The Evolution of the Primary System Design of the MYRRHA Facility

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Abstract. MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) is a multipurpose research facility being developed since 1998 at SCK•CEN, based on the Accelerator Driven System (ADS) concept where a proton accelerator, a spallation target and a lead-bismuth cooled subcritical reactor are coupled. MYRRHA will demonstrate the ADS full concept by coupling these three components at a reasonable power level to allow operation feedback, scalable to an industrial demonstrator, and allow the study of efficient transmutation of high-level nuclear waste.

The MYRRHA research facility will be able to work in both critical as subcritical modes and will allow fuel developments for innovative reactor systems, material developments for GEN IV and fusion reactors, and radioisotope production for medical and industrial applications. MYRRHA will contribute to the development of Lead Fast Reactor (LFR) technology and in critical mode it will play the role of European Technology Pilot Plant in the roadmap for LFR.

In the beginning of 2014, SCK•CEN has consolidated a coherent version of the primary system. This version 1.6 of the primary system forms the basis for the pre-licensing activities. In this paper, the evolution of design of MYRRHA is presented in detail with regard to the primary system and also the current investigations towards a new release will be mentioned.

Key Words: nuclear energy, accelerator-driven systems, lead-bismuth, primary system.

1. Introduction

From the early conceptual design of the MYRRHA Accelerator Driven System (ADS), where a cyclotron was coupled to a subcritical reactor by means of a windowless spallation target, to the current detailed design of a multipurpose research facility with a high-energy linear accelerator and a window spallation target, many design changes have been necessary to solve the engineering challenges to fulfil the requirements.

MYRRHA is the flexible experimental accelerator-driven system (ADS) in development at SCK•CEN in replacement of its material testing reactor (MTR) BR2. The MYRRHA-facility is conceived as a flexible irradiation facility, able to work since revision 1.4 in both subcritical and critical modes. Both modes of operation have their specific energy and flux distributions which permit a wide range of applications, from fuel developments for innovative reactor systems, material developments for GEN IV systems, material developments for fusion reactors, to radioisotope production for medical and industrial applications.

MYRRHA will also demonstrate the ADS full concept by coupling the three components (accelerator, spallation target and subcritical reactor) at reasonable power level to allow operation feedback, scalable to an industrial demonstrator and allow the study of efficient transmutation of high-level nuclear waste. Since MYRRHA is based on the heavy liquid metal technology, lead-bismuth eutectic, it will be able to significantly contribute to the development of Lead Fast Reactor Technology and in critical mode, MYRRHA will play the role of European Technology Pilot Plant in the roadmap for LFR.

In this paper the system requirements and the current primary system design are first introduced. In section 4 the rationale of the technical evolution of the primary system design is presented. Finally also the current issues are discussed and the studies towards a new release of the primary system design are briefly indicated.

2. System Requirements

The project has started as a small irradiation facility (150 MeV, 1.5 MWth), having the production of radioisotopes for medical purposes as its single objective. In 1998, the purpose of the project has been extended gradually to become a material testing reactor for material and fuel research, to study the feasibility of transmutation of minor actinides and to demonstrate the principle of the ADS at a reasonable power scale (above 50 MWth). Since then, the project is called MYRRHA. The targeted application catalogue of the project and the subsequent technical requirements is detailed in following list.

- The system will demonstrate the ADS full concept in representative conditions scalable to an industrial ADS. For this a minimum power of 50 MWth is needed.
- The system should in ADS mode also incorporate a provision for material developments for fusion reactors which need irradiation volumes of at least 1000 cm^3 with high constant fast flux level ($\Phi > 1$ MeV = $1 \sim 5 \cdot 10^{14}$ n/cm² ·s), representative irradiation temperature and a representative ratio appm He/dpa(Fe) in the range of 5 to 25.
- Transmutations studies in representative conditions should be performed. The study of the efficient technological transmutation of high-level nuclear waste, in particular minor actinides, requests high fast flux intensity ($\Phi > 0.75$ MeV = 10^{15} $n/cm^2 \cdot s$).
- The system should be able to be used as a fast spectrum research reactor for material and fuel research. For this purpose, the reactor has to be operated as a flexible fast spectrum irradiation facility allowing for fuel developments for innovative reactor systems, which need irradiation rigs with a representative flux spectrum, a representative irradiation temperature and high total flux levels ($\Phi_{tot} = 5 \cdot 10^{14}$ to 10^{15} $n/cm^2 \cdot s$).
- Radioisotope production for medical and industrial applications shall be considered. The production of radioisotopes requests very high thermal flux levels ($\Phi_{thermal}$ = 2 to $3 \cdot 10^{14}$ $n/cm^2 \cdot s$) due to double capture reactions.
- MYRRHA can act as a technology demonstrator and a test platform for Heavy Liquid Metal (HLM)-cooled reactor technology for Gen IV systems and HLM-based SMR’s.

In addition the following technical requirements have to be taken into account in the design:

- The maximum allowable core thermal power is limited to 100 MW. The cooling systems should be dimensioned with 10 MW of margin to account for the heat dissipation of pumps and the decay heat of polonium.
- The decay heat removal systems should be passive.
- The reactor fuel should reach the above mentioned objectives based on a fast reactor MOX core.

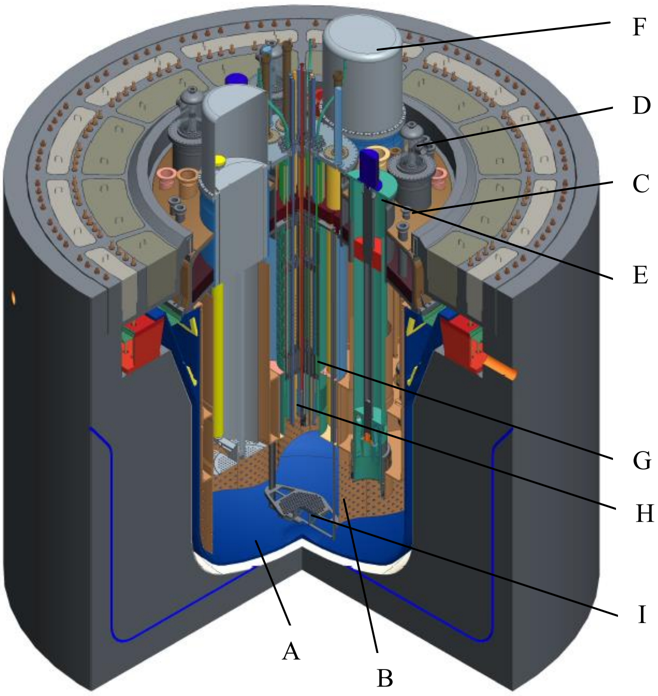
3. Current design

The current design [1,2] of MYRRHA (see FIG. 1), revision 1.6, consists of a pool-type Accelerator Driven System (ADS) with the ability to operate in critical mode cooled by liquid lead-bismuth eutectic (LBE). Consequently, all the primary systems are housed within the reactor vessel. The reactor is located in the reactor pit which features a liner able to serve as secondary containment in case of a reactor vessel leakage or break. The reactor cover closes the reactor vessel and supports all the components. The reactor core is included in the core barrel and consists of 211 positions. Such positions are filled, among others, with fuel assemblies, control rods, scram rods, the spallation window, in-pile sections, reflector assemblies, instrumentation and surveillance capsules. From these core positions 55 are accessible from the cover and are called Multifunctional Channels (MFC). In the multi-functional channels (MFC) control rods, scram rods, spallation window, in-pile sections, instrumentation and surveillance capsules are installed from the top. Because of the structures above the core, the fuel and reflector assemblies have to be loaded from underneath. Thanks to the buoyancy, the fuel and reflector assemblies do not need locking devices to hold them on the core support structure. However, in order to avoid any small position changes of the fuel assemblies inside the core during operation, a core restraint system fixes the radial position of the fuel assemblies. This core restraint system acts on the lower end of the fuel assemblies. For refuelling this core restraint system is pushed out towards the reactor bottom.

Two in-vessel fuel-handling machines, installed permanently in the reactor, handle the loading and the unloading of the fuel assemblies to the in-vessel fuel storages, which are integrated into the diaphragm. Due to the chosen manipulator concept, the most compact design is obtained by using two independent machines, each covering the half of the core and serving the half of the in-vessel fuel storage positions. The diaphragm separates the cold, high pressure LBE from the hot, low pressure LBE and contains the in-vessel fuel storages and the pump casings.

The diaphragm is connected, together with the cover, to the reactor vessel. The diaphragm consists of two horizontal plates connected to each other by vertical shells allowing some components to reach the lower plenum. Due to this design, several volumes exist in-between the two horizontal plates. Two of these volumes house part of the pumps and the heat exchangers. Each pump casing lodges one pump and two heat exchangers. Four volumes are dedicated for the in-vessel fuel storage. These storages are cooled during operation mainly by the forced circulation of LBE imposed by the pumps, while during shutdown cooling is ensured by natural circulation. The tubes connecting both plates are named chimneys and are the penetrations for those components needing to access the cold plenum. The penetrations of the pumps and the heat exchangers foresee however an additional structure, named sleeve. Such structure is conceived in order to allow a reasonably leak tight penetration through the diaphragm but also to allow the different thermal dilatation of the components with respect to the diaphragm.

The four primary heat exchangers extract the power of the primary system exchanging it with the secondary system. The head imposed by the pumps aspirates the hot LBE from the hot plenum into the heat exchangers. After being cooled, the LBE flows into the pump casings and then through the pumps themselves. This concept mitigates the LBE corrosion by reducing the temperature of the fluid inside of the pumps. In particular, these are sized in order to be able to pump the LBE through the core balancing also the head losses of all the other sections of the primary system. The number of heat exchangers and pumps is optimised in function of the space utilisation inside the reactor vessel and the symmetry of the coolant flow. This leads to a configuration with two heat exchangers and one pump on each of the two sides of the reactor.



A. Reactor vessel
B. Diaphragm
C. Reactor Cover
D. Primary Heat Exchanger
E. Primary Pump
F. In-Vessel Fuel Handling Machine
G. Core Barrel
H. Reactor core
I. Core Restraint System

FIG. 1. MYRRHA rev. 1.6

Some new components have been introduced in the design of the reactor, namely the Failed Fuel Detection Device (FFDD) and the Fuel Transfer Device (FTD). The first one is able to detect whether a fuel assembly placed in there has some failed fuel pins. The FTD instead is dedicated to the transfer of fresh fuel assemblies into the reactor and the removal of the spent assemblies.

Besides the above mentioned systems, two redundant LBE Conditioning Systems (LBECS) are foreseen to filter and condition the LBE to the necessary levels to ensure the chemical protection of the reactor components. Coupled to this system are also the extraction pumps, whose task is to extract the LBE from surface of the hot plenum where most of the impurities are expected to gather. The LBE is then pumped towards the LBECS.

The Primary Cover Gas and Ventilation System (PCGVS) is also implemented in the reactor design. This is in charge of the continuous filtering and monitoring of the cover gas of the reactor.

In the design revision 1.6, a system dedicated to the mitigation of an overpressure event in the primary system is also implemented. This is the Pressure Relief System (PRS) which is placed outside the primary vessel and, through a rupture disk placed on the reactor cover, limits the pressure in the primary cover gas to the maximum admissible pressure of 6 bara.

The LBECS, PCGVS and the PRS are external systems to the reactor vessel.

4. Design evolution

4.1.The ADONIS project (1995 – 1997)

The coupling between an accelerator, a spallation target and a subcritical core has been studied for the first time at SCK•CEN in collaboration with Ion Beam Applications (IBA, Louvain-la-Neuve) in the frame of the ADONIS project (1995-1997). ADONIS was a small irradiation facility, based on the ADS concept, having the single objective to produce radioisotopes for medical purposes and more particularly 99Mo as a fission product from highly enriched 235U fissile targets. The proposed design was of limited size with an cyclotron of 150 MeV and a core with a power of around 1.5 MWth. The system was a thermal spectrum machine and therefore water was used as coolant and moderator.

The ad-hoc scientific advisory committee recommended extending the purpose of the ADONIS machine to become a material testing reactor for material and fuel research, to study the feasibility of transmutation of the minor actinides and to demonstrate at a reasonable power scale the principle of the ADS. The project, since 1998 is called MYRRHA.

4.2.MYRRHA Draft 2 (1998 – 2005)

At mid-2002, a first pre-design file of MYRRHA [3,4], with a core nominal power of 30 MWth, was submitted to an International Technical Guidance Committee for reviewing. This international panel consisted of experts from research reactor designers, ADS development, reactor safety authorities and spallation target specialists. No show stopper was identified in the project but some recommendations were made. The design was upgraded and the MYRRHA project team has opted for as much as possible mature or less demanding technologies in terms of research & development. In its 2005 version, MYRRHA consisted of a proton accelerator of the cyclotron type delivering a 350 MeV, 5 mA beam to a windowless liquid LBE spallation target that in turn couples to a LBE cooled, subcritical fast core of 50 MW thermal power. This design is called MYRRHA Draft-2 and was published in early 2005. As can be seen from FIG. 2 it is a highly integrated, compact system with all auxiliaries inside the standing pool of 4.4 m diameter and 7 m height.

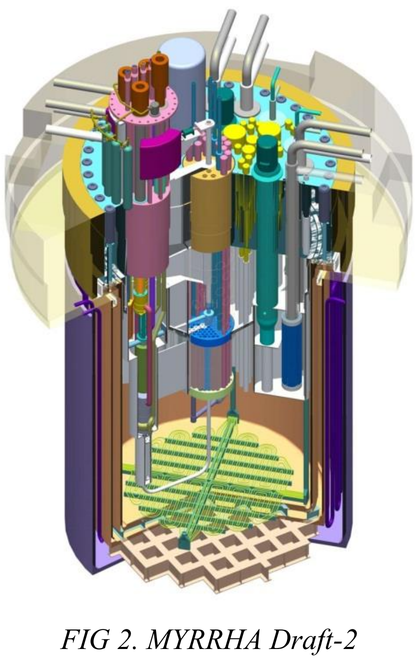


FIG 2. MYRRHA Draft-2

4.3.MYRRHA XT-ADS (2005 – 2009)

This 2005 design was used as a starting base within the FP6 EUROTRANS integrated project [5], which resulted in the XT-ADS [6] (Experimental Demonstration of the Technical Feasibility of Transmutation in an Accelerator Driven System) design, where a linear proton accelerator delivers a 600 MeV, 3.2 mA beam into the windowless spallation target.

Because of safety considerations the power density of the core was lowered, resulting into a larger core and for seismic resistance a hanging vessel was opted. The lower power density resulted into a larger core and a slightly higher power. Notwithstanding the power increase, the neutronic performances lowered and still the vessel dimensions increased to a diameter of 6 m and a height of 11 m. Also all auxiliaries were moved outside the reactor vessel.

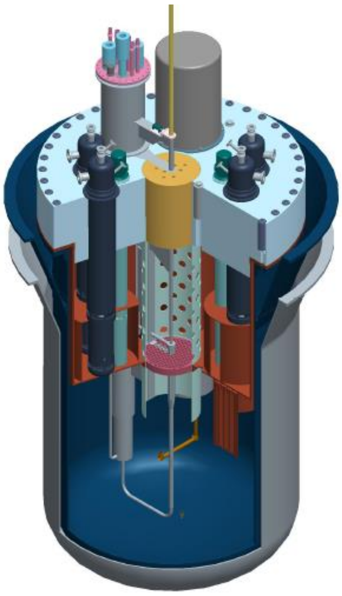


FIG. 3. MYRRHA XT-ADS

4.4.MYRRHA FASTEF (2009 – 2012)

The EUROTRANS project revealed that the performances of the XT-ADS design was not fully answering the requested performances. Therefore the XT-ADS design was taken as a starting point for the work performed in the FP7 CDT project [7,8], which resulted in the MYRRHA-FASTEF (MYRRHA Fast Spectrum Transmutation Experimental Facility) design. The design of MYRRHA-FASTEF, also referenced as the revision 1.4 design, is shown in FIG. 4.

One major difference in objectives of MYRRHA-FASTEF compared to MYRRHA/XT-ADS and the other predecessors is the fact that the FASTEF needs to be able to operate as a sub-critical system as well as a critical system. The change from cyclotron to linear accelerator in MYRRHA XT-ADS allowed the increase in proton energy from 350 MeV to 600 MeV. This modification led to an important reduction of the specific heat load at the target level and an improvement of the neutronic performance. In addition to this evolution of the MYRRHA accelerator, the realization and the successful execution of the MEGAPIE project at PSI, with SCK•CEN as one of the funding partners, resulted in the re-evaluation of the spallation target leading to the current window design without a dedicated cooling loop [9]. This major design modification with a spallation window considerably simplifies the mechanical construction, not only of the spallation target but also of the surrounding structures. Additionally this optimization resulted to integrate Si-doping units close to the core. On the other hand the additional requirements led to an increase in size, resulting to vessel dimensions of 7,5 m in diameter and 13 m in height.

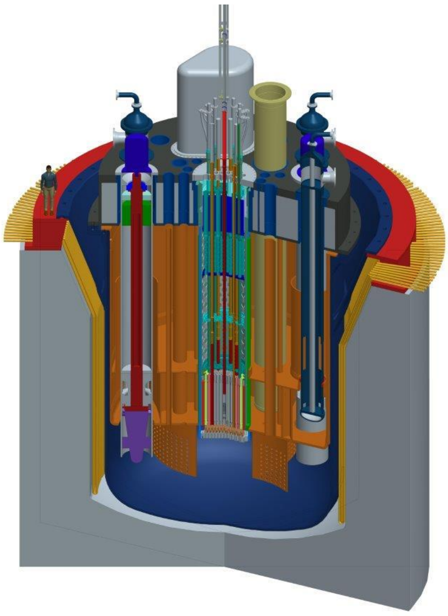


FIG. 4: MYRRHA-FASTEF (revision 1.4)

4.5.MYRRHA Revision 1.6 (2012 – 2014)

After finalization of revision 1.4 several issues resulted in the necessity to redesign MYRRHA. These issues are the consequence of the parallel research and development performed during the design phase. The problems discovered in revision 1.4 are indicated in the following list.

- The stresses in the core support structure are too elevated without taking into account the environmental effects of the LBE or the irradiation effects on the structural material.
- From material and safety standpoint the safety critical structural components should not be irradiated above 2 dpa in the component's live-time, since the material database in the codes did not allow this.
- Higher neutron flux at the silicon doping units is needed to assure the production capacity and the requested quality.
- A decrease of the Pu-enrichment from 35% to 30% is requested.
- The increase of the fuel burn-up is demanded.
- An additional emergency system to cope with an imposed severe accident was proposed.

New solutions were developed and some problems were avoided by design resulting in the current revision 1.6. The important changes in the design are:

- A new core unit is developed, including a core support structure in stainless steel, avoiding the high thermal stresses and avoiding possible environmental effects of LBE with other materials.

- Also the Si-doping units are integrated into the core unit, providing the units with the needed neutron flux and avoiding the contradictory requirement of lower fluence at the core barrel.
- Additional shielding between the core and the barrel reduces the fluence in the barrel to an acceptable value of 2 dpa in 10 years. The fuel assemblies also increased in length to reduce the irradiation of the core support structure to 2 dpa in 10 years.
- The amount of core positions increased from 151 to 211 to accommodate the additional fuel assemblies necessary to compensate the decrease of the Pu-enrichment and to increase the fuel burn-up.
- The existing Reactor Vault Air Cooling System, which performance was limited and not capable of coping with a severe accident with degraded fuel, was replaced by the Reactor Vessel Auxiliary Cooling System and the Top-Cooling System.

These changes induced several modifications on other components:

- The IVFHM increased in size to cope with the larger core.
- The mass flow rate also increased because of the larger core and therefore the primary pumps had to be adapted.
- Because of the higher flow rate, the reactor temperatures changed slightly, impacting the primary heat exchangers.

Further design analysis indicated some necessary design improvements such as the new cover, the relaxation of the curvature at the IVFHM and the implementation of manufacturing guidelines at the diaphragm. All the modification resulted in an additional increase of the reactor vessel diameter to 10.4 m and the height to 16 m. The different contributions to the size increase are difficult to assign but in a first order one can estimate that about 20% of the size increase is related to the enrichment decrease and the reduced irradiation of the barrel. Si-doping is responsible for 30% of the size increase and finally 50% is possibly related to the relaxation of mechanical stresses and conformance to design guidelines and codes.

5. New developments

MYRRHA rev. 1.6 is a coherent and consistent design that is able to respond to the requested catalogue of applications. However, by applying construction codes to the mechanical design of the different in-vessel components and implementing more stringent safety recommendations for the design of the primary system, the primary system dimensions have increased significantly over the period 2005-2014.

Furthermore, new R&D insights beginning 2014 indicate an increased volatility of Po due to an interaction with water which results into the recommendation of using double wall heat exchangers to exclude the steam generator tube rupture event. Also, new experimental results obtained in the material R&D programme show evidence of severe localized corrosion at the maximum allowed oxygen concentration in MYRRHA. It was proposed to relax the maximum allowed oxygen concentration in LBE to mitigate the corrosion. But material studies on corrosion behaviour revealed the primary importance of temperature over oxygen concentration in preventing corrosion to occur. The request of relaxation of the LBE oxygen concentration to mitigate the localized corrosion was thus changed into a temperature shift to lower maximum operating temperatures with corresponding low shutdown temperature.

Both R&D issues, the increased Po-volatility and the severe localized corrosion, can be avoided or mitigated by design but the consequence is the size increase of the primary heat exchangers which will have an important impact on the reactor dimensions.

From 2015 size reduction opportunities are explored to counter the mentioned dimension increase which also influence the project cost. Additionally a transport study defined the maximal dimensions of the major components transportable to the MYRRHA site as local manufacturing is excluded. Now different studies are performed which will form the basis for an optimized reactor design still responding to the application catalogue and complying with the dimensional limitation.

One of the finalized study is the possible increase of the maximum fluence level for critical structural components which will result in a first size reduction. This study concluded that a maximum of 10 dpa in the component's lifetime can be allowed provided that dedicated "ITER-grade" 316LN material is used. Another objective is the confirmation of two innovative solutions to improve the heat transfer properties of double wall heat exchangers reducing its size. The confirmation of feasibility consists of the evaluation of the total heat transfer rate of these two alternatives by means of an experiment and the assessment of the manufacturability of the heat exchangers. A challenging ongoing development is the study of an In-Vessel Fuel Handling Machine (IVFHM) with an additional articulation to reduce the footprint and to increase the reach of the machine to be able to cover the loading activities with one IVFHM. This new layout of the reactor consisting of one IVFHM with an additional articulation and several heat exchangers and pumps follows from a preliminary concept assessment performed in 2015.

6. Conclusions

SCK•CEN is proposing to replace its ageing flagship facility, the Material Testing Reactor BR2, by a new flexible irradiation facility, MYRRHA. Considering the international and European needs, MYRRHA is conceived as an ADS-based flexible fast spectrum irradiation facility able to work in both sub-critical and critical mode.

Additional requirements, safety issues and R&D findings triggered the evolution of the mechanical design of the reactor. This evolution led up to the continuous increase of the dimensions of the reactor, increasing the costs and complicating the transport. We currently are focusing in obtaining a more compact design by studying innovative components as double-wall heat exchangers, fuel handling machines and alternative configurations. These elements will form the input for the next revision of the MYRRHA Primary System.

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