Nuclear Engineering and Design 326 (2018) 392–402

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Investigation on upper bounds of recriticality energetics of hypothetical core disruptive accidents in sodium cooled fast reactors

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ABSTRACT

One key research goal for GEN-IV systems is an enhanced safety compared to the former Sodium Cooled Fast Reactor concepts. A key issue is built-in safety and the capability to prevent accidents and to demonstrate that their consequences do not violate aimed-at safety criteria. From the beginning of SFR development the Core Disruptive Accident (CDA) has played an outstanding role in the safety assessment. Under core disruptive accident conditions with core melting the fuel might compact, prompt criticality might be achieved and a severe nuclear power excursion with mechanical energy release might be the consequence. Numerous safety analyses accompanied the development and the licensing procedures of past fast reactor projects. A central issue of all analyses was the assessment of a realistic upper bound of energetics especially related to recriticalities in disrupted core configurations. Striving for an even higher safety level for next generation reactors a new strategy focused on the development and introduction of preventive and mitigative measures both to reduce the chance for a severe accident development and to mitigate its energetics. For assessing the effectiveness of these measures the knowledge of the CDA behavior is essential. In this context and on basis of new code developments, new experimental insights and extended studies for many reactor types of different power classes over the recent years, the issue of a realistic upper bound of energetics of the late core melt phases is again of relevance. Of special interest is the identification of natural and intrinsic mechanisms that limit the escalation of energetics. The current paper deals with these issues and tries to add supportive facts on the limits of CDA energetics. The evaluation of results of mechanistic SIMMER-II and SIMMER-III/IV analyses performed for various core designs and power classes and specific model case studies in 2D and 3D geometry indeed supports the idea of a limit of recriticality energetics. Intrinsic mechanisms exist, which limit the escalation energetics even in case of a strong blockage confinement suppressing any fuel discharge and allowing on-going sloshing recriticalities. In the light of the available information and taking into account relevant scientific publications and studies by the international community on the subject, one could conclude that an upper bound for energetics in the range given in the paper can be deduced.

1. Introduction

The Sodium-Cooled Fast Reactor (SFR) as advanced reactor concept has the highest technical maturity level among Generation IV systems. It has been built already in large, commercial scale and operated for many years. Extensive experience exists in the full range of design, licensing, operation and handling of incidents and accidents. A key research goal of GEN-IV systems is an enhanced safety compared to the former SFR concepts (Gif IV Technology Roadmap, 2002). In particular, the achievement of a robust architecture against abnormal situations and the robustness of the safety demonstrations should result in clearly demonstrable safety improvements. The defense in depth concept is the key to achieve the robustness in safety (Fiorini, 2009). A key issue is built-in safety and the capability to prevent accidents and to demonstrate that their consequences do not violate aimed-at safety criteria.

However, from the beginning of SFR development in the 1950s, the Core Disruptive Accident (CDA), also coined 'Bethe-Tait' Accident, has played an outstanding role in the safety assessment, as the SFR core is not designed in the most neutronically reactive configuration. Under core disruptive conditions with core melting the fuel might compact, prompt criticality might be achieved and a severe nuclear power excursion with mechanical energy release might be the consequence. The following list of literature (Bohl, 1979; Maschek and Asprey, 1983; Kondo et al., 1985; Theofanous and Bell, 1984; Gouriou et al., 1982)

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https://doi.org/10.1016/j.nucengdes.2017.11.002
Received 6 June 2017; Received in revised form 25 October 2017; Accepted 2 November 2017

reflects some work and the analyses performed in the past for oxide fuel cores.

A central issue of all analyses was the assessment of a realistic upper bound of energetics especially related to recriticalities in the disrupted core configuration. The analyses showed some potential for energetics in the core melt phases. Striving for an even higher safety level for next generation reactors a new strategy focused on the development and introduction of preventive and mitigative measures both to reduce the chance for a severe accident development and to mitigate its energetics. The first focus of prevention and mitigation of energetics was by optimizing and reducing the sodium void worth of the cores, such controlling the energetics of the early accident phases. This however led to the detrimental effect to shift the energetics problem to the later core melt phases and the recriticality problem in large molten fuel pools. In the recent years one also concentrates on getting controllability of the later accident phases by measures coined 'Controlled Material Relocation' (CMR) (Ieda et al., 1994; Maschek, 1995; Endo et al., 2002; Sato et al., 2009). These measures are under investigation and one wants to identify their effectiveness to minimize the consequences of CDAs. For assessing the effectiveness of these measures the knowledge of the general CDA behavior is essential.

With new code developments, new experimental insights and extended studies for many reactor types of different power classes over the recent years, one could now again try to investigate the problem of a realistic upper bound of energetics of the late core melt phases and identify natural and intrinsic mechanisms that limit the escalation of energetics. The current paper deals with these issues and tries to add supportive facts on the limits of CDA energetics.

2. Mitigating measures and mechanisms

We mostly concentrate on mitigation effects in oxide fueled cores in case a CDA e.g. caused by an Unprotected Loss of Flow accident (ULOF) could not be prevented. In the past, safety research has been focused mainly in obtaining a sort of controllability of the early accident phases, especially by optimizing the core reactivity coefficients as e.g. the sodium void worth. This has now achieved a satisfactory level of optimization as reported in Vasile (2015), guaranteeing either a prevention of core degradation or at least eliminating any energetics. As described, new work concentrates on gaining 'controllability' of the later accident phases with their potential of extensive core melting and recriticalities. The objective is to mitigate or eliminate any severe energetics development. One key measure to obtain control is via introducing adequate design measures to guarantee a timely and sufficient fuel discharge from the core, a 'Controlled Material Relocation' (CMR) (Ieda et al., 1994; Maschek, 1995; Endo et al., 2002; Sato et al., 2009; Tobita et al., 1999) to achieve a neutronically subcritical core configuration. The idea of a recriticality free core promoted mainly in Japan is realized via CMR measures on the subassembly level before enlarging the molten region. Special Fuel Assemblies with Inner DUct Structure (FAIDUS) are the adopted concept that allows a large fuel escape path in case of local fuel melting (Sato et al., 2009; Tobita et al., 1999). In the CAPRA project (Languille et al., 1995; Maschek and Struwe, 2000) aiming at burning Plutonium and Minor Actinides the reactor core had a very high PU-enrichment. To cope with the recriticality problem it was proposed to modify and use the numerous diluents in the core for fuel discharge (Maschek and Struwe, 2000). As each diluent was surrounded by 6 fuel elements, a timely and sufficient fuel discharge via accessing the diluents (basically an empty tube) could be envisioned in case of a core melt accident. For the French ASTRID reactor again CMR measures are proposed that work via an empty tube structure named Mitigating Transfer Tubes (TT-DCS-M) (Bachrata et al., 2015). Some tubes are positioned in the inner core zone with most of the tubes surrounding the second core zone.

If the designed mitigating measures for fuel discharge are not effective within the time-slot of core melting, a nuclear power excursion has to be expected. Therefore, it is of interest, if under such conditions natural and intrinsic mitigating effects exist that limit the energetics. The issue of an upper bound of energetics of a CDA and of connected recriticalities was a permanent point of discussion in the safety assessment of fast reactors (Bohl, 1979; Maschek and Asprey, 1983; Kondo et al., 1985; Theofanous and Bell, 1984; Risikoorientierte Analyse, 1982; Nakai, 2010). Special focus was on 'bottled-up' whole core pools, where fuel could only be discharged after recriticalities which melted away the blockages or broke them up mechanically.

In the current paper, we therefore focus on mitigating phenomena of recriticalities triggered by sloshing fuel motions (Maschek et al., 1992a) in case of a large core-wide melt pool. Sloshing recriticalities have to be expected in the so-called transition phase of a CDA when core exits are blocked by fuel and steel blockages and insufficient fuel has been discharged from the core region (Maschek et al., 1992a,b). The fuel motion is triggered by gravity, pressure sources or by the neutronic power profile itself. The Transition Phase (TP) is characterized by a progressive core disruption where local multi-phase fuel/steel pools grow radially after hexcan destruction. The early transition phase is characterized by incoherent fuel motion within intact hexcan structure. The occurrence of high reactivity ramp rates to lead to an energetic disassembly is considered to be fairly unlikely. In the early transition phase due to the low temperature and pressure levels no rapid and sufficient material discharge can be expected for reactors without special material discharge provisions. Phenomena are driven by strong feedback effects and strong nonlinearities exist. A 'competition' between fuel losses and material motion exists deciding over the energetics potential of the transition phase. The formation of larger connected fuel pools with inherent neutronic and thermal–hydraulic instabilities, meaning that it does not exist a stable boiled-up pool, can finally result in a large-scale and coherent sloshing motion, a global fuel compaction and a recriticality with a nuclear power excursion. This power excursion finally disassembles the core and might lead to a mechanical load of the vessel structures (Flad et al., 2017). This coherent large scale fuel motion is a phenomenon which therefore needs the highest attention (Maschek et al., 1992a,b).

In general, two different outcomes from the TP can be envisioned. One outcome is the above described route via severe recriticalities and a core disassembly. The disassembly leads to re-melting of blockages or their mechanical destruction including the above core structures. The other route is a non-energetic route directly into the Post Accident Heat Removal Phase (PAHR) in case sufficient fuel can be unloaded from the core during the later melt-down phase. The discharge is enabled by a re-melting of existing blockages and opening fuel discharge paths directly through the subassembly subchannels, the hexcan gaps or via the Control Rod Guide Tube (CRGTs) channels.

The findings on the transition phase are mainly based on calculations with the SIMMER code family. Starting even with SIMMER-II (Bohl and Luck, 1990), which has been applied for TP analyses of intermediate size and large size reactors projected and built in the 70s and 80s of the last century. Due to weaknesses of SIMMER-II it was necessary to develop a new code generation, just named for continuity also SIMMER, namely the SIMMER-III and SIMMER-IV codes (Kondo et al., 1992, 1999; Yamano et al., 2003, 2008, 2012). SIMMER-III is a two-dimensional (2D), SIMMER-IV a three-dimensional (3D), multi-velocity-field, multi-phase, multi-component, Eulerian, fluid-dynamics code system coupled with a structure model for fuel-pins, hexcans and general structures, and a space-, time- and energy-dependent transport theory neutron dynamics model. The new SIMMER codes are capable of representing the important physical phenomena in detail and include a comprehensive consideration of multidimensional effects and address the multidisciplinary nature of reactor accidents with complex interactions between different phenomena. The accident scenario is followed 'mechanistically', including all different phenomena and complex interactions with state of the art modeling and parameter ranges. The newly developed ASTERIA code (Ishizu et al., 2012), belongs into