Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 23-24, 2019

Preliminary Evaluation of Clad Ballooning Test with Multi-dimensional Entire Rod Analysis Module (MERCURY)

Sung-Uk Lee [a*], Hyochan Kim [a] , JinSu Kim [b], Jeong Whan Yoon [b]
[a]*Fuel Safety Research Division, Korea Atomic Energy Research Institute, 989-111 Daedeok-daero, Yusung-gu, Daejeon, South Korea*
[b]*Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, 291, Daehak-ro, Yuseong-gu, Daejeon, South Korea*
[*]Corresponding author: leesunguk@kaeri.re.kr

1. Introduction

In the current situation where the stability of nuclear power plants is important, in order to maintain the integrity of nuclear fuel cladding, it is necessary to construct a proper mitigation system against design based accident such as loss of coolant accident (LOCA). Large deformation and rupture of the cladding during the LOCA can block coolant flow and reduce reactor cooling, which can lead to serious accidents. Many experiments and analyzes have been conducted by many researchers over the past several decades to understand LOCA related phenomena. In addition, fuel performance codes have been developed that can predict and simulate this phenomenon. In general, FRAPTRAN [1] has been used to simulate fuel rod behavior in transient conditions such as LOCA and REA (Rod Ejection Accident). KAERI is also developing a multi-dimensional entire rod analysis module (MERCURY) to simulate cladding deformation in the event of a design based accident.

In this paper, MERCURY has been evaluated against the results of PUZRY test (made by KFKI AEKI) [2], which is a separation effect test (SET) to analyze ballooning of the cladding only and bursting at high temperature. We try to identify the problems that occur in the evaluation code and define the direction of improvement.

2. Clad Ballooning Test

2.1 PUZRY test

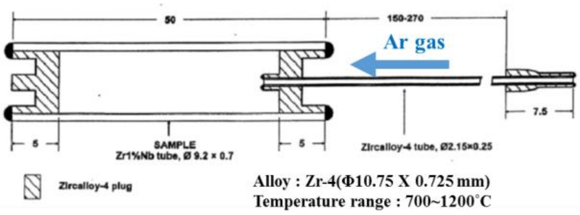


Fig. 1. Schematic drawing of the Zircaloy-4 tube specimen for ballooning test. [2]

The size of cladding was 50 mm long with an internal / external diameter of 9.3 / 10.75 mm, as shown in Fig. 1. The experiments were usually used for analyzing ballooning and burst tests using unirradiated, non-oxidized Zircaloy-4 tubes. A total of 31 test tube specimens were tested to show the results for the induction furnace, and while maintaining a constant temperature in the range of 700-1200°C. The internal pressure was increased at a constant rate until rupture occurred.

2.2 Evaluation model

The pressure rise rate during a large break LOCA is currently 2 to 4 bar/s, but the maximum pressure rise rate in the test is one digit lower. It is recommended to simulate with the test at the highest pressure rise rate to avoid the effects of long-term exposure to high levels of stress. Since anisotropic properties have not yet been applied to the analysis module under development, experiments were selected to be evaluated based on the isotropic properties of the Zr β-phase. In general, zircaloy β-phase occurs at temperatures above 1000°C. Therefore, three cases of the highest pressure rate in the temperature range with beta phase are selected as shown in Table I.

Table I: Selected model during PUZRY tests

	Temperature (˚C)	Pressure rate (bar/s)
PUZRY-08	1000	0.076
PUZRY-10	1100	0.071
PUZRY-12	1200	0.072

3. MERCURY Code

MERCURY is designed to enable thermo-mechanical coupled analysis to evaluate the integrity of the nuclear fuel in the event of an accident. In order to explain the behavior of nuclear fuel, a total of eight detailed modules such as gap conduction between pellet and cladding, oxidation heat, Burn-up, etc. were added to the existing coupled thermomechanical analysis.

3.1 Creep model

The material model embedded in MERCURY is the form of a creep, which represents large deformation at high temperatures. The creep equation is expressed as the Norton-Bailey form as shown in Equation 1. The parameters of the creep model were applied using coefficient values defined by Rosinger [3]

$$\dot{\varepsilon} = A\sigma^{n} \exp\left(-\frac{Q}{RT}\right) \qquad (1)$$

3.2 Failure criteria of the analysis

In order to simulate a PUZRY test, it is necessary to define the failure criteria as the test was run until it burst. In reference code, burst stress and strain are used as failure criteria for cladding. Burst strain is mainly used to determine breakage. As shown in Fig. 2, the data obtained from the burst test shows that the results were very scattered because the test was performed under various conditions. As a result, the burst criteria used in NUREG 0630 and FRAPTRAN are also different. In this study, the burst strain defined by FRAPTRAN is used, and the burst strain increases with increasing temperature within the test range of 1000-1200°C.

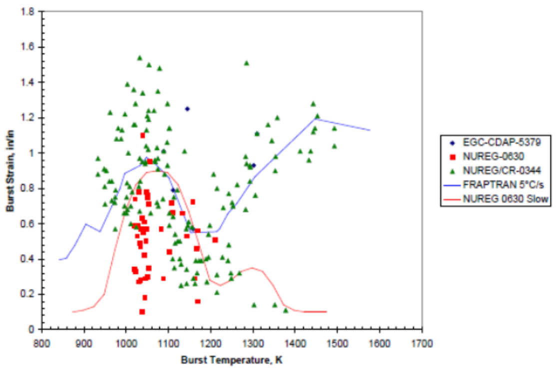
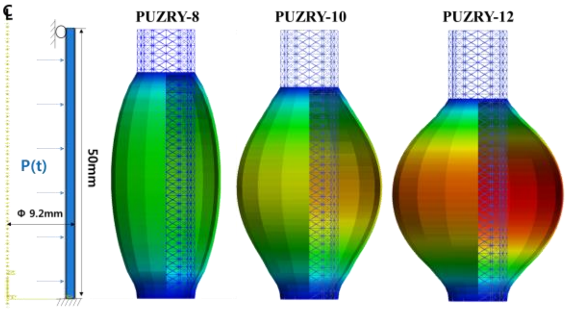


Fig. 2. Permanent burst strain data and FRAPRAN prediction (blue line) [1]

3.3 Results of the analysis model

The PUZRY experiment was modeled as an axisymmetric shape, as shown in Figure 3 (a). As shown in Table 1, the analysis was conducted under isothermal conditions by increasing the pressure according to time. The results obtained from MERCURY analysis are shown in Fig. 3 (b).



(a) (b)

Fig. 3. (a) Analysis model for ballooning test and (b) Results of the analysis

The experimental and analytical results are briefly compared to the burst times and maximum hoop strain of Table II. For burst times, tests and simulations show similar results. However, at maximum hoop strain, there is a tendency to be different between the simulation and test. In the case of testing, the strain decreases as the temperature increases, while in the case of analysis, the strain increases as the temperature conditions increase. This is considered to be due to the fact that the burst criteria of FRAPTRAN increases with temperature is applied.

Table II: Comparison between experiment and analysis results at PUZRY test

		PUZRY-8	PUZRY-10	PUZRY-12
Exp.	Burst Time(sec)	116.7	92.0	80.0
	Max. hoop Strain (%)	80	73	72
Analysis	Burst Time(sec)	110.97	95.76	80.18
	Max. hoop Strain (%)	110	184	235

4. Conclusions

Various conditions such as a physical property model and a fracture criteria are could set in the nuclear fuel performance evaluation code, and the analysis results would be various. For example, if the NUREG 0630 criteria is adopted, it is expected to show the same tendency as the experimental results, since the burst strain decreases as the temperature rises at high temperatures. Therefore, in order to evaluate the test, it is necessary to analyze the effects of using different creep model at high temperature. Since the failure criteria of FRAPTRAN is considering high-temperature oxidation, it is necessary to analyze the different failure criteria to evaluate the PUZRY test, which is to assess the behavior of the fresh material under non-oxidation condition. In the future, we will try to analyze the characteristics of the evaluation code considering to above two factors and evaluate the test data performed using the actually irradiated cladding at Studsvik.

ACKNOWLEDGEMENTS

This work has been carried out under the Nuclear R&D Program supported by the Ministry of Science and ICT. (NRF-2017M2A8A4015024)

REFERENCES

[1] K. J. Geelhood, W. G. Luscher, J.M. Cuta, I. A. Porter, FRAPTRAN-2.0 : A computer code for the transient Analysis of Oxide Fuel Rods, PNNL-19400, May, 2016.
[2] E. Perez-Feró, Z. Hózer, T. Novotny, G. Kracz, M. Horváth, I. Nagy, A. Vimi, A. Pintér-Csordás, Cs. Győri, L. Matus, L. Vasáros, P. Windberg, L. Maróti, Experimental

Database of E110 Claddings under Accident Conditions, EK-FRL-2011-744-01/04, 2012
[3] F. J. Erbacher, H. J. Neitzel, H. Rosinger, H, Schmidt, and K. Wiehr, Burst Criterion of Zircaloy Fuel Cladding in a Loss-of-Coolant Accident, in Zirconium in the Nuclear Industry(Fifth Conference), ASTM STP 754, American Society for Testing and Materials, Philadelphia, pp. 271-283, 1981