Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 19-20, 2022

Evaluation of Power to Burst during LOCA in APR1400 by FAMILY Code

Joosuk Lee, Young-Seok Bang, Kyunglok Baek
Korea Institute of Nuclear Safety
62 Gwahak-ro, Yusong-gu, Daejeon, 305-338, Republic of Korea
Tel: +82-42-868-0784, Fax: +82-42-868-0045
Email: jslee2@kins.re.kr

1. Introduction

During a loss-of-coolant accident (LOCA) in light water reactor (LWR) nuclear power plants, fuel pins can be bursted in a core-wide due to excessive deformation of cladding. If the fraction of bursted fuel pin is significant, coolability can be impaired caused by the dispersion of fragmented fuel pellets as well as the reduction of coolant flow area [1,2]. In this perspective, evaluation of fuel pin burst in a core-wide is important to the assurance of core coolability.

Previously Korea Institute of Nuclear Safety (KINS) has developed an audit methodology on fuel pin burst evaluation during LOCA [3]. Schematics of the methodology is shown in Fig. 1. It is developed based on the statistical treatment with the combination of numerous uncertainty parameters. In the methodology, fuel pin power before LOCA initiation is used as a measure for the assessment of pin burst. Utilizing this methodology, limit curves of power to burst can be constructed, and fraction of pin burst can be assessed successively.

KINS has been developing FAMILY (FRAPTRAN And MARS-KS Integrated for Safety AnaLYsis) computer code that integrates MARS-KS and FRAPTRAN [4]. MARS-KS is an audit computer code for assessing system thermal-hydraulic behavior in KINS [5]. FRAPTRAN is an audit code for fuel performance analysis in US.NRC [6]. Recently high temperature cladding deformation model based on creep behavior is implemented in the FAMALY, and it shows the better prediction capability than the previous BALON2 model [7]. Fuel relocation model is also slightly modified to better prediction of fuel packing fraction, especially for high burnup regions [8].

In this paper, power to burst curves with a probabilistic statement are developed by the recent version of FAMILY code. Fraction of fuel pin burst in a core-wide during LOCA is assessed in APR1400 plant. Fuel relocation effect on power to burst is assessed as well.

2. Analysis Details

2.1 Burst power analysis

The 16x16 PLUS7 fuel with ZIRLO cladding in APR1400 was modeled for a large-break LOCA safety analysis. Initial states of fuel pin before accident are calculated by FRAPCON-4.0 fuel performance code [9], and transient fuel behaviors for a LOCA period are analyzed by the FAMILY code. For the cladding burst assessment, a well-known strain-based NUREG-0630 fast ramp criterion is adapted [10]. Newly adapted creep based cladding deformation model is used for the simulation of ballooning [7].

For the LOCA analysis, reactor core in APR1400 is divided into one hot channel and one average channel, and single fuel pin was allocated in the hot channel. Active fuel length divided into 40 evenly spaced axial nodes. Top-skewed axial power profile is given as the boundary condition. Burst analysis has been performed from 0 to 60 MWd/kgU fuel burnup.

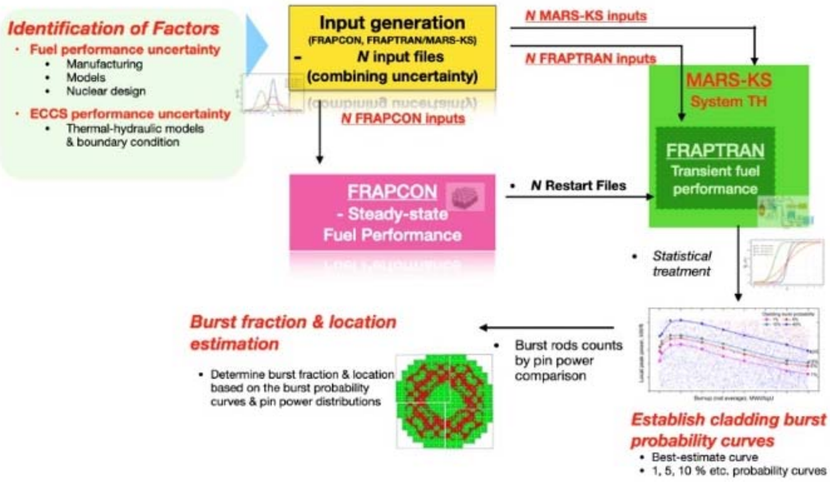

Fig. 1. Schematic of fuel pin burst evaluation methodology [3]

2.2 Considered uncertainty factors and assessment

Considered fuel and thermal-hydraulic uncertainties are 37 and 21 parameters, respectively. Fuel uncertainty are composed of 10 manufacturing and 27 model parameters. Details on the selection and the ranges of uncertainty parameters can be founded in previous work [3]. In this anaysis ucertainty of packing fraction of fuel pellet is included additionally. Imposed uncertainty is ±2 standard deviation (σ) with an unform probability distribution function. 1 σ is evaluated as 0.030 [3]. For the factorization of thermal-hydraulic uncertainty to the pin burst, 21 parameters are chosen. The basis is originated from a realistic evaluation methodology for the regulatory audit of LOCA safety analysis [11].

Monte Carlo method is used to get the cladding burst probability at 8 different fuel burnups from 0 to 60 MWd/kgU. In each burnup, 5000 FRAPCON and FAMILY inputs are generated by MOSAIQUE software by simple sampling technique [12].

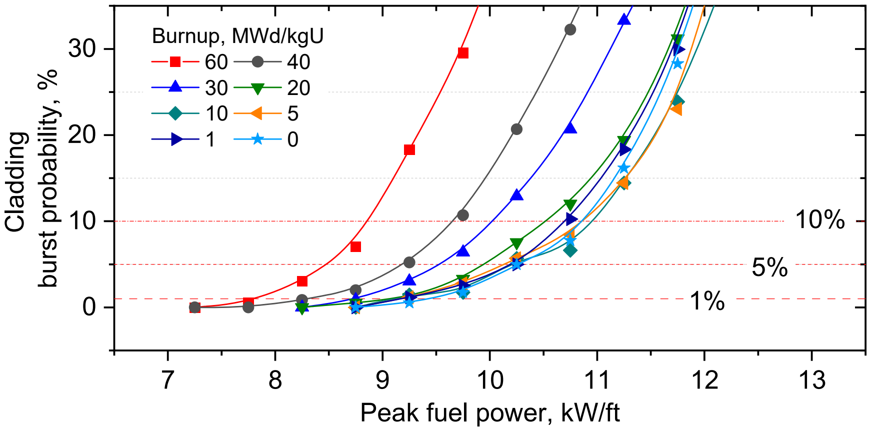

Fig. 2. Changes of cladding burst probability as a function of peak fuel power with burnup change

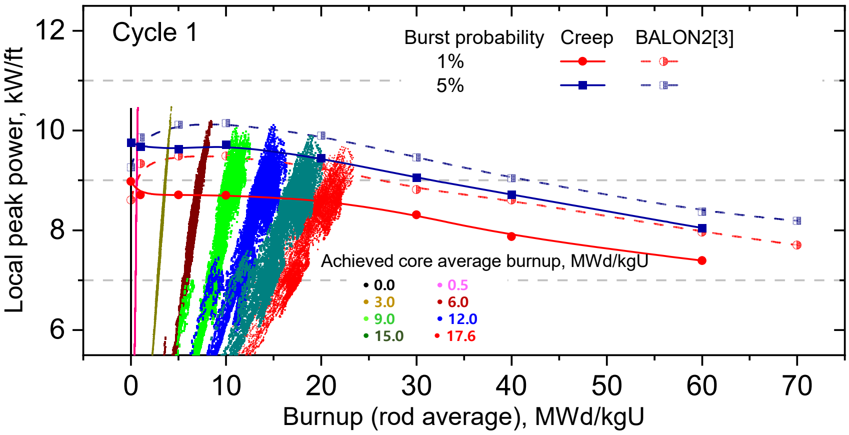

Fig. 3. Power to burst curves and local fuel pin powers in APR1400 initial core (cycle 1)

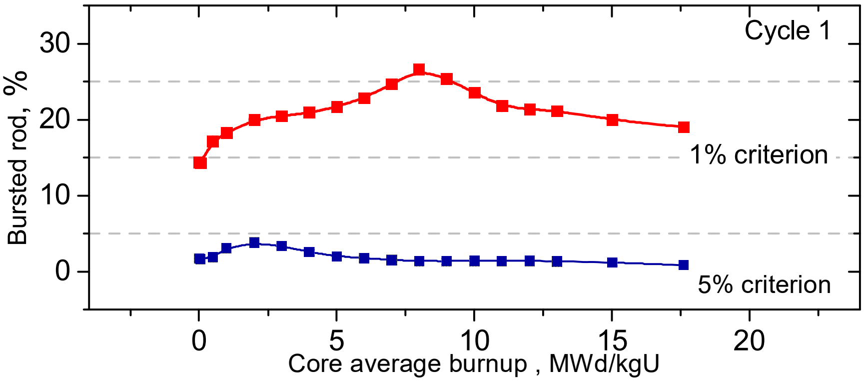

Fig. 4. Evolution of fuel pin burst fraction in APR1400 initial core (cycle 1)

3. Results and Discussion

3.1 Probability curves of power to burst

Fig. 2 shows cladding burst probability as a function of fuel power with the specific fuel burnup. As expected, high burnup fuel is vulnerable to burst. At 60 MWd/kgU burnup, cladding burst is started at around ~7 kW/ft local peak power, and the burst probability increase gradually with increasing power. Similar behaviors are observed irrespective of fuel burnup even though the starting powers for pin burst are different. Fuel burnup from 0 MWd/kgU to ~10 MWd/kgU condition shows similar evolution curves and shows relatively higher resistant to the pin burst.

Fig. 3 shows the constructed cladding burst probability curves with a fuel burnup domain. These curves are constructed with 95 % confidence interval upper bound plus 5 % lowered burst powers due to the local power uncertainty (F_Q) from nuclear design codes. At fresh fuel, 1 % burst probability is attained as fuel power reaches 9.0 kW/ft, and the burnup moves to 1 MWd/kgU, the power slightly decreases to 8.7 kW/ft. This power maintained until ~10 MWd/kgU burnup. Then further increase of the burnup has induced the reduction of burst power to 7.4 kW/ft at 60 MWd/kgU. Such a reduction of the burst power from ~10 MWd/kgU to 60 MWD/kgU is attributed to the degradation of fuel performance, mostly caused by the degradation of fuel thermal conductivity and fission gas release. The same trends are observed at the burst probability curves of 5 % and 10 %, except that the required powers have increased to the higher power regions.

As shown in Fig. 3, cladding plastic deformation models show different cladding burst probability curves. Except for the low burnup condition, less than ~1 MWd/kgU, creep model shows lower burst powers. When comparing 1 % and 5 % probability curves between two models, creep model has induced ~0.7 kW/ft and ~0.4 kW/ft lower power than the BALON2, respectively. But fresh fuel condition, BALON2 model shows ~0.4 kW/ft and ~0.5 kW/ft lower burst powers, respectively. This behavior needs to be studied further.

3.2 Evaluation of core-wide fuel pin burst

Fuel pin burst fraction during LOCA can be evaluated by the comparison between the burst probability curves and each fuel pin power in the core. Fig. 3 also shows the comparison between constructed cladding burst probability curves and evolutions of each fuel pin power during operation at the initial core of APR1400.

In a regulatory analysis, fuel failure is counted deterministically based on the given failure criterion for the assurance of conservatism. As shown in Fig. 4, if 1 % probability curve is employed as a deterministic burst criterion, the burst fraction at beginning of cycle (BOC) of initial core is estimated as 14.4 %. The fraction is increased continuously with burnup increase. It reaches maximum 26.6 % at 8 MWd/kgU burnup (core average) and reduces to 19.0 % at end-of-cycle (EOC). As 5 % probability curve is used as the criterion, the fraction is 1.75 % at BOC, and it increases to 3.8 % at 2 MWd/kgU, then reduced to 0.8 % at EOC. This analysis shows that the burst fraction is significantly affected by the burst criterion.

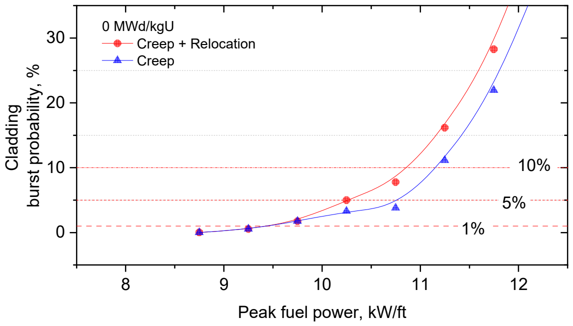

Fig. 5. Effects of fuel relocation on cladding burst probability. Fresh fuel (0 MWd/kgU) condition.

3.3 Fuel relocation effect

Influence of fuel relocation on cladding burst probability is shown in Fig. 5. As the relocation model is considered, earlier burst of cladding is observed except for the very low burst probability region. Generally, fuel relocation induces about 0.2~0.5 kW/ft burst power reduction. However, fuel relocation does not affect the burst power below ~1 % burst probability region as observed in Fig. 5.

4. Summary

Core-wide fuel pin burst in APR1400 during LOCA are evaluated based on the previously developed audit methodology in KINS. Recently developed FAMILY computer code is used for the evaluation. High temperature cladding creep model is used and fuel relocation model is added additional uncertainty parameter. Followings are main results of this study.

- Cladding burst probability curves represented as a peak fuel power within the fuel burnup of 60 MWd/kgU are established successfully. From fresh to ~10 MWd/kgU fuel shows similar and relatively higher burst power. After ~10 MWd/kgU burnup, it is reduced and the lowest burst power is attained at 60 MWd/kgU.
- Fuel pin burst criteria show significant effect on the fuel pin burst fraction. The maximum burst fraction is 26.6 % and 3.8 %, respectively, when 1 % and 5 % burst probability curves are used as the deterministic burst criterion.
- Cladding deformation models between creep and BALON2 show different cladding burst probability. Creep model results in conservative results than the BALON2 model except for the low burnup region, less than ~1 MWd/kgU.
- Fuel relocation induces earlier burst of cladding. Generally, it reduces about 0.2~0.5 kW/ft burst power except for the very low burst probability region.

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).

REFERENCES

[1] OECD/NEA/CSNI/R(2016)16, "Report on Fuel Fragmentation, Relocation and Dispersal", July 2016.

[2] Young Seok Bang et.al., "Multidimensional prediction of the effect of flow blockage in SCTF S1-01 experiment using MARS-KS code", Annals of Nuclear Energy 152 (2021) 108028.

[3] Joosuk Lee, Young Seok Bang, "Evaluation of core-wide fuel pin burst during LOCA in APR1400", Nuclear Engineering and Design 371 (2021) 11095.

[4] Joosuk Lee at.al., "Validation of Fuel/Thermal-Hydraulics Coupled Computer Code and Development of Fuel Models", KINS/RR-1849 Vol.4, 2021.11.

[5] KINS, 2018, MARS-KS code manual, volume II: input requirements, KINS/RR-1282 (Rev.1), Daejeon, Korea.

[6] K.J. Geelhood et. al., "FRAPTRAN-2.0: A Computer Code for the Transient Analysis of Oxide Fuel Rods", May 2016, PNNL-19400, Vol.1. Rev2.

[7] Joosuk Lee et.al., "Development of cladding deformation model at high temperature for FAMILY code application", KINS/RR-2196, 2021.11.

[8] Joosuk Lee, Young Seok Bang, "Effects of Fuel Relocation on Fuel Performance and Evaluation of Safety Margin to ECCS Acceptance Criteria in APR1400 Plant", preparation for submission.

[9] K.J. Geelhood et. al., "FRAPCON-4.0: A Computer Code for the Calculation of Steady-State, Thermal-Mechanical Behavior of Oxide Fuel Rods for High Burnup", PNNL-19418, Vol.1. Rev.2, September 2015.

[10] D.A. Power, R.O. Meyer, "Cladding Swelling and Rupture Models for LOCA Analysis", April 1980 NUREG-0630.

[11] Bang, Y.-S., Cheong, A., Lee, J., 2018. Development of Safety Evaluation Technology for New Design Features and New Safety Criteria. KINS, KINS/GR-627.

[12] Lim, H.-G., Han, S.-H., Jeong, J.J., 2011. MOSAIQUE – A network based software for probabilistic uncertainty analysis of computerized simulation models. Nuclear Engineering and Design 241 (5), 1776–1784.