Development of Regulatory Audit Methodologies for Cr-coated ATF Cladding: A Scoping Analysis on LOCA Safety

Joosuk Lee, Hyedong Jeong, 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

After the Fukushima Daiichi nuclear power plant accident in March 2011, various concepts of Accident Tolerant Fuel (ATF) were proposed worldwide, and some are currently being tested as lead test rods (LTRs) and lead test assemblies (LTAs) [1]. In response to this situation, KEPCO Nuclear Fuel (KNF) and Korea Atomic Energy Research Institute (KAERI) are also actively developing ATF and plan to load them into the domestic PWR core as LTRs in 2024 [2]. Accordingly, regulatory audit methodologies including computer codes and review guidance have to be developed to ensure core safety.

One of the most promising concepts for near-term application in ATF is Cr-coated Zircaloy cladding. The coating thickness ranges around ~20 microns, while the substrate is maintained as zirconium alloys. This provides beneficial effects on licensing applications because not only the mechanical and material properties are similar to conventional zirconium alloys, but the nuclear properties used for core design are also similar. However, there are distinct differences, especially in corrosion characteristics during steady-state and accident conditions, due to the different kinetics of chromium oxide (Cr_2O_3) formation compared to zirconium oxide (ZrO_2) [3]. The embrittlement mechanisms induced by high-temperature oxidation are also different. This raises questions about the validity of emergency core cooling system (ECCS) Acceptance Criteria, which must be met for safety analysis.

For regulatory audits, computer codes must be developed. KINS has recently developed a FAMILY computer code for a detailed analysis of fuel behavior during design basis accidents, including loss-of-coolant accidents (LOCAs) [4]. In this study, the code was slightly modified to reflect the Cr-coated characteristics, particularly for high-temperature oxidation and high-temperature creep behaviors. Steady-state fuel performance was also evaluated by modifying the FRAPCON4 fuel performance code. Using these codes, the effects of Cr-coated cladding on LOCA safety analysis are preliminarily assessed.

2. Model Development

2.1 Steady-state model

Cr-coating on zirconium alloys can alter the thermal/mechanical properties of cladding due to its different mechanical properties and fabrication process. However, the thickness of the coating is generally very small, below ~20 microns, resulting in limited changes in thermal/mechanical properties of cladding. Therefore, the same properties with zirconium alloys are assumed in this study. Regarding corrosion and creep properties, the following assumptions are made:

- *Corrosion:* After initial parabolic oxidation kinetics, the oxide thickness was reduced to 1/20 of the ZIRLO cladding model, resulting in well below ~5 microns of Cr_2O_3 formation at a fuel burnup of 60 MWd/kgU [5].
- *Creep:* Thermal creep was reduced to 1/10 of the ZIRLO cladding model to give a small amount of thermal creep, but irradiation creep is maintained [6].

2.2 Transient model

The mechanical properties of zirconium alloy cladding are used for the coated cladding fuel performance, except for high-temperature oxidation, creep deformation, and burst. The following assumptions are made:

- *High-temperature oxidation:* The oxidation mechanisms of coated cladding are complex, such as the formation of Cr_2O_3 and ZrO_2, $ZrCr_2$ intermetallic, Cr diffusion, etc. depending on the oxidation progress. In this study, the following oxidation kinetic model is considered only by considering the protective effects of Cr_2O_3 [7]. This will be valid before complete consumption of the Cr-coating layer.

$$k_p = 2.69\mathrm{x}10^{-3}\exp(-120{,}000/RT)\ [\mathrm{m/s}^{0.5}]$$

where, R = gas constant, 8.314 [J/mol-K]
T = temperature [K]

- *Creep deformation and burst:* H. Rosinger creep deformation model is adjusted to reduce the plastic deformation of cladding by the factor of 0.64. Burst strain also reduced by the factor of 0.64. A reduction factor of plastic strain and burst strain is derived from the experimental data of Cr-coated M5 cladding [8].

3. Modeling for Safety Analysis

The 16x16 PLUS7 fuel with ZIRLO and Cr-coated ZIRLO cladding in the APR1400 reactor were respectively modeled for a large-break LOCA safety analysis. The initial states of the fuel rod before the accident initiation were calculated by the FRAPCON4.0P1 fuel performance code [9], with modifications described in section 2.1. Transient fuel behaviors during the LOCA period were analyzed by the FAMILY code [4], with modifications described in section 2.2. For the LOCA analysis, the reactor core in APR1400 was divided into one hot channel and one average channel, and a single fuel rod was allocated in the hot channel. The fuel rod was divided into 40 evenly spaced axial nodes.

The safety analysis was performed at a fuel burnup of 30 MWd/kgU, as it gives the most significant impacts regarding fuel relocation perspectives [10]. Slightly modified Quantum Technology fuel relocation model is considered in this analysis [10]. The local peak fuel power before accident initiation was set to 14.1 kW/ft. Constraints on the cladding deformation due to the contact of adjacent fuel rods were imposed. When the cladding hoop strain at a specific axial node reached 78.6% (based on the outer diameter of the cladding), the plastic deformation at the node stopped, and the deformation propagated in the axial direction. The strain-based NUREG-0630 fast ramp criterion was used for cladding burst evaluation [11].

An uncertainty analysis was also performed by considering fuel and thermal-hydraulic uncertainties. Details on the parameters are described in reference 12. A non-parametric statistical method was used to quantify the uncertainty of peak cladding temperature (PCT) and equivalent cladding reacted (ECR). Carthcart-Pawel oxidation model was used for the measure of the ECR [13]. A simple random sampling method was used to produce 124 inputs, and calculations were performed. In a single set, the 3rd highest PCT among the calculated 124 PCTs was captured to assure a 95% probability/95% confidence level. In the case of ECR evaluation, the 1st highest ECR among the calculated 124 ECRs was used. This is believed to conservatively satisfy the 95% probability/95% confidence level.

4. Fuel Performance Assessment

4.1 Steady-state fuel performance

A comparison of fuel performance between ZIRLO and Cr-coated ATF cladding fuel is shown in Fig. 1. Fig. 1(a) displays the evolution of ZrO_2 and Cr_2O_3 oxide thickness, which reached up to 56.1 μm and 4.6 μm, respectively, at 60 MWd/kgU. Fig. 1(b) illustrates the permanent hoop strain of cladding. As fuel burning progressed, negative cladding hoop strain was observed due to inward cladding creep at an initial fuel burnup of

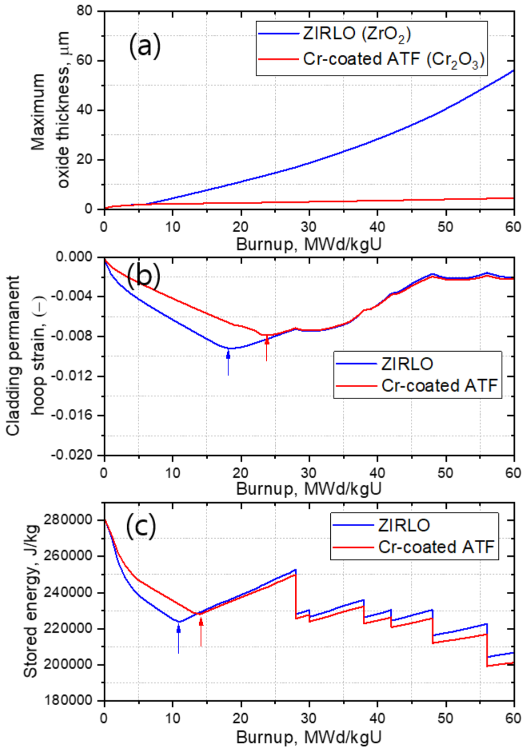

Fig.1. Comparison of (a) oxide thickness, (b) cladding permanent hoop strain and (c) stored energy between ZIRLO and simulated Cr-coated ATF cladding.

up to ~20 MWd/kgU. ZIRLO cladding exhibited a greater negative strain than ATF cladding. The minimum strain was observed at 19 and 24 MWd/kgU burnup in ZIRLO and Cr-coated ATF cladding, respectively. These differences are clearly attributed to the reduction of thermal creep in ATF cladding. After those fuel burnups, cladding strains gradually increased due to cladding contacts on the fuel pellet. Fig. 1(c) depicts the changes in stored energy. At the initial burning stage, up to ~10 MWd/kgU, stored energies were reduced in both claddings, but ZIRLO fuel displayed lower energy than the ATF-clad fuel. Minimum energies were observed at 11 and 14 MWd/kgU in ZIRLO and ATF fuel, respectively. After these points, the energies increased. After 14 MWd/kgU burnup, ZIRLO fuel showed slightly higher energy than ATF fuel. This was due to the higher temperature rise in the ZrO_2 layer caused by a larger thickness of the oxide layer. These fuel performances were well coincided with the prescribed corrosion and creep models of Cr-coated ATF cladding, as described in 2.1.

4.2 Transient fuel performance

Fig. 2 shows the PCT evolution curves during LOCA. In case of ZIRLO cladding fuel, as depicted in Fig. 2(a), the base case blowdown and reflood PCT values are 1177.0 K and 1142.1 K, respectively. Among the 124 cases assessed, the third highest blowdown and reflood PCT values are 1292.3 K and 1288.7 K, respectively.

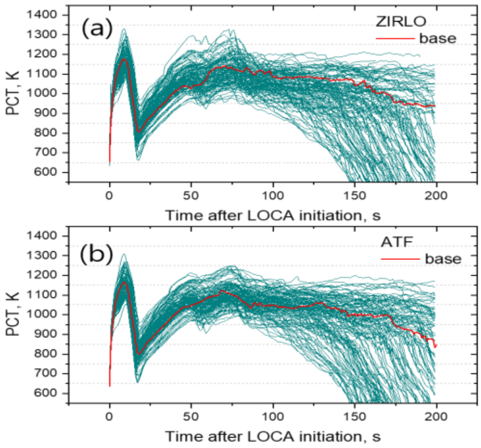

Fig. 2. Evolution of 124 PCT curves during LOCA, (a) ZIRLO and (b) Cr-coated ATF cladding

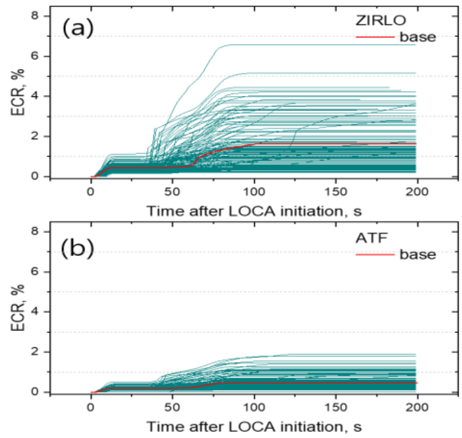

Fig. 3. Evolution of 124 ECR curves during LOCA, (a) ZIRLO and (b) Cr-coated ATF cladding

On the other hand, in case of Cr-coated ATF fuel, shown in Fig. 2(b), the base case blowdown and reflood PCT values are 1165.4 K and 1123.1 K, respectively. The third highest blowdown and reflood PCT values are 1269.3 K and 1247.8 K. These results indicate that the ATF cladding can lead to a reduction of 11.6 K and 19.0 K in the base case blowdown and reflood PCT values, respectively. Moreover, the third highest PCT values in blowdown and reflood phase are also reduced by 23.0 K and 40.9 K, respectively.

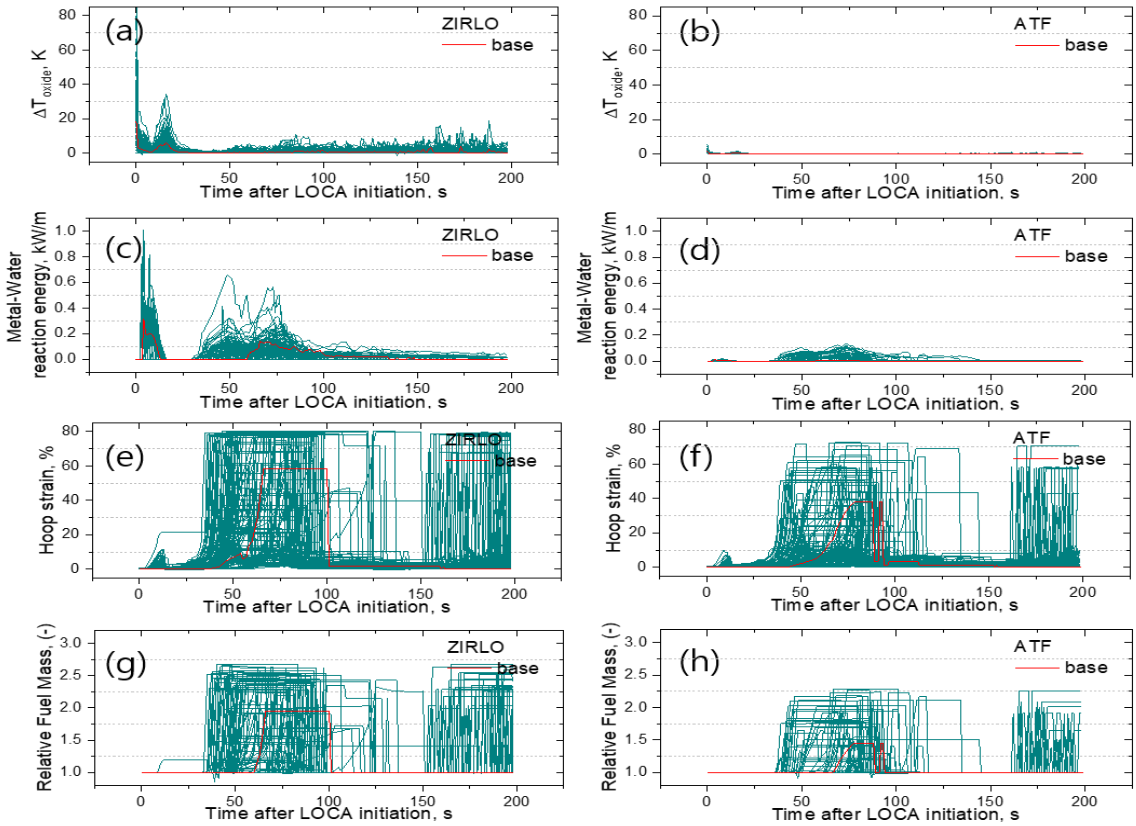

Fig.4. Comparison of 124 performance behaviors of oxide temperature rise((a), (b)), Metal-Water reaction energy((c), (d)), Hoop strain of cladding((e), (f)), and relative fuel mass((g), (h)) in ZIRLO and Cr-coated ATF cladding along the PCT node

Fig. 3 presents the evolution curves of ECR during LOCA. In case of ZIRLO cladding fuel, as depicted in Fig. 3(a), the base case ECR value is 1.6 %. Among the 124 cases assessed, the highest ECR value is 6.5 %. On the other hand, in case of Cr-coated ATF fuel shown in Fig. 3(b), the base case ECR value is 0.5 %, and the 1st

highest ECR value is 1.9 %. These results indicate that the use of ATF cladding can also lead to a reduction of 1.1 percent point (%/p) and 4.6 %/p of ECR, respectively.

The changes in PCT and ECR values are caused by various factors such as the changes in oxide temperature rise, Metal-Water reaction energy, plastic deformation of cladding, and the resultant relocation of fuel mass along the PCT node. Fig. 4 illustrates the behaviors of these parameters during a LOCA transient in both ZIRLO and ATF cladding. Fig. 4(a) and (b) show the difference in oxide temperature rise between the two cladding materials. In ZIRLO cladding, the maximum PCT rise during the blowdown phase is around 30 K, whereas in ATF cladding, it remains almost zero throughout the LOCA transient. Fig. 4(c) and (d) show the difference in Metal-Water reaction energy. In ZIRLO cladding, the maximum energy reaches around ~1 kW/m during the blowdown period, and another high reaction energy appears during the reflood period. However, in ATF case, the energy is almost zero during the blowdown phase and small amount of energy, less than ~ 0.1 kW/m, is observed during the reflood period. Fig. 4(e) and (f) show the hoop strain. In ZIRLO cladding, the hoop strain reaches about ~80 % in many cases, whereas the ATF cladding does not reach up to ~80 %. Fig. 4(g) and (h) show the relative fuel mass. As coinciding with the hoop strain of cladding, the ATF cladding shows relatively lower relocated fuel mass than the ZIRLO cases. Fig. 4 clearly shows the reasons for the occurrence of lower PCT and ECR in Cr-coated ATF cladding.

5. Summary

A scoping LOCA safety analysis of Cr-Coated ATF cladding was performed using steady-state and transient fuel performance codes developed with the help of experimental evidence and assumptions. Followings are results obtained preliminarily.

- The fuel stored energy in Cr-coated ATF fuel is higher than in conventional ZIRLO fuel up to ~15 MWd/kgU burnup. However, after this burnup, a slightly higher stored energy is obtained in ZIRLO cladding.
- During LOCA, a Cr-coated ATF cladding exhibits lower PCT and ECR values than ZIRLO cladding due to the reduced initial oxide thickness, Metal-Water reaction energy, and reduced plastic deformation and burst strain of ATF cladding, which reduced the significance of fuel relocation.
- Cr-coated ATF cladding seems to be beneficial to fuel safety during LOCA, but further detailed model development is necessary to construct a robust audit methodology based on experimental evidence.

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