Safety analysis of the MYRRHA facility with different core configurations

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Abstract

In the framework of the IAEA Coordinated Research Project on "Studies of Innovative Reactor Technology Options for Effective Incineration of Radioactive Waste", a benchmark exercise was undertaken to analyse the behaviour of the MYRRHA facility in various accidental conditions. The transients were simulated by means of the RELAP and SITHER codes and the following set of accident scenarios was considered: loss of flow, loss of heat sink, overpower transient, overcooling and partial blockage of a subassembly. In addition, those accidents were simulated in two different situations depending on whether the proton beam is cut off (protected case) or not (unprotected case). In the IAEA benchmark two sub-critical core configurations are considered: a typical core configuration composed only of (U-Pu)O_2 MOX fuel assemblies and another one including additional U-free minor actinides fuel assemblies. The present paper summarized the main results obtained with the first core configuration.

1. Introduction

Since 1998, SCK•CEN in partnership with many European research laboratories, is designing a multipurpose ADS for R&D applications –MYRRHA– and is conducting an associated R&D support programme. MYRRHA is an Accelerator Driven System (ADS) under development at Mol in Belgium and aiming to serve as a basis for the European experimental ADS to provide protons and neutrons for various R&D applications. It consists of a high power linac proton accelerator delivering a 350 MeV*5 mA proton beam to a windowless liquid Pb-Bi spallation target that in turn couples to a Pb-Bi cooled, sub-critical fast core of ~50 MWth. A brief description of the MYRRHA facility is provided in section 2.

In the framework of the IAEA Coordinated Research Project on "Studies of Innovative Reactor Technology Options for Effective Incineration of Radioactive Waste" [1], a benchmark exercise was undertaken to analyse the behaviour of MYRRHA in various accidental conditions. This exercise may be seen as a prolongation of the safety analysis already carried out in the PDS-XADS project of 5th framework programme (FP) of the European Commission [2]. The thermal-hydraulic behaviour of MYRRHA is simulated by means of two codes, RELAP and SITHER, very shortly described in section 3, and the different accidental scenarios are listed in section 4. The IAEA benchmark considers two sub-critical core configurations: a typical core configuration composed only of (U-Pu)O_2 MOX fuel assemblies and another one including additional U-free minor actinides fuel assemblies, the later one being dedicated to operate MYRRHA as an experimental small-scale minor actinides "transmuter". In this paper the main results obtained with the first core configuration are presented in section 5. Preliminary studies – not shown here – were performed with the second core configuration. They do not indicate significant variations of the safety characteristics.

2. MYRRHA description

A pool-type design has been chosen for MYRRHA, not only from a safety point of view (in acknowledgement of the inertia of many hundreds of tons of LBE), but also to provide an extremely flexible core management for the fuel sub-assemblies and the experimental irradiation devices. Also, the design has been made in such a way that all in-vessel components can be removed and replaced during the lifetime of the installation for maintenance. Figure 1 shows an overview of the machine with its most important components. The hot primary coolant is separated from the cold one by means of the diaphragm which divides the volume of the vessel in an upper hot zone and a lower cold zone. The coolant - liquid lead-bismuth eutectic (LBE) - is circulated from one zone to the other by four primary pumps. The LBE is heated in the core up to 337°C (in nominal conditions) and cooled back to 200°C by means of eight primary heat exchangers (PHX) of which the secondary side is water at 25 bars. Each primary pump delivers the LBE mass flow for two in parallel operating heat exchangers. The 4 pumps and the 8 PHXs are installed in 4 casings at the periphery of the vessel. The secondary cooling is provided by two loops, each loop comprising 4 PHXs.

The sub-critical core is made up of 99 channels, surrounding the spallation loop, which are available to house fuel sub-assemblies (SA) or experimental devices. Several fuel configurations can be arranged, but in average 45 channels contain MOX SAs. All the channels have to be loaded with a SA, even if the latter is an empty box or is filled with dummy fuel pins or experimental rigs. The sub-critical core is surrounded by the core barrel whose function is to prevent the fuel SAs to move away from each other. Seventeen channels are located under penetrations in the reactor cover and can host in-pile section (IPS) irradiation devices having their own irradiation conditions independently of those of the MYRRHA core. Each fuel SA contains 91 pins arranged in a triangular lattice.

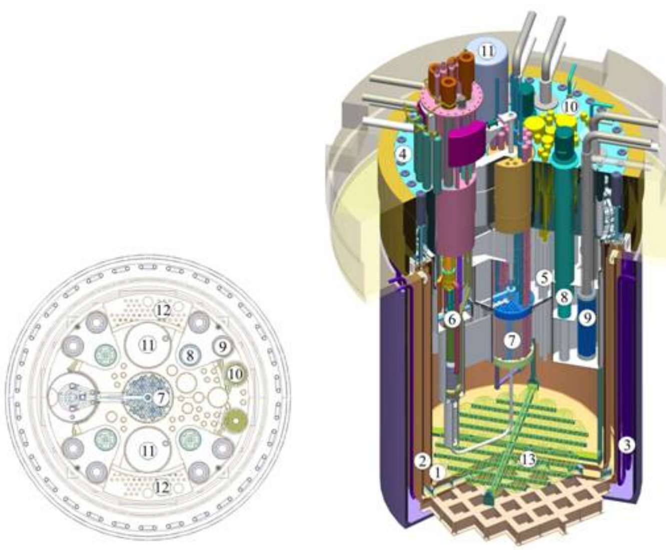
The interference of the core with the spallation loop and proton beam line, the fact that the room situated directly above the core will be occupied by lots of instrumentation and IPS penetrations, and core compactness result in insufficient space for fuel handling to (un)load the core from above. Hence, the fuel handling is performed from underneath the core. On a top of that due to the higher density of LBE, the fuel SAs are floating in the core coolant, therefore the fuel assemblies are kept by buoyancy under the core support plate. Because of the presence of the off-centre position of the spallation loop, there are two fuel handling systems that are inserted in penetrations of the reactor cover on opposite sides of the core.

Spent fuel still generates decay heat and must remain in the coolant for some time after the reactor is shut down. To avoid excessive delay between two operation cycles, it was chosen to store the spent fuel at the periphery of the reactor in two dedicated zones and let it cool there. Each fuel storage provides sufficient positions to store a full core loading.

The spallation loop is characterized by an off-centre layout (the confinement vessel of the spallation loop is located beside the sub-critical core). Several reasons justify such a configuration, the main one is the need of a high neutron flux in the sub-critical core. The LBE contained in the feed tank flows by gravity in an annular tube surrounding the proton beam tube. The flow rate is determined by the tube geometry and by the height difference between the LBE free surfaces in the feed tank and in the spallation target. The LBE recirculation in the loop is insured by a mechanical pump. In addition, a magneto hydraulic pump is foreseen to provide the fine tuning of the feed flow. A LIght Detection And Ranging (LIDAR) system measures the vertical position of the target free surface and adjusts the flow of the magneto hydraulic pump in order to keep constant the position of the free surface.

For safety reasons MYRRHA, like any reactor, is equipped with an Emergency Cooling System (ECS). This ECS is designed to meet all MYRRHA cooling needs, provided that the proton beam is shut off. The residual heat to be evacuated is then composed of the decay heat of the reactor core, the decay heat in the core storage and the heat in the LBE due to the ^{210}Po decay. The most severe situation is a total station black-out where all the normal cooling systems are unavailable. The LBE flow will only be insured by natural convection mechanisms and its cooling will only be provided by the ECS. Since the ECS is intended to be a strong line of defence, it has the characteristics of being fully redundant and passive. This means that two independent systems are present, each capable of fulfilling the cooling needs. It also implies that the ECS is based on passive principles: no pumps or fans, no power-operated valves, no active pressurizer … Each system is basically composed of an emergency heat exchanger (EHX), a check valve at the bottom of the EHX, a closed water circuit operating in natural convection mode, an air cooler and a natural draft chimney.

More details on the MYRRHA can be found in [3].



1. inner vessel
2. guard vessel
3. cooling tubes
4. cover
5. diaphragm
6. spallation loop
7. sub-critical core
8. primary pumps
9. primary heat exchangers
10. emergency heat exchangers
11. in-vessel fuel transfer machine
12. in-vessel fuel storage
13. coolant conditioning system

Figure 1: bulk cut-views of the MYRRHA ADS

The main parameters of the MYRRHA facility are listed in Table 1, from which the size of the machine can easily be figured out.

Table 1: MYRRHA general characteristics

Core diameter	1,000 mm
Core height	1,800 mm
Fuel active length	600 mm
Vessel inner diameter	4,400 mm
Vessel total height (lid not included)	7,000 mm
Vessel internal volume	abt. 100 m^3
LBE volume	abt. 65 m^3
Vessel cover thickness	abt. 2 m
Gas plenum height above the coolant	< 500 mm
Nominal power	50 MW_{th}
Primary coolant	LBE
Coolant pressure	atmospheric + hydrostatic
Core inlet temperature	200 °C
Core average outlet temperature	337 °C
Coolant average velocity in the core	2.0 m/s
Primary coolant flow rate (nominal)	2,500 kg/s
Secondary coolant	Water or steam

3. Codes and models

The analysis of the accidents was performed with two codes: RELAP5 mod 3.2 and SITHER. The RELAP code has been adapted for the use of liquid Lead-Bismuth Eutectic by Ansaldo Nucleare [4]. It is used for transients requiring the simulation of the whole system, like loss of flow and loss of heat sink accidents.
SITHER is a code originally developed by SCK•CEN for simulating the thermal-hydraulic behaviour of core assemblies in LMFBRs, as well in steady state as in transient situations [5]. It is appropriate for the simulation of fast transients for which the core behaviour is the main concern. The inlet conditions (velocity, temperature) are assumed to remain constant during the transients. Typical examples are overpower transients and sub-assembly blockages.

The RELAP model of MYRRHA can be subdivided into 6 main parts:

1. The lower plenum corresponding to the volume of fluid located below the core level. It is modelled by a branch (volume with multiple connections) receiving the fluid released by the pumps and reinjecting it into the core and medium plenum;
2. The medium plenum containing the volume of fluid around the core barrel, above the lower plenum and below the diaphragm. It represents the leaks through the diaphragm and is modelled by an annular volume linking the lower and upper plena;
3. The upper plenum made up of the hot fluid volumes above the core and the diaphragm. It is modelled by 2 pipes connected by cross flow junctions simulating the flow through the apertures of the core barrel above the core. The top level of this plenum corresponds to the LBE free surface level and it is connected to a time dependent volume fixing the reference pressure;
4. The sub-critical core containing 99 sub-assemblies (SA) (45 fuel SAs, 54 dummy Sas corresponding to what is called "reference configuration" in MYRRHA Draft-2 [3]). The 45 fuel SAs are subdivided into 9 hydraulic 'group' channels, each one representing a

group of SAs, and one single channel corresponding to the hottest fuel pin channel (in order to determine the maximum fuel, clad and coolant temperatures in the core);

5. The main cooling loop including the 4 groups of pump-HX (each group has one pump and 2 PHXs). In order to simulate partial loss of flow and loss of heat sink accidents, one group is modelled separately and the 3 other groups are merged in an equivalent one. The flow is distributed between the groups by means of a fictitious annular volume. The loop includes also the 2 secondary lines, each line being connected to one of the 2 PHXs that each pump-HX group contains;
6. The 2 emergency cooling loops, each one containing a EHX, a secondary water circuit and a tertiary air circuit. The heat is released to the environment via air-coolers. The loops are designed to work fully in natural circulation mode in any circuit (LBE, water, air).

In the present version of the model the spallation loop is only modelled as a constant heat source inside the core, when the accelerator is in operation.

A schematic representation of this model is provided in Figure 2 below.

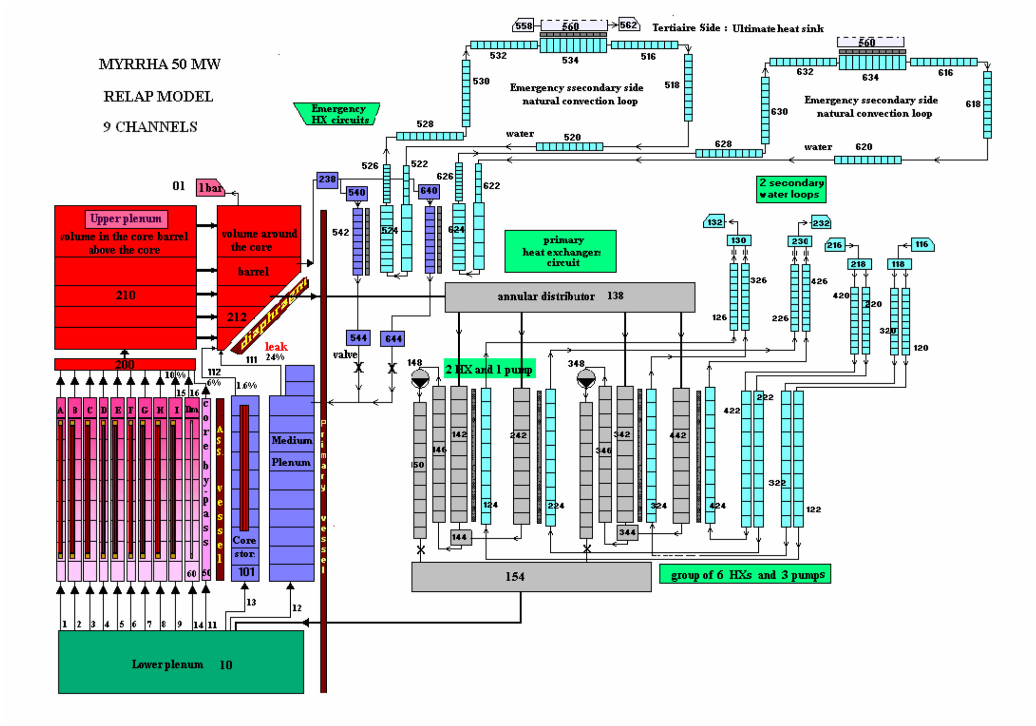


Figure 2: schematic representation of the RELAP model of MYRRHA

The SITHER code is based on the single fuel rod channel approximation, i.e. a fuel sub-assembly is represented by only one fuel rod with its associated coolant. For the transients simulated by SITHER the calculations were performed with the hottest fuel pin in the core.

4. List of transients

The transients simulated by means of RELAP and SITHER are listed below in Table 2.

Table 2: list of transients considered for MYRRHA analysis

Transient	*Description*	*Code*
Protected TOP	**Protected transient overpower at hot full power resulting from a reactivity jump**	**SITHER**
Protected LOF	**Protected loss of flow resulting from the total loss of circulation pumps in the primary system**	**RELAP**
Protected LOH	**Protected loss of heat sink resulting from the total loss of the secondary cooling systems**	**RELAP**
Protected LOF&LOH	**Combination of a protected LOF and LOH (station blackout)**	**RELAP**
Protected SAB	**Partial blockage at the inlet of one subassembly where the cross sectional area is reduced**	**SITHER**
Protected overcooling	**Instantaneous water temperature drop from 145°C to 40°C at the inlet of the primary heat exchangers (secondary side)**	**RELAP**
Unprotected TOP	**Unprotected transient overpower at hot full power resulting from a reactivity jump**	**SITHER**
Unprotected LOF	**Unprotected loss of flow resulting from the total loss of circulation pumps in the primary system**	**RELAP**
Unprotected LOH	**Unprotected loss of heat sink resulting from the total loss of the secondary cooling systems**	**RELAP**
Unprotected LOF&LOH	**Combination of an unprotected LOF and LOH**	**RELAP**
Unprotected SAB	**Partial blockage at the inlet of one subassembly where the cross sectional area is reduced**	**SITHER**
Unprotected overcooling	**Instantaneous water temperature drop from 145°C to 40°C at the inlet of the primary heat exchangers (secondary side)**	**RELAP**
BOP	**Beam overpower at hot full power**	**SITHER**

A distinction is made between the protected transients and the unprotected transients. For the first category the accelerator is shut down during the transient. A delay of 3 seconds is applied between the accident initiation and the effective proton beam shut down. Unprotected accidents occur in case of failure of the accelerator shut down system and the spallation neutron source is supposed to be maintained to its nominal value. It means in particular that no feedback exists from the primary system thermal-hydraulics to the spallation loop behaviour.

5. Results

Owing to the limited space granted to the paper, only the most representative results are selected in this section, in particular for transients that can be considered as envelop cases. The first of those transients is the protected loss of flow combined with a loss of heat sink (LOF&LOH), consecutive for instance to a station blackout. Figure compares the power released by the core with the heat rates removed by the secondary and emergency cooling systems (SCS, ECS): the SCS unavailability inherent to the LOH is clearly shown, while the ECS reveals its high capacity of heat removal, indicating that actually only one EHX with its associated circuit is able to insure a sufficient cooling of the primary system. The maximum fuel temperature at core mid-plane and the maximum clad temperature at core outlet are exhibited in Figure . They evolve to very safe values: after a short peak up to 522°C, due to the delay between the pump trip and the accelerator shutdown, the clad temperature comes down significantly below its nominal value, whereas the core power drop makes the fuel temperature decrease to low values. Obviously the core integrity is still better guaranteed in case of separate protected LOF or LOH accidents, which are both less severe than the LOF&LOH situation.

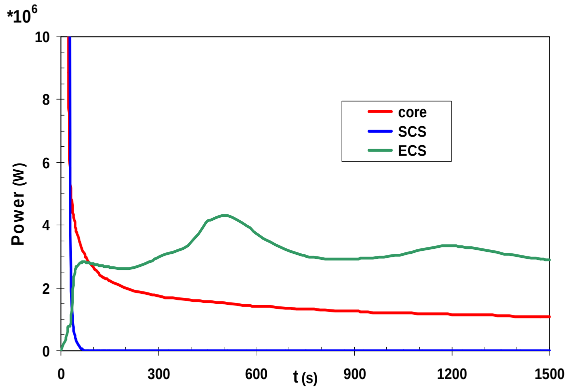


Figure 3: protected LOF&LOH core and cooling systems powers

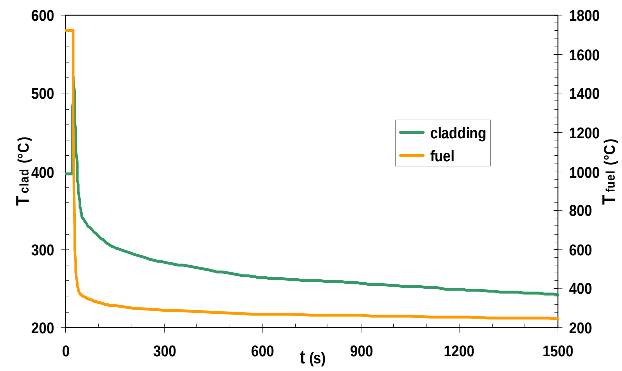


Figure 4: protected LOF&LOH maximum clad and fuel temperatures

This core integrity however is jeopardized in case of unprotected LOF as shown on Figure and Figure . During the first phase of the transient, the rate of heat removed by all the heat exchangers (PHXs and EHXs) in free convection mode is much lower than the core power, and the core temperatures (fuel and cladding) grow very quickly as soon as the accident is initiated. The safety criterion on cladding is strongly exceeded after a few seconds. Then, due the high temperatures reached by the coolant within the core, natural convection develops much more intensively, the power evacuated by the heat exchangers begins to compensate the core power and the fuel and clad temperatures are stabilizing (note that the core was assumed to stay undamaged during the whole transient). As the EHXs are not dimensioned to remove the nominal core power, it is evident that an unprotected LOH will lead to severe core damage. Nevertheless the large thermal inertia of the primary system provides a relatively long grace time before the safety criterion on cladding is exceeded. RELAP calculations (not shown here) estimated this grace time at about 15 minutes. Less severe consequences obviously are not expected in case of unprotected LOF&LOH.

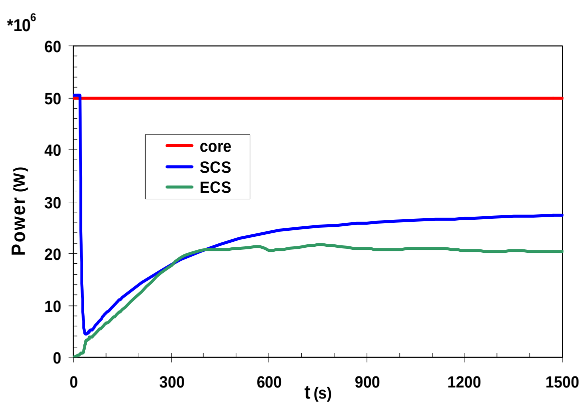


Figure 5: unprotected LOF core and cooling systems powers

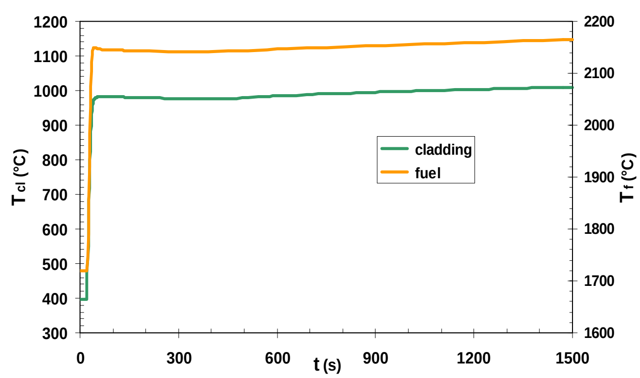


Figure 6: unprotected LOF maximum clad and fuel temperatures

The overcooling transient results from a sudden decrease of the water temperature at the inlet of the secondary side of the PHXs. In the present study the water temperature was supposed to drop from 145°C to 40°C. The main risk of such an event is LBE freezing inside the heat exchangers with possibility of blockages. The LBE temperatures at the inlet and outlet of the PHXs (primary side) were calculated by RELAP in the unprotected case and they are plotted in Figure . The LBE outlet temperature is stabilized at 127.5°C, i.e. slightly above the theoretical melting temperature (123.5°C). Owing to the fact the presence of impurities may raise this melting temperature by quite some degrees, blockages of the PHXs by LBE freezing in principle could not be excluded. However when frozen LBE layers begin to develop inside a heat exchanger, the characteristics of this latter one are changing and the RELAP model of the PHXs is not able to take into account these variations. A more sophisticated modelling of LBE freezing in a heat exchanger has been developed in a home-made code [6], showing that a total blockage of the PHXs is only possible with water temperatures significantly lower than 40°C. On the other side, if the overcooling accident is 'protected' (proton beam off), the LBE heating in the core is considerably reduced and a total blockage becomes unavoidable. This means that the term 'protected' is here not really opportune and that the accelerator shutdown **may not** be triggered in this particular case.

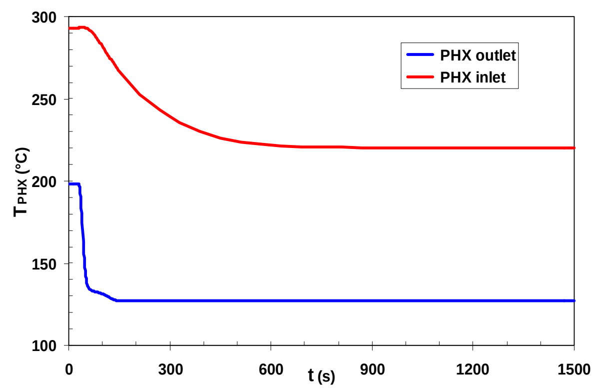


Figure 7: unprotected overcooling
LBE temperatures at inlet and outlet of the

Overpower transients (TOP) considered in the present study are initiated by accidental insertion of reactivity in the core. One of the main possible causes is the voiding of a specific region of the core. Although MYRRHA is designed to have a negative voiding coefficient in reactivity, voiding of exclusively the inner fuel sub-assemblies however would result in a maximum reactivity insertion $\Delta\rho$ of 410 pcm. This might be due to a HX tube leak, with steam bubbles entering the primary circuit. This amount of reactivity insertion is taken as the basis for an overpower transient in design basis condition (DBC). Liquid water insertion in the core might lead to prompt criticality, this is a design extended condition (DEC) and it has to be proven that sufficient protection exists against this event. The TOPs were simulated with the SITHER code. Figure and Figure display the results for the unprotected transients. The temperature increase in the fuel rod is very limited for $\Delta\rho$ = 410 pcm (ΔT = 126°C in the fuel, 17°C in the cladding). A reactivity insertion $\Delta\rho$ > 2000 pcm is necessary to exceed the safety criterion on fuel, while clad failure has only to be feared for much higher values. For protected TOPs the clad and fuel temperatures fall very rapidly just after the accelerator shutdown, i.e. in the present case 3 seconds after the accident initiation.

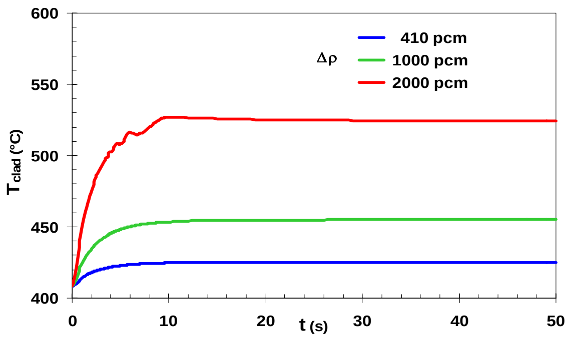


Figure 8: unprotected TOP maximum clad temperature

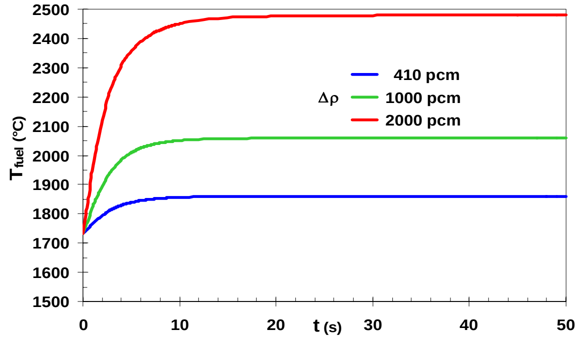


Figure 9: unprotected TOP maximum fuel temperature

Partial blockages of fuel sub-assemblies (SA) were analysed with the SITHER code. The single fuel rod approximation of the model did not allow to take into account radial heat transfer effects. Several degrees of blockage were considered, each one corresponding to a given value of the flow reduction factor f_R. The results for the unprotected case are shown in Figure and Figure . It can be observed that the safety criterion on cladding is exceeded for a flow reduction factor of 30%, whereas the fuel does not yet melt with this value. In the protected situation the temperatures decrease very rapidly just after the accelerator shutdown, i.e. in the present case 3 seconds after the accident initiation. From Figure it clearly appears that a very early detection of the blockage is crucial to prevent damage extension in the SA. However it has to be reminded that a simultaneous blockage of several SAs is a very unlikely event and that practically core damage will be limited to only one SA.

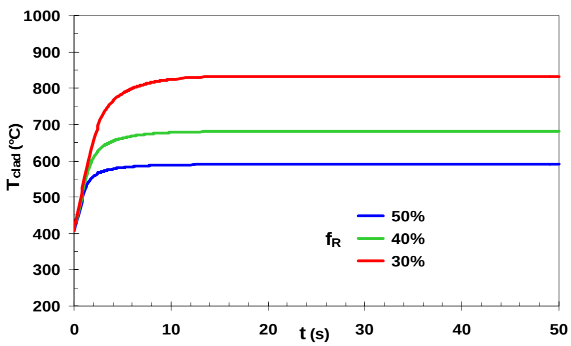


Figure 10: unprotected SA blockage maximum clad temperature

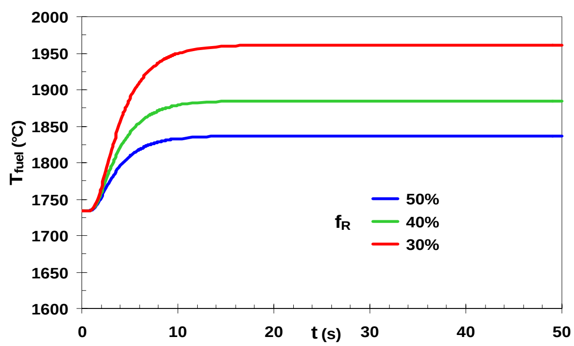


Figure 11: unprotected SA blockage maximum fuel temperature

6. Conclusions

The calculations performed with the RELAP and SITHER have shown that the MYRRHA design is able to face up very efficiently to protected loss of flow and loss of heat sink accidents. In unprotected conditions, the most critical situation is encountered with the loss of flow case, for which the grace time is only a few seconds before the safety criterion on fuel cladding is exceeded. On the other hand unprotected loss of heat sink accidents allow much longer grace times (~15 minutes).

Overcooling transients caused by a sudden drop of the water temperature in the secondary circuits do not lead to excessive LBE freezing in the heat exchangers provided that the accelerator is not shutdown. With this condition water temperatures as low as 40°C are acceptable and total blockages of the heat exchangers have not to be feared.

Accidental reactivity insertions up to 2000 pcm in the sub-critical core do not generate core damages, even in unprotected conditions. Under this limit value the maximum fuel temperature stays below 2500°C. Cladding temperatures are much lower than the safety criterion.

Partial blockages in core sub-assemblies may lead to cladding failure if the cross sectional area of the flow is reduced to 30%. A very early detection of the blockage is crucial to mitigate the accident consequences. Nevertheless in any case the core damages will be limited to the affected sub-assembly.

One of the main outcomes of the safety analysis of MYRRHA is the need of an extremely reliable system of accelerator shutdown in order to avoid unacceptable consequences of accidents, especially in the case of LOF. However it has to be emphasized that the windowless concept developed by SCK•CEN for the spallation target could prevent such unprotected situations if an adequate coupling between the primary system and spallation loop behaviours is introduced. Further investigations in that direction are presently under way.

The same analysis is conducted for the MYRRHA core configuration where the MOX fuel is (partially or entirely) replaced by MA U-free fuel.

References

[1]. W. Maschek, A. Stanculescu, "IAEA CRP on Studies of Advanced Reactor Technology Options for Effective Incineration of Radioactive Waste", GLOBAL 2005, Tsukuba, Japan, Oct 9-13 (2005).

[2]. J. Pirson et al. (2004), "Safety Systems and Analysis of the Small-scale XADS: Sizing, Drawings and Analysis Report". Deliverable 66 of the PDS-XADS FP5 project.

[3]. H. Aït Abderrahim et al., "MYRRHA Pre-Design File – Draft 2", SCK•CEN Report R-4234, June 2005 (2005)

[4]. RELAP5/Mod3 Code Manual, Volume 1: Code Structure, System Models and Solution Methods, NUREG/CR-5535-V1, June 1995.

[5]. B. Arien, J. Daniëls, "SITHER: a module for steady and unsteady thermohydraulic calculations in single fuel rod channels", internal report 63-151/80-88, Mol, SCK•CEN, 1980.

[6]. B. Arien, "Modelling of Lead-Bismuth Freezing in the Heat Exchangers of the MYRRHA Facility", Internal report (to be published), Mol, SCK•CEN, 2006.