a Cyclotron based European Multipurpose **ADS** for **R&D (MYRRHA)**. Pre-design study completion

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Introduction and Abstract - *One of SCK•CEN's core competencies is and has at all times been the conception, design and realisation of large nuclear research facilities such as BR1, BR2, BR3, VENUS reactors, LHMA hot-cells, or HADES underground research laboratory (URL) for waste disposal. SCK•CEN has then operated these facilities successfully thanks to the high degree of qualification and competency of its personnel and by inserting these facilities into international research networks, contributing hence to the development of crucial aspects of nuclear energy. One of the main SCK•CEN research facility, namely BR2, is nowadays arriving at an age of 40 years just like the major materials testing reactors (MTR) in the world and in Europe (i.e. BR2 (B-Mol), HFR (EU-Petten), OSIRIS (F-Saclay), R2 (S-Studsvik)). The MYRRHA facility in planning has been conceived as potentially replacing BR2 and to be a fast spectrum facility complementary 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 nuclear R&D.*

Furthermore, the disposal of radioactive wastes resulting from industrial nuclear energy production has still to find a fully satisfactory solution, especially in terms of environmental and social acceptability. As a consequence, most countries with significant nuclear power generating capacity are currently investigating various options for the disposal of their nuclear waste. Scientists are looking for ways to drastically reduce (by a factor of 100 or more) the radio-toxicity of the High Level Waste (HLW) to be stored in a deep geological repository, and to reduce the time needed to reach the radioactivity level of the fuel originally used to produce energy. This can be achieved via the development of the Partitioning and Transmutation and burning MAs and to a less extent LLFPs in Accelerator Driven Systems. The MYRRHA project contribution will be in helping to demonstrate the ADS concept at reasonable power level and the demonstration of the technological feasibility of MA and LLFP transmutation under real conditions.

A resume for the choice of the basic parameters for and a short description of the conceptual design along with a justification for the specific choice will be given and matched against the purpose and task catalogue the facility should be serving. The complementary research and development effort needed for its realisation is also briefly listed.

I. PRINCIPLE FEATURES OF THE CONCEPTUAL DESIGN OF THE MYRRHA FACILITY

As MYRRHA project is in a very evolving stage, the subcritical reactor design is now conceived as a standing vessel as compared to the previous design of a hanging vessel[1, 2]. In accordance with the above, the MYRRHA team has developed the MYRRHA project based on the coupling of an upgraded commercial proton cyclotron with a liquid Pb-Bi windowless spallation target, surrounded by a Pb-Bi cooled sub-critical neutron multiplying medium in a pool type configuration (Figure 1). The spallation target circuit is fully immersed in the pool and is interlinked with the core but its liquid metal content is separated from the core coolant. This comes as a consequence of the windowless design presently favoured in order to utilise low energy protons on a highly compact target at high proton beam power density in order not to loose out on core performance.

The core pool contains a fast-spectrum subcritical core, cooled with liquid metal (LM) Pb-Bi eutectic, and several islands housing thermal spectrum regions located in In-Pile Sections (IPS) at the periphery of the fast core or in 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. The central hexagon position (or the three central hexagons, depending on the adopted fuel assembly design) is (are) left free for housing the spallation module. The core is made of fuel assemblies composed of MOX typical fast reactor fuel (Superphenix like fuel rods) with Pu contents of 30% and 20%.

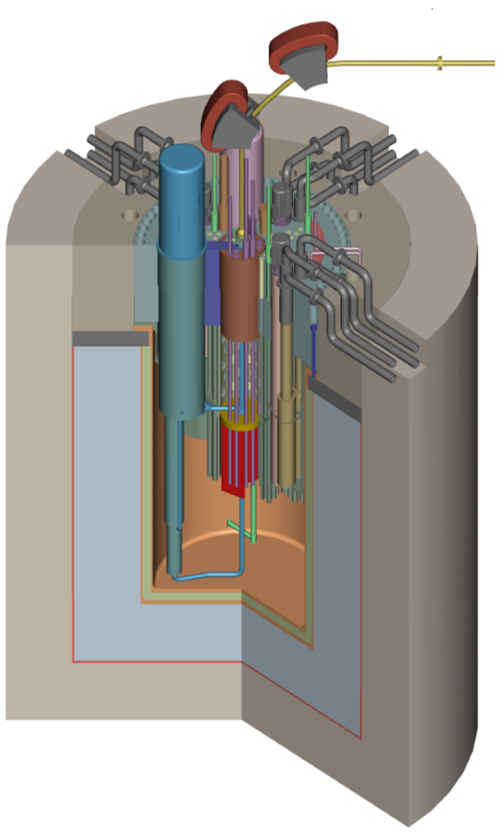

Figure 1: MYRRHA Sub-critical reactor with proton beam injection from the top

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 warm 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 gravity 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 the bottom in and out of the core structure. The pool will also contain the liquid metal main pumps, the heat exchangers towards water as the secondary cooling and the above robotic units for the handling tasks under liquid metal.

The spallation circuit , interlinking with the core, connects directly to the beam line and therefore ultimately to the accelerator vacuum. For pumping around the LM and for cooling, 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 and it further on contains services for the establishment of proper vacuum as well as corrosion limiting conditions.

The device is shown in Fig. 1 with the double-wall pool containment vessel, with inner diameter of ca 4 m and a height of close to 6 m, surrounded by a vessel providing a roughly 1.5 m water shielding that 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.

II. TASK PROFILE

Along the above design features, the MYRRHA project team is developing the MYRRHA project as a multipurpose neutron source 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 (20 to 30 MWth) to allow operation feed-back and reactivity effects mitigation,
- ***MAs transmutation studies:*** need for high fast flux level ($\Phi_{>0.75MeV}=10^{15}$ n/cm².s)
- ***LLFPs transmutation studies:*** need for high thermal flux level ($\Phi_{th}=1$ to 2.10^{15} n/cm².s)
- ***Radioisotopes for medical applications:*** need for high thermal flux level ($\Phi_{th}= \sim 2.10^{15}$ n/cm².s),
- ***Material research:*** need for large irradiation volumes with high constant fast flux level ($\Phi_{>1 MeV}=1 \sim 5.10^{14}$ n/cm².s),
- ***Fuel research:*** need irradiation rigs with adaptable flux spectrum and level ($\Phi_{tot}=10^{14}$ to 10^{15} n/cm².s),
- ***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 various reactivity injection,
- 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. Indeed as we intended to achieve the operability of MYRRHA before 2010, the project team has favoured the mature technologies or the less demanding in terms of development, for example concerning fuel and accelerator. Nevertheless, not all the components of MYRRHA are existing of the shelf. Therefore, a thorough R&D support programme for the risky points of the project has been started and is summarised in this report.

III. DESIGN FEATURES/PARAMETERS AND THEIR JUSTIFICATION

I. MYRRHA: Critical Reactor versus ADS

Regarding the listed applications above, except those related to ADS demonstration, one can ask why would one not go for a critical reactor? Indeed, nowadays material and fuel research are conducted in critical MTRs, radioisotopes are produced in these machines, transmutations studies could be also conducted in critical reactors; but:

- Using critical thermal reactor technology, even when going to very high dense cores and very high enriched fuel (93% W/o ^{235}U), the highest total flux level one can achieve is 10^{15} n/cm².s, mainly dominated by thermal flux (about 80%). In principle, these flux levels can be used for LLFPs transmutation experiments but they will already require very long irradiation times (1 to 2 years) for obtaining burn-up levels of the 1~2% that are needed for performing relevant radiochemistry analysis with uncertainties limited to a few percents. These are the minimum transmutation levels needed for integral validation experiments. Since in an ADS the absolute flux level is determined by the spallation neutron source intensity, one can overcome these intrinsic limitation of the critical reactor.
- Due to the same limitation for the thermal flux level, radioisotopes production will be limited to the classical isotopes produced via single capture or fission reactions used mainly for diagnostic purposes in nuclear medicine departments. But if one is considering the curative radio-isotopes like α-emitters that are produced by double capture or long-lived generators such as ^{188}W for ^{188}Re that is produced also by double capture, one needs to go to thermal flux levels above the 10^{15} n/cm².s. Therefore, the ADS option would be an asset also here.
- MAs transmutation asks for fast spectrum irradiation, as one should favour fission reactions as compared to capture reactions. In fast spectrum critical reactors once again the total flux level is about 10^{15} n/cm².s whereas the most effective part of the neutron spectrum for favouring the fission of the MAs lies above 0.75 MeV. Therefore, as in the case of the transmutation of LLFPs, the ADS whose flux level is driven by the spallation source intensity will permit higher flux levels than the critical fast reactor. This is certainly an advantage especially for an experimental facility where one would be conducting development experiments and thus would desire to run accelerated experiments as compared to the real MAs burner machine.
- For structural material research under irradiation or fuel research and development, these research topics can be conducted evenly in MTRs as well as in an experimental ADS. Nevertheless, one can mention here the need for a fast spectrum irradiation facility that would be complementing a thermal spectrum one that would be available in 2010. Indeed, hardening the irradiation spectrum of a thermal MTR such as RJH by spectrum tailoring techniques would be very demanding and will never reach the flux levels that can be obtained in a fast spectrum ADS.
- Besides these applications that can be completed in a MTR but with better performances in an ADS, one should mention that all the R&D activity related to the ADS development can be triggered only if one is developing and building such a facility. The challenging aspect of such a project should be stressed here as an incentive for maintaining the know-how and the expertise in the nuclear field. Nuclear energy is contributing to a large extent to the provision of electrical power in Europe and will still do so for the next 2 decades at

least, even if the present phase-out strategy is maintained as the future policy in Europe. The development of such an innovative 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, such as the RJH project, it looks to us that choosing the ADS orientation is the most relevant option for developing a new fast spectrum R&D facility.

II. 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, that is proportional to the proton beam current at a particular energy, and the sub-criticality level of the core. Thus having in mind the targeted performances required by the different applications considered in MYRRHA system, as summarised below:

$\Phi_{>0.75\ MeV}$ = 1. x 10^{15} n/cm².s at the locations for Minor Actinide (MA) transmutation,
$\Phi_{>1\ MeV}$ = 1. x 10^{13} to 1.0 x 10^{14} n/cm².s at the locations for structural material and fuel irradiation,
$\Phi_{thermal}$ = ~2. x 10^{15} n/cm².s at locations LLFPs transmutation or radioisotope production.

Taking into account that the MYRRHA facility is intended to be put into operation before 2010, it is obvious that one has to stay away from too revolutionary solutions for the accelerator that is to deliver the needed proton beam as well as from fuel options with a high degree of needed development.

Considering the above-mentioned constraints, we had to fix the sub-criticality level of the sub-critical assembly in order to define the needed beam power intensity to achieve the above performances. 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 situation that can lead to reactivity variation such as: Doppler effect, realistic water intrusion, temperature effect, voiding effect of the spallation module, voiding effect of the coolant in the core and core compaction. We found that the majority of those effects would bring a negative reactivity injection or a limited positive reactivity injection not leading to criticality in any case when starting at a Ks of 0.95.

To design a sub-critical core having a Ks of 0.95 and a fast spectrum it was obvious to go towards existing fast reactor MOX fuel technology for keeping the design time and building time within the time frame of the project. Thus the upper limit of the fuel enrichment we put to ourselves was 30% W/o total Pu with the Pu vector of reprocessed fuel from PWRs.

Having fixed the sub-criticality level – determining the nuclear gain - as well as the desired neutron flux in the position of the irradiation location for MA transmutation this will determine the required strength of the neutron spallation source. Nevertheless, one still has a degree of freedom in achieving the needed performances in the core via the geometrical design of the core especially the central hole in the core that will be housing the spallation target module. In order to achieve the above-mentioned performances at the modest total power level aimed at, we had to limit the central hole diameter to a maximum diameter of 120 mm, thus putting the above irradiation location for the MAs at roughly 5 cm radius. 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, intra-nuclear cascade as well as evaporation processes - 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 proton energy chosen, 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 are already stressed to the limit and have high uncertainties with regard to material properties suffering from swelling and radiation embrittlement. As a result of these constraints and the comparison with other designs, we favoured the windowless spallation target design in the MYRRHA project.

III. The Required Accelerator

Having fixed the sub-criticality level, we historically started the design work with a 250 MeV x 2 mA cyclotron as advised by the Ad-hoc MYRRHA Scientific Committee and that would have been a slight upgraded machine from the cyclotron developed by IBA for the proton therapy application. However, this beam power level does not allow to meet the neutronic performances demanded from the core. Therefore, we first had to increase the proton energy to 350 MeV, as the gain on the neutron intensity due to the energy increase is more than linear. Indeed, the neutron multiplicity at 250 MeV is ~ 2.5 n/p whereas it is ~5-6 n/p at 350 MeV. Despite this energy increase of the incident protons we also had to increase the proton current to 5 mA to arrive at the required source strength. The final proton beam characteristics of 350 MeV x 5 mA then permitted to reach a fast neutron flux of 1.10^{15}n/s (E>0.75 MeV) at an acceptable MA irradiation position under the geometrical and spatial restrictions of sub-critical core and spallation source. This upgrade is also regarded as being within the reach of the extrapolated cyclotron technology of IBA who currently propose to generate the above proton specifications by accelerating 2.5 mA of H_2^+ ions to 700 MeV and to split the latter into protons by stripping on a foil. 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 and well within the conceptual extrapolation of the SINQ to the "PSI Dream Machine" with the proton parameters of 1 GeV x 10 mA.

The above concept needs a demanding vacuum design of the beam path to avoid stripping gas stripping and a stripper design with high effective lifetime and coping with high thermal loads. The MYRRHA cyclotron would consist of 4 magnet segments of about 45° (cf. the figure below) 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 5000 t. The handling of only part components need lifting capabilities of at least 125 t, and according provisions in the building need to be made.

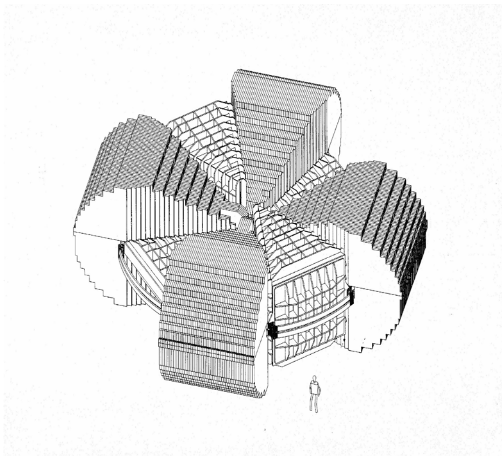

Figure 2 : Schematic view of the MYRRHA HPPA (High Power Proton Accelerator) Cyclotron.

IV. 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 fast reactor fuel technology. As we wanted to limit the technological development to the choice of cladding material being compatible with Pb-Bi, the initial request was to limit the Pu enrichment to maximum 30% in weight and the maximum linear power to 500 W/cm. With the low proton energy chosen (350 MeV), leading to a spallation neutron source length of ca 13 cm (penetration depth of protons), it was also decided to limit the core height to 60 cm. This height is compatible with the purpose of MYRRHA to be an irradiation facility for technological developments. 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 Superphenix hexagonal fuel assembly (122 mm plate-to-plate 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 also consider now in parallel a smaller fuel assembly, 85 mm plate-to-plate, with 61 fuel pins per assembly allowing a larger flexibility in the core configuration design. The active core height is kept to 60 cm and the maximum core radius is 100 cm with 99 hexagonal positions. Not all the positions are filled with fuel assemblies but could contain moderating material (e.g. ZrH_2 pins filling 6 hexagons around a hexagonal position that becomes a thermal neutron flux trap with $\Phi_{th} = \sim 2.10^{15}$ n/cm².s). There are 19 core positions accessible through the reactor cover and principally capable of housing thermal flux traps. At these positions hexagons could also be housing fast neutron spectrum experimental rigs equipped with their own operating conditions control supplied by services above the reactor cover. All the other position can be housing either fuel assemblies or non-instrumented experimental rigs. About 1/2 of the positions should be filled with fuel assemblies to achieve a Ks of 0.95.

It is worth mentioning here one particularity of the Pb-Bi as a coolant. Indeed, due to its high-density (10.7 g/cm^3), the fuel assemblies will be floating in this coolant. Therefore, we decided not to plug the fuel assemblies in a supporting plate but to implant them from beneath in the top core plate that is fixed to the central support column and diaphragm separating the cold zone from the hot zone of the primary circuit of the reactor. The fuel assemblies as well as any non-instrumented experimental rig or moderating assembly will be then manipulated from beneath for its positioning in the core. By doing so one is easing the access to the experimental position from the top of the reactor.

Two interim storages for the used fuel 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. Calculations have shown that in their intended position and with the amount of foreseen shielding they will not contribute to the criticality of the subcritical core.

V. Operation Fuel Cycle

The MYRRHA operation cycle will be determined by the Ks drop as a function of the irradiation time or core burn-up. Taking into account the power density distribution in the core, we ran evolution calculations for the core and we observed the following: an initial Ks sharp drop of about 1800 pcm (Ks: 0.95 $\rightarrow$ 0.932) after 5 days of irradiation time due to the fission product build-up. After reaching a sort of equilibrium we observe than a smooth decrease of Ks with a slope of 5 pcm/day.

Thus the first operational procedure has to deal with overcoming the initial Ks drop: either by an active compensation - higher initial Ks that can be compensated by partial coolant voiding as the voiding coefficient is negative - or by a passive one - conditioning the fuel assemblies thanks to a pre-irradiation outside the core for a longer period than 5 days. Both approaches are presently still under consideration.

The targeted operating regime is 3 months of operations and 1 month for core re-shuffling, loading, and maintenance. This will lead to Ks drop per cycle of 450 pcm at maximum, as this value is not taking into account the coupled effect of the linear power drop during the operation. This will correspond to a multiplication factor drop from 20 to 18.3 thus about ~9%. Core re-shuffling with bringing the less burned peripheral fuel assemblies towards the core centre would allow compensating partially this loss of Ks.

The intermediate cooling time between 2 irradiation cycles does bring an extra accumulation of absorbing materials via delayed radioactive decay. The objective is to maintain the Ks drop within 10% range by using core reshuffling and partial reloading of fresh fuel with a total residence time of the fuel in the core of 3 years i.e. 810 EFPD (equivalent full power day). This objective looks to be achievable but needs more investigation.

VI. 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) and then by optimising the operation parameters and the fuel rod bundle design. 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). This power level is comparable with that needed for the proton beam. Beside that, a gas-cooled ADS is less robust under accidental conditions than an ADS cooled by liquid metal. A depressurisation accident is the major safety concern. Very special means must be anticipated, in order to cool down the core at the reduced pressures of gas. MYRRHA being intended as a flexible experimental facility made the use of gas as impractical as incompatible with this goal. 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 and thus the radiation damage it would undergo, the risk of LOC and LOF accidents, the difficulty of the inter-linking of the spallation target loop with the primary reactor cooling loop due to the above mentioned optimisation process. Finally one should mention the desired flexibility in loading and unloading experimental devices.

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.

VII. 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. The following reactivity perturbation initiating conditions have been studied in the MYRRHA system: power increase leading to average temperature increase, Doppler effect, spallation source level positioning (leading to voiding or filling of the central channel in the core with Pb-Bi), partial core voiding due to fuel elements blockage. All these situations led to negative reactivity effects. Whereas the following situation: pitch compaction, loading faults (30% enriched fuel assemblies loaded instead of 20%), water ingress from in the core, could lead to slight or heavy reactivity increase and thus have been taken care off in the design to avoid their occurrence.

From the safety point of view, the aim is to reduce both 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? 'Sufficient' here means that no fuel damage occurs.

When the emergency cooling was studied in a first approach, the design of the MYRRHA sub-critical reactor was not yet well advanced and it was therefore impossible to simulate the free circulation accurately, so that only very rough models could be used. The purpose of the study was to provide very general indications on the possibility of cooling the reactor by natural convection.

Due to the lack of detailed information on the whole of the reactor design, a parametric approach has been followed. Three main free parameters were used: the total pressure drop in the primary circuit, the cross-sectional area of the pipes simulating the primary circuit and the difference of height between the core and the heat exchanger, or respectively the emergency heat exchanger should the flow of secondary water cooling in the main heat exchangers stop as well.

The main conclusions of the study are the following ones:

- even in the worst cases, the coolant temperature remains much lower than the Pb-Bi boiling point, so that no loss of heat transfer caused by vapour formation at the clad-coolant interface has to be feared;
- 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, but this is limited by design constraints, especially with the pool reactor concept;

For the future, those results will have to be confirmed,

- firstly, by refining the data for which some uncertainties subsist, such as the power decrease as a function of time,
- secondly, when the circuit design will be better defined, by using more sophisticated tools, like RELAP5 adapted for lead-bismuth, which could allow to model and simulate the system much more accurately.

VIII. Summary of the expected performance of the Proposed Design

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. The table below is summarising the main parameters of both configurations of MYRRHA.

Table I : Summary of the 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^{2}s	0,94	
	first fuel ring		0,83	0,85
	Max Flux >0 .75 MeV			
	close to the target	10^{15} n/cm^{2}s	1,30	
	first fuel ring		1,17	1,16
	Number of fuel pins		2286	2745

IV. LISTING OF THE COMPLEMENTARY R&D PROGRAM

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 either started or is about to commence Research into the areas of in our opinion 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. This first part is described in a paper at this conference[3] where the problem at its possible solution. For the second case SCK·CEN presently carries out the **V**acuum **I**nterface **C**ompatibility **E**xperiment, 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 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, slightly different in the case of main coolant and spallation loop is 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 programs, 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, on the time scale MYRRHA is intended the proposed choices have to be hardened by experimental evidence and a program has been conceived and is experimental reparation that can be found in another paper at this conference[4] .
- 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. Their use is intended in the classical ultrasonic testing tasks as well as in further applications in ranging by beacon triangulation as well as finally by use in phased arrays to provide full “visualisation“. 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 program is in development in which key operations will be studied under LM in model form.

V. MYRRHA PROJECT TIME SCHEDULE AND CONCLUSION

The project time schedule is given below in which we are indicating the aimed at main milestones, namely:

- end of 2001, by which a decision is needed for the start of the detailed engineering phase and where a budget increase would be needed not only for the funding of the team to be devoted for this detailed design but also for the engagement into the testing of larger scale elements needed in the design such as heat exchangers or fuel assemblies mock-up in Pb-Bi,
- end of 2003, by which the detailed engineering design as well as the business planning should be well advanced for allowing the decisions for starting the building phase of the sub-assemblies. In parallel the R&D support programme for corrosion and spallation module design should have delivered their results to allow the start of the construction,
- end of 2006, by which we anticipate the completion of the building for the erection and individual commissioning of larger components (accelerator, spallation module and sub-critical core structure mid-2008 by which the integration of the sub-components and commissioning of the full ADS should talk place
- Beginning of 2010, which should see the beginning of MYRRHA at full power operation for routine use of the facility

The present time schedule is subject to modification depending on the outcome of the detailed engineering design that would reveal an important need for R&D support programme for the present design and on the approval procedure in combination with the availability of the corresponding funding of the project.

MYRRHA is a challenging facility from many point of views therefore we are convinced that it will trigger a renewal of R&D activities within the fission community.

Its development will attract young talented researchers and engineers looking for challenges. It will be a new irradiation facility for research and development in Europe for future innovative energy systems.

VI. CONCLUSIONS

With regard to the ADS deployment based solely on LINAC accelerators as presently thought within the ADS community, one can ask if it is worth working on a cyclotron based ADS. We believe that the answer is clearly YES, because :

- ADS development is a long run development and feedback operational experience need to be accumulated very soon,
- experimental ADS can be realized faster via the cyclotron route for that purpose, in economical way
- reliability improvements achieved for cyclotrons can be transferred to LINAC’s
- multi-accelerator ADS can be a route for improving beam reliability then multi-cyclotron vs. a large LINAC deserve a serious analysis

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