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Development of cladding ballooning/burst model in FAMILY code based on creep model at high temperature

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1. Introduction

The study of fuel behavior under accidental conditions is a major concern in the safety analysis. The consequences of design basis accidents for a loss of coolant accident (LOCA) should be studied and quantified in safety criteria (e.g. PCT(Peak Cladding Temperature) and ECR(Equivalent Clad Reacted) in order to prevent severe core damage that could result from fuel rod failure, fuel ejection into coolant, loss of core coolability, and fission product release into the primary circuit of the pressurized water reactors. Those criteria have been established in the 1970s on the basis of several experimental programs performed with fresh or low burnup irradiated fuel. However, economic concerns led utilities to consider the increase of the average burnup (up to 60 MWd/kgU) of the fuel [1].

Recently, a revision of ECCS acceptance criteria similar to USNRC's 10CFR50.46c has been prepared in Korea [2]. The revised criteria include that fuel models during LOCA should be taken into account because fuel behaviors affect PCT and ECR that are figure of merit for safety analysis. It is understood that the fuel rod undergoes thermo-mechanical deformation of cladding, exothermic high temperature oxidation, cladding burst and FFRD (fuel fragmentation, relocation and dispersion) during LOCA.

Therefore, KAERI and INU are supporting KINS to develop a fully coupled MARS-KS/FRAPTRAN computer code for safety analysis [3]. In the coupled code system, thermal barrier model for oxide and CRUD(Chalk River Unidentified Deposit) and fuel relocation model in fuel module as high burnup fuel characteristics were updated and verified [4]. KINS has been developing a fully integrated computer code between fuel performance and system TH code, named as FAMILY(**F**RAPTRAN **A**nd **M**ARS-KS **I**ntegrated for Safety Ana**LY**sis), can evaluate the TH behaviors and their uncertainties completely, because the TH conditions around fuel rod are calculated iteratively between two codes [5].

In FAMILY code, BALON2 model originated from FRAPTRAN2.0P1 is applied as cladding ballooning/burst model. The BALON2 model assumes that the ballooned cladding can be perturbed and locally bended to concentrate local stress on cladding [6]. However, practical investigation of cladding ballooning cannot explain assumptions of BALON2 model (perturbation, bending). Due to lack of validity on the assumption, accuracy of BALON2 for prediction of ballooning and burst needs to be improved compared to experimental result and code benchmark. Furthermore, theoretical variables (i.e.; Z_{bend}, t_{incre}) in BALON2 affect amount of ballooning strain and burst time remarkably. Those variables do not represent any physical meaning for cladding ballooning and burst. Therefore, the model is not appropriate for best-estimated methodology that safety analysis code applies. To overcome the limitation of theoretical model for ballooning and burst, recent fuel analysis codes to simulate cladding behavior during LOCA take into account creep model at high temperature.

In this study, cladding ballooning model in FAMILY is updated as creep model at high temperature. For development of new model in FAMILY, the model is incorporated in FRAPTRAN2.0P1 stand alone in advance. The methodology for ballooning model is also updated for the better prediction. Burst criteria is updated as strain criteria based on NUREG-0630 criteria [7]. New model incorporated in FRAPTRAN2.0P1 stand alone was validated against out-of-pile and in-pile experiment as assessment inputs.

2. New cladding ballooning/bust model and methodology

In this section creep model at high temperature, burst criteria and new methodology are described.

2.1 Creep model at high temperature

Previous researchers proposed creep model to describe cladding ballooning for accident condition as form of Arrehenius equation. Cladding creep behaves as function of temperature, stress, strain and so on as shown in equation (1). (Norton law)

$$\frac{d\epsilon_\theta}{dt} = A_\theta f(x)\exp(-\frac{Q}{RT})\sigma_\theta^n \qquad (1)$$

Many researchers have also found out parameters of creep equation. Representatively, Rosinger et al. measured axial displacement of cladding by LVDT using Joule heating to obtain creep parameters [8]. Table 1 shows creep parameters for α, β, and α+β.

Table 1: Creep parameters for each phase of Zircaloy-4 [8]

Parameter	Unit	α-phase	β-phase	(α+β)
n	-	5.89	3.78	2.33
A_{Θ}	$MPa^{-n}s^{-1}$	1 489	3.97	0.15
Q/R	K	38 487	17 079	12 316

Parameters can be differentiated as measurement and heating method. In this work, the parameters shown in Table 1 are applied.

2.2 Burst criteria model

FRAPTRAN2.0P1 owns stress criteria and strain criteria to judge cladding burst [9]. Since BALON2 model applies stress criteria, local stress of cladding can be concentrated using bending factor and time increment. Figure 1 shows comparison of strain criteria in FRAPTRAN2.0P1 and NUREG-0630 criteria that consists of Slow-ramp(~5K/s) correlation and Fast-ramp(28K/s~) correlation. It was determined based on large amount of experimental database. In figure 1, 1 ℃/s, 14 ℃/s, and 28 ℃/s represent heating rate of burst experiments.

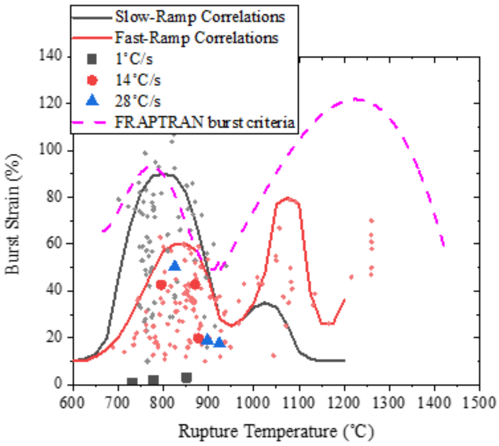


Fig. 1. Comparison of cladding burst strain criterion

Because FRAPTRAN selects bounding methodology for burst criteria, new burst strain criteria need to be required for best-estimated analysis. Furthermore, strain criterion is crucial to determine burst strain and time when creep model is applied to ballooning model. Therefore, new burst strain criteria model is implemented. To cover burst criteria for intermediate ramp rate (5~28K/s), the interpolated strain criteria are imposed.

2.3 Methodology for new model

To calculate cladding ballooning in FRAPTRAN2.0P1, the code uses the following methodology; FRACAS model calculates stress and strain of cladding for each axial node. When instability plastic hoop strain of cladding among axial nodes exceeds over 0.05, BALON2 calculates strain and stress of the node that exceeds over 0.05. For the rest of axial node, only thermal strains are calculated. It is called as instability method in this work.

Scheme of cladding ballooning calculation causes discontinuity of cladding strain behavior because governing equation of BALON2 model is not closely linked to that of FRACAS model. Double ballooning simulation is not allowed with the scheme. Unlike BALON2 model, creep model calculates strain in FRACAS model as an extension of inelastic strain calculation. Therefore, new cladding ballooning model does not take into account instability method. It means that ballooned strain can be calculated in FRACAS model and the subroutine is called by FRACAS.

3. Validation of model

To validate creep model against out-of-pile data and in-pile data, single effect test, named as DIMAT, was chosen. In the case of in-pile data, assessment input files of FRAPTRAN2.0P1 are used.

3.1 Validation with DIMAT results

An experimental apparatus named 'DIMAT' (Deformation In-situ Measurement Apparatus by image-analysis Technique) was developed with an IR furnace using a non-contact optical image analysis technique for measuring real-time deformation of a high temperature cladding tube [10]. For validation of cladding ballooning model, updated FRAPTRAN2.0P1 that incorporates creep model simulates DIMAT experiment. Original model(BALON2) also calculates the experiment for comparison. Figure 2 shows the comparison with experimental result(DIMAT;red dot line), original model (noball=0;blue two dot line), and new model(noball=2;solid black line).

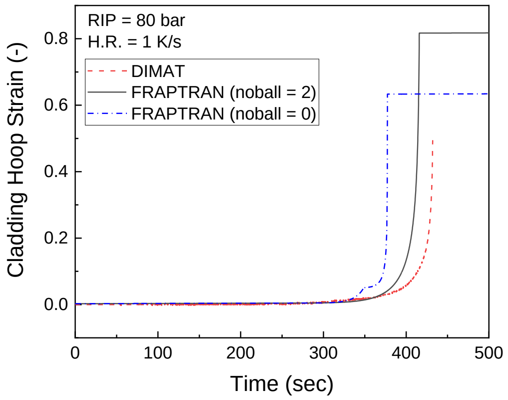
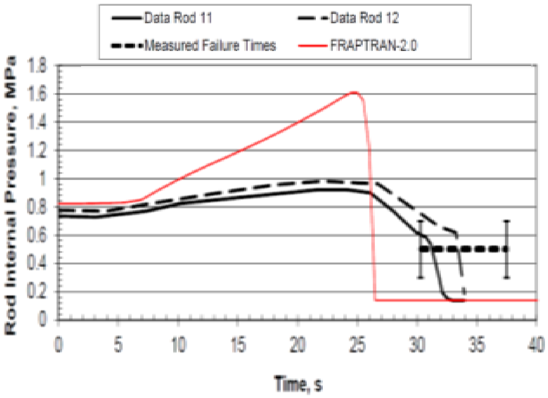


Fig. 2. Comparison of cladding ballooning behavior (DIMAT; experiment, noball=2; creep model, noball=0; BALON2 model)

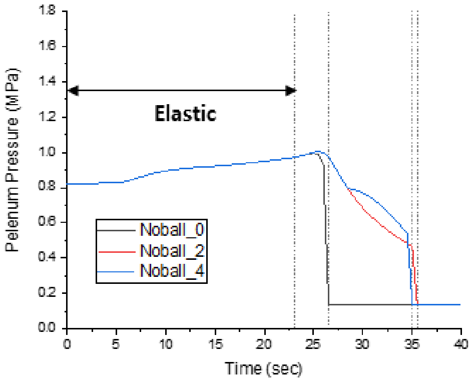
It is demonstrated that hoop strain calculated by creep model is matched well against experiment compared with hoop strain calculated by BALON2 model. In figure 2, discontinuity of BALON2 result is observed near 350 s. The instability method that BALON2 model takes induces the discontinuity that does not represent practical behavior. On the other hand, discontinuity of creep model does not exist.

3.2 Validation with in-pile data

FRAPTRAN2.0P1 provides assessment input package including in-pile and out-of-pile experiment [11]. Additionally, assessment report also includes experiment results. To make sure improvement of new model, calculation results by new model and original model are compared with experimental result. Figure 3 shows comparison results in the case of FRF2 test.



(a) Experimental result



(b) Simulation result (noball=0; BALON2 model, noball=2; creep model, noball=4; creep model with instability method)

Fig. 3. Comparison of simulation result with new model and original model

While original model predicts early burst time (approximately 25s) against experiment, burst time (approximately 35s) predicted by creep model is almost similar to experimental result. It is demonstrated that improvement of prediction accuracy results from updating cladding ballooning model and burst criteria. To investigate effect of rod internal pressure by instability method, 'noball=4' option(creep model with instability) is applied. As shown in figure 3(a), instability method affects rod internal pressure because calculated void volume is related to number of ballooned node. Pressure with instability option is higher than pressure without instability option because instability method restricts cladding ballooning of the rest of axial nodes. Restriction of cladding ballooning induces reduction of void volume. In the view of practical behavior, instability option is not appropriate to describe cladding ballooning and simulate rod internal pressure.

4. Conclusions

To improve cladding ballooning and burst model, cladding ballooning and burst model were developed and implemented into FRAPTRAN2.0P1. Instead of BALON2 model, creep model is applied and instability method is not used. Burst strain criteria is also updated. As validation result, prediction of cladding behavior by new creep model is improved in terms of hoop strain and burst time. For the future, new model and methodology will be implemented to FAMILY code. Safety analysis that takes into account new fuel model will be conducted by FAMILY code.

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