MYRRHA, A MULTIPURPOSE ACCELERATOR-DRIVEN SYSTEM FOR R&D PRE-DESIGN STUDY COMPLETION

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Abstract

SCK•CEN in partnership with IBA S.A. is designing a multi-purpose ADS for R&D applications – MYRRHA – and is conducting an associated R&D programme. In a first stage, the project focuses mainly on demonstration of the ADS concept and safety research on sub-critical systems. In a later stage, the device will also be dedicated to research on structural materials, nuclear fuel, liquid metals and associated aspects and on sub-critical reactor physics. Subsequently, it will be used for research on applications such as nuclear waste transmutation and radioisotope production. The MYRRHA system is expected to become a major research infrastructure for the European partners involved in the ADS Demo development.

The preliminary conceptual design of MYRRHA was completed by mid-2002 and an intensive R&D programme started in 1997, is accompanying the development of this project. This paper will report on the conclusion of the pre-design study of June 2002 and on the methods and results of the R&D programme.

1. Introduction

One of SCK•CEN's core competencies is and has at all times been the conception, design and realisation of large nuclear research facilities. One of the main SCK•CEN research facilities, namely BR2 (a 100-MW Material Testing Reactor) is nowadays arriving at an age of 40 years just like the major MTRs in the world. The MYRRHA facility in planning has been conceived as potentially replacing BR2 and to be a fast spectrum facility complementary at European level to the thermal spectrum RJH (Réacteur Jules Horowitz) facility, in planning in France. This situation would give Europe a full research capability in terms of irradiation capabilities for nuclear R&D.

Furthermore, the disposal of radioactive wastes has still to find a fully satisfactory solution, especially in terms of environmental and social acceptability. Scientists are looking for ways to drastically reduce the radio-toxicity of the high level waste (HLW) to be stored in a deep geological repository as to reduce the time needed to reach the radiotoxicity level of the fuel ore originally used to produce energy. This can be achieved through the development of the partitioning and transmutation and burning minor actinides (MA) and to a less extent long-lived fission products (LLFP) in accelerator-driven systems (ADS). The MYRRHA project contribution will be to demonstrate the ADS concept at reasonable power level and the demonstration of the technological feasibility of MA and LLFP transmutation under realistic conditions and the economical assessment of this option as waste management option.

2. Principle features of the conceptual design of the MYRRHA facility

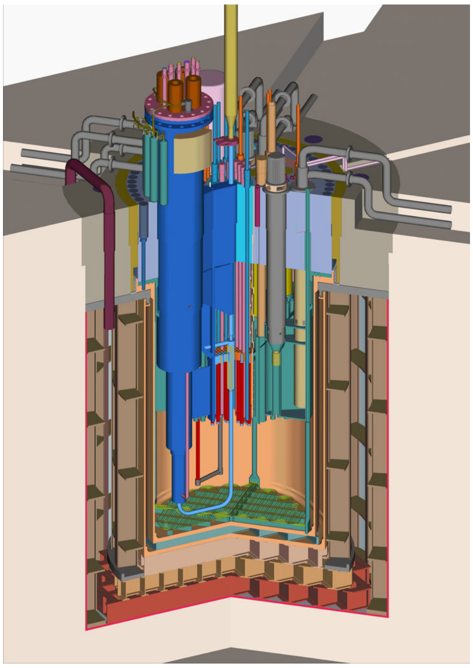
The MYRRHA project is based on the coupling of a proton accelerator with a liquid Pb-Bi windowless spallation target, surrounded by a Pb-Bi cooled sub-critical neutron multiplying medium in a pool type configuration with a standing vessel (Figure 1). [1,2] The spallation target circuit is fully immersed in the reactor pool and interlinked with the core but its liquid metal contents is separated from the core coolant. This is a consequence of the windowless design presently favoured in order to use low energy protons on a very compact target at high beam power density in order not to loose on core performance.

The core pool contains a fast-spectrum sub-critical core cooled with liquid metal (LM) Pb-Bi eutectic and several islands housing thermal spectrum regions located in in-pile sections (IPS) in the fast core. The core is fuelled with typical fast reactor fuel pins with an active length of 600 mm arranged in hexagonal assemblies. The three central hexagons are left free for housing the spallation module. The core is made of fuel hexagonal assemblies of 85 mm flat-to-flat, composed of MOX typical fast reactor fuel (Superphénix like fuel rods) with total Pu-contents of 30% and 20%.

The core structure will be mounted on a central support column coming from the lid and being stabilised by the diaphragm, the separating septum between the cold and hot LM coolant, which is fixed ultimately to the rim of the double-wall vessel. Since access from the top is very restricted and components introduced into the pool will be buoyant due to the high density of the LM, the loading and unloading of fuel assemblies is foreseen to be carried out by force feed-back controlled robots in remote handling from underneath. The pool will also contain the liquid metal main pumps, the heat exchangers using water as secondary fluid and the two fuel handling robots.

The spallation circuit connects directly to the beam line and ultimately to the accelerator vacuum. It contains a mechanical impeller pump and a LM/LM heat exchanger to the pool coolant (cold end). For regulation of the position of the free surface on which the proton beam impinges (whereby this defines the vacuum boundary of the spallation target), it comprises an auxiliary MHD pump. Further on, it contains services for the establishment of proper vacuum and corrosion limiting conditions.

Figure 1. **MYRRHA vertical view**



The device is shown in Figure 1 with the double-wall pool containment vessel (inner diameter of ca. 4 m and height close to 6 m), is surrounded by a vessel providing roughly 1.5 m water biological shielding which is in turn surrounded by concrete to a nominal thickness of 1.5 m as the ultimate biological shield. This shield will be closed above the lid by forming an α-compatible hot cell and handling area for all services to the machine.

3. Task profile

Along the above design features, the MYRRHA project team is developing the MYRRHA project as a multipurpose irradiation facility for R&D applications on the basis of an accelerator-driven system (ADS). The project is intended to fit into the European strategy towards an ADS Demo facility for nuclear waste transmutation. It is also intended to be a European, fast neutron spectrum, irradiation facility allowing various applications. As such it should serve the following task catalogue:

- *ADS concept demonstration:* coupling of the 3 components at rather reasonable power level (around 40 MWth) to allow operation thermal feed-back and reactivity effects mitigation.
- *Safety studies for ADS:* to allow beam trips mitigation, sub-criticality monitoring and control, optimisation of restart procedures after short or long stops, feedback to reactivity injection.
- *MA transmutation studies:* that need high fast flux level ($\Phi_{>0.75\text{MeV}} = 10^{15}$ n/cm².s).
- *LLFP transmutation studies:* that need high thermal flux level ($\Phi_{\text{th}} = 1$ to 2.10^{15} n/cm².s).
- *Medical radioisotopes:* that need also high thermal flux level ($\Phi_{\text{th}} = \sim 2.10^{15}$ n/cm².s).
- *Material research:* that needs large irradiation volumes with high constant fast flux level ($\Phi_{>1\text{ MeV}} = 1 \sim 5.10^{14}$ n/cm².s).

- *Fuel research:* that needs irradiation rigs with adaptable flux spectrum and level ($\Phi_{tot} = 10^{14}$ to 10^{15} n/cm².s).
- *Initiation of medical and new technological applications* such as proton therapy and proton material irradiation studies.

The present MYRRHA concept is driven by the flexibility and the versatility needed to serve the above applications. Some choices are also conditioned by the timing of the project: as we intend to achieve the operability of MYRRHA around 2010, the project team has favoured mature or less demanding technologies in terms of development. Nevertheless, not all the components of MYRRHA are existing. Therefore, a thorough R&D support programme for the "risky" points has been started since 1997 and is summarised in this report.

4. Design features and parameters and their justification

1. MYRRHA: Critical reactor versus ADS

Regarding the listed applications above, one could ask why not to go for a critical reactor? Indeed, nowadays material and fuel research is conducted in critical MTR, radioisotopes are produced in these machines, transmutations studies could be conducted in critical reactors, **but** choosing the ADS route will trigger the possibility of demonstrating the ADS concept and will make available higher flux levels (thermal and fast) as these are driven by the spallation source. The R&D of an innovative ADS project will be an asset for attracting a new generation of scientists and engineers towards the nuclear sector. For all these reasons and particularly the complementarity to a future European MTR, SCK•CEN considers the ADS orientation as the most relevant option for a new fast spectrum R&D facility.

2. The main design parameters of MYRRHA

The performances of an ADS in terms of flux and power levels are dictated by the spallation source strength, which is proportional to the proton beam current at a particular energy and the sub-criticality level of the core. The sub-criticality level of 0.95 has been considered as an appropriate level for a first of kind medium-scale ADS. Indeed, this is the criticality level accepted by the safety authorities for fuel storage. Besides this aspect, we considered various incidental situations that can lead to reactivity variation and found that the majority of those effects would bring a negative reactivity injection or a limited positive reactivity injection not leading to criticality when starting at a Ks of 0.95.

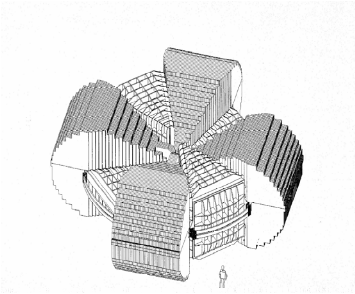
Fixing the sub-criticality level – determining the nuclear gain – and the desired neutron flux in the position of the irradiation location for MA transmutation determines the required strength of the neutron spallation source. In order to achieve the above-mentioned performances at the modest total power level aimed at, we have to limit the central hole diameter to a maximum diameter of 120 mm. As a consequence of this constraint and on the other hand having the need of a minimum lateral Pb-Bi target volume for allowing an effective spallation process, the proton beam external diameter is limited to ~70 mm whereby the beam profile will be shaped by time averaging of a scanned pencil beam. The required spallation source intensity to produce the desired neutron flux at this location is close to 2.10^{17} n/s. At the chosen proton energy of 350 MeV, this requires 5 mA of proton beam intensity and this in turn would lead to a proton current density on an eventual beam-window of order 150 µA/cm². This is by at least a factor of 3 exceeding the current density of other attempted window design for spallation sources which already have high uncertainties with regard to material properties suffering from swelling and radiation embrittlement. As a result, we favoured the windowless spallation target design in MYRRHA.

3. *The required accelerator*

The proton beam characteristics of 350 MeV×5 mA allow to reach a fast neutron flux of 1.10^{15}n/cm².s ($E_{>0.75\ \mathrm{MeV}}$) at the MA irradiation position under the geometrical and spatial restrictions of the sub-critical core and the spallation source. These performances are regarded as being within the reach of the extrapolated cyclotron technology of IBA. Compared to the largest continuous wave (CW) neutron source – SINQ at PSI with its cyclotron generated proton beam of 590 MeV and 1.8 mA – it is a modest extrapolation.

The MYRRHA normal conducting cyclotron would consist of 4 magnet segments of about 45° (Figure 2) with 2 acceleration cavities at ca 20 MHz RF frequency. The diameter of the active field is of order of 10 m, the diameter of the physical magnets of order of 16 m with a total weight exceeding 5 000 t. Due to these very large dimensions, a supra-conducting magnets cyclotron option as well as a LINAC option are presently under evaluation.

Figure 2. **MYRRHA high power proton accelerator cyclotron**



4. *Sub-critical core configuration*

As already mentioned above due to the objective of obtaining a fast spectrum core and the criterion that no revolutionary options were to be considered, we started the neutronic design of the sub-critical core based on MOX classical fast reactor fuel technology. The fuel assembly design had to be adapted to the Pb-Bi coolant characteristics especially for its higher density as compared to Na.

A first core configuration with typical Superphénix hexagonal fuel assembly (122 mm flat-to-flat with 127 fuel pins per assembly) with a modified cell pitch to answer the requested performances has been conceived. Nevertheless, this configuration is subject to the large radial burn-up and mechanical deformation stress gradients that will make fuel assemblies re-shuffling difficult or even impossible. Therefore, we moved towards a smaller fuel assembly, 85 mm flat-to-flat, with 61 fuel pins per assembly allowing a larger flexibility in the core configuration design. The active core height is kept to 600 mm and the maximum core radius is 1 000 mm with 99 hexagonal positions. Not all the positions are filled with fuel assemblies but could contain moderating material (to create thermal neutron flux trap with $\Phi_{th} = \sim 2.10^{15}$ n/cm².s). There are 19 core positions accessible through the reactor lid capable of housing experimental devices equipped with their own operating conditions control supplied by services above the reactor lid. All the other position can be housing either fuel assemblies or non-on-line serviced experimental rigs.

Both present designs of MYRRHA (large fuel assembly and small fuel assembly) are delivering the expected performances in terms of fast and thermal fluxes, linear power in the core and total power. Table 1 is summarising the main parameters of both configurations of MYRRHA.

Table 1. **MYRRHA facility performances**

	Neutronic Parameters	Units	Values	
			Large asssembly Configuration	small asssembly Configuration
Spallation Source	Ep	MeV	350	
	Ip	mA	5	
	n/p-yield		6,0	
	Intensity	10^{17} n/s	1,9	
Sub-critical Core	K_{eff}		0,948	
	K_s		0,959	0,965
	Importance Factor		1,29	
	$MF = 1 / (1 - K_s)$		24,51	28,64
	Thermal Power	MW	32,2	35,5
	Average Power density	W/cm^3	231,5	
	Peak linear Power	W/cm	475,4	582
	Max Flux > 1 MeV			
	close to the target	10^{15} n/cm^2s	0,94	
	first fuel ring		0,83	0,85
	Max Flux >0 .75 MeV			
	close to the target	10^{15} n/cm^2s	1,30	
	first fuel ring		1,17	1,16
	Number of fuel pins		2286	2745

Two interim fuel storages are foreseen inside the vessel on the side of the core fixed to the diaphragm. They are dimensioned for housing the equivalent of two full core loadings ensuring this way that no time consuming operations must take place in the out-of-vessel transfer of fuel assemblies or waiting for the about 100 days of cool-down.

The MYRRHA operation fuel cycle will be determined by the Ks drop as a function of the irradiation time or core burn-up. The targeted operating regime is 3 months of operations and 1 month for core re-shuffling, loading and maintenance. This will lead to a drop in Ks of about 1 000 pcm at maximum (16% drop in multiplication factor) which has only a minor effect at the locations for MA transmutation (18% flux reduction). Core reshuffling would allow to partially compensate this loss of Ks.

5. MYRRHA Sub-critical reactor configuration

Due to the main objective of the MYRRHA facility of obtaining very high fast flux levels, it was obvious that we should go towards a design of a fast reactor core. As we wanted to realise our objectives within a limited time development and due to the high linear power to be achieved it is obvious that a gas fast reactor option was very difficult to realise. Indeed, at normal operation conditions, the thermal-hydraulic problems related to use of helium (or carbon dioxide) coolant in the MYRRHA sub-critical core could be resolved only by using high pressures (100-150 bar). However, even at such high pressure, the power of circulation in the gas loop is very high (~2 to 4 MW for CO_2 or He as compared to 0.2 MW for Pb-Bi). Beside that, a gas-cooled ADS is less robust under accidental conditions than an ADS cooled by liquid metal e.g. for a depressurisation accident. Therefore we discarded the gas option in our design.

When considering the liquid metal option two designs were possible: the loop and the pool options. The loop option has been discarded due to the very high vessel exposure, the risk of LOC and LOF accidents, the difficulty of the interlinking of the spallation target loop with the primary reactor cooling loop. Finally one should mention the desired flexibility in loading and unloading experimental devices that can be more easily achieved in the pool design.

The pool design has been favoured because it avoids the penetration from beneath of the spallation target circuit into the main vessel and thus enhances the safety of the design. It allow also having an internal interim storage easing the fuel handling. The natural circulation (free convection) for the extraction of the residual heat removal in case of loss-of-heat-sinks (LOHS) is certainly easier to achieve, particularly with the large thermal inertia that is also an argument in favour of this design. With the addition of a gravity-fed emergency heat exchanger the free convection can be ensured practically indefinitely, even for complete loss of power.

6. *Safety considerations*

Even if for ADS one of the main characteristics that is desired is to achieve an inherent safety of the system, one should not underestimate the safety considerations for preparing the licensing of such an innovative system. As stated above, a number of reactivity perturbation initiating events have been studied in the MYRRHA system. They either lead to negative reactivity effects or to a reactivity increase. The latter cases were taken care off in the design to avoid their occurrence.

From the safety point of view, the aim is to reduce the probability of the events and their associated off-site consequences in order to avoid the need of extensive countermeasures and to offer the Licensing Authorities the possibility of simplifying or declaring not necessary the off-site emergency planning. This is the well know “in depth defence safety approach” that is followed in the MYRRHA design.

One of the main accidents to be considered is the loss of flow accident resulting from the failure of the circulation pumps. In such a case, natural convection will take over and the following question arises immediately: is the natural circulation sufficient to remove the decay heat released by the core after reactor shutdown? A first parametric approach to study the emergency cooling has shown that:

- even in the worst cases, the coolant temperature remains much lower than the Pb-Bi boiling point (no loss of heat transfer caused by vapour formation at the clad-coolant interface);
- the fuel behaviour is fully safe, because the power drop in the reactor very rapidly reduces the fuel temperature, averting any risk of melting;
- concerning the clad behaviour, the situation is less comfortable: a peak of temperature is observed at the beginning of the transient, proportionally to the flow deceleration, and a maximum temperature nearing 700°C is reached in the present design configuration;
- lowering of temperatures in the fuel rods, in particular in the cladding, can be obtained:
    - by minimising the pressure drops in the circuit, e.g. by reducing as much as possible the local pressure losses,
    - by increasing the difference of elevation between the heat exchanger and the core.

Currently these results are being refined by refining the data for which some uncertainties subsist and by using more sophisticated and accurate tools, like RELAP5 adapted for lead-bismuth.

7. *VII Remote handling system*

The proposed MYRRHA project at SCK•CEN will require remote handling for all maintenance operations on the machine Primary Systems and Associated Equipment. Experience from similar projects [3,5] has shown the importance of considering the implications of remote handling on the design of the plant from the earliest stage. Oxford Technologies Ltd (OTL) has been granted a contract for studying the implications of remote maintenance on the design of the MYRRHA machine and the overall project management. The study was conducted and reported herein following the first four steps of the whole life-cycle approach that has previously been used successfully by Oxford Technologies Ltd for the implementation of the remote maintenance system for the JET Tokamak. [2]

The study includes an analysis of the remote handling requirements of MYRRHA, defines an approach to be used for ensuring the implementation of a plant suitable for remote handling and concludes with a concept proposal for a system suitable for the fully remote maintenance of MYRRHA over its entire working life.

A remote handling system based on the Man-In-The-Loop principle implemented with two bi-lateral force reflecting servo-manipulators working under Master-Slave mode has been recommended. The slave servo-manipulators will be commanded by remote operators using kinematically identical master manipulators supported with CCTV feedback. The manipulators will have additional robotic capabilities to maximise operational capabilities. The slave manipulators will be positioned close to the task environment by means of remotely controlled transporters with sufficient reach and degrees of freedom to position the slaves at all relevant locations around the MYRRHA machine. The concept relies on the ability of the servo-manipulators and the video feedback systems to create a sense of presence for the operators at the task location. In practise all of the MYRRHA maintenance tasks will be performed directly by personnel using the arms, a range of cameras and cranes in much the same way as if they were next to the MYRRHA machine themselves. The remote manipulators and transporters will have computer controlled features which will enhance and simplify the operations.

5. The complementary R&D programme

Despite the fact that we intend to build this facility with a high degree of conventional technology there are a number of features which do not comply with this. Therefore, SCK•CEN has since 1997 started an ambitious support research programme and is developing it according to the requests coming from the progressing design. The support R&D programme covers the following areas of highest uncertainties:

- The windowless spallation target design. Here we investigate the confluent flow pattern of the target formation co-axial with the proton beam on the one hand and the compatibility of the LM flow towards the accelerator vacuum on the other hand.
- For the first part, a number of the design activities have been and are being performed to study the flow behaviour and to obtain an adequate design. Successful experiments have been performed using water and mercury as simulating fluids. Optimisation experiments with water are currently going on. The results of these experiments will be carried over to experiments with the real fluid Pb-Bi. Computational Fluid Dynamics calculations are performed in parallel and are indispensable as it is impossible to experimentally simulate the heat deposition by the proton beam without actually having a beam. In summary, the results of these activities, although not yet totally conclusive, look very encouraging to yield the desired target configuration. [4]
- For the second part SCK•CEN presently carries out the Vacuum Interface Compatibility Experiment, in short VICE. In a large (ca. 6 m high) UHV vessel of spallation loop dimensions we attempt to quantify the emanation of ca 130 kg of Pb-Bi LM at 500°C in the vacuum pumping geometry relevant for MYRRHA and try to assess the resulting vacuum conditions albeit without being able to provide the proton beam in this experiment.

- The LM corrosion aspects of the coolant are of high concern to us because MYRRHA would be the first facility in the western world to use the technology other than for experimental evaluation. By keeping close to present knowledge, mainly worked out in the Russian nuclear programmes, and making use of the knowledge now being acquired by European laboratories with which we collaborate, the MYRRHA design uses moderate temperatures and controlled oxygen contents of the LM (the key to the corrosion issue). Nevertheless, for MYRRHA the proposed choices have to be hardened by experimental evidence. A programme has been conceived and experimental results are under way. [6]
- The third aspect concerns the handling operations under LM, i.e. the force-feedback mechanical aspects as well as the sensors and the fact that the medium is opaque and monitoring under light visibility is not an option. We have started the development of ultra-sonic sensors with the required properties to work under LM though not in direct contact with it. The concentrated effort is directed to ensure in the first place the safe and controlled loading and unloading of the SC but will eventually be widened to all operations under LM. A test pool programme is in development in which key operations will be studied under LM in model form.
- As the remote handling approach is presently favoured for the operation and maintenance, it is clear that a R&D support programme should be launched in this area of robotics under liquid metal reduced visibility and hot condition. This programme is under preparation in collaboration with OTL Ltd.

6. Time schedule and conclusion

At mid-2002, the MYRRHA pre-design file has been submitted to an International Technical Guidance Committee for reviewing the pre-design phase as achieved for the MYRRHA project. This international panel consisted of expert from research reactor designers, reactor safety authorities, spallation target specialists. The conclusions and recommendations of this panel were as follow:

- no show stopper are identified in the project;
- give more attention to safety case studies and iterate to the pre-design before entering the detailled engineering phase;
- address some R&D topics that can lead to timing bottlenecks very soon such as fuel pin and assembly development and qualification;
- make a decision on the accelerator option (cyclotron vs. Linac) and eventually revisit beam parameters.

The project time schedule is given below in terms of main milestones, for decisions for the next steps:

- End of 2003 for the finalisation of the conceptual engineering design as well as the business planning to be advanced to allow the decisions for starting the detailed engineering phase of the project. In parallel the R&D support programme for corrosion, the spallation module design, the instrumentation for visualisation under liquid metal, the complementary robotics studies should have delivered their results to allow the start of the detailed engineering phase with a certain degree of confidence.
- The period of 2004-2006 is planned for the detailed engineering design of the concept and the supportive engineering R&D support programme.

- Beginning of 2007 for the start of the building for the erection and individual parts of the projects.
- Beginning of 2011 for the integration of the sub-components and commissioning of the full ADS.
- End of 2012 for the start of the operation of MYRRHA at full power operation for routine use.

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