MYRRHA PRIMARY HEAT EXCHANGER TUBE RUPTURE: PHENOMENOLOGY AND EVOLUTION

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ABSTRACT

In the framework of MYRRHA Project, a pool-type experimental and material testing irradiation facility operated with Lead Bismuth Eutectic (LBE) coolant and able to operate in both sub-critical and critical mode is designed to be built in Mol, Belgium, in SCK•CEN domain.

In addition to the material testing function, targets of the MYRRHA reactor are to prove the feasibility of the ADS technology as Minor Actinides (MAs) burner and to act as a demonstrative plant for future Gen-IV heavy metal cooled reactors.

SCK•CEN entered the pre-licensing phase for the MYRRHA reactor. In order to provide the safety authority all the required data, a complete safety analysis must be performed, studying the transients defined by the list of postulating initiating events.

In particular, an accident with potential serious consequences is the Primary Heat Exchanger Tube Rupture (PHXTR), involving the sudden release of single phase or two-phase water from a tube break in a hot liquid metal pool. This accident evolution is strongly characterized by the design of the MYRRHA Primary Heat eXchanger (PHX) and its direct surroundings in the reactor vessel and by the thermal-hydraulical conditions of the MYRRHA primary and secondary cooling system.

In the first phase of a PHXTR accident, the water in the Secondary Cooling System (SCS) is released in the Primary System (PS) pool in regime of choked flow due to the pressure difference. Being the water released in an overheated, low-pressure environment, a flashing with potential sudden specific volume increase is expected.

The heat transfer phenomena leading to the phase change velocity depend by the actual number of bubbles released in the hot liquid metal pool, function of the actual break size and shape. Its characterization is important for the definition of the overall specific volume increase and for the estimation of the water mass fraction redirected through the Primary Pump in the reactor Lower Plenum, with the risk of void insertion in the core and consequent reactivity excursion.

A simplified calculation model to evaluate the history of any given bubble distribution generated by any water flow rate through any break has been set up. The main purpose is to describe the evolution of the main system state variables during the accidental event, by checking the potential insurgency of any reactor safety issue due to pressure peaks or core void insertions.

KEYWORDS
Heat Exchanger, Tube Rupture, Accident Analysis, Heavy Liquid Metal

1. INTRODUCTION

MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) is a pool-type Accelerator Driven System (ADS) with the ability to operate also as a critical reactor.
MYRRHA main targets can be summarized as:

- Flexible fast-spectrum irradiation facility [1]
- Minor Actinides (MAs) transmutation demonstrator [2]
- ADS demonstrator [3]
- GEN-IV European Technology Pilot Plant (ETPP) in the roadmap for Lead Fast Reactor (LFR) [4]

The MYRRHA project has been recognized as a high priority infrastructure for nuclear research in Europe. Several European FP6 and FP7 projects had, as main target, to finalize a preliminary design of the MYRRHA reactor:

- FP6 IP-EUROTRANS [5], leading to the finalization of MYRRHA/XT-ADS version of MYRRHA in June 2008
- FP7 Central Design Team (CDT) [6], defining the MYRRHA/FASTEF version in March 2012
- FP7 MAXSIMA [7] (started in November 2012, ongoing), more focused on the MYRRHA safety analyses and component qualification

The outcome of these European FP projects has been partly used to define the latest version of the MYRRHA design, which has been finalized in June 2014 [8] and is currently in the verification phase. Though representing the current status, such version is not definitive: the MYRRHA design is still evolving taking into account results from the parallel R&D program.
SCK•CEN has actively participated in these FP6 and FP7 projects focusing on the safety analysis through use of system codes by performing code-to-code comparison of steady-state and transient calculations on the MYRRHA reactor operating in sub-critical and critical mode.

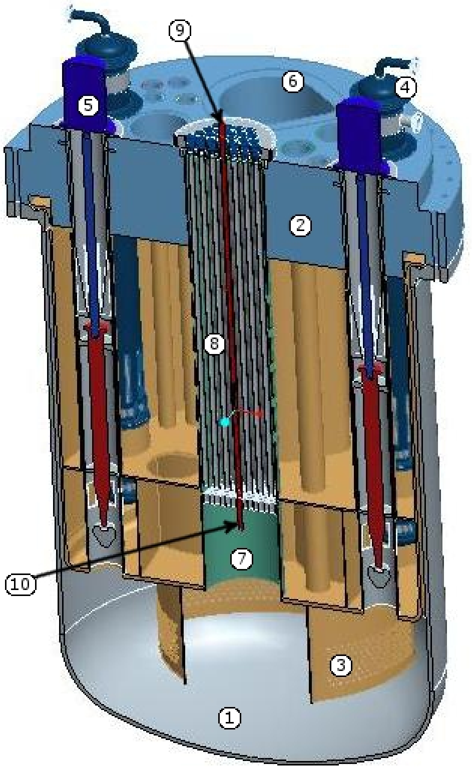
2. MYRRHA PLANT GENERAL DESCRIPTION

MYRRHA is a pool-type Accelerator Driven System (ADS) with the ability to operate also as a critical reactor. This flexibility is reflected in the definition of two different reactor configurations defining the two operating modes. The main differences can be retrieved in the reactor core, but the overall primary system thermal balance is also affected.
With exception of the core and the accelerator proton beam tube (the latter only present in sub-critical mode), the plant structure does not change in function of the operating mode.

The cores in both configurations (in brackets the values concerning the sub-critical mode) are characterized as follows (Figure 3 and 4):

- Maximum power: 100 MW (70 MW)
- Fuel Assemblies: 108 (72)
- In-Pile Sections: 4 (6)
- Control Rods: 6 (6 absorbing devices used only for long term reactivity control)
- Safety Rods: 3 (0)
- First dummy row: 48 (84)
- Second dummy row: 42 (42)

A general overview of the MYRRHA primary system and its main components is provided in Figure 1[1]:



1. Reactor vessel
2. Reactor cover
3. Diaphragm
4. Primary heat exchanger
5. Pump
6. In-vessel fuel handling Machine
7. Core barrel
8. Above core structure
9. Core plug
10. Spallation window

Figure 1. Overview of the MYRRHA reactor (in ADS mode) [8].

MYRRHA plant primary system is cooled by liquid Lead-Bismuth Eutectic (LBE, 45% Pb, 55% Bi) [9]. This choice shows several advantages with respect to other typical liquid metals used in nuclear applications (mainly Na and pure Pb):

- More operation flexibility (and limited problems towards primary coolant freezing) thanks to the low melting temperature of the eutectic (~125 °C), which allows to operate a fast-spectrum irradiation facility with a relatively high core temperature difference without incurring in corrosion problems
- Low chemical interaction with water and air excluding the possibility for fire or explosions

A drawback connected with use of LBE as primary coolant is the accumulation of radioactive isotopes (mainly Po^{210}), which could pose difficulties during primary system maintenance or in case of accidental conditions in terms of radiological releases.
Further details on LBE properties are available in [9, 10].

The primary system is completely enclosed in the primary vessel (pool-type system). The primary LBE coolant flows from the lower plenum into the core (T ~ 270 °C) to remove the core power (100 MW in critical mode) and, from there, into the upper plenum where it mixes with the cold by-pass flow. The average upper plenum temperature is 325 °C. Four Primary Heat eXchanger (PHX) units receive the LBE

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[1] Some of the MYRRHA plant components are still under development

from the upper plenum, which then flows into two Primary Pumps (PPs), (each PP serving two PHXs). From the PPs the LBE is reinserted into the lower plenum.

The cold lower plenum is separated from the hot upper plenum by the Diaphragm, an inner vessel structure supporting the core barrel and the penetrations for the PHXs and the PPs. Above the LBE free surface level an inert gas layer (nitrogen) separates the primary coolant from the reactor cover.

The primary system is linked to four independent Secondary Cooling Systems (SCSs) through the four PHX units. Each secondary system is operated in a forced-flow regime with a two-phase water mixture at 16 bar (~200 °C): the water enters the PHX in almost saturated conditions and exits with a quality ~0.3. The moisture is then separated in a steam drum, from where the steam is directed towards an air condenser (one per secondary loop) and the water is recirculated to the PHX. In normal operation, the secondary water temperature is kept constant by the control system, letting the primary LBE conditions to change in function of the core loading.

The steam dissipates the heat to the external environment through the tertiary system air condenser and is then recirculated into the steam drum. Each tertiary system contains an air fan operated in forced circulation and logically connected to the steam drum pressure for power removal balance (Figure 2).

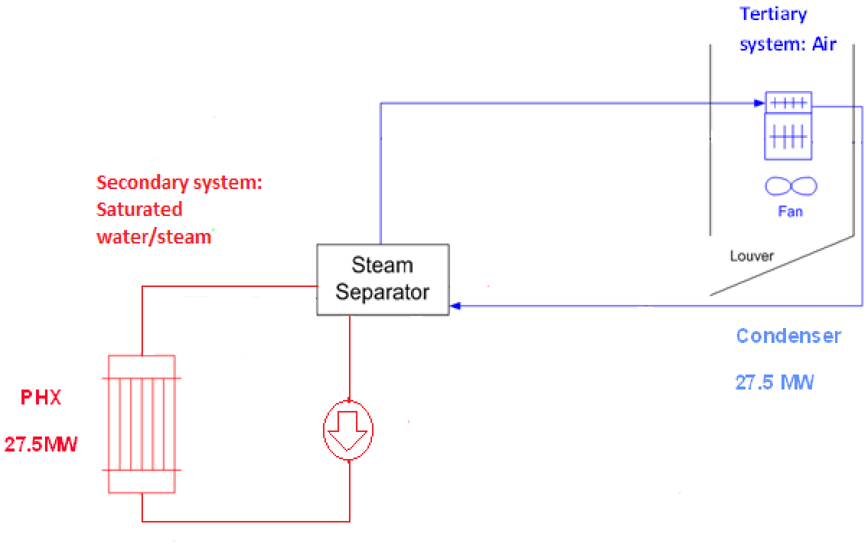


Figure 2. Secondary Cooling System (single loop) schematic concept [8].

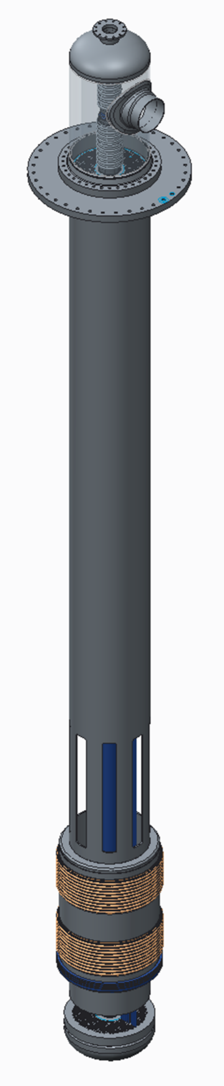
All three systems are designed to operate in forced circulation (active mode) during normal operation. Nevertheless, the plant must also be able to remove the decay heat in accidental conditions in passive mode. Two systems are devoted to DHR function in accidental conditions:

- DHR system 1 function is accomplished by the secondary and tertiary cooling systems, assumed able to operate in passive mode (if required).
- DHR system 2 function relies on the Reactor Vessel Auxiliary Cooling System (RVACS): it relies in liquid water flooding the reactor cavity in order to remove the heat from the vessel external surface and passively deliver it to a series of heat exchangers.

Despite the maximum core power of 100 MW, the plant has been designed for a maximum nominal power of 110 MW to take into account all additional heat sources, such as In Vessel Storage Tank (IVST), pump power, Po decay heat, γ-heating, spallation target power, etc.

3. PRIMARY HEAT EXCHANGER GENERAL DESCRIPTION

The PHX design (Fig. 3) chosen for MYRRHA is a counter-current shell-and-tube concept consisting of:



- 684 stainless steel (AISI 316L) tubes
- 2 tube plates
- A double-walled central feedwater pipe connected to the secondary system recirculation line
- A double-walled bottom head, collecting feedwater and connected to the tube bundle
- A top head, providing connection with the riser pipe of the secondary system
- An external shroud separating LBE in the hot plenum from LBE flowing in the PHX

All metallic surfaces separating primary LBE from secondary water, with the exception of tube bundle for heat transfer coefficient efficiency reasons, present a double-walled structure as countermeasure against LBE-water interaction in case of leakage/break: as a consequence, the bottom head and the feed-water pipe are double walled, while the external shroud and the top head maintain a single wall structure because no risk of interaction of LBE and water is involved in case of failure.

In normal operation conditions, LBE from the hot plenum (~325 °C) enters the PHX from the inlet openings in the external shroud. The flow is then directed downwards, through the tube bundle, where the actual heat exchange takes place. Outlet openings, directing the LBE flow towards the PPs, provides the exit path for the cold (~270 °C) LBE.

On the secondary side, water at a pressure of 16 bar at nearly saturated conditions (~200 °C) flows down the central down-comer pipe into the PHX bottom head and then upwards through the tubes where it is heated by the counter-current flowing LBE, thus producing a water steam mixture with a final quality of ~0.3. A summary of the main thermal-hydraulic PHX parameters is shown in Tab. I.

Table I. MYRRHA PHX main thermal-hydraulic parameters

Parameter	Unit	Value
PHX unit power	MW	27.5
PHX LBE inlet temperature	°C	325
PHX LBE outlet temperature	°C	270
PHX LBE mass flow rate	kg/s	3450
PHX water inlet temperature	°C	200
PHX water mass flow rate	kg/s	47
PHX water pressure	bar	16
PHX water outlet quality	-	0.3
PHX water outlet void fraction	-	0.9

Figure 3. Primary Heat Exchanger [8].

As shown in Figure 3, the tube bundle is extended from the bottom tube plate to the top tube plate, as normal for shell-and-tube HXs. However, in MYRRHA design, the LBE inlet is placed at ~ 2.5 m from

the bottom plate, instead of being located at the top of the component. This configuration defines an "active length" for the tube bundle of ~2.1 m where the LBE flow actually takes place.
The hot LBE free surface level is in contact with the tube bundle. Above the free surface, cover gas fills the space between shroud and feedwater pipe. Several other objectives can be achieved by adopting such configuration:

- The two-phase flow is well developed inside the PHX tubes from the inlet up to the top of the component, with no phase separation to be expected within the tubes
- High aspect ratio providing a better counter-current flow development through the bundle
- Only one tube plate (and hence one set of welding's) is located under LBE. The upper tube plate is positioned above the hot free surface

There are, on the other hand, several possible disadvantages coming from this design approach:

- High two-phase pressure drop in the tube bundle, with potential increase of dynamic instabilities and consequent need to design a suitable orifice to generate enough pressure drop in the monophasic (inlet) zone [11]
- The notable tube length could lead to important mechanical stresses in the tube plates
- The tube bundle is in contact with the free surface zone leading to possible problems due to differential thermal expansion and level fluctuations resulting in thermal fatigue

4. PRIMARY HEAT EXCHANGER TUBE RUPTURE SCENARIO

The Steam Generator / Heat Exchanger tube rupture scenario has been investigated in detail for PWR (water coolant, loop type plants). However, for a pool type reactor featuring HLM as coolant, the scenario is indeed completely different.
The general problem of a Heat Exchanger/Steam Generator Tube Rupture (HX/SGTR) involving pressurized water entering a Heavy Liquid Metal (HLM) pool has come to an interest with the study of critical and sub-critical pool-type systems in which the water, as secondary coolant, is directly present into a component located inside the primary vessel.

The main differences characterizing the XH/SGTR accident in a HLM pool type reactor are enlisted as follows:

- The Secondary Cooling System pressure is higher than the Primary System, resulting in water entering the primary pool
- The physical and chemical interactions between the fluids are different
- The accident evolution, and the associated radiological consequences follow different sequences

For what concerns MYRRHA, the accident assumes the name of "Primary Heat Exchanger Tube Rupture", or PHXTR. It is classified as a DBC2 event [8], which reflects a high probability of occurrence during the reactor operation.
Therefore, the accidental event characterizing such scenario must be completely reassessed to demonstrate the plant capability to withstand without exceeding failure limits.
The most concerning issues can be summarized as follows:

- Primary System excessive pressurization caused by the water flashing in the LBE pool
- Possible radioactive product releases, mainly Po and Po-based mixtures
- Potential entrainment of steam bubbles (voids) into the core with consequent reactivity insertion

4.1. PHXTR Sequence Description

A typical PHXTR scenario evolution foresees the following phenomena:

- PHX pressurized tube break generating two-phase critical (choked) flow water-steam moisture release into the primary pool
- Generation of a source term for bubble formation, growth and collapse
- A pressure wave release in the primary vessel due to the liquid water sudden expansion and phase change ("flashing") in a superheated HLM environment

The main physical phenomena and the risks involved in a HX/SGTR accident evolution can be summarized in the following list of phenomena:

- Primary coolant sloshing and displacement induced by the pressure wave and consequences on the neighboring vessel internals
- Coolant-coolant interaction (CCI) and steam explosion
- Multiphase transport of part of the steam bubbles (voids) into the core with reactivity insertion

As first step towards the analysis of such accidental event, the quantity of water released in the primary pool must be properly assessed. Moreover, the new thermodynamic state must be identified and the evolution of the water bubbles must be evaluated. The rest of the paper will focus on these specific items.

4.1.1. Two-phase water mixture critical mass flow rate

The two-phase pressurized water moisture flowing in the PHX tubes is at saturated or nearly-saturated conditions (16 bar, ~ 200 °C), while the LBE in the primary pool is not pressurized (only hydrostatic pressure must be accounted for, which reaches a maximum of ~3 bar at PHX tube bundle bottom). Such thermodynamic conditions, associated with the PHX tube geometry described above, are enough to determine a choked flow regime for the water leaking through the postulated PHX tube break. A double-ended guillotine break is assumed (providing, through a diameter of 14 mm, a flow section of $1.54 \cdot 10^{-4}$ m^2) for the water tubes in order to evaluate the maximum two-phase critical mass flow rate.
Several two-phase critical flow models classes, based on different assumptions, have been studied and applied:

- Homogeneous Equilibrium Model (HEM)
- Mechanical non-equilibrium
- Thermal non-equilibrium
- Full non-equilibrium

Among these classes, the most reliable models appear to be based on thermal non-equilibrium: such models assume the same velocities for the two phases, but allow having different phasic temperatures. This, in turn, allows having metastable states in one of the two phases; specifically, the persistence of the liquid phase before flashing in the hot pool is foreseen. This increases the value of the flow rate leaking through the break.
The most known choked flow models available in literature (and valid within the interval of interest) have been applied to the problem. Table II summarizes the results obtained by the application of these models.

Table II. Results from different choked flow models applied to PHXTR scenario

Model	Value (kg/s)	Assumptions
Henry-Fauske HEM	0.763	HEM
Moody	1.602	Mechanical non-equilibrium
Fauske	**4.457**	Thermal non-equilibrium
Leung-Grolmes	2.885	Thermal non-equilibrium
Moody	**3.904**	**Thermal non-equilibrium**
Burnell	**4.563**	**Full non-equilibrium**
Modified Henry-Fauske	**4.303**	**Thermal non-equilibrium**

A mass flow rate value of 4.3 kg/s can be assumed as reference. Such result has been confirmed by a RELAP5-3D simulation. It is interesting to note how the modified Henry-Fauske model, providing one of the best predictions, is the choked flow model recommended by RELAP5-3D user's guidelines input manual [12]. For this reason, the value predicted by the Modified Henry-Fauske model is selected, despite others (namely, the Fauske and the Burnell model) provides very close critical flow predictions.

4.1.2. Bubble initial characterization

Once injected in the primary pool, the amount of water must be characterized. It is possible to determine the bubble size, shape, and initial rising velocity according to the problem boundary conditions by referring to the Morton and the Bond number, usually applied to characterize the shape of bubbles or drops moving in a surrounding fluid or continuous phase:

- Morton number: viscous forces vs. interfacial forces in LBE → Bubble shape $[\frac{g*\mu_c^4*\Delta\rho}{\rho_c^2*\sigma^3}]$
- Bond number: gravity forces vs. interfacial forces $[\frac{\Delta\rho*g*d}{\sigma}]$

After the evaluation of these two non-dimensional numbers, it is possible to evaluate (Figure 4) the corresponding bubble Reynolds number which, in turn, defines the initial bubble velocity. The characteristic bubble dimension d is in principle unknown, although it is reasonable to assume it would be close to the tube break dimension. Therefore a bubble characteristic dimension distribution can be assumed and, from this, the characteristic bubble Reynolds number.
Finally, the bubble velocity distribution can be derived.

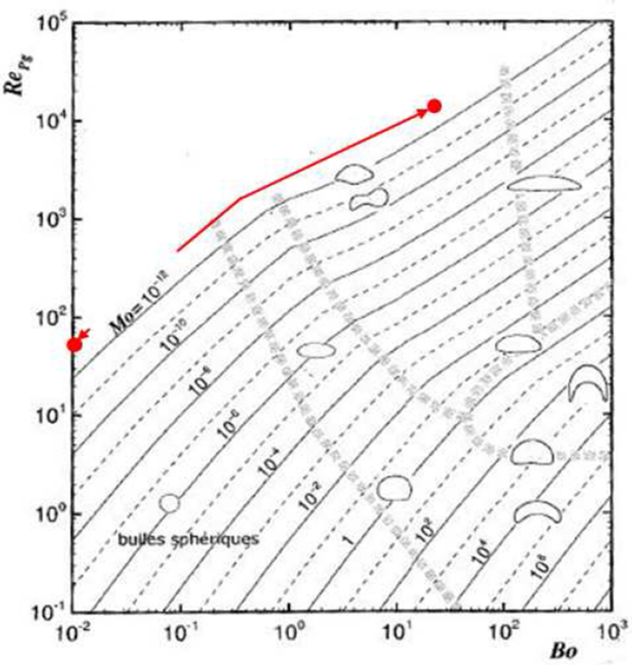


Figure 4. Relation between Morton, Bond and Reynolds bubble numbers [13].

4.1.3. Bubble growth and collapse model

Any water injection in Primary System will bring moisture from a pressurized, relatively cold environment (SCS) to a hot pool at nearly atmospheric pressure. As a result, the water will tend to assume a new thermodynamic state according to the new conditions, which will be superheated. Such state, if assumed for liquid water (thermal non-equilibrium hypothesis), is not stable and the (initially) liquid bubble will undergo a transient in terms of geometrical and state properties (radius, pressure, density, temperature).

A specific differential equation system has been developed to follow the water bubble growth. Again, thermal non-equilibrium hypothesis is assumed (different temperatures for liquid and vapor phases):

- Mechanical equilibrium over bubble surface (Rayleigh-Lamb-Plesset equation)

$$\rho_l\left[\frac{\partial^2 r}{\partial t^2}+\frac{3}{2}\left(\frac{\partial r}{\partial t}\right)^2\right]=P_v-P_l-\frac{2\gamma}{r}-\frac{4\mu}{r}\frac{\partial r}{\partial t} \qquad (1)$$

- Energy balance over bubble surface [13]

$$\sigma_0(T_1^4-T_2^4)\left\{\frac{1}{A_2}+\left(\frac{1}{\varepsilon_1}-1\right)\left[\left(\frac{\rho'}{\rho''}+1\right)\frac{R_{in}^3}{R_d^3}-\frac{\rho'}{\rho''}\right]^{-\frac{1}{3}}\right\}^{-1}+0.255\sqrt{\frac{\gamma'' r(T_1-T_2)}{2R_d}}\sqrt[4]{R_d g\rho'\rho''}=-r\rho'\frac{dR_d}{dt} \qquad (2)$$

- Clausius-Clapeyron equation (water two-phase state equation, relationship between pressure and temperature along phase boundaries)

$$\ln\frac{P_v}{P_l}=-\frac{h_{gl}}{R_g}\left(\frac{1}{T_v}-\frac{1}{T_l}\right) \qquad (3)$$

- Ideal gas state equation

$$P_v = \rho_v R_g T_v \qquad (4)$$

Solving this equation system provides time evolution of the following variables:

- Bubble liquid radius
- Bubble vapor pressure
- Bubble vapor density
- Bubble saturation (liquid) temperature

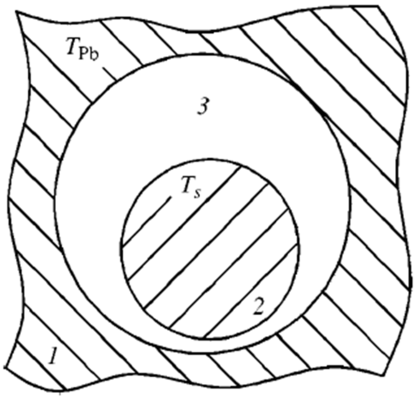
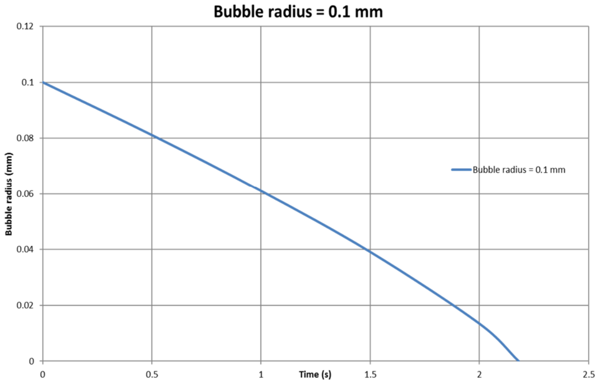
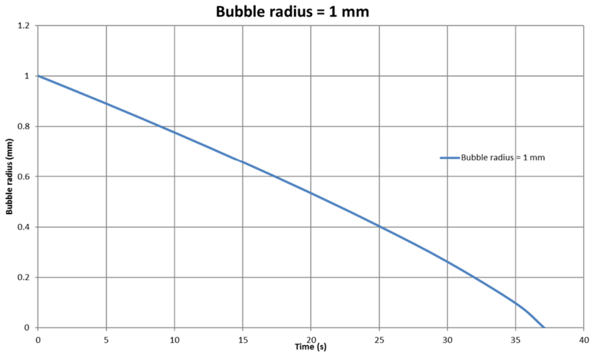


Figure 5. Schematic representation of vapor layer growing from a superheated liquid bubble surrounded by LBE [14].

The bubble evolution is followed until collapse. A number of cases considering different initial bubble radii and their consequent evolution over time in the primary pool is provided. Different initial radii are considered.





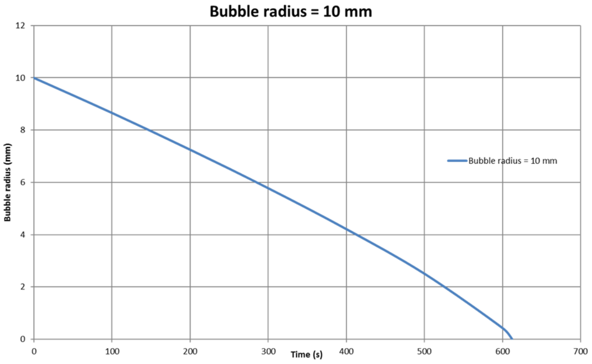


Figure 6 (a, b, c). Examples of bubble growth in LBE pool.

As can be noted from Figure 6, a bubble generated by a double-ended guillotine break (diameter ~ 10 mm) will collapse within 600 s, while smaller sizes (~1 mm) will collapse in less than 40 s. According to the bubble initial dimensions, different evolutions within the Primary System boundaries are foreseen: it is possible for the bubble to reach LBE pool surface or it can be entrained by Primary Pump, or interact with other bubbles well before the natural collapse. Smaller bubbles can collapse before different interaction occurs.

5. FUTURE DEVELOPMENTS: PHXTR ACCIDENT ASSESSMENT

To properly follow the cumulative behavior of the bubble distribution released by a PHXTR event, finally assessing the impact of such accident on the reactor, however, it is necessary to use an advanced calculation tool. A SIMMER-III model has been previously developed at SCK•CEN for this specific purpose. It is planned to upgrade this model to match the current MYRRHA plant reference design.

It is expected a similar numerical tool would require a certain validation effort. In the framework of FP7-MAXSIMA project [7], a MYRRHA PHX mock-up has been built, installed and tested in the CIRCE LBE facility at ENEA-Brasimone site, with the specific purpose to make the (world première) first HX tube rupture experiment. The experimental facility design concept and the setup of properly defined boundary conditions has been carefully planned to meet MYRRHA-like conditions in the best way, and a definition of a complete test matrix to cover different PHXTR cases has been finalized. The experiments have been successfully carried out in February 2017 (data post-processing are still ongoing).

6. CONCLUSIONS

MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) is a pool-type Accelerator Driven System (ADS) with the ability to operate also as a critical reactor.
An accident with potential serious consequences is the Primary Heat Exchanger Tube Rupture (PHXTR), involving the sudden release of single phase or two-phase water from a tube break in a hot liquid metal pool. This accident evolution is strongly characterized by the design of the MYRRHA Primary Heat eXchanger (PHX) and its direct surroundings in the reactor vessel and by the thermal-hydraulical conditions of the MYRRHA primary and secondary cooling system.
As first step towards the analysis of such accidental event, the quantity of water released in the primary pool must be properly assessed. Moreover, the new thermodynamic state must be identified and the evolution of the water bubbles must be evaluated.

The main conclusions can be summarized as follows:

- The maximum water critical mass flow rate leaking from a broken PHX tube (double ended guillotine break) is ~4.3 kg/s
- This value, together with the thermodynamic properties of the fluids, allows to evaluate the initial state of the bubble distribution forming at tube break
- A differential equation system allows the evaluation of bubble growth and collapse under any thermodynamic condition, specifically defining bubble liquid radius, vapor pressure and density and saturation temperature

A SIMMER-III model is being built to simulate the bubble distribution interaction with reactor internals. This calculation tool will be evaluated towards the full scale HXTR experiment performed at ENEA-Brasimone, currently in post-process phase.

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