On the Physics of a Core Disruptive Accident in a Heavy Liquid Metal Fast Reactor

- Case Study: MYRRHA -

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Introduction

As global energy demand continues to rise, ensuring a safe, reliable, and low-carbon source of energy becomes increasingly important. **Nuclear energy** plays a pivotal role in meeting these challenges, particularly through the advancement of nuclear technologies such as **fast-spectrum reactor** systems [1]. These innovative technologies offer the potential for greater sustainability by making better use of available fuel and enabling the **closing of the nuclear fuel cycle** through transmutation [1, 2]. With their ability to provide continuous and low-carbon power, advanced fast-spectrum reactors stand as a cornerstone in the pursuit of a resilient and environmentally responsible energy landscape.

Unlike traditional nuclear reactor cores, which sustain the fission chain reaction by thermalised neutrons, these **advanced reactors** are designed to maintain the **fission chain reaction** by relying on **fast neutrons**. Despite the advantages offered by the fast neutron spectrum, such reactor cores are susceptible to a specific accident sequence that may result in the release of a significant amount of energy, endanger their confinement structures, and lead to the release of radioactive material into the environment.

A fast-spectrum reactor core is not designed to operate in its most reactive configuration [1]. As a result, the fission chain reaction sustained in such a system (i.e., the system reactivity) may increase due to changes in system geometry and/or the rearrangement (i.e., compaction) of fuel material. It is, therefore, possible for a core degradation event to lead to a **runaway chain reaction**, excessive power buildup, and **disruption of the reactor core**. This sequence, referred to as a **Core Disruptive Accident** (CDA), has traditionally been analysed for public consequence considerations in Sodium Fast Reactors (SFRs) [1, 3].

More specifically, a conservative core degradation sequence leading to a CDA was postulated in order to set an upper-bound limit for the design of containment structures.

These accidents, however, have never been (comprehensively) studied within the framework of **Heavy Liquid Metal Fast Reactor** (HLMFR) technology, due to the lack of sufficient technological development of an HLMFR design, as well as the difficulty in justifying the possibility of a CDA occurring in an HLMFR in the first place. Regardless of the possibility and probability of its occurrence, a **fundamental understanding** of this **accident sequence** and the ability to **quantify its consequences** have played a crucial role in the development, **safety demonstration**, **and deployment** of SFR technology. In order to ensure that the development of HLMFR technology keeps pace with the rapidly evolving energy market, its resilience to the most severe accidents and the ability of its confinement structures to withstand considerable energy releases must be demonstrated. Due to the significant differences between the two technologies (which are primarily rooted in the coolant properties [4]), the knowledge and experience acquired in the context of SFR safety studies cannot be directly applied to HLMFR technology. The aforementioned differences, therefore, warrant the development of approaches and models specific to HLMFR technology.

Through the development of **simplified**, **yet robust and innovative solutions**, this research is conducted to provide a fundamental understanding of the **physics and phenomenology** of the events preceding a **CDA in an HLMFR** and the CDA itself, with a particular focus on the reactor core of **MYRRHA** [2]. This research relies on a novel, **purposefully developed simulation suite** to provide a qualitative understanding of the physical mechanisms governing a CDA in an HLMFR and a quantitative estimate of the associated fission energy release and the potential consequences. Despite the fact that it does not involve experimental work, the knowledge and results obtained are primarily intended to serve as the basis for the design and evaluation of the reactor vessel and containment structures and, if the need for experimental programmes becomes evident in the future, to support the design of the necessary experimental facilities.

Ultimately, the output of this research provides a **fundamental contribution** to confirming the in-vessel and in-containment retention of the radioactive material following the most severe accidents in an HLMFR and provides a crucial step towards a **definitive safety demonstration of HLMFR technology** as a whole. In doing so, this research represents a **pioneering work** intended to ensure that HLMFR technology remains competitive in the energy market and will contribute to the establishment of a robust and diversified energy mix.

Physics of a Core Disruptive Accident in a Heavy Liquid Metal Fast Reactor

In the absence of computational tools (the development and validation of which would require enormous resources and would delay the deployment of HLMFR technology by decades) capable of accurately tracking the movement of fuel material following a core degradation event (i.e., determining whether fuel compaction would occur), this research proposes **postulating an extremely conservative**

core degradation event resulting in a CDA, and subsequently developing models necessary for modelling and understanding the CDA sequence itself. The postulated sequence will result in an exponential power increase, followed by core disruption. In doing so, the potential mechanical impact on the primary system is maximised and the conditions necessary for the **design and verification of the reactor vessel and the confinement structures** are obtained. The physics and phenomenology of this core disruptive phase are modelled in detail to qualitatively understand its governing mechanisms and to determine the amount of energy released during the CDA sequence in an HLMFR.

The extremely conservative core degradation sequence leading to a CDA, postulated to remain conservative and **envelop all possible scenarios** that may occur during and following a core degradation event, is graphically illustrated in Figure 1, where black denotes the solid fuel material, blue the Heavy Liquid Metal (HLM) coolant, grey the structural material, red the molten fuel material, and white the vapour of either fuel or HLM coolant.

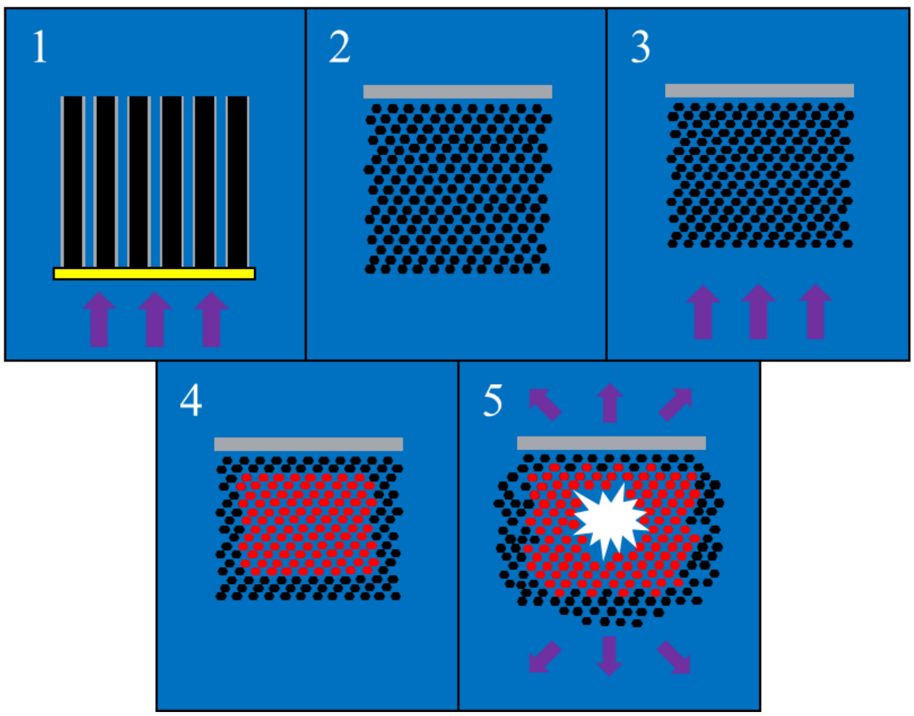

Figure 1. Simplified graphical illustration of a CDA taking place in an HLMFR.

Limited operational experience with HLMFRs, which predominantly consists of military applications in the former Soviet Union, has demonstrated that core blockage events can result in severe core degradation and, in more extreme cases, core meltdown [5]. These accidents, coupled with the limited knowledge and experience regarding the behaviour of HLMs as reactor coolants, make it difficult to practically eliminate a core blockage scenario. A **homogeneous full core blockage** (indicated in yellow in Figure 1 - 1) is therefore postulated as the **initiating event**.

Since the melting point [6] of the structural materials (i.e., stainless steel) is lower than the boiling point of the HLM coolant [4], the postulated enveloping case assumes the loss of structural materials by melting to occur instantaneously across the entire core. It is further assumed that this material relocates to the region above the fuel and contributes to the **formation of a blockage** (Figure 1 - 2). The porosity of this blockage is assumed to be such that it allows the coolant to flow through but prevents the passage of the fuel. Following the loss of cladding, fuel pellets/fragments remain suspended in the coolant (recall that the densities of the oxide fuel and the HLM coolant are similar [4, 6]). In addition to the assumptions above, it is postulated that primary circuit pumps are running at full power, thus creating a **forced coolant flow** that **compacts the fuel material** against the blockage (Figure 1 - 3). This fuel compaction is accompanied by a continuous **increase in system reactivity** and ultimately results in the **achievement of promptcriticality**.

The dynamics of the power buildup that occurs following the achievement of promptcriticality is determined by a variety of system and accident parameters. The behaviour of neutrons in such a configuration is dominantly influenced by the materials present in and around the degraded reactor core, with the most significant effect identified to be a **substantial increase in prompt neutron generation time** (a parameter determining the rate of power increase in the promptcritical range) as compared to the intact core configuration. This effect is demonstrated to be a consequence of the **absence of structural materials** in and around the degraded reactor core [7].

Due to the thermophysical properties of the oxide fuel material (i.e., low thermal diffusivity [6]), the **majority of fission energy** introduced into the system is **retained within the fuel**, with only a fraction (on the order of a few percent of the total fission energy input) transferred to the surrounding HLM coolant. The phenomena occurring in the fuel, therefore, play the most important role in determining the overall dynamics of the transient (e.g., the Doppler effect, reactor core expansion, etc.). A particularly important event during a CDA in an HLMFR is identified as the **melting of the fuel** (Figure 1 - 4). The rapid expansion of the fuel contributes to the overall expansion of the core and introduces enough negative reactivity to **terminate the reactivity transient** (i.e., it leads to Neutronic Shutdown, after which the power level begins to decrease). The thermophysical properties of the HLM coolant (i.e., high volumetric expansion coefficient [4]) imply that, despite the limited amount of **heat transferred to the coolant**, its **thermal expansion** plays a substantial role in the overall expansion of the degraded core and strongly affects the reactivity transient. Heat transfer phenomena are, therefore, identified to play an important role in determining the overall dynamics of a CDA sequence in an HLMFR.

The potential **presence of non-condensable gas** in a degraded reactor core, attributed to gaseous fission products and the filling gas initially contained in fuel pins, is demonstrated to have a significant impact on the **dynamics of system expansion**. Before effective displacement of the fuel material can occur, material expansion must initially take place internally to compensate for the presence of this non-condensable gas [1, 3]. This implies that almost no net expansion of the degraded system takes place before the non-condensable gas is sufficiently compressed, thus introducing a **delay in reactor core expansion** and the associated reactivity effect and resulting in an important increase in the fission energy release.

Despite the achievement of Neutronic Shutdown as a result of fuel melting, continuous energy input in the system following the power reversal and heat transfer from the fuel to the coolant will result in the **vaporisation** of one or both of the **degraded core materials** (Figure 1 - 5). This vaporisation will ultimately disperse the fuel material, resulting in the achievement of **permanent subcriticality**. The mechanical impact of such a sequence, however, may endanger the reactor vessel and the confinement system of an HLMFR, thus calling for an as accurate as possible estimate of the fission and mechanical energy released during and following a CDA.

Modelling of a Core Disruptive Accident in a Heavy Liquid Metal Fast Reactor

A fundamental understanding of the myriad phenomena involved in such a complex accident sequence requires an appropriate 'probe'. Since separate-effect and/or integral experiments are, for various reasons, extremely difficult to perform, the decision is made to initially approach the problem from a more theoretical perspective. Starting from the **fundamental laws and principles of physics**, a CDA in an HLMFR is investigated to gain an understanding of the governing physical mechanisms, estimate the associated fission energy release, and examine its dependence on various system and accident parameters. To achieve this, a carefully selected **set of mathematical models** is established, and a dedicated multiscale, multiphysics simulation tool is developed to obtain its solution.

Figure 2 provides a simplified graphical illustration of the proposed modelling approach. The choice of a **multiphysics modelling** approach is necessary, as this sequence involves a **multitude of phenomena** across different areas of physics (i.e., neutron physics, heat transfer, fluid dynamics, etc.), with the selection of a **multiscale modelling** approach justified by the need to obtain information on these phenomena over different **geometric scales** (e.g., locally important effects of heat transfer vs. the global neutronic behaviour of the system). To ease the initial stage of development, obtain a solution at a reasonable computational cost, and ensure the conservative nature of the obtained solution, a set of carefully selected and rigorously examined simplifying assumptions is adopted.

Neutron physics and, more generally, **reactor kinetics** phenomena, are addressed at the geometry scale of the **degraded reactor core**. The dynamics of reactivity and power transients are modelled within the Point Reactor Kinetics [1] framework, with complementary calculations performed using the Monte Carlo code Serpent 2 [8].

The local nature of the **heat transfer** phenomena calls for the treatment of these effects at the geometry scale of the **fuel pellet/fragment**. The dynamics of temperature increase, heat transfer and phase change phenomena are modelled by solving the generalised heat transfer equation [1] and by relying on the Effective Heat Capacity method [9].

Fluid dynamics and fuel displacement phenomena are addressed at the geometry scale of the spherical **reactor core shell**, where the solution of the Navier-Stokes equations [1], coupled with the equations of state of different degraded reactor core materials [4, 6], provides information on the relative displacement of the fuel material and the overall expansion of the degraded reactor core.

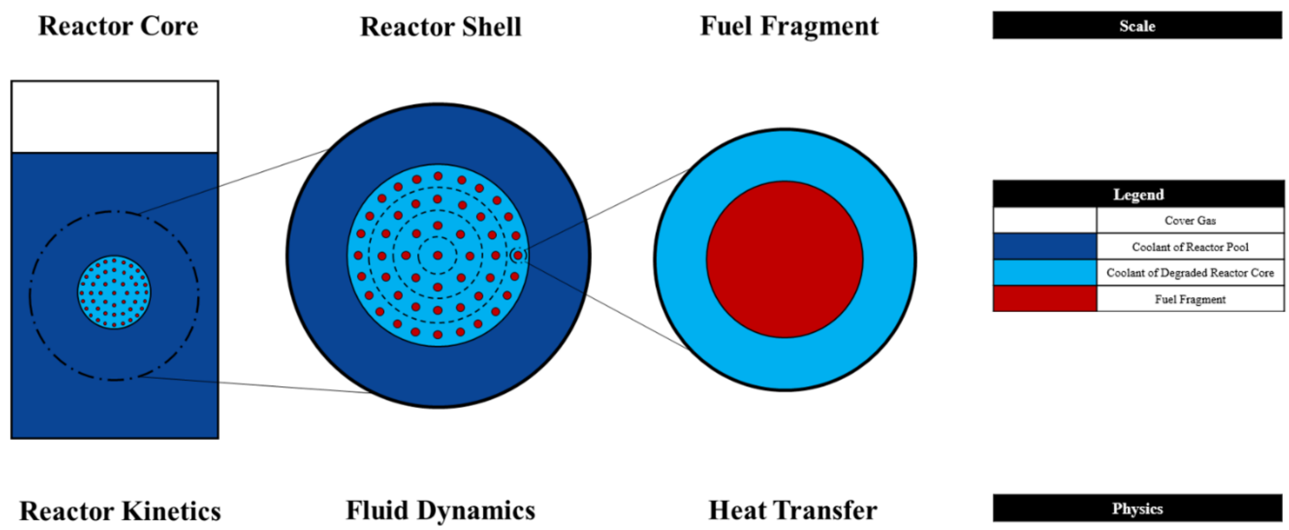

Figure 2. Simplified graphical illustration of the adopted modelling approach and the considered geometry scales.

Ultimately, to ensure accurate modelling of the **interplay between different physical processes**, the developed models are carefully coupled to one another (e.g., the power level obtained in the Reactor Kinetics module serves as the basis for determining the volumetric heat source in the Heat Transfer module; displacement of the fuel material in the Fluid Dynamics module serves as the basis for determining the associated reactivity effect in the Reactor Kinetics module, etc.). Given the highly coupled nature of the transient, ensuring accurate **coupling of different models** and the correct exchange of data between them plays a crucial role in enabling accurate modelling of the accident sequence.

Overview of Results

To enhance confidence in the obtained results, the simulation suite developed as part of this research has been partially validated and rigorously verified. While separate-effect and, in particular, integral validation remain outside of the scope of this research, the results have been compared with those obtained by the severe accident code **SIMMER-III** [10]. SIMMER-III is a well-established and mature severe accident code, developed to support safety studies of SFR technology and validated for this application. Although it has not been validated for HLMFR technology (and could therefore not be fully relied upon for this research), the **close agreement between the results** of the two independent solutions (which are found within a ~3 % margin) greatly increases confidence in the outcomes produced by both models. This comparison indicates that the phenomena driving the dynamics of a CDA sequence can be effectively represented using a relatively simple set of models grounded in fundamental laws and principles of physics. The numerical solution of the governing equations, on the other hand, has been rigorously verified through a series of well-established methods available in the literature.

Following the confirmation of its performance, the extensive application of the developed simulation suite has led to the **identification and qualitative understanding of the governing physical mechanisms**, which are discussed in Chapter 2 of this Extended Summary. Moreover, these simulations have established the (conservative) **upper bound for the fission energy release** (normalised to the nominal power of the reactor core) at $\mathbf{\sim 160}\ {}^{J}/_{W}$. This outcome represents a critical input for studies evaluating the mechanical impact of a CDA on the primary system of an HLMFR.

The fission energy release during a CDA is demonstrated to be highly sensitive to the **presence of non-condensable gas**, which delays the overall expansion of the degraded core. The **power level** of the system at the moment at which the promptcriticality is achieved, as well as the **rate of reactivity insertion**, have also been found to significantly influence the fission energy release. The high sensitivity of fission energy release to these parameters is attributed to their strong impact on the maximum reactivity reached during a CDA sequence.

Given the nuclear and atomic properties of HLMs, the significance of considering **prompt gamma heating of the coolant** throughout the CDA sequence becomes apparent. A dedicated extension of the simulation suite has provided crucial insights into this process, demonstrating that the almost immediate heat transfer to the coolant by prompt gamma rays (as compared to the 'slow' heat diffusion) results in an early and important system expansion. This, in turn, leads to the introduction of negative reactivity, resulting in a **reduction in the fission energy release** by as much as a factor of two.

When using **models of similar level of maturity** to estimate normalised fission energy release in both **SFR and HLMFR technologies**, the results suggest that a CDA in an HLMFR would produce a lower energy release per unit of reactor core power. This finding indicates that **HLMFR technology may offer an advantage in terms of response to a CDA**. Further research, aimed at enhancing the understanding of the physics and phenomenology, as well as improving the modelling of a CDA sequence in an HLMFR, is expected to confirm this conclusion and provide valuable improvements to the estimates of normalised fission energy release.

The potential for a CDA to endanger the **integrity of MYRRHA's primary system** has been assessed by relying on the **mechanical energy conversion factor** (i.e., the fraction of fission energy released during a CDA that is transformed into mechanical energy within the primary system) and the **increase in static pressure** within the primary system. The low value of the mechanical energy conversion factor (estimated at ~ 0.1 %) indicates that only a limited fraction of the fission energy released during a CDA contributes to mechanically loading the primary system. Pressurisation of the primary system following the worst-case CDA, on the other hand, results in pressure level that may exceed the current design requirements but remain within the domain of events that safety systems could cope with and are therefore **unlikely to compromise the structural integrity of the primary system**.

Conclusion

To accelerate the deployment of novel and innovative fast-spectrum reactor systems, it is essential that their definitive **safety demonstration** can be carried out. This research endeavour aims to address a crucial aspect of this requirement for **HLMFR technology**, with a particular focus on the reactor core of **MYRRHA**. The in-vessel and in-containment retention strategies, introduced to minimise the impact of potential accidents on the public, have been critically examined by postulating the most severe accident sequence relevant to a fast-spectrum reactor core: the **Core Disruptive Accident**.

Within the framework of this research, a CDA sequence in an HLMFR has been **investigated in a comprehensive manner for the first time**. To achieve this, a novel approach was conceived, and its rigorous scientific implementation executed. This process ultimately led to the development of a dedicated simulation suite, the performance of which has been verified within different frameworks.

This **pioneering research work** establishes a **fundamental understanding** of the physical mechanisms governing a CDA sequence in an HLMFR and provides a **quantitative estimate** of the associated fission and mechanical energy release. The obtained results offer a foundation for the confirmation of the adopted mitigation strategies. In doing so, it addresses critical requirement necessary to **lay the foundation of an era** of safe, reliable, and sustainable **nuclear reactor technology**.

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