MYRRHA project: An Accelerator Driven System (ADS) prototype

Hamid Aït Abderrahim

Scientific Staff
Hamid Aït Abderrahim, Peter Kupschus, Katrien Van Tichelen, Edouard Malambu, Jean-Luc Bellefontaine, Fernand Vermeersch, Philippe Benoit, Baudouin Arien, Klaas van der Meer, Marcel Willekens, Gilbert Bergmans, Enrico Lucon, Rachid Chaouadi, Thierry Aoust, Serge Bodart, Pierre D'hondt

Supporting staff
Jozef Oeyen, Stefan Dekelver, Francis Van Gestel

Background

Nuclear energy has to cope with critical topics to resolve the economical question of increasing energy demand and, in particular, the public acceptability demands:

increasing the absolute safety of the installations
managing more efficiently the nuclear waste

In that respect, the development of a new type of nuclear installation coping with above constraints of technological as well as socio-economical nature may be of high importance for the future of sustainable energy provision. An **A**ccelerator **D**riven **S**ystemor, in short ADS, – a subcritical core operated as a nuclear amplifier fed with primary neutrons by a spallation source – has the potential to cope with above constraints and to pave the way to a more environmentally safe and acceptable nuclear energy production. Fundamental and applied R&D are crucial in the development of these technologies and demand the availability of appropriate prototype installations. These prototype installations have to enable and have to deal with these R&D-issues related to accelerator driven system development.
The continuation of nuclear science and engineering demands the availability of research installations, i.e. research reactors, and those are currently subject to constraints related to ageing, high operational costs, deep refurbishment or even replacement. A new, inherently safe, and economically viable system is called for that could be used in a modular way for dedicated applications, to extend known research domains and explore new ones.

Programme

In answer to the demands for the availability of an appropriate prototype installation and to the need to update its current irradiation potential, SCK•CEN, the Belgian Nuclear Research Centre, has launched the MYRRHA Project in partnership with IBA, Ion Beam Application s.a., the world's leading cyclotron manufacturer for the medical industry. In the beginning of 1999, the partners have started a joint conceptual design phase of roughly to years after which a final decision on the Project would be taken. The MYRRHA Project aims to investigate the design, development and realisation of a versatile neutron source based on ADS. It focuses on the conception of a modular and flexible radiation source and irradiation facility equally matched to both, regional R&D needs and internationally research programmes in the field of waste transmutation and ADS development. It could therefore serve as an important step towards a European ADS demonstrator since MYRRHA needs to deals with and master a high fraction of R&D issues whose solutions are essential for the development of the ADS technology.

More generally, MYRRHA is intended as versatile proton and neutron source for various R&D topics. In this way, it could be a Material Testing Facility (MTF). The applications being considered, can be grouped in three complexes:

enhancement and triggering of new R&D activities where competencies are existing at SCK•CEN, such as in waste transmutation, in ADS technology and in liquid metal embrittlement studies;

initiation of new competencies at SCK•CEN, such as medical applications (proton therapy, development of new neutron-based isotopes) and neutron beam applications;

continuation and later on, expansion towards ADS of the ongoing R&D programs at SCK•CEN in the fields of reactor materials, fuel and reactor physics research.

The research topics for the use of a MYRRHA facility considered in the present design are:

waste transmutation studies of Minor Actinides (MA) and Long Lived Fission Products (LLFP);

ADS technological demonstration;
structural material studies for PWR, Fusion and ADS;
nuclear fuel behaviour studies for PWR, BWR and ADS;
radioisotope production for medical and industrial applications;
neutron and proton beam applications and neutron and proton therapy.

Currently the study and preliminary conceptual design of the MYRRHA system is going on, the basic engineering has started and a conclusion of this phase is being envisaged for the end of 2000.

Achievements

In 1999, based on a set of applications considered as of primary importance for the SCK•CEN activities and for the MYRRHA project, the project team focused its effort towards optimising a high-performance device with a maximum neutron flux for MA irradiation experiments of 1.10 15 n/cm 2 .s with neutron energies exceeding 0.75 MeV and about 3.10 15 n/cm 2 .s for all energies. The total output power of this research device was to be kept at a minimum and for the k eff of the subcritical core a value of 0.95 is aimed at, the maximum value of a radio-active fuel storage thus demonstrating the inherent safety of this concept. Although the final concept was not yet concluded at the end of the year the choice of the above parameters drove the concept to adopt a very compact core of dimensions 500 mm active height and 560 mm diameter with relatively high radial gradients in neutron flux as well as thermal power, a MOX fuel with radially taylored Pu enrichment of up to 30% and linear powers of up to 500 W/cm. The total power could be limited to about 25 MW. However, it was necessary to increase the parameters of the cyclotron accelerator to nominally 350 MeV / 5 mA whereby a trade-off of higher voltage against lower current is still being considered. This results in a point source of slightly exceeding 10^{17} s^{-1} of primary spallation neutrons.

Design proposals are being worked on for the MYRRHA ADS components as described in more detail in the following.

The Accelerator

IBA is conducting design studies on the accelerator required for MYRRHA. The negative ion cyclotron technology that IBA pioneered was dropped for the higher energies required for MYRRHA. The choice was made to use positive ion, i.e. proton acceleration in a separate sector cyclotron. The design and the preliminary calculations were conducted for 80 MeV injector cyclotron followed by a six sectors booster cyclotron, able to accelerate 2 mA of proton beam at 350 MeV. This design will now be checked for upgrading to 5 mA. The booster cyclotron would require an injector cyclotron with energy of at least 40 MeV. However, the alternative possibility of accelerating from low energy (e.g. 2 MeV) up to 350 MeV with a single cyclotron is attractive from a simplicity, reliability and cost viewpoint. The first computer modelling indicates that a design with four straight sectors of 45° would be able to accelerate protons up to 390 MeV before reaching the beam stability limits. Beam reliability will be the most stringent technical parameter that will dominate the final choice.

The Spallation Source

As the use of relatively low-energy protons is foreseen and as the design of a window is a high-risk engineering task – particularly because of the high current density implied by the very compact design and the unknown embrittlement effects- a windowless design has been selected for the spallation target. The project team has identified three main risk areas to be assessed for the chosen design.

Basic spallation cross section data

The flux characteristics in an ADS are driven by the spallation neutron source intensity and there is a lack of experimental spallation data in the range of considered proton energies. Therefore, SCK•CEN has decided to assess in collaboration with PSI (CH) and NRC Soreq (Is) the basic data of the spallation reaction when bombarding a thick Pb-Bi target with protons at energies close to values which are considered for MYRRHA (E_p = 350 to 590 MeV). The experimental program - conducted by a joint team from the three institutes at the PSI proton irradiation facility (PIF) - started in December 1998 and is due to finish by May 2000. The irradiation has been carried out and the expected data under evaluation from this program are:

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

Feasibility of the windowless design
The design of this windowless target is very challenging: a stable free surface, controllable in vertical position, needs to be formed in the tight space available within the fast core (outer Ø 130 mm for the nozzle arrangement, 72 mm Ø for the target tube). This free surface will be bombarded with protons, giving rise to a concentrated heat deposition dispersed over 15 cm starting from the surface (for a proton energy of 350 MeV). The heat - a large fraction of the 1.75 MW of the beam - needs to be convectively removed away from the free surface 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 has started in June 1999 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. The experiments have shown the possibility of creation and control of a stable free surface in the previous MYRRHA configuration. 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.
As the spallation target design is a crucial point for the MYRRHA project, confirmation experiments must be performed with the real fluid, Pb-Bi, at the actual temperatures. In view of this, a collaboration with Forzungszentrum Karlsruhe (FZK, Germany) is being set up for inserting the MYRRHA spallation target head in the KALLA Pb-Bi-loop which has a working temperature of about 250°C. These experiments are foreseen during the second half of 2000, depending on the commissioning of the KALLA loop.

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 optimising 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 in free surface and low Prandtl number flow. This effort is being backed-up at UCL using the FLUENT code. Moreover, a collaboration agreement with NRG (Nl) is set up for more CFD calculation with the Star-CD code.

Compatibility of the windowless free surface with the proton beam line vacuum
As the free surface of the liquid metal of the spallation source will be in contact with the vacuum of the proton beam line, there is concern about the quantitative assessment of emanations from the liquid metal. These can lead to the initial release of volatile roducts, Pb and Bi vapours, and of spallation or activation products like Hg or Po. The 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 type and quantities of emanations, SCK•CEN is preparing the experiment VICE (**V**acuum **I**nterface **C**ompatibility **E**xperiment). VICE will permit to study the coupling of a pool containing more than 100 kg of Pb-Bi eutectic, heated to temperatures up to 500°C, with a vacuum tube under high-vacuum conditions preferably down to 10 -6 mbar simulating the proton beam line, both combined in a UHV stainless-steel

vessel. A mass spectrometer will measure the initial and final outgassing of light gasses and the metal vapour migration. To prevent the vessel from liquid metal corrosion, the possibility of Mo or W coating is currently being investigated. The full experiment is in a preparation stage and its first phase is intended to be carried out during the third quarter of 2000.

The Subcritical core

To develop an ADS such as MYRRHA, neutronic calculation methods have to be applied to demonstrate the feasibility, to optimise the design configuration and to support the engineering layout. SCK•CEN is completing an optimisation effort of the subcritical core taking into account the requirements and constraints concerning:

the use of fuel technology existing in Europe: oxyde fuel with Pu contents ranging between 20 to 35% for the fast zone and PWR type fuel for the thermal zone;

the use of existing technology for the coolant: Pb or Pb-Bi for the fast zone and H_2O or solid matrix (Be, C, $^{11}B_4C$) for the thermal zone;

the achievement of the neutron flux levels required by the different applications considered:

$\Phi_{>0.75\ MeV} = 10^{15}$ n/cm².s for MA transmutation at the locations close to the spallation source, $\Phi_{>1\ MeV} = 10^{13}$ to 10^{14} n/cm².s at the locations for structural material and fuel irradiation, $\Phi_{th} = 2\sim3.10^{15}$ n/cm².s at locations for LLFP transmutation or radioisotope production;

the operation of the fuel in sound and safe conditions: the average fuel pin linear power should not exceed 500 W/cm;

the maximum of total power of the subcritical core: ranging from 20 to 30 MW;
the inherent safety from the point of view of sub-criticality and for this to keep the k_{eff} 0.95 under all conditions;

the performances of the required spallation source and thus the performances of the accelerator, leading under above conditions to required 350 MeV and 5 mA;

the central hole for the feeder head of the windowless spallation target that cannot be larger than about 130 mm outer diameter under the above conditions;

the optimisation the fuel assemblies to be able to create supplementary irradiation channels by removing a fuel assembly;

the assessment of the impact on safety of the whole system by considering a thermal zone surrounding fully the fast zone or by considering islands of thermal zones at the periphery of the fast zone.

The calculation tools and computer programs adopted at SCK•CEN are sketched in the following: The calculations are split into two main steps: the high-energy spallation neutron source calculations and the low-energy ones. High and medium energy (> 20 MeV) neutron transport calculations are made using the HETC-KFA2 module in the HERMES code system.

Neutronic calculations below 20 MeV are carried out using either Monte Carlo codes (MCNP4B or TRIPOLI 3.4) or deterministic codes (DORT, TORT). The present preliminary calculations had been performed using the DORT3.2 code with multi-group cross-sections prepared from a library based on ENDF/B-V using the SCALE-4.4 code package**.**

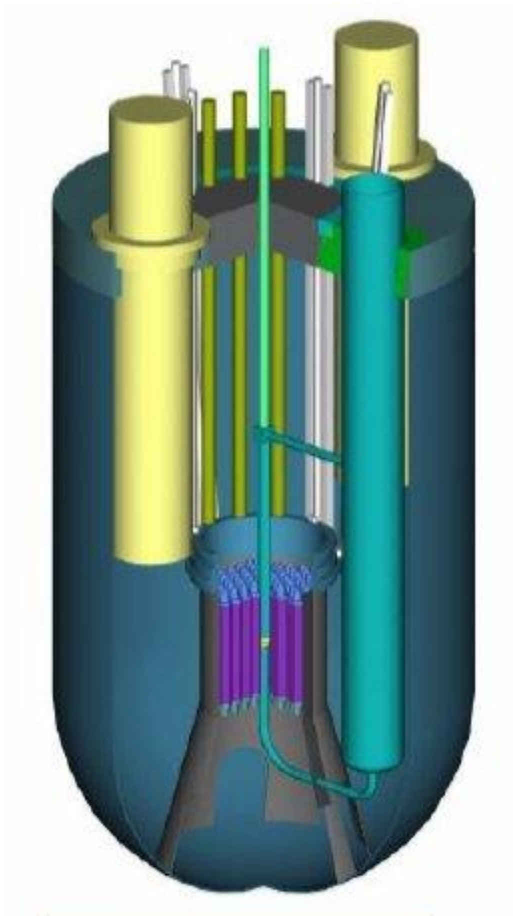
The present core configuration resulting from these calculations (cf. table below), at this moment being limited to the fast zone only, matches almost the above items list. This core configuration will be supplemented by thermal zone islands at the periphery to see whether one can fulfil all the remaining duties, with minor implications to the fast core. Once these tasks are completed, we foresee in the first half of 2000 the study of dynamic and kinetic behaviour of the subcritical core. The assessment will concern the operational point of view - operational cycle length, core management policy, impact of burn-up on core performances – and the safety point of view - reactivity insertions, maximum accident to be considered for licensing etc.

	Spallation Source parameters	E_p = 350 MeV	
		I_p=2 mA	I_p= 5 mA
	Source intensity (E<20 MeV) (x 10^{16} n/s)	4,9	12,3
	MF = 1 / (1 - K)	19,15	19,15
	K	0,948	0,948
	Thermal Power (MW)	10,0	25,0
	Avg Power density (W/cm^3)	87	218
meters	Peak linear Power (W/cm)	191	477
ra	Max Flux >0 .75 MeV (x 10^{14})	4,5	11,2
re pa	# fuel pins (MOX 30% & 15%)	2646	2646
Co	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

MYRRHA Spallation Source parameters

Engineering and Safety Studies for MYRRHA

Configurational studies using the Pro/ENGINEER CAD system have been started to develop mechanical design specifications and to study the remote handling requirements of fuel management and systems maintenance. These studies have been complemented by thermo-hydraulic calculations of core cooling under normal operations and emergencies. From the latter ones it appears that in the chosen configuration linear power densities of up to 800 W/cm can be safely handled and that the up to 10 % of nominal power after beam switch-off can be coped with by free convection provided an emergency heat exchanger can maintain a minimum cooling requirement.



3-D Design Study of MYRRHA

The overall configuration adopted is that of a pool in which the subcritical core and most subsystems are submerged in the Pb-Bi eutectic, with the beam entering from above and being guided by a beam tube to the spallation source in the center of the core. On the way to establish a safety assessment report (SAR) for MYRRHA, the project team is working to evaluate among other problems three items of primary importance for the entire project:

the maximum k eff- value one can accept for keeping the MYRRHA system inherently safe in all circumstances;

the maximum accident scenario that should be considered for the licensing of the MYRRHA system;

the range in quality and duration of proton beam trips that can be accepted without harm for the core and the vessel internal structures and that can be tolerated without being obliged to shut down the system. Particularly this item will be of general importance for all future ADSs.

Collaborations

Existing collaborations:

• NRC Soreq (Is): basic spallation data;

PSI (CH): basic spallation data;
ENEA (I): spallation source thermal-hydraulics, core dynamics;
UCL (B): spallation source design and simulation experiments with water;
IBA (B): cyclotron design and construction;
FZR (D): measurement of spallation target flow properties.

Collaboration agreements are in preparation with:

FZK (D): spallation source testing with Pb-Bi;
RIGA (Lv): spallation source testing with Hg;
NRG (NL): CFD modelling and system safety assessment;
CEA (F): subcritical core design, alternative window design for the spallation target, system studies, and MUSE experiments;

CEA(F)-PSI (CH): MEGAPIE target experiment;
AEKI (H): neutron beam design and use.

Contacts in view of collaborations exist with:

Sweden : participation in MYRRHA;
ISTC Project 559: Pb-Bi target design for LANL;
USA : ATW roadmap international collaboration;
BELGATOM (B) : core design and fuel loading policy and fuel procurement; confinement building and auxiliary systems.

Scientific output

K. Van Tichelen, J-L Bellefontaine, E. Malambu, H. Aït Abderrahim, “MYRRHA Project, a windowless ADS Design”, Proceedings of the 3 rd International Conference on Accelerator Driven Transmutation Technologies and Applications (ADTTA ’99), edited by Hron M., Lelek V., Mikisek M., Sinor M., Uher J., Zeman J., Praha, Czech Republic (1999).

H. Aït Abderrahim, K. Van Tichelen, Ch. De Raedt, E. Malambu, P. Kupschus, "MYRRHA, A Multipurpose Accelerator Driven System (ADS) for R&D: Potential Use for Fission Studies", Seminar on Fission, Pont d'Oye (Belgium), October 6-8, 1999.

H. Aït Abderrahim, "Belgian Activities in the Field of ADS: MYRRHA Project**,** a Multipurpose ADS for R&D", IAEA, AGM to review National ADS Programs Taejon, Republic of Korea, November 1-4, 1999.