Effect of Flow Blockage and Fuel Relocation on Core Cooability during Loss of Coolant Accident

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1. Introduction

In the recent Loss of Coolant Accident (LOCA) studies, some new phenomena were identified to affect the clad embrittlement for its typical transient scenarios: corrosion outside the clad, oxygen behavior and hydrogen pickup inside the clad. These studies provides useful information on the LOCA fuel behavior for the revision of the Emergency Core Cooling System (ECCS) acceptance criteria, while some issues remain to be resolved; one of them is the effect on core coolability of the phenomena in the ballooned and burst zone (BBZ) such as fuel relocation, blockage. A State-Of-the Art Review (SOAR) is being made of the past programs which examined physical phenomena in the BBZ, including the IRSN study [1] and the ongoing international test programs in Halden reactors. This SOAR will enhance our understanding of fuel relocation and flow blockage in the BBZ, while their quantitative effects are to be assessed on core coolability.

In this study, a strategy is proposed to assess how flow blockage and fuel relocation have effect on core coolability in LOCA conditions.

2. Core Geometry during LOCA Transient

The LOCA results from a break in the primary circuit that leads to RCS depressurization with power decrease to its decay heat level. As a consequence, the fuel rods undergo the following evolution: clad temperature increase and dry-out, transfer of the stored energy from the fuel to the clad, clad ballooning with possible contact with the neighboring rods, burst failure around 800℃ (ductile region for Zirconium-based clad) and fuel relocation inside the ballooned zone. At higher temperature cladding oxidation occurs and is developed till the clad is cooled by the ECC water. Without ECC injection into the core, there will be a severe core damage characterized by exothermic metal-water reaction, eutectic melting of fuel and clad, material dissolution and relocation, molten pool, etc. Even for ECC injection available, the collapse of rods, which can result in loss of core coolability, is likely to occur for the cladding sufficiently oxidized. Therefore retention of clad ductility is a key parameter for ECCS design against LOCA. The oxidation embrittlement process follows:

a. Increased coolant temperature increases the reaction rates with the cladding and increase the conversion of the cladding surface into thicker ZrO_2 films
b. As the clad temperature passes the levels where α to β transformations start and finish, the resulting structure consists of the growing ZrO2 layer, a zirconium alloy layer with a very high oxygen content which stabilizes the α-phase (a fcc structure), the bulk cladding which is in the β-phase (a bcc structure).
c. Initiation of the quenching phase by the emergenct core cooling (ECC) water cools the cladding back down through the β to α transformation temperature and the bulk cladding is re-transformed from the β into the α phase and referred to as the "prior or former β phase". In this phase oxygen is diffused from the α-phase layer into the underlying β- phase.

During the blowdown period, the clad ballooning and burst occurs, where the flow channel can be partially and fully blocked and some fragmented fuel particles located above the ballooned region of a fuel rod will be thus relocated into the enlarged volume of the balloon under the influence of gravity and pressure differences. The two have effect on core coolability, by decreasing heat transfer from clad to coolant, then increasing clad temperature and clad oxidation. The burst strain and phase change occurs depending on the clad temperature, as seen in Fig. 1.

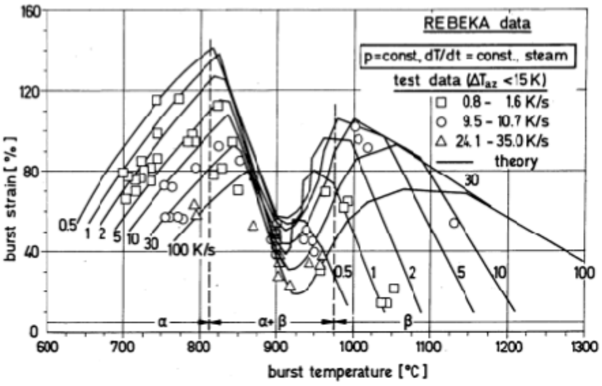

Figure 1. Burst Strain vs. Burst Temperature of Zircaloy Cladding from REBEKA test [2]

Since publication of NUREG-0630 [3], there were some LOCA blockage tests showing that 71 % blockage value considered in the report is no longer valid. There are also questions for what is the size and configuration of blockage to be developed in the BBZ. In particular, the fuel relocation effect is disregarded in the LOCA analysis. Detailed review of the out-of and in-pile tests for single rod and multi-rods of the out-of and in-pile tests for single rod and multi-rods are further needed to obtain the insights on the state of core geometry during LOCA transients.

3. Proposed Strategy

To account the combined effects of fuel relocation and blockage for the LOCA core coolability analysis, the idea is first to perform a sensitivity analysis for their effect on the core coolability at various configurations of flow blockage and fuel relocation. The COBRA-TF module in the MARS-KS code can be used to evaluate the combined effects of blockage (flow area reduction) and fuel relocation (axial heat flux distribution with protrude peak). Core modeling for sensitivity analysis for blockage size and length, and heat flux distribution is performed, where blockage size is defined as the ratio of the blockage area over the total flow area of a fuel assembly as seen in Fig. 2.

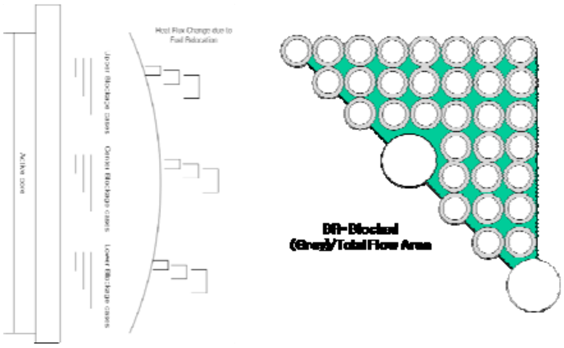

Figure 2 Modeling for Sensitivity Analysis for Heat Flux Distribution and Blockage Size and Length

The analysis results will show how much the hot pin clad temperature and oxidation are affected by various configurations of flow blockage and fuel relocation. Their configuration plausible during the LOCA heatup condition may be defined by the aforementioned SOAR.

Another one to be asked for a research is revision of the ECCS analysis approach. In accordance with the newly proposed USNRC LOCA criteria, reduction of the ECR margin at increased burnup is anticipated by the effects such as clad corrosion, double-sides oxidation. An exemplary calculation was performed to estimate the burnup effect on the ECR margin using FRAPCON-3.4a and FRAPTRAN-1.4. The TH B.C. was arbitrarily selected from the values obtained from MARS-KS1.2 calculation for a large break LOCA at the rated full power. Figure 3 shows comparison of the ECR margin calculated at beginning of cycle (BOC) and burn-up of 30 MWD/MTU.

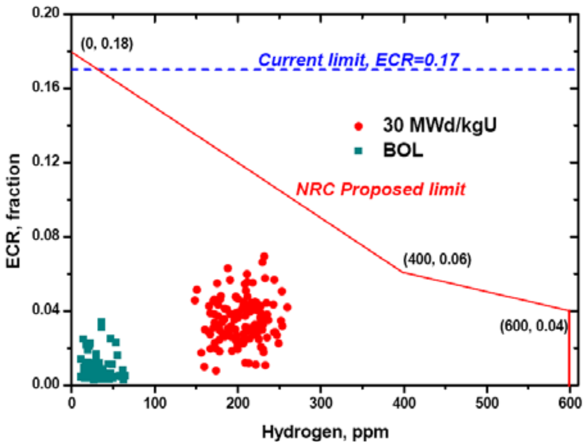

Figure 3 Exemplary ECR Calculation for Zircaloy-4 fuel at BOL and 30 GWd/MTU Burnup []

This example, although performed for a single pin and a fixed TH condition, shows that the effects of fuel material and burnup are a significant contributor to the ECR margin reduction. Besides, many fuel performance parameters such as conductivity, oxygen diffusion, ballooning, fuel relocation are to be considered for core coolability analyses, together with various TH conditions. Considering the importance of fuel behavior at high burn-up fuel, the R&D plan is to develop the revised ECCS analysis approach, including a coupled analysis of the system TH code, MARS-KS and FRAPCON/FRAPTRAN. Then the effect of flow blockage and fuel relocation on clad temperature and ECR, if quantified in advance, can be considered in the results.

4. Concluding Remarks

A strategy was proposed to assess how flow blockage and fuel relocation have effect on core coolability in LOCA conditions. These phenomena in particular are significant for highly burned fuel rods of zircaloy-based clad. ECCS effectiveness needs to be evaluated by considering physical parameters, which can affect the clad embrittlement.

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