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Investigation of the recriticality potential during reflooding phase of Fukushima Daiichi Unit-3 accident

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ABSTRACT

The paper presents an investigation of the potential for the recriticality phenomenon occurrence during core reflooding at the time of early in-vessel phase of the Fukushima-Daiichi Unit 3 (1F3) accident. A Monte Carlo criticality analysis was performed using the SERPENT code for STEP-3 BWR fuel type. The analysis was conducted for a representative core unit cell composed of four assemblies in three dimensions. The MELCOR computer code was used as the source of the accident progression and thermal-hydraulic input. A data exchange framework between MELCOR and SERPENT was developed and employed. The calculations reveal that for the applied MELCOR model, recriticality occurs due to simultaneous control blades loss, fuel rods intactness and non-borated water injection. It suggests that during reflooding even a relatively small fraction of the core covered with water and without control blades is sufficient to lead to the critical condition. Additionally, a sensitivity analysis for various control blade survival fractions was performed.

1. Introduction

1.1. Recriticality during reflooding

In the course of a severe accident of the BWR reactor, after control blades degradation occurring together with unborated (or low borated) water reflooding, there is a possibility of the recriticality. As a consequence of the core uncovery and an intensive heat-up, the B_4C absorber material forms the eutectic mixture with stainless steel (blade sheath). The mixture has lower liquidus temperature (about 1250 °C) and it may relocate into the lower parts of the core and the vessel (Steinbrück, 2014). Boron carbide, steel and Zircaloy (from channel boxes) may also form a eutectic mixture which melts at the temperature lower than the Zircaloy melting point. On the other hand fuel rods have much higher melting temperatures. Within the uncovered core, fuel degradation may occur several minutes after the control blades disintegration. The arrival of the cold unborated water during that time window, heavily improves moderation and leads to the effective neutron multiplication factor increase and there is a risk of the critical state. Should the super-prompt power burst occur, it may release large quantities of energy in the fuel and lead to its degradation (Frid et al., 2001). An important problem for the whole accident progression after the first burst (power peak), is the formation of a quasi-steady state having long-term high power generation. An additional significant heat source may lead to an earlier containment integrity loss due to the pressurization (Frid et al., 2001; Scott et al., 1990). The concern about the RPV integrity loss caused by a missile formation or mechanical damage due to the energy release is not justified (Scott et al., 1990).

A recriticality during reflooding is a recognized issue since the late eighties (Scott et al., 1990) and it was studied extensively with different methodologies in the nineties and early days of 2000s. An early study, which in fact inspired this work, was performed by Mosteller and Rahn (Mosteller and Rahn, 1994). They applied MCNP4 as a Monte Carlo solver and CASMO as a source of the isotopic compositions. They investigated Peach Bottom-2 (PB-2) BWR core represented by two-dimensional unit cell of four 8 × 8 assemblies with various burn-ups and reflective boundary conditions. It showed that at least 10% of the absorber material is enough to prevent critical state. A different study by Bassam uses a multigroup diffusion solver called TWODANT to obtain eigenvalues for two-dimensional unit cell with four assemblies and reflective boundary condition (Bassam and Witt, 1994). The approach was similar to that of Mosteller and Rahn and PB-2 type assembly was applied likewise. It is required to lose more than 95% of the control blades and there should be no boron in the water in order to reach the critical state (Mosteller and Rahn, 1994).

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Several later studies were performed with more sophisticated techniques with neutron kinetics/dynamics codes in conjunction with thermal-hydraulics system codes. It allowed transient simulation of the phenomenon and the estimation of the energy generation (Höjerup et al., 1997; Frid et al., 1999, 2001; Nilsson et al., 2000). For instance a large project called SARA funded by the European Commission (1997–1999) analysed that problem extensively for the total loss of electric power scenarios in Nordic BWRs. It investigated the consequences of the super-prompt power burst followed by quasi-steady state power generation and containment response. The basic aim was to develop accident management recommendations and to assess the reactor's safety. MELCOR, MAAP4 and SCDAP/RELAP5 severe accident codes were used to predict accident progression and SIMULATE-3K, APROS and RECRIT codes were used for neutron kinetics. They predicted localized high power density re-criticalities in numerous studied cases (Frid et al., 1999, 2001; Nilsson et al., 2000).

The Monte Carlo methods were applied in few studies in the past, as they have practical limitations. It is possible to obtain neutronic state of the core in one particular point of time without neutron-kinetic simulation. It allows to assess if the critical state is possible but it does not estimate the consequences. Constant development of the Monte Carlo methods with coupled Multi-Physics opens a potential route for transient simulations in the future (Aufiero et al., 2015).

In spite of all studies done in the past, we decided to use a Monte Carlo method with a somewhat different approach. The methodology is similar to those presented in Mosteller and Rahn (1994) and Bassam and Witt (1994) with extensions. We believe that former works slightly suffer, due to their two-dimensional nature. Those two works concluded, that less than about 10% of control rods survival fraction leads to recriticality and it is in some sense misleading. Basically, the reactor core is a three dimensional object and from the criticality safety point of view it may be significant. During BWR severe accident with reflooding, there is a high risk that there would be a huge core part without control rods in the top and intact absorber in the bottom part of the core. In such a case, there may be a lot of control blades maintained in the core and their survival fraction may be large (calculated for the 3D fraction not the 2D case). Nevertheless, neutron multiplication factor is a global quantity and we can imagine a critical state of the whole system with only small part without control blades in the top. Authors' basic intention was to develop a methodology similar to those presented in Mosteller and Rahn (1994) and Bassam and Witt (1994), however for three dimensional cases, applying contemporary tools. Furthermore, we performed an investigation of STEP 3 BWR fuel type which was present during Fukushima accident and we assessed the potential for recriticality. Moreover, a basic sensitivity study for control blades survival fraction was performed. The MELCOR code was used as a core state and thermal-hydraulic conditions source. The SERPENT was applied as a neutron transport solver. A data exchange framework for MELCOR and SERPENT was proposed and it allows one-way-coupling between those two codes.

1.2. Fukushima Daiichi NPP

During Fukushima accident, the reactors were partially flooded with fresh and sea water. The injected water was borated but not all the time. Particularly, in the case of 1F3 which is studied in this work, the fresh water that was injected from 9:25 until 12:20 (42.7 h–45.6 h) on March 13 was borated (TEPCO, 2012). The boron was also added to the seawater at 8:52 on March 14 (66.1 h after the earthquake). Nevertheless, there is no information available about the boration of the seawater that was injected from 46 h 26 min until 58 h 24 min. Hence, it is probable that the seawater was not borated during the reflooding phase.

In general, if any core was at least partially intact, with fractional degradation of the control rods, a reflooding sequence with high enough water flow rate and no boron could have led to conditions favourable for recriticality. To our knowledge, currently, there is no publicly available evidence of the recriticality in any of the damaged reactors during reflooding. This issue was suggested in some works (EPRI, 2013). It is possible to imagine that the recriticality occurred but it was short, local and not very strong in consequences, hence difficult to be noticed. The investigation of the problem if such a situation was possible, seems to be legitimate. In unit three (1F3), available analyses showed that the core was still partially intact during reflooding – 48 h after accident initiation. This issue is investigated in more details in the next section as in our opinion the risk for recriticality was the highest for this unit.

It is rather not possible to obtain reflooding type recriticality in unit 1F1, as after the rapid core uncover, there was no reflooding of the partially intact core (Sevón, 2015b). In the case of 1F2, it is a reasonable option to investigate recriticality potential. In many studies (SNL, 2012; Phillips et al., 2012; Sevón, 2015a; EPRI, 2013) a core uncovery is present with water level being below BAF (Bottom of Active Fuel) for a few hours and followed by reflooding sequence. It is less probable than for 1F3 due to the possible heavy core degradation during that time. It cannot be completely excluded without proper analysis, as the available studies reveal different active core reflooding and uncovery sequences.

An alternative problem, similar to the reflooding, is the possibility of the recriticality after water slug transfer to the core after steam explosion caused by the molten material relocation to the lower plenum (Miettinen, 2002; Sehgal and Dinh, 2002). It is considered as theoretically possible but characterized by a very low probability and it was not assessed in this work.

It is worth to mention that there are some other possibilities for the recriticality phenomenon to occur in Fukushima NPP. The first is the risk of the recriticality in the lower plenum within core debris and molten corium. It was, for instance, analysed with Monte Carlo methods for 1F2 unit (Jeong, 2014). After the core meltdown and before the RPV breach, the molten core might have formed a critical configuration. A favourable fissile mass configuration with separated absorber, proper water inventory and low boric acid content are able to lead to the critical state. Nevertheless, proper conditions seem to be characterized by a very low probability due to conservative assumptions. However, it cannot be absolutely excluded. Investigations of the complex corium physics and thermo-chemistry are necessary to estimate the chances for occurrence of the favourable conditions for the critical state.

In November 2011 short lived Xe-135, which is a fission product, was observed in the Primary Containment Vessel (PCV) of the Fukushima Unit 2. There were concerns about the risk of the recriticality in the core remnants. Finally, it was shown that the phenomenon was not caused by the recriticality. The observed short-lived fission products were created by the spontaneous fissions of the Curium isotopes (Thomé et al., 2012). What is more, the issue of the recriticality in formed debris in the long term after the meltdown is believed to be actual. Degraded cores and the debris are in uncertain state and they have to be constantly cooled by the cold and unborated water. The assurance of the sub-criticality is quite important, mainly because of gradual core remnants chilling and increases of the reactivity. It is mainly an effect of the reactivity feedbacks. Moreover, the sub-criticality would be a crucial issue during dismantling and defueling procedure (Tonoike et al., 2015). A large amount of work was performed to investigate criticality safety for damaged PWR TMI-2 core and debris (GPU

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