteristics of the facility. In this paper, we will report on the status of the pre-design study as of June 2000 as well as on the methods and results of the R&D programme. © 2001 Elsevier Science B.V. All rights reserved.

*Keywords:* Accelerator driven system (ADS); Partitioning & transmutation; Irradiation technology

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## 1. Introduction

SCK·CEN, the Belgian Nuclear Research Centre, and IBA s.a., Ion Beam Applications, are developing jointly the MYRRHA project, a multipurpose neutron source for R&D applications on the basis of an Accelerator Driven System (ADS). This project is intended to fit into the European

strategy towards an ADS Demo facility for nuclear waste transmutation.

The R&D applications that are considered in the future MYRRHA facility can be grouped in three blocks: (i) continuation, and extension, towards ADS of the ongoing R&D programmes at SCK·CEN in the field of reactor materials, fuel and reactor physics research; (ii) enhancement and triggering of new R&D activities such as nuclear waste transmutation, ADS technology, liquid metal embrittlement; (iii) initiation of medical applications such as proton therapy and PET production.

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The present MYRRHA concept, as described below, is determined by the versatility of the applications it would allow. Further technical and/or strategic developments of the project might change the present concept.

The design of MYRRHA needs to satisfy a number of specifications such as:

- achievement of the neutron flux levels required by the different applications considered in MYRRHA:
- $\Phi_{>0.75 \text{ MeV}} = 1.0 \times 10^{15} \text{ n/cm}^2\text{s}$  at the locations for minor actinides (MA) transmutation,
- $\Phi_{>1 \text{ MeV}} = 1.0 \times 10^{13}$  to  $1.0 \times 10^{14} \text{ n/cm}^2\text{s}$  at the locations for structural material and fuel irradiation,
- $\Phi_{\text{th}} = 2.0$  to  $3.0 \times 10^{15} \text{ n/cm}^2\text{s}$  at locations for long-lived fission products (LLFP) transmutation or radioisotope production;
- subcritical core total power: ranging between 20 and 30 MW;
- safety:  $k_{\text{eff}} \leq 0.95$  in all conditions, as in a fuel storage, to guarantee inherent safety;
- operation of the fuel under safe conditions: average fuel pin linear power  $< 500 \text{ W/cm}$ .

## 2. MYRRHA present design status

In its present status of development, the MYRRHA project [1] is based on the coupling of an upgraded commercial proton cyclotron with a liquid Pb–Bi windowless spallation target, surrounded by a subcritical neutron multiplying medium in a pool type configuration (Fig. 1). The spallation target circuit is fully separated from the core coolant as a result of the windowless design presently favoured in order to utilise low energy protons without reducing drastically the core performances.

The core pool contains a fast spectrum core, cooled with liquid Pb–Bi or Pb, and several islands housing thermal spectrum regions located in In-Pile Sections (IPS) at the periphery of the fast core. The fast core is fuelled with typical fast reactor fuel pins with an active length of 600 mm arranged in hexagonal assemblies of 122 mm plate-to-plate. The central hexagon position is left free for

housing the spallation module. The core is made of 18 fuel assemblies of which 12 have a Pu content of 30% and 6 a Pu content of 20%.

The MYRRHA design is determined by the requirement of versatility in applications and the desire to use as much as possible existing technologies. The heat exchangers and the primary pump unit are to be embedded in the reactor pool. The accelerator is to be installed in a confinement building separated from the one housing the subcritical core and the spallation module. The proton beam will be impinging on the spallation target from the top.

### 2.1. Accelerator

IBA, a company that has designed the world reference cyclotron for radioisotope production and other machines, is in charge of the design of the accelerator. The accelerator parameters presently considered are 5 mA current at 350 MeV proton energy. The positive ion acceleration technology that is envisaged is to be realised by a two-stage accelerator, with a first cyclotron as injector accelerating protons up to 40–70 MeV and a booster further accelerating them up to 350 MeV (Fig. 2). This option is not yet frozen: a trade-off of higher proton energy against current is being explored. Other designs, to go in one step from the ion source energy injection up to the 350 MeV desired energy, or accelerating  $\text{H}_2$  molecules with stripping at the final energy stage for beam extraction, are in the assessment phase. For more details, see Section 3.1.

### 2.2. Spallation target

The spallation target is made of liquid Pb–Bi. The Pb–Bi is pumped up to a reservoir from which it descends, through an annular gap ( $\varnothing_{\text{outer}}$ , 130 mm), to the middle of the fast core. Here, the flow is directed by a nozzle into a single tube penetrating the fast core ( $\varnothing_{\text{outer}}$ , 80 mm). At about the position of the nozzle a free liquid metal surface is formed, which will be in contact with the vacuum of the proton beam guideline. No conventional window is foreseen between the Pb–Bi free surface and the beam in order to avoid

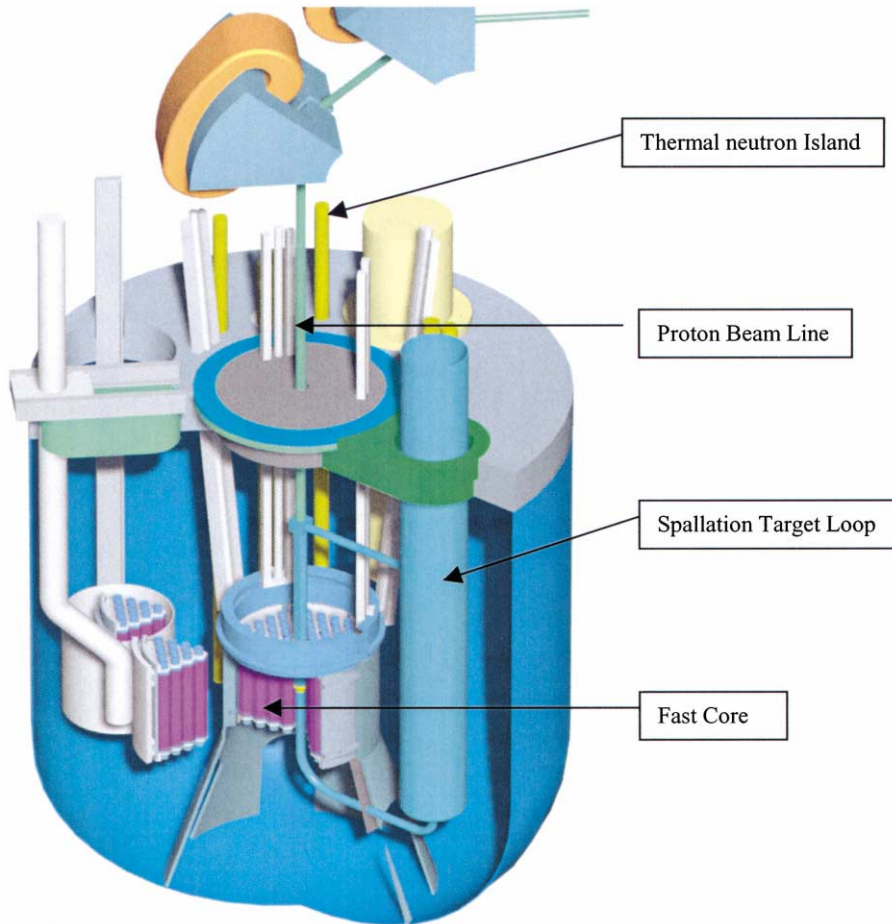


Fig. 1. Global view of the present design of MYRRHA.

difficulties in engineering this component and to keep the energy losses at a minimum. When the Pb–Bi has left the fast core region, it is cooled and pumped back to the reservoir.

The MYRRHA windowless spallation module is given special attention in the present pre-design phase because of its particular features, as illustrated in [2] and summarized in Section 3.2.

### 2.3. Subcritical system

The design of the subcritical assembly will have to yield the neutronic performances and provide the irradiation volumes required for the considered applications. In order to meet the goals of material

studies, fuel behaviour studies, radioisotope production, transmutation of MA and LLFP, the subcritical core of MYRRHA must include two spectral zones: a fast neutron spectrum zone and a thermal spectrum one.

#### 2.3.1. Fast zone description

The fast core will be placed centrally in a liquid Pb–Bi or Pb pool, leaving a central hexagonal assembly empty for housing the spallation target. It consists of hexagonal assemblies of MOX FR-type fuel pins with a Pu-content,  $\text{Pu}/(\text{Pu}+\text{U})$ , ranging from 20% to 30%, arranged in a triangular lattice with a pitch of 10 mm. The fuel pins have an active fuel length of 50 cm (but could

be increased to 60 cm to achieve the requested performances) and their cladding consists of 9% Cr martensitic steel. The fuel pins are arranged in typical FR fuel hexagonal assemblies with an assembly dimension of 122 mm plate-to-plate. The fast zone is made of 2 concentric crowns, the first one consisting of 6 highly enriched fuel assemblies (with 30% Pu content) and the second one of 12 fuel assemblies of which 6 are 30% enriched and 6 are 20% enriched.

Neutronic calculations coupling the high energy transport code HETC and the lower energy neutron transport deterministic code DORT have been carried out for simulating typical configurations of the fast core and led to encouraging results

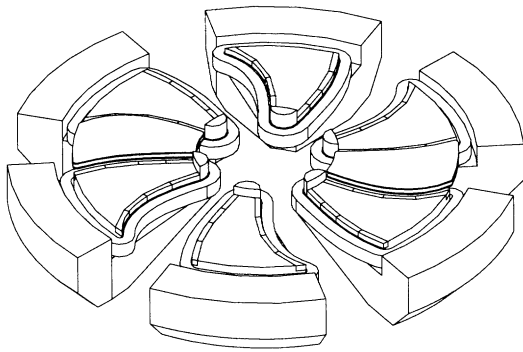


Fig. 2. Lower half of the magnets with the acceleration electrodes of a 350 MeV MYRRHA booster cyclotron.

showing that the targeted performances could be achieved. Table 1 illustrates the preliminary results we obtained for a particular configuration with an active length of 50 cm but in which the fuel assemblies were not well simulated [3].

### 2.3.2. Thermal zone description

The initial design, with a water pool surrounding the fast core zone and housing the thermal neutron core zone, has been completely changed for evident safety reasons (water penetration into the fast zone). In the present approach the thermal zone will be kept at the fast core periphery, but it will consist of various In-Pile Sections (IPS) to be inserted in the Pb–Bi liquid metal pool from the top of the reactor cover. Each IPS will contain a solid matrix made of moderating material (Be, C,  $^{11}\text{B}_4\text{C}$ ) on which a total leakage flux of  $1\text{--}3 \cdot 10^{15} \text{ n/cm}^2\text{s}$  will impinge. Local boosters made of fissile materials can be considered depending on the particular performance needed in the thermal neutron IPS. Black absorbers settled around the IPS could ensure the neutronic de-coupling of the thermal islands from the fast core.

In addition to the spallation target, the fast core and the thermal islands, the pool will contain other components of a classical reactor such as heat exchangers, circulation pumps, fuel loading and handling machines, and emergency-cooling provisions.

Table 1  
Achievable performances in the MYRRHA subcritical core

Spallation source parameters		$E_p = 350 \text{ MeV}$	
		$I_p = 2 \text{ mA}$	$I_p = 5 \text{ mA}$
Source intensity ( $E < 20 \text{ MeV}$ ) ( $\times 10^{16} \text{ n/s}$ )		4.9	12.3
Core parameters	$\text{MF} = 1/(1-K)$	19.15	19.15
	K	0.948	0.948
	Thermal power (MW)	10.0	25.0
	Avg power density ( $\text{W/cm}^3$ )	87	218
	Peak linear power ( $\text{W/cm}$ )	191	477
	Max flux $> 0.75 \text{ MeV}$ ( $\times 10^{14}$ )	4.5	11.2
	# Fuel pins (MOX 30% & 15%)	2646	2646
	MOX-30%- zone ID (cm)	12.8	12.8
MOX-15%- zone ID (cm)	34.2	35.2	
Fast core OD (cm)	55.5	55.5	

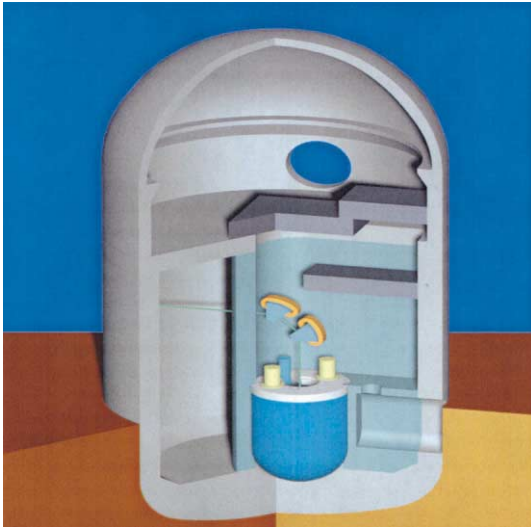


Fig. 3. MYRRHA in a confinement building that is inaccessible during operation.

#### 2.4. Confinement building

Parallel to the core and the spallation module design, attention is given to the confinement building where the MYRRHA subcritical reactor including the spallation module will be located. The accelerator will be kept in a separate confinement building to facilitate the maintenance and inspection procedures.

For the subcritical reactor building, three options are being assessed:

- re-using an existing confinement building where the operators are not allowed to enter during the operation of the system, as illustrated in Fig. 3;
- re-using an existing confinement building where the operators are allowed to enter during the operation of the system, which means that the dose exposure is less than  $10 \mu\text{Sv/h}$ . A preliminary assessment showed that lateral shielding of 1 m steel followed by 2 m heavy concrete would be necessary for achieving such a radiation level due to the very high neutron leakage. These preliminary estimates are based on analytical estimates as well as on MCNP modelling [4];
- designing a completely new building with the 2 options considered above.

### 3. MYRRHA associated R&D programme

For the period 1999–2000, the MYRRHA project team is performing a detailed conceptual design and is completing the needed R&D effort to assess the main technical risks of this design for the accelerator and the spallation source, the most important parts of the system, as outlined below.

#### 3.1. Accelerator

IBA is conducting preliminary design studies on the accelerator required for MYRRHA. The present design of the subcritical core requires the accelerator to deliver a 350 MeV, 5 mA proton beam. This 1.75 MW CW beam has to satisfy a number of requirements, some of which are unique in the world of accelerators up to now. At this level of power it is compulsory to obtain an extraction efficiency above 99.5% and a very high stability of the beam, but on top of that, the ADS application needs a reliability well above that of common accelerators, bringing down the beam trip frequency (trips longer than a few tenths of a second) to below 1 per day. The design principles are based on the following lines of thought.

- Statistics show that the majority of beam trips is due to electric discharges (both from static and RF electric fields). Hence, the highest reliability requires to minimize the number of electrostatic devices, which favours a single stage design.
- In order to obtain the very high extraction efficiency, two extraction principles are available: through a septum with well separated turns, or by stripping.
- The beams are dominated by space charge. Therefore, one needs careful transverse and longitudinal matching at injection, and avoiding of cross talk between adjacent turns (by an enhanced turn separation) if a separated turn structure is required for the extraction mechanism.

The space charge dominated proton beam needs a 20 mm turn separation at 350 MeV if a septum extraction has to be implemented. This solution requires the combination of a large low-field magnet and of very high RF acceleration voltages

for realizing such a large turn separation, and also an electrostatic extraction device. In view of what precedes, this solution is not well suited for very high reliability operation.

Extraction by stripping does not need separated turns. It may be obtained by the acceleration of  $H^-$  ions, but the poor stability of these ions makes them extremely sensitive to electromagnetic stripping (and hence beam loss) during acceleration. The use of  $H^-$  would, therefore, lead to the use of an impractically large magnetic structure. A possible solution is to accelerate 2.5 mA of  $HH^+$  ions up to 700 MeV, where stripping transforms them into 2 protons of 350 MeV each, thus, dividing the magnetic rigidity by 2 and thereby allowing to extract. This solution reduces the problems related to space charge since only half of the beam current is accelerated. However, the high magnetic rigidity of a 700 MeV  $HH^+$  beam imposes a magnetic structure with a pole radius of almost 7 m, leading to a total diameter of the cyclotron of close to 20 m. The cyclotron would consist of 4 individual magnetic sectors, each of them spanning  $45^\circ$ . At the present stage of R&D this option appears to be the most appropriate one.

### 3.2. Spallation source

The choice of a windowless design was influenced by the following considerations:

- At about 350 MeV, an incident proton delivers 7 MeV kinetic energy per spallation neutron. Almost 85% of the incident energy exits the target in the form of “evaporation” energy of the nuclei. The addition of a window would diminish the fraction of the incident energy delivered to the spallation neutrons [5].
- A windowless design avoids vulnerable parts in the concept, increasing its reliability and avoiding a very difficult engineering task.
- Because of the very high proton current density ( $>130 \mu\text{A}/\text{cm}^2$ ) and the low-energy proton beam we intend to use, a window in the MYRRHA spallation module would undergo severe embrittlement.

The project team has identified three main risks to be assessed for this windowless design:

#### 3.2.1. Need for basic spallation data

Since the flux characteristics in an ADS are determined by the spallation neutron intensity and since there is a lack of experimental spallation data in the proton energy range considered, SCK · CEN is assessing, in collaboration with Paul Scherrer Institute (PSI-Switzerland) and Nuclear Research Centre Soreq (NRC-Soreq, Israel), basic spallation reaction data when bombarding a thick Pb–Bi target with protons at energies close to the values that are considered for MYRRHA ( $E_p = 350\text{--}590$  MeV). A joint team from the three institutes conducted the experimental programme at the PSI proton irradiation facility (PIF). The programme started in December 1998 and is due to finish by the end of May 2000 for the experimental part. The analysis of the data is still going on and expected to be finalised by the end of 2000. The expected data from this programme are:

- neutron yield or amount of spallation neutrons per incident proton (n/p yield);
- spallation neutron energy spectrum;
- spallation neutron angular distribution;
- spallation products created in the Pb–Bi target.

#### 3.2.2. Feasibility of the windowless design

The design of the windowless target is very challenging: a stable and controllable free surface needs to be formed within the small space available in the fast core ( $\varnothing_{\text{outer}}, 140$  mm). This free surface will be bombarded with protons, giving rise to a large and concentrated heat deposition (1.75 MW) dispersed over a 15 cm depth starting from the surface for a proton energy of 350 MeV. This heat needs to be removed to avoid overheating and possible evaporation of the liquid metal.

To gain confidence and expertise in the possibility of creating a stable free surface, SCK · CEN is conducting an R&D program in collaboration with the thermal-hydraulics department of the Université Catholique Louvain-la-Neuve (UCL, Belgium). Within this R&D program, water experiments on a one-to-one scale are performed.

Water is used because of its good fluid-dynamic similarity with Pb–Bi. This programme has been complemented by velocity field measurements in collaboration with Forschungszentrum Rossendorf (FZR, Germany) using ultrasonic velocity profile and hot-wire techniques. Currently, the design of the spallation target is being fine-tuned and adapted to the latest geometrical constraints imposed by the neutronics of the fast core.

A confirmation experimental programme making use of Hg as a fluid is in progress at the Institute of Physics at the University of Latvia (IPUL) at Riga. As a final confirmation, we will run experiments with the real fluid at the actual temperatures in collaboration with Forschungszentrum Karlsruhe (FZK, Germany) where the MYRRHA spallation target head will be inserted in their KALLA Pb–Bi loop, which has a working temperature of about 250°C.

In parallel with the experiments, numerical simulations using Computational Fluid Dynamics codes are performed, aimed both at reproducing the existing experimental results and giving input for the optimisation of the head geometry in the experiments. The CFD calculations will also be used to investigate the flow pattern and temperature profile in the presence of the proton beam, which cannot be simulated experimentally at this stage. At SCK·CEN the CFD modelling is performed with the FLOW-3D code which is specialised for free surface and low Prandtl number flow. This effort is being backed up at Université Catholique Louvain-la-Neuve (UCL, Belgium) using the Fluent code. Moreover, a collaboration agreement with Nuclear Research Group—Petten (NRG, The Netherlands) is set up for more CFD calculations with the Star-CD code. Details on this R&D associated programme can be found in [2].

### 3.2.3. Compatibility of the windowless free surface with the proton beam line vacuum

As the free surface of the liquid metal spallation source will be in contact with the vacuum of the proton beam line, SCK·CEN is concerned about the quantitative assessment of emanations from the liquid metal. These can lead to the release of volatile spallation products, Pb and Bi vapours

and of Po, which will be formed by activation of Bi. These radioactive and heavy metal vapours can contaminate the proton beam line and finally the accelerator, making the maintenance of the machine very difficult or at least very demanding in terms of manpower exposure.

In order to assess the feasibility of the coupling between the liquid metal of the target and the vacuum of the beam line and to assess the types and quantities of emanations, SCK·CEN is preparing the VICE experiment (Vacuum-Interface Compatibility Experiment), studying the coupling of a vacuum stainless steel vessel containing 130 kg Pb–Bi, heated up to 500°C, with a vacuum tube ( $10^{-4}$ – $10^{-6}$  Torr) simulating the proton beam line. A mass spectrometer will measure the initial and final out-gassing of light gasses and the metal vapour migration. To protect the vessel from liquid metal corrosion, the possibility of Mo and W coating is currently being investigated. The full experiment will be commissioned during the third quarter of 2000. First results are expected in early 2001.

## 4. MYRRHA international collaborations

The MYRRHA project, in its design phase, during its construction, and also in its future operational stage is and will be an international collaboration project. Agreements have already been signed and collaborations are in progress with:

- Nuclear Research Centre (NRC, Israel): basic spallation data;
- Paul Scherrer Institute (PSI, Switzerland): basic spallation data, MEGAPIE;
- Ente per le Nuove tecnologie, l'Energia e l'Ambiente (ENEA, Italy): spallation source thermal hydraulics, core dynamics;
- Université Catholique de Louvain-la-Neuve (UCL, Belgium): spallation source design;
- Ion Beam Applications (IBA, Belgium): cyclotron design and construction;
- Forschungszentrum Rossendorf (FZR, Germany): instrumentation for the spallation target;

- Forschungszentrum Karlsruhe (FZK, Germany): spallation source testing with Pb-Bi;
- Nuclear Research Group (NRG, The Netherlands): CFD modelling and system safety assessment;
- Commissariat à l'Énergie Atomique (CEA, France): subcritical core design, MUSE experiments, system studies and window design for the spallation target;
- Institute of Physics of University of Latvia, Riga (IPUL, Latvia): spallation source testing with Hg.

Contacts that may lead to additional collaborations exist with:

- RIT, Sweden: participation in MYRRHA;
- International Science and Technology Centre (ISTC), Contact Expert Group of the Project 559, IPPE Obninsk, Russia: PbBi target design;
- LANL et al., USA: Accelerator Transmutation of Waste (ATW) project;
- AEKI, Hungarian Nuclear Energy Institute: modelling of the spallation source;
- Belgonucleaire, Belgium: fuel and core design, fuel loading policy and fuel procurement;
- Tractebel Energy Engineering, Belgium: confinement building and auxiliary systems.

## 5. Funding sources for the MYRRHA project

An accurate evaluation of the needed investment to build MYRRHA and an analysis of the potential sources of funding is expected to be completed by the end of the pre-design phase end-2000–mid-2001. Since the MYRRHA project is likely to be attractive for several types of scientific and industrial groups at the regional, national and

international level, SCK·CEN and IBA will explore funding possibilities at all of these levels.

## 6. Conclusions

Accelerator Driven Systems can become an essential and very viable solution to the major remaining problems of nuclear energy production. The MYRRHA system would provide the indispensable first ADS step towards a European ATW installation without forcing to freeze all options of ADS (liquid Pb–Bi versus gas, pool versus loop, subcriticality level, mitigating tools for reactivity effects, etc.).

MYRRHA is an innovative project that will trigger different research and industrial activities in fields such as accelerator reliability, nuclear waste management (transmutation), development of new materials, environmental medicine, structural material corrosion and embrittlement, and safety of nuclear installations. Increasing knowledge and know-how in these fields will contribute to aspects of sustainable development and offer a potential for industrially applicable spin-offs.

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