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REGULAR ARTICLE — OPEN ACCESS

On physics of a hypothetical core disruptive accident in Multipurpose hYbrid Research Reactor for High-tech Applications – MYRRHA

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Abstract. The sensitivity of the reactivity of a fast reactor core to changes in its geometry and/or fuel relocation calls for particular attention with regard to criticality events. A category of these events, the so-called Core Disruptive Accidents (CDAs), are intensively studied in the safety assessment of Sodium-cooled Fast Reactors (SFRs), and more recently also in the case of other systems. Differences between SFRs and Heavy Liquid Metal Fast Reactors (HLMFRs) are significant and therefore warrant an understanding of phenomena and the development of models specific to HLMFRs. This paper provides a qualitative overview of the physics relevant to the investigation of a CDA in HLMFR, with a particular application to the Multipurpose hYbrid Research Reactor for High-tech Applications – MYRRHA. At first, a core compaction mechanism viable for an HLMFR has been postulated. In what follows, simulation by an already existing severe accidents code, as well as modelling based on fundamental physics and engineering, have been performed. It is demonstrated that, for a linear insertion of reactivity due to hypothetical core compaction, the reversal of reactivity evolution happens due to the Doppler effect and the thermal expansion of core materials. Subsequent expansion by fuel melting terminates the prompt-critical event and makes the system delayed-supercritical. Successive fuel and/or coolant boiling is responsible for the hydrodynamic disassembly of the core and it therefore effectively terminates the transient.

List of acronyms

CDA	Core Disruptive Accident
HCDA	Hypothetical Core Disruptive Accident
HLMFR	Heavy Liquid Metal Fast Reactor
LBE	Lead-Bismuth Eutectic
MOX	Mixed-Oxide
MYRRHA	Multipurpose hYbrid Research Reactor for High-tech Applications
PRK	Point Reactor Kinetics
SFR	Sodium-cooled Fast Reactor
SIMMER	S_n, Implicit, Multifield, Multicomponent, Eulerian, Recriticality

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1 Introduction

The Multipurpose hYbrid Research Reactor for High-tech Applications (MYRRHA) is a flexible irradiation facility currently under development at the Belgian Nuclear Research Centre (SCK CEN). MYRRHA is a pool-type, fast-neutron-spectrum facility cooled by liquid Lead-Bismuth Eutectic (LBE) and coupled to a linear particle accelerator in order to enable its operation in subcritical mode. It can also operate in critical mode when the core contains enough fissile material to sustain a nuclear chain reaction [1].

Among the variety of goals MYRRHA aims to fulfil, there is the demonstration of the Accelerator-Driven System for the transmutation of high-level nuclear waste [1,2] and the Heavy Liquid Metal Fast Reactor (HLMFR) technology, provision for advanced material development aimed both at nuclear fission and fusion technology, and medical radioisotope production.

In the case of a severe accident, MYRRHA intends to rely on an in-vessel retention strategy as it is believed to be the most robust strategy in limiting the radiological consequences of a Core Disruptive Accident (CDA) for the population. This implies that it has to be confirmed that the reactor vessel can withstand the (potentially high) mechanical load caused by a prompt-critical severe accident. Since a fast reactor core, in contrast to a Light-Water Reactor core, is not designed to be in its most reactive configuration, a core degradation with a fuel relocation can result in core compaction that could increase the reactivity beyond the prompt-critical level [3,4]. This could further lead to a large power excursion that might expose the vessel to high mechanical forces, challenging its integrity and hence its confinement function.

This paper aims to establish the physics and phenomena relevant for the transition/secondary phase of a CDA in the core of MYRRHA, up to and not further than the neutronic disassembly of the reactor core (thus the mechanical energy release and structure loading assessment are not covered in the discussion). This is further backed up by the calculations performed with the S_n, Implicit, Multifield, Multicomponent, Eulerian, Recriticality (SIMMER) computer code and a numerical model currently being developed at SCK CEN, aimed at studying CDA scenarios in HLMFR cores. This paper focuses on a qualitative discussion of the relevant physics and phenomena, as well as a description of the employed models.

2 Core disruptive accident

The reactivity of a fast-spectrum reactor core can be very sensitive to the relocation of the core material. As already mentioned, this is due to the fact that the core of an intact HLMFR is not designed to operate in its most reactive configuration [3,4]. It is therefore theoretically possible that a change of geometry and/or rearrangement of the core material might result in a prompt-critical reactivity excursion (as an indication, the maximum value of reactivity observed in this work is ∼3$) and an explosive energy release inside the vessel.

A CDA represents a sequence of events that eventually leads to prompt-criticality followed by a core hydrodynamic disassembly and the corresponding neutronic shutdown [3]. Depending on the nature of the CDA, the released energy and the load on the vessel might differ significantly.

In the past, these CDAs have been intensively studied for Sodium-cooled Fast Reactors (SFRs). Although these accidents were always classified as "highly unlikely", many designs of SFR containment structures were strongly influenced by the outcomes of these studies [3]. A CDA scenario hypothesized to occur in a fast reactor core was initially proposed by Hans Bethe and John Tait in 1956 [5], for the safety studies of the Dounreay Fast Reactor. The scenario assumed the following: upon loss of coolant, the metallic fuel, and its cladding, would melt and eventually collapse due to gravity, thereby forming a prompt-critical configuration. Bethe and Tait made a simplified, conservative model to estimate the energy released in such a case before the core would ultimately be disassembled by the pressure of fuel vapor generated as a consequence of the power excursion. In the years that followed, specialized computer codes were developed in order to describe CDAs in a best estimate approach, yielding less conservative estimations of the energy release. These codes also attempted to follow the whole sequence of events, from the initiating event up to the hydrodynamic disassembly of the reactor core, by coupling dedicated models of different phenomena at a mechanistic level. The aforementioned codes are, however, extensively validated only for SFRs.

The differences between SFRs and HLMFRs are significant and the development of dedicated models is necessary to assess the energy release of a CDA in an HLMFR core. For example, the boiling point of LBE is much higher than the one of Sodium; so in contrast to SFRs, no extensive coolant boiling prior to a prompt-critical event is expected in MYRRHA [3,6]. On top of that, the densities of Mixed-Oxide (MOX) fuel and LBE are similar. This implies that the core compaction mechanism commonly assumed in the case of SFRs, dominantly driven by the gravitational collapse of fuel, can be excluded as a compaction mechanism in HLMFRs.

Inspired by the approach and work of Bethe and Tait, research on CDA in an HLMFR core will start with a theoretical and simplified model. This model aims to identify which phenomena influence the disassembly of the reactor core and the extent of energy released in such an event. The experience accumulated and the tools developed for SFRs will provide an important reference and aid in this research.

2.1 Core disruptive accident in heavy liquid metal fast reactor

Due to the above-mentioned differences between SFRs and HLMFRs, many established sequences of events assumed to lead to a CDA in an SFR are not valid for an HLMFR. Recall that the typical scenario in SFR is the gravitational collapse and compaction of molten fuel and steel once the coolant is not present in the system. In an HLMFR, the coolant will be present in the system prior to and during the core compaction (due to its high boiling point, which largely exceeds the melting point of steel). Also considering the similar density of MOX fuel and the coolant, it is evident that a gravitationally driven fall and/or sinking cannot lead to a large reactivity insertion rate as in the case of SFR.

Taking this into consideration, a different core compaction mechanism for an HLMFR core has to be hypothesized. The compaction mechanism considered for the MYRRHA core and described in this paper is the one that is believed to lead to the maximum core compaction rate and therefore to the most conservative assessment of the thermal energy released during the event. Due to the extremely low probability of the hypothesized sequence of events happening, a CDA in an HLMFR is often referred to as a Hypothetical Core Disruptive Accident (HCDA).

Since gravity is not a credible core compaction force (due to the similar densities of fuel and LBE), the only external force left to be the driver of core compaction is believed to be the drag by the flow. In all possible events, including loss of forced flow and/or loss of reactor core protection (control and safety rod systems), the first degradation phenomenon in an HLMFR core is the melting (or dissolution) of the cladding [7]. The proposed bounding case assumes this to have happened instantly in the whole core, which is an extremely conservative hypothesis.

The hypothetical sequence of events leading to the core compaction in MYRRHA is assumed to be the following: the fuel in the reactor core is initially assumed to have lost all the cladding. Cladding is furthermore assumed to have been relocated, due to melting and subsequent freezing, to the region above the active core region and to have made a blockage there (the resolidified cladding material "floats" on top of the active zone). The porosity of this blockage is assumed to be such that it allows the LBE to flow through it but prevents the passage of the fuel (fragments). Fuel is furthermore assumed to be fragmented and suspended in the coolant (recall that the fuel itself has a similar density as the LBE). On top of previous assumptions, it is postulated that the primary circuit pumps are still running and hence creating a forced coolant flow that compacts the fuel against the blockage formed above the active zone of the core. This leads to fuel compaction and the consequent increase in reactivity.

In the opinion of the authors, the herein proposed (conservative) scenario maximizes the reactivity insertion rate in the MYRRHA core.

3 Modelling of a hypothetical core disruptive accident

Since the HCDA involves various physical phenomena, mostly in a non-linear coupled framework, the development of an accurate purely analytical model is deemed almost impossible. However, there is a variety of ways to assess the magnitude of the released energy in an HCDA.

The analytical model initially developed by Bethe and Tait for SFRs is based on a theoretical and simplified sequence of events: a prompt-critical sphere of molten metallic fuel heats up until the formation of fuel vapor at its center. This is followed by an expansion due to the buildup of internal pressure which ultimately inflates the sphere into a (deeply) sub-critical configuration. This model is subject to a number of simplifying and conservative assumptions that lead to the decoupling of the involved phenomena [5], therefore significantly simplifying the solution. Nonetheless, the model is suitable to provide a conservative assessment of the energy released during a CDA in an SFR.

In the years that followed, specialized computer codes were developed in order to estimate HCDAs in a best estimate approach. One of these severe accident codes is the SIMMER computer code. SIMMER-III is a two-dimensional, three-velocity-field (reactor core materials are assigned to one of the three existing velocity fields), multiphase, multi-component, Eulerian particle/fluid-dynamics code coupled with a space- and energy-dependent neutron-dynamics code [8]. Compared to the original Bethe and Tait model, SIMMER can address cases of significantly higher complexity. SIMMER was originally developed for use in the safety analysis of SFRs and was later adapted to be used for the same purposes in HLMFRs. The adaptations of the code include the introduction of the material properties of the coolant and the corresponding equation of state, as well as some additional minor modifications. Nonetheless, the majority of the physical phenomena and the corresponding modeling are as in the case of SFR. Some of these models were validated for applications to SFR safety analysis [9] but were, regrettably, never extensively validated for use in HLMFR.

Therefore, a simplified and conservative in-house model has been developed at SCK CEN and implemented in order to provide an assessment of the order of magnitude of the energy released during an HCDA in MYRRHA and to be further compared to SIMMER-III. This model couples the solution of the heat transfer problem, the mechanical-dynamics, and the neutron-dynamics. In addition, it involves a couple of simplifying assumptions that either have negliable impact or have a conservative impact on the solution.

3.1 Hypothetical core disruptive accident solver

In what follows, a brief description of the in-house developed model, from here on referred to as HCDA Solver, is provided. In addition, Figure 1 provides a simplified overview of the reactor pool (left), computational domain, and its anticipated state at the beginning and the end of the simulation (middle), as well as the corresponding legend (right). It is useful to return to Figure 1 while reading through this section.

In order to reduce the computational burden of simulations, the reactor core is initially assumed to be spherical.

The solution of neutron dynamics relies on the theory of Point Reactor Kinetics (PRK), whereas all necessary PRK parameters, as well as the corresponding reactivity feedback coefficients, are calculated by employing the Serpent 2 Monte Carlo code [10]. The set of PRK equations reads as in equation (1) [11]:

$$\begin{aligned}\frac{\mathrm{d}P\left(t\right)}{\mathrm{d}t} &= \frac{\rho\left(t\right)-\beta_{\mathrm{eff}}}{\Lambda}\cdot P\left(t\right)+\sum_{i}\lambda_{i}\cdot\zeta_{i}\left(t\right)\\ \frac{\mathrm{d}\zeta_{i}\left(t\right)}{\mathrm{d}t} &= \frac{\beta_{i}}{\Lambda}\cdot P\left(t\right)-\lambda_{i}\cdot\zeta_{i}\left(t\right)\\ \rho\left(t\right) &= \rho_{\mathrm{comp}}\left(t\right)+\sum_{i}\alpha_{i}\cdot SV_{i}\left(t\right)\end{aligned} \tag{1}$$

where P denotes the power, t the time, ρ the reactivity, β the delayed neutron fraction, Λ the neutron generation time, λ the decay constant of delayed neutron precursors, ζ the adjusted or "reduced" concentration of delayed neutron precursors [11], ρ_{comp} the reactivity inserted due to compaction of the reactor core, α the reactivity feedback

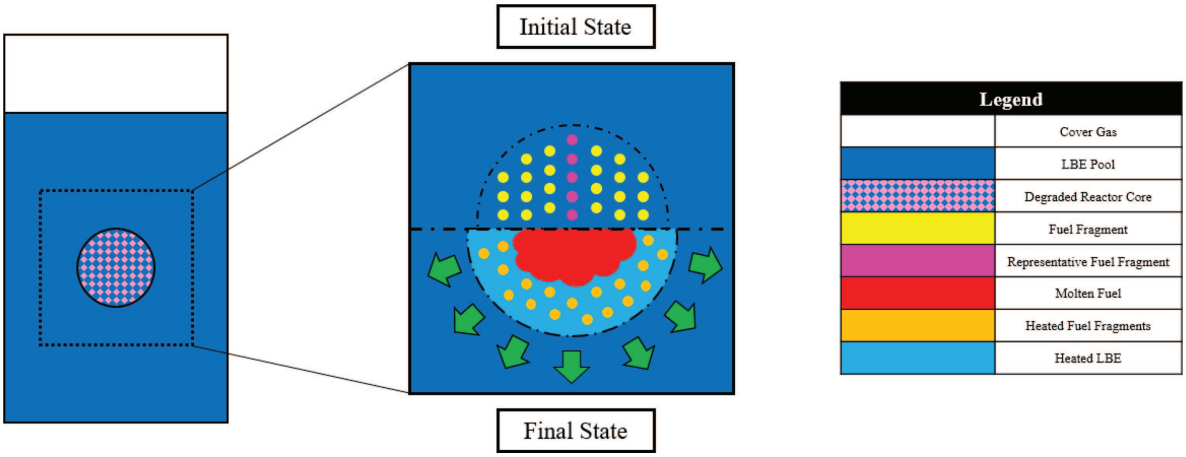

Fig. 1. Simplified overview of the reactor pool and the computational domain. The upper section of the computational domain represents the state of the core at the beginning of the transient, whereas the lower section represents the state of the core at the end of the simulation.

coefficient for a particular feedback effect and SV the state variable corresponding to the reactivity feedback effect.

Several reactivity feedback effects are considered: the nuclear Doppler effect, the thermal expansion of solid fuel, the thermal expansion of liquid LBE, the reactivity effect related to the fuel melting, and the thermal expansion of liquid fuel. The corresponding reactivity feedback coefficients are calculated by running a number of Serpent 2 cases and subsequently calculating the rate of change of reactor core reactivity with respect to the change of the corresponding state variable. The reactivity feedback coefficients are expressed either in $\frac{\text{pcm}}{K}$ or $\frac{\text{pcm}}{\%_{\text{vol}}}$.

Before and up to the hydrodynamic disassembly of the reactor core, heat transfer is solved at the fuel fragment level, under the assumption that the fuel fragment is spherical and that the heat transfer happens only due to conduction. The heat transfer equation in its general form reads as in equation (2) [12]:

$$\rho(T)\cdot c_p(T)\cdot\left(\frac{\partial T(t)}{\partial t}+\vec{v}(t)\cdot\nabla T(t)\right)=\nabla k(T)\cdot\nabla T(t)+q'''(t) \quad (2)$$

where ρ denotes the mean density, T the temperature, c_p the specific heat at constant pressure, t the time, v the flow velocity, k the thermal conductivity and q''' the volumetric heat generation rate. Equation (2) is reported in its general form, but some simplifications, allowed by the nature of the transient, can be introduced. For example, due to a low velocity of coolant with respect to the fuel fragments during the transient (i.e. $v \approx 0$), as well as due to the timescale of the entire transient, convective heat transfer can be neglected.

Since it plays an important role in an HCDA, a model of phase change, of both the fuel and the coolant are introduced. It relies on the so-called effective heat capacity method [13]. This method uses a pseudo material with an increased heat capacity near the melting temperature that simulates the latent heat of fusion so that the material absorbs the same amount of heat as the latent heat does during phase transition. By doing so, the latent heat of the phase change, along with the temperature-dependent thermal properties of different phases of the reactor core materials (e.g. density, thermal conductivity, etc.) are accounted for.

In order to feed the neutron-dynamics solver with the necessary state variables, information on the average reactor core state is required. The sought-average state is acquired by averaging results obtained for the representative fuel fragments. Since the reactor core geometry is assumed to be spherical, representative fuel fragments are identified as fuel fragments along the core radius and are indicated in magenta in Figure 1.

System pressure buildup is caused by the thermal expansion of core materials and phase changes [3,5]. Calculation of this pressure relies on the solution of the mass conservation equation and the simplified momentum conservation equation and is currently under further development. The conservation equations employed to calculate system pressure buildup are reported in their general form in equation (3) [14]:

$$\frac{\partial\rho(t)}{\mathrm{d}t}+\vec{\nabla}\cdot(\rho(t)\cdot\vec{v}(t))=0 \quad (3)$$
$$\rho(t)\cdot\frac{D\vec{v}(t)}{\mathrm{D}t}=-\vec{\nabla}p(t)+\rho(t)\cdot\vec{g}+\vec{\nabla}\cdot\overline{\overline{\tau}}$$

where ρ denotes the mean density, t the time, v the flow velocity, p the pressure, g the gravity acceleration and τ the deviatoric stress tensor.

A simplified coupling scheme of the above-described models (i.e. Eqs. (1) through (3)) is presented in Figure 2. It should be noted that the models presented in blue are related to neutron-dynamics, the models presented in red are related to heat transfer, and the models presented in green are related to mechanical-dynamics and pressure buildup.

Results obtained by the HCDA Solver have been compared to the results obtained by the significantly more complex and mature severe accidents code SIMMER-III and it has been verified that the HCDA Solver can perform comparatively well prior to boiling onset. By doing

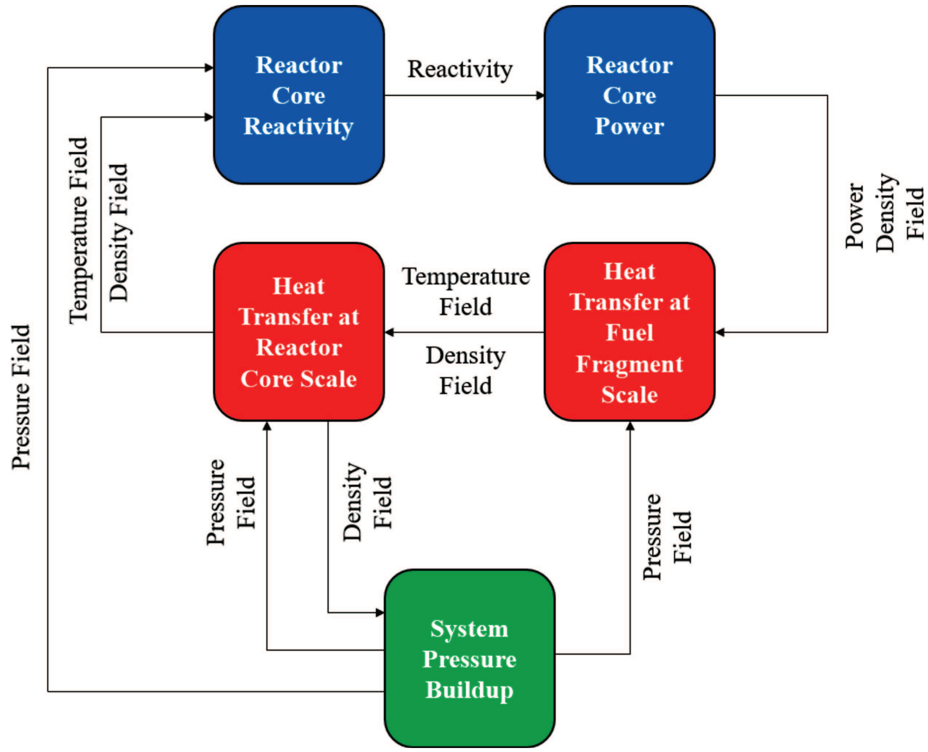

Fig. 2. Simplified coupling scheme of the described HCDA Solver.

this, code-to-code verification (for this specific transient) has been successfully performed. It can therefore be stated that the HCDA Solver seems to be able to model appropriately the physics relevant for an HCDA in an HLMFR core.

4 Phenomenology of a hypothetical core disruptive accident in a heavy liquid metal fast reactor

As already mentioned, this paper aims to provide a qualitative discussion of the physics relevant to an HCDA in an HLMFR core such as MYRRHA.

A postulated sequence of events leading to HCDA in an HLMFR has been reported in Section 2.1: *Core Disruptive Accident in Heavy Liquid Metal Fast Reactor*. The initial state of the system is that of a uniform mixture of fuel fragments and LBE (i.e. the *degraded* reactor core). Recall that the steel is presumed to have left the active core region by buoyancy and that it is not present in the system. The presented results are obtained by SIMMER-III and by the in-house developed model, HCDA Solver.

4.1 Core compaction and reactivity insertion

Since the core degradation phase is highly dependent on the specific core degradation scenario, the core compaction is currently modeled by a linear insertion of reactivity versus time. The linear reactivity insertion rate is the sole parameter used to describe the core compaction mechanism. Core compaction is therefore simulated by artificially increasing the reactivity of the core according to the compaction rate defined by the assumed compaction mechanism: degraded core compaction by a nominal forced flow. The core disruption by the prompt-critical power release is efficiently instantaneous and this justifies the assumption that it is independent of the actual compaction mechanism.

Results discussed and presented in the scope of this work are based on an input reactivity insertion rate that corresponds to the uniform compaction of the core by the nominal forced flow. By running two subsequent Serpent 2 calculations that correspond to a degraded core of nominal size and completely compacted degraded core (i.e. maximum theoretical packing density of spherical fuel particles) and by assuming this compaction to have happened at the flow velocity that corresponds to nominal forced flow (this is a conservative assumption), the amplitude of reactivity insertion rate is calculated to be 170$/s.

4.2 Power buildup and reactivity reversal

An increase in the core reactivity results in an increase in core power. For as long as the reactivity of the core is below the effective fraction of delayed neutrons in the core (1$), the power increase is mainly driven by the dynamics of delayed neutrons. This means that the power increase in this reactivity range (0$–1$), defined as delayed-supercriticality, is slow (i.e. dominated by the decay constant of delayed neutron precursors, λ, which is of the order of seconds, i.e. between 0.2 s and 55 s) [11]. In this phase, the reactivity feedback effects are small when compared to the reactivity inserted due to core compaction. This means that the reactivity evolution is dominantly driven by the core compaction.

When the core reactivity exceeds 1$, the nuclear chain reaction is dominantly driven by prompt neutrons and the power increase is much faster (i.e. dominated by the prompt neutron generation time, Λ, which is on the order of (fractions of) microseconds) [11]. This moment is defined as the moment of *super-prompt-criticality* and denotes the beginning of the power peak. Due to the high thermal energy input in the system, the reactivity feedback effects start becoming more important.

One of the important reactivity feedback effects is the Doppler effect, linked to the increase in the fuel temperature and the corresponding cross-section resonance broadening effect [4]. This effect results in the reduction of the core reactivity. An increase in the fuel temperature additionally leads to its thermal expansion and the consequent expansion of the entire reactor core. This core dimension augmentation leads to an increase in neutron leakage from the core and a corresponding reduction of the core reactivity. Heat transfer from the fuel to the surrounding LBE coolant results in thermal expansion of the coolant and reduction of the core reactivity due to the same reasons as mentioned above. As a consequence of very fast thermal feedback in the prompt-critical region, the sum of these reactivity feedback effects is of the same order of magnitude as the reactivity inserted in the system due to the hypothetical core compaction. The moment of *reactivity reversal* is defined as the moment when the overall reactivity reaches its maximum and starts reducing. It is important to remember that at the moment of reactivity reversal, the core reactivity is still above 1$. This means that the power increase rate remains high due to the fact that the nuclear chain reaction is still driven by the prompt neutrons.

4.3 Neutronic shutdown

Shortly after the moment of reactivity reversal, the fuel melting temperature is reached in the central regions of the core. *Fuel melting* introduces an additional negative reactivity feedback effect: since the phase change is associated with an increase in the fuel volume, it results in an increase in the core size, a decrease in the average core density, and additional neutron leakage. The reactivity feedback effect related to fuel melting is high enough to drive the overall core reactivity below 1$, into the delayed-supercritical zone. This occurs almost immediately upon the onset of the fuel melting. The moment when the core reactivity reaches the delayed-supercritical zone is the moment of the *neutronic shutdown*. At the moment of the neutronic shutdown, the power peak reaches its maximum [11].

4.4 Hydrodynamic core disassembly

Even though the reactor power has reached its maximum and is on the decrease after the reactor reaches neutronic shutdown, its absolute value is still very high. This means that the negative reactivity feedbacks continue to increase in magnitude and therefore continue to override the reactivity inserted due to hypothetical core compaction. The internal energy increase of the fuel and the heat transfer to the LBE eventually lead to *fuel* and/or *LBE boiling*. These two phenomena rapidly increase the system pressure and cause a *hydrodynamic disassembly* of the core, accompanied by a negative reactivity feedback of high magnitude that counters all the hypothetical reactivity insertion [3,5]. This results in the complete disassembly of the core and a corresponding dispersion of fuel. The reactivity feedback effect rated to the fuel dispersion is high enough to almost instantaneously reduce the core reactivity far below the critical state and make the entire configuration deeply subcritical.

The hydrodynamic disassembly of the core is assumed to override any hypothetical core compaction mechanism and will therefore effectively terminate the transient.

It should however be noted that the complete dispersion of the fuel might be prevented due to the presence of the supporting structures in the reactor pool. If that is the case, a sudden collapse of the created fuel and/or LBE bubble can lead to the new fuel compaction and therefore represents a viable recriticality mechanism. The potential for recriticality due to a variety of reasons will be addressed in the follow-up of this work.

4.5 Pressure buildup

Core compaction and the consequent power pulse result in a substantial pressure buildup in the system. This pressure buildup is caused by the expansion of core materials and the phase change.

As a brief reminder, the power profile of a reflected homogeneous critical sphere is parabolic [3,5]. As a consequence, the thermal expansion and phase change are more pronounced in the center of the core, as will the system pressure. Due to this pressure buildup in the center of the system, the location of the fuel and LBE boiling shifts towards the periphery of the core.

A simplified analytical model of the core material expansion (as a consequence of the thermal expansion or phase change from solid to liquid) shows that for as long as the system remains highly incompressible (i.e. does not contain non-condensable gas or vapor), no displacement inside the degraded reactor core is taking place at velocities higher than the speed of sound and no important local pressure is built up. This type of system is usually referred to as the "hard system". The subsonic behavior of a (hard) system significantly simplifies the mechanical modeling of an HCDA.

It is important to stress that the full disassembly occurs by vaporization of the fuel and/or LBE and that a more complicated hydrodynamic model is required to describe this phase of the transient.

4.6 Importance of reactivity insertion rate

A parametric study has been performed with SIMMER-III, in which the reactivity insertion rate was varied up

Table 1. Initial conditions of degraded reactor core as employed in simulation of HCDA in MYRRHA. This simulation is performed by employing HCDA Solver.

Initial condition	Value
Power	100 MW
Reactivity	0$
Reactivity insertion rate	170$/s
Degraded core radius	0.71505 m
Fuel volume fraction	0.14
Fuel temperature	1700 K
LBE volume fraction	0.86
LBE temperature	600 K

Table 2. Timing of the most important events expected to occur during the HCDA in MYRRHA. These results are obtained by employing HCDA Solver.

Event	Timing [ms]
Beginning of reactivity insertion	0
Super-prompt-criticality	8.137
Reactivity reversal	21.074
Fuel melting	23.082
Neutronic shutdown	24.432
Fuel boiling	24.683
LBE boiling	/
Hydrodynamic core disassembly	>24.683

to the highest reactivity insertion rate that can physically occur in the core of MYRRHA. The scenario corresponds to the uniform compaction of a degraded reactor core by the nominal forced flow, as discussed in Section 2.1: *Core Disruptive Accident in Heavy Liquid Metal Fast Reactor* of this paper.

This parametric study showed that the released thermal energy increases with the increase of the reactivity insertion rate. The same study also showed that the sequence of the most important events expected to occur during the transient does not change as a function of the reactivity insertion rate. It should however be noted that the timing (relative to the beginning of the reactivity insertion) of the above-mentioned events does differ significantly.

5 Illustrative preliminary results

This section provides a brief, illustrative overview of the numerical results obtained for a reference test case. The presented preliminary results are obtained by application of HCDA Solver. The transient follows the phenomenology described in Section 4: *Phenomenology of Hypothetical Core Disruptive Accident in Heavy Liquid Metal Fast Reactor* of this paper.

Table 1 provides an overview of the initial conditions, whereas Table 2 contains the timing (relative to the beginning of the reactivity insertion) of the most important events expected to occur during the transient. The core reactivity and power evolution are represented in Figure 3. Since the HCDA Solver still does not include an appropriate hydrodynamic model of boiling, the simulation is terminated when the boiling onset is reached.

6 Future work

Concerning further developments in research of an HCDA in an HLMFR core, several points require attention.

It has been discovered that the 11 energy group structure, used as an input to the neutron-dynamics solver of SIMMER-III, is not suitable to accurately reproduce the neutron-dynamics of the prompt-critical event in the core of an HLMFR. By employing 72 energy group structure that accounts for seemingly important effects in the epithermal energy range, almost identical results to those of continuous-energy Monte Carlo simulation were achieved. Authors are therefore currently working on the development and generation of a better suited energy group structure and the corresponding cross-section library.

Furthermore, the in-house developed model used in this study is expected to perform accurately in a hard system until the onset of boiling. Due to the constraints imposed by the application of the PRK model [4,12], as well as the simplified treatment of the boiling process, further development of the model is currently being carried out to enable coverage of the transient beyond the boiling onset.

The herein described accident and the corresponding modeling are aimed at the assessment of the released thermal energy in a "hard system". It considers the complete absence of non-condensable gas that might be trapped inside the degraded reactor core, such that the expansion of the core materials directly translates into the expansion of the entire core. However, the presence of non-condensable gas in the system would delay the expansion of the core and increase the released thermal energy, since it would prevent the expansion of the core until the non-condensable gas is sufficiently compressed. The authors are currently investigating the potential for the presence of non-condensable gases and expansion of the current models to account for their presence.

Finally, a model will be developed for the conversion of the released thermal energy into mechanical energy and the calculation of the corresponding loads on the primary system. By doing so, an estimate of the viability of the in-vessel retention strategy will be performed.

7 Conclusions

This work provides an overview and a discussion of the physics relevant for an HCDA in an HLMFR, with the core of MYRRHA as an example. The work presented in

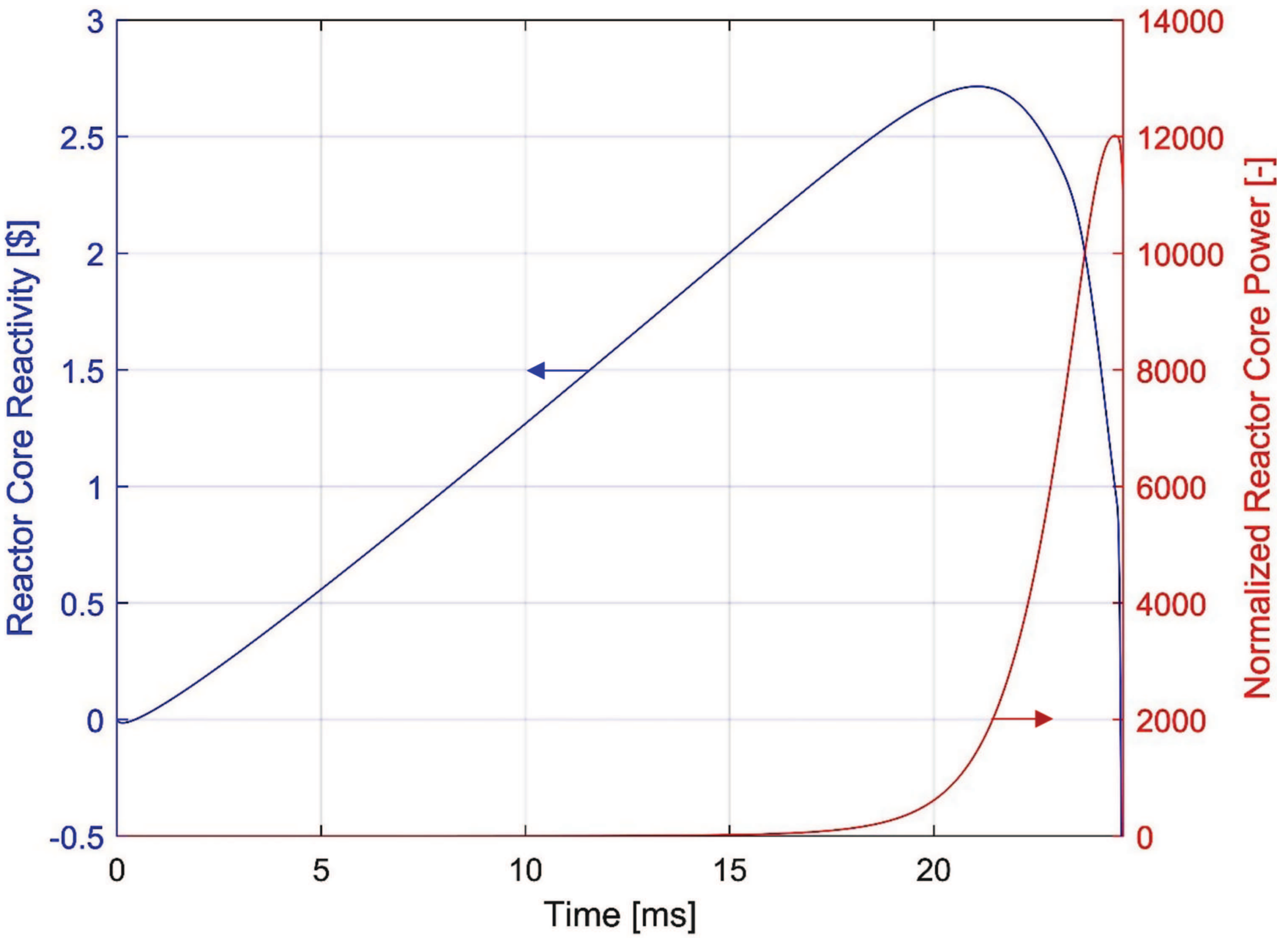

Fig. 3. Evolution of the reactor core reactivity and the corresponding reactor core power as calculated by employing the HCDA Solver.

the framework of this paper aims to support the mechanical calculation of the MYRRHA reactor vessel. In order to challenge the vessel's integrity and hence its confinement function, a conservative estimate of the energy released during an HCDA is to be used. To that goal, an assessment of the released energy during an HCDA is calculated by employing two codes: well-established severe accidents code SIMMER-III (originally developed for SFRs) and an in-house developed, simplified model describing multiphysics of such an accident.

In the framework of the above-described simplified model, some of the most important conclusions are as follows:

1. the sequence of events expected to occur during an HCDA in MYRRHA is as follows:
   i Super-prompt-criticality
   ii Reactivity reversal
   iii Fuel melting
   iv Neutronic shutdown
   v Fuel and/or LBE boiling
   vi Hydrodynamic disassembly;
2. reactivity feedback effects start playing a dominant role when super-prompt-criticality has been reached;
3. thermal expansion of the reactor core materials, together with the Doppler effect, exceed the maximized hypothetical reactivity insertion and results in the reactivity reversal;
4. fuel melting results in the neutronic shutdown of the reactor core;
5. fuel and/or LBE boiling results in the hydrodynamic disassembly of the reactor core;
6. for the range of reactivity insertion rates assumed to be possible in the case of an HCDA in MYRRHA, the sequence of events expected to occur during the accident does not depend on the reactivity insertion rate.

Even though classified as "highly unlikely", severe accidents need to be considered in the framework of the MYRRHA safety studies. The hope is that independent of the initiating event and the core compaction scenario, the physics of a CDA in an HLMFR core inherently limits the released thermal energy and the conversion to mechanical load to a level that can be sustained by the primary system.

Upon detailed analysis of the accident, this work identifies all the relevant processes and the corresponding physics necessary to provide a conservative upper-bound estimate of the released thermal energy during such an accident.

Conflict of interests

The authors declare that they have no competing interests to report.

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Data availability statement

This article has no associated data generated and/or analyzed.

Author contribution statement

The following authors have contributed to this research: Đorđe Petrović – model development, performing the calculations, processing the data, and writing the manuscript; Matteo Zanetti – research conceptualization, model development supervision, and manuscript revision; Guy Scheveneels – research conceptualization, model development supervision, and manuscript revision; Andrei Rineiski – model development, and manuscript revision; Xue-Nong Chen – SIMMER-III model development and manuscript revision; William D'haeseleer – manuscript revision.

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