Transactions of the Korean Nuclear Society Autumn Meeting
Yeosu, Korea, October 25-26, 2018

MARS Calculation of LBLOCA Using Multiple Fuel Rods under Limiting Burnup Condition

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1. Introduction

Since the proposed revision of Emergency Core Cooling System (ECCS) performance rule, 10 CFR 50.46c was announced, a research has been conducted to improve the understanding of the high burnup fuel behavior and its impact on Loss-of-Coolant Accident (LOCA) [1]. Succeeding the research, Korea Institute of Nuclear Safety (KINS) has conducted his research on that issue since 2018. For a reliable assurance of the safety margin of the LOCA for the entire fuel cycles, a capability to calculate LOCA at the limiting condition of burnup is required. The present paper is to discuss the effort related to the development of KINS capability and regulatory position, especially focusing on the limiting condition on that topic.

2. Methodology

For the general purpose of the KINS capability development, a method was proposed [2] and improved and expanded as in Fig. 1. Changed are as follows:

(1) The methodology was designed such that the various burnup states over the entire fuel cycles would be investigated to confirm the limiting case based on the nuclear design documents. However, a scoping calculation assuming a combination of conservative conditions of radial power peaking and burnup can be performed for purpose of scoping.

(2) Swelling and rupture of cladding may have impact on the peak cladding temperature (PCT) and peak local oxidation (PLO), thus, additional steps were introduced to implement the effect.

In the methodology, the burnup related parameters such as fuel dimension, gap pressure, etc. are determined from the calculation by FRAPCON code [3]. It was due to the current developmental situation of the MARS-FRAPCON consolidated code [4] and the whole calculations will be replaced by the consolidated code. The major features of the methodology can be found in reference [2].

The process developing a specific input deck for MARS code [5] may be a repetitive and time consuming work especially when multiple hydraulic channels and multiple heat structures for the various fuel rods with different burnup and power are involved. To facilitate this work, a simple FORTRAN program, MUFIG was developed to generate the MARS input. The function of MUFIG is to generate the followings:

1) Heat structures
   - Source distribution of multiple fuel rods
   - Radial peaking fallout due to burnup
   - Initial oxide thickness from FRAPCON calculation
2) Material property tables (thermal conductivity & heat capacity)
   - modified NFI model for pellet
   - oxide-effective conductivity for cladding
3) Hydraulic volumes, associated junctions, and crossflow junctions for core
4) Minor/plot edit variables (httmax, htomax, clout)

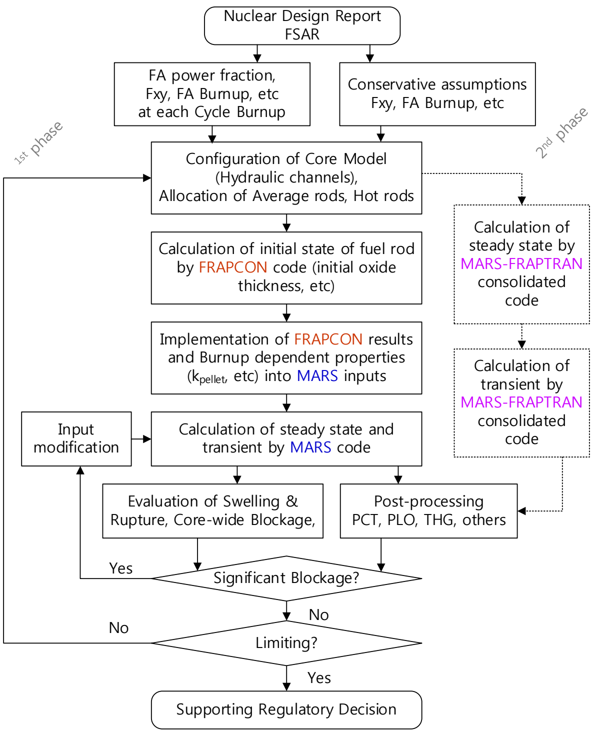
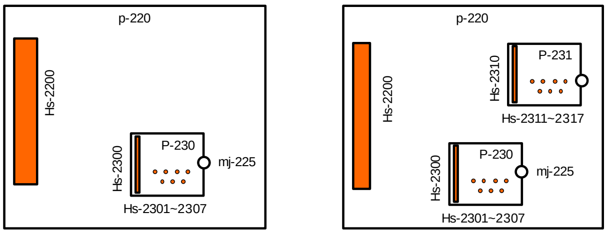


Fig.1 Overall methodology

3. Application to APR1400

The methodology above was applied to the second fuel cycle of Shinkori Unit 3 [6]. The limiting core average burnup which may lead to the limiting PCT and PLO was selected to 30 GWD/MTU from the previous study.

Fig. 2 shows two simplified noding diagram of the core, which models the core by 1 hot channel (case p1) and 2 hot channels (case p2) with 1 average channel, respectively. Fuel rods were modeled by 1 average rods, 1 and 2 hot assembly rods and 7 and 14 hot rods, respectively. Table 1 lists the burnup and radial peaking factors for the heat structures. All the nodalization of the plant except the core is the same as the one in reference [1].



a.Case p1 b. Case P2

Fig.2 Noding diagram of the cases P1 and P2

Table 1: Burnup and radial peaking factors

	Bu	Radial peaking factor		
Cases		P1	P2	
Average. FA	30	1	1	1
Hot FA	30	1.3	1.3	1.3
Hot rod 1	0	1.543	1.543	1.465
HR rod 2	10	1.543	1.543	1.465
HR rod 3	20	1.543	1.543	1.465
HR rod 4	30	1.543	1.543	1.465
HR rod 5	40	1.362	1.362	1.362
HR rod 6	50	1.182	1.182	1.182
HR rod 7	60	1.002	1.002	1.002

The radial peaking factors of hot rods in Table 1 were conservatively selected based on the design document. Fig. 3 shows a comparison of ratio of maximum radial peaking factor in actual design with the conservatively assumed ratio along the burnup. Conservative correlation of the fallout of radial peaking factor with the burnup was used in the present study.

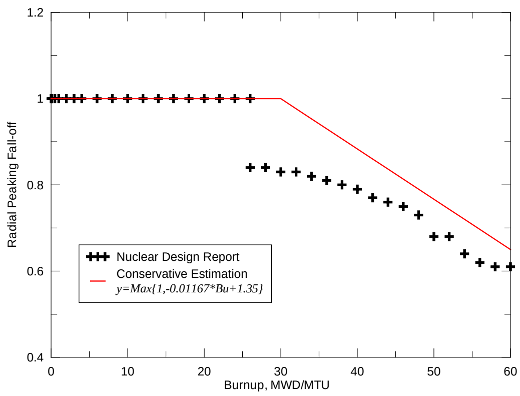


Fig. 3 Fallout of radial peaking factor

Figures 4 and 5 show the calculated fuel cladding temperature and peak oxide thickness for the case P1. The maximum values of two parameters were obtained for the hot rod 4 (at radial falloff=1.0 and Bu=30 GWD/MTU).

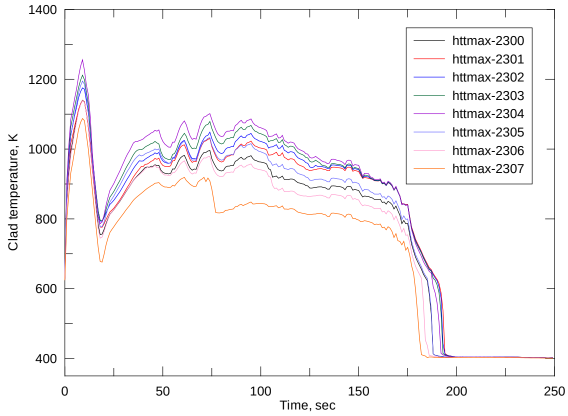


Fig. 4 Comparison of cladding temperatures of case P1

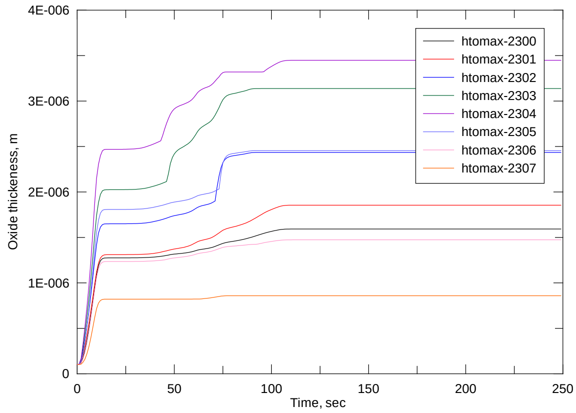


Fig. 5 Comparison of peak oxide thicknesses of case P1

Fig. 6 shows a comparison of the calculated data with the new proposed acceptance criteria in terms of equivalent cladding reacted (ECR) and hydrogen pickup contents. The calculated result was far below the acceptance criteria, however, they will be further increased if uncertainty was considered according to the requirements.

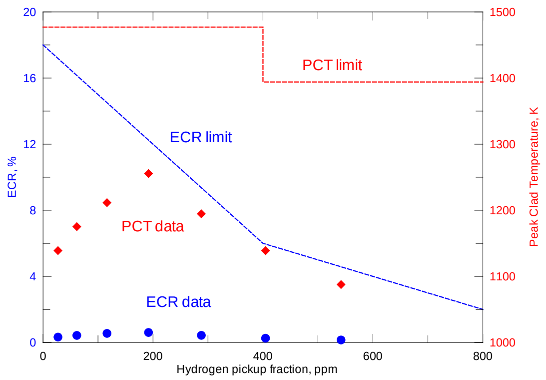


Fig. 6 Comparison of PCT and ECR with the limits

Fig. 7 shows a distribution of cladding outer radius at time 140 second for the case P1. The part of cladding ranging from 12 to 16 of the 20 axial positions was swelled for all hot rods and 4 hot rods were ruptured.

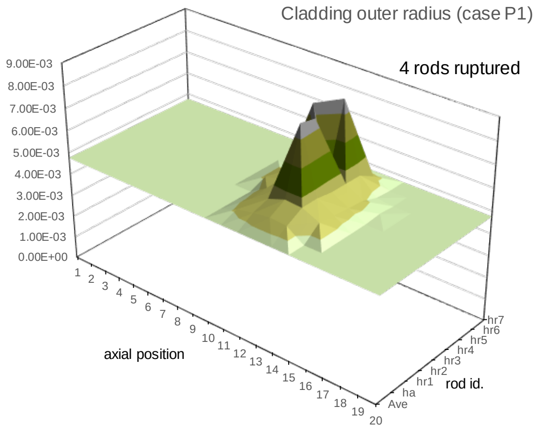


Fig. 7 Cladding outer radius at 140 seconds of case P1

To layout the potential range of burnup and radial peaking factor to rupture, the case P2 was calculated as shown in Fig. 2 and Table 1. The second hot channel of the case P2 has the same assembly peaking and a slightly lower peaking (95% of the case P1) for hot rods. Fig. 8 shows a comparison of cladding temperature between case P1 and case P2. Almost identical behavior was found, which indicated that the cladding thermal response was not changed significantly by additional hot channel having the similar power.

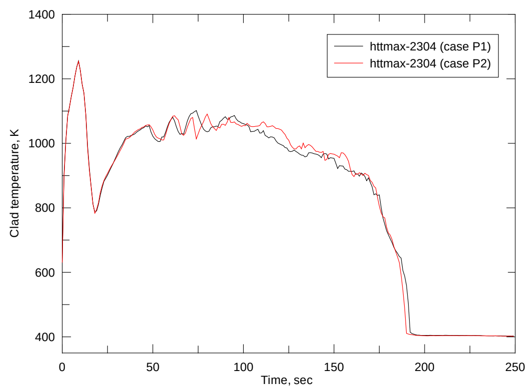


Fig. 8 Comparison of cladding temperatures between case P1 and case P2

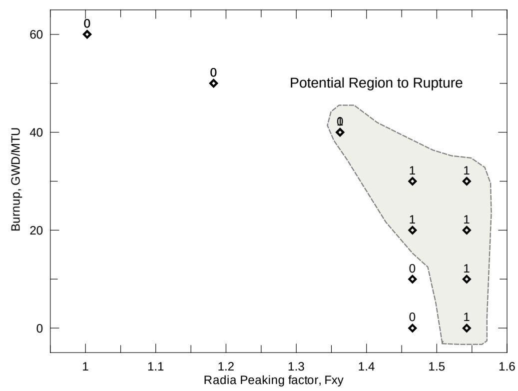


Fig. 9 Potential region of rupture

From the case P2, the rupture of three hot rods was found. Fig. 9 shows locations of hot rods in terms of radial peaking factor and burnup with a mark of rupture. The ruptured rod was marked by '1'. From this map, we can estimate the potential region of rupture painted in grey color. The hot rod at burnup 40 GWD/MTU was not ruptured in P1 calculation but ruptured in P2 calculation. Thus additional hot rod having the refined burnup and radial peaking factor around the 40 GWD rod should be calculated and investigated.

4. Conclusion

The LBLOCA at limiting burnup condition and with conservative radial power peaking was calculated by MARS-KS code with multiple fuel rods. A program, MUFIG was developed to facilitate the input generation for the multiple fuel rods modeling. The methodology was found to be effectively applied to the regulatory auditing calculation on the burnup related issue. Two cases of one hot channel and two hot channels were considered, which did not show significant difference in cladding temperature behavior. Through the calculations the potential range of cladding rupture in terms of burnup and radial peaking factor can be identified.

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ACKNOWLEGEMENT

The preparation of this paper was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KOFONS), granted financial resource from the Nuclear Safety and Security Commission (NSSC), Republic of Korea (No. 1805004-0118-SB110).