Considerations of Regulatory Audit Methodology due to applying Chromium-coated Accident Tolerant Fuel to Reactor Core

Dong-Young Lee*, Tae-sun Ro, Bub-Dong Chung, and Soon-Joon Hong
FNC Tech. Co. Ltd., Floor 32, Heungdeok IT Valley, 13 Heungdeok 1-ro, Giheung-gu, Yongin-si, Gyeonggi-do, 16954, South Korea
Corresponding author: dylee273@fnctech.com

Keywords: Accident Tolerant Fuel(ATF), Audit Regulatory Methodology,

1. Introduction

In 2022, the European Parliament decided to include nuclear energy in EU taxonomy under the condition of mandatory application of Accident Tolerant Fuel (ATF), and recently, there are plans for conducting Lead Test Rod (LTR) and Lead Test Assembly (LTA) loaded with Cr-coated ATF, which has been domestically developed [1]. Many studies were performed in the field of thermal-hydraulic and safety analysis in preparation for ATF loading, specifically focusing on regulatory audit methodologies [2–9].

In this study, thermal-hydraulic effects due to the loading Cr-coated ATF in reactor core were investigated. Based on these effects, the information of improving regulation audit code(MARS-KS) and additional consideration for safety review guidelines were intended to be provided for LBLOCA.

The purpose of this paper is to systematically review the past studies on the effect of Cr-coating in the context of regulatory audit methodology for design basis accident, and to further analyze the aspects that have been inadequately addressed. This compilation can be utilized in the audit calculations of regulatory organization and also provide designers with considerations regarding the adoption of Cr coating. The scope of discussion in this paper includes the effects of thermal phenomena due to Cr coating (Chapter 2), improvements in regulatory audit codes (Chapter 3), and the influence on LOCA calculations (Chapter 4).

2. Thermal hydraulic effect due to Cr-coating

In this chapter, the thermal-hydraulic effects as the Cr-coated ATF was applied to reactor core were described. The effects include geometry, properties, surface roughness, boiling heat transfer, and oxidation characteristics.

2.1 Effects of geometry and property

Since the Cr-coated ATF was coated without change of Zr cladding thickness to maintain the strength of cladding, the hydraulic diameter of core and flow area are decreased [4]. In the case of cladding thickness increase without change of property, the blowdown PCT for LBLOCA decrease, and reflood PCT does not show consistent trend [4, 5].

As the thermal conductivity and heat capacity of Cr are larger than Zr, the equivalent thermal conductivity and heat capacity of Cr-coated cladding are larger than bare Zr cladding. The blowdown PCT for LBLOCA decrease due to the differences of thermal properties, however, reflood PCT does not show consistent trend [4, 5, 8, 9].

2.2 Effects of surface roughness

Surface characteristics and roughness of cladding could be varied depending on the method of Cr coating. In the case of surface roughness increase, the pressure drop in reactor core is increases, however, the effect to PCT on LOCA is negligible [10].

2.3 Effects of boiling heat transfer

The Cr coating may affect to critical heat flux(CHF) and minimum film boiling temperature or film boiling heat transfer as shown in table I [4].

Table I: Previous Studies on Thermal Performance Changes Due to Cr Coating [4]

Heat transfer	Heat transfer difference compare with bare Zr cladding (%)	Note
CHF	67–180	Previous studies
Film	30–100	RELAP5-3D assessment

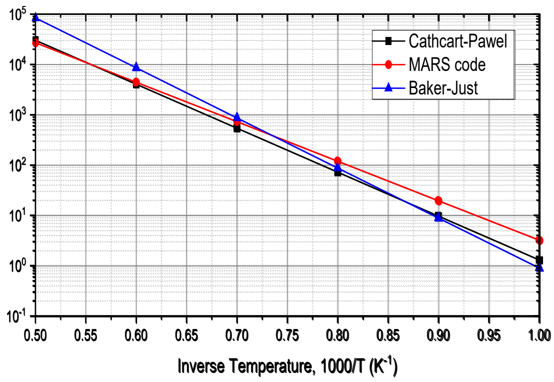
In the case of CHF, the effect of Cr-coating is already shown in Table I. This seems that the CHF is significantly influenced by the surface treatment method after coating. In MARS-KS code, when only coefficient of CHF correlation is changed, the blowdown PCT for LOCA has resulted in changes of tens of Kelvin, although there does not show to be a clear tendency with the increase or decrease of CHF. It is believed to be influenced by other parameters affecting PCT besides CHF during blowdown phase. The reflood PCT exhibited a significant increase or decrease in response to both an increased and a decrease CHF coefficient increase or decrease [4].

For post-dryout or quenching heat transfer, it seems that the heat transfer phenomena are influenced by the surface condition. In the case where surface condition is altered due to the Cr coating, experimental heat transfer coefficient in film boiling region varied from 30% to 100% compared to RELAP5-3D calculation results [xx]. This reduction of film boiling heat transfer has effect of delaying the quenching time and increasing the reflood PCT for LOCA [4].

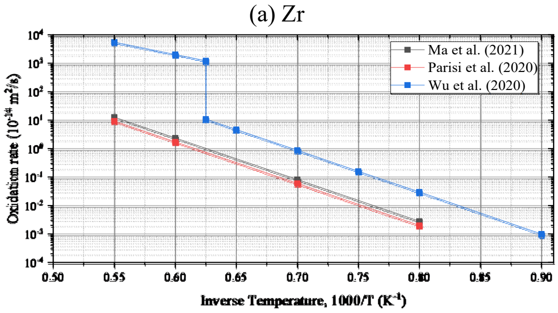
It is hard to find literature specifically studying the effect of Cr coating on nucleate and transition boiling, considering the nature of continuous heat transfer change along the boiling curve, it is reasonable to expect difference in nucleate and transition boiling. The precise heat transfer changes in this regard may be subject to change based on the further experimental studies [4].

2.4 Characteristics of Cr oxidation

As shown in Fig. 1, the oxidation resistance of Cr is significantly superior to that of Zr. The model of Wu et al. [11] exhibits a distinct trend of rapid oxidation increase near 1200℃, differing from other models. This is attributed to the eutectic point of Cr and Zr [6].



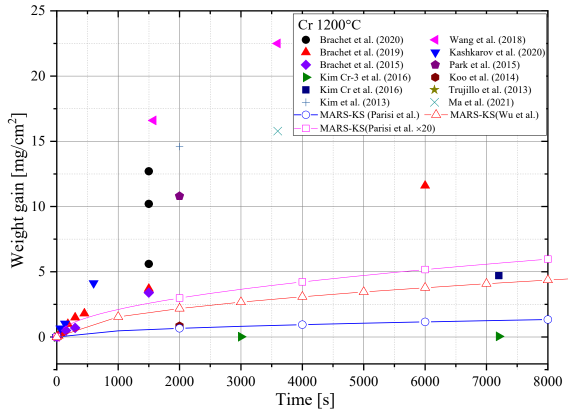
(a) Zr



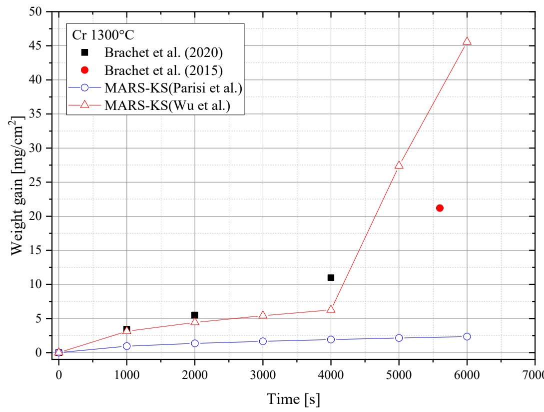
(b) Cr

Fig. 1. Reaction rate versus temperature.

Figure 2 presents the results of oxidation experimental studies on Cr-coated cladding and calculation results using MARS-KS applying the oxidation models shown in Fig. 1 (b). The experimental studies exhibited substantial scatter at 1200℃, whereas the results at 1300℃ showed relatively lower data points. This substantial scatter is believed to stem from the coating method and thickness. Applying the model of Wu et al. [11] in MARS-KS, at 1200℃, it shows somewhat lower predictive oxidation compared to existing experimental studies, while 1300℃, it exhibits relatively appropriate predictive performance.



(a) Cr 1200℃



(b) Cr 1300℃

Fig. 2. Calculation results of weight gain using the model of Parisi et al. (2020) and Wu et al. (2020) compared with existing experiment data.

3. Improvement of MARS-KS

Applying Cr-coated cladding raises the need for improvements in the MARS-KS code. This includes the implementing multi-layer model, implementing Cr-coated cladding oxidation model, material/mechanical property models of the Cr coating; interaction between Cr coating layer with Zr cladding, and boiling heat transfer models induced by the Cr-coated layer. In this paper, the multi-layer model and oxidation model for Cr-coated cladding will be described.

3.1 Multi-layer model

Since the existing gap conductance model embedded in MARS-KS just allows the single layer for cladding, the implement of multi-layer model for Cr-coated cladding is necessary to analyze Cr-coated ATF. In past study, the multi-layer model was implemented into MARS-KS to evaluate the blowdown PCT and reflood PCT in LBLOCA. However, simulating the entire nuclear fuel, including the crud layer outside the coating layer, with five difference materials is not feasible, and it is impossible to model the Cr coating layer with multiple nodes [6].

3.2 Chrome oxidation model

It is necessary to implement a oxidation model for the Cr-coated layer. In the past study, the oxidation model for Cr-coated cladding was implemented and evaluated. The results from implementing the model of Wu et al. [11] predicted high-temperature steam oxidation experiments at 1300℃ relatively accurately.

4. Review of KINS-REM

4.1 Additional consideration in safety review guidelines

For safety review guidelines in Korea, some additional consideration to apply Cr-coated cladding is needed. As reported in USNRC [7], the effects of coating on thermal-hydraulic are usually negligible but just associated with coated surface. Therefore, present CHF correlation in MARS-KS could be applied when the surface conditions are the similar. However, the variation in CHF heat transfer performance due to chromium coating is significant, and its effect is substantial. The influence on post-dryout (PDO) heat transfer is also prominently observed. Therefore, the development of specific CHF and PDO heat transfer models or correlations for the upcoming Cr-coated cladding is of importance, along with ensuring their quality.

LOCA PCT affected by Cr coating, and low oxidation rate of Cr is anticipated to results in low hydrogen generation, potentially leading to changes in Specified Acceptable Fuel Design Limit (SAFDL). The effect of this could introduce additional considerations for accident analysis. In the case of LOCA accidents, oxidation can occur due to high-temperature steam exposure. However, due to significant dispersion in the results from oxidation experiment in previous studies, the development of an oxidation model specific to Cr-coated cladding is necessary.

Cr coating is generally expected to have a positive effect on nuclear fuel rod performance; however, in cases where there are negative effects, a broader assessment should be conducted [12]. Additionally, changes in surface conditions due to coating cracking or delamination can lead to shifts in boiling heat transfer modes or the formation of hot spots, potentially causing localized corrosion. These effects need to be taken into consideration during the review process.

4.2 Additional consideration in KINS-REM

The evaluation process of KINS-REM [13], which is a kind of Best Estimate Plus Uncertainty (BEPU) based methodology for regulation audit calculation extends the uncertainty parameters to 22 of which 11 are related with MARS-KS. Among these parameters, all except for the Dittus-Boelter correlation are associated with anomalous heat transfer and could be influenced by the Cr-coated layer. The range of parameters considered for the heat transfer performance change is presented in table II [5].

Table II: Uncertainty parameters for present MARS-KS analysis [5]

No	Models or Uncertainty Parameters	Cr coating effect	Present Uncertainty Range	Combined Uncertainty Range
1	Groeneveld CHF lookup	0.67 ~1.8	0.17~1.8	0.114~3.24
2	Dittus-Boelter liquid convection	1	0.606~1.39	0.606~1.39
3	Dittus-Boelter vapor convection	1	0.606~1.39	0.606~1.39
4	Chen nucleate boiling	0.67 ~1.8	0.53~1.46	0.355~2.628
5	Zuber CHF correlation	0.67 ~1.8	0.38~1.62	0.255~2.916
6	Chen transition boiling	0.3 ~1.0	0.54~1.46	0.162~1.46
7	Weismann TB correlation	0.3 ~1.0	0.5~2.0	0.15~2.0
8	Bromley film boiling	0.3 ~1.0	0.428~1.58	0.128~1.58
9	QF Bromley correlation	0.3 ~1.0	0.75~1.25	0.225~1.25
10	Forslund-Rohsenow FB	0.3 ~1.0	0.5~1.5	0.15~1.5
11	Vapor correlation(reflood)	0.3 ~1.0	0.5~1.5	0.15~1.5

5. Conclusions

The heat transfer performance changes due to the Cr coating were investigated. Not only the CHF and PDO heat transfer but also the heat transfer rate for nucleate boiling and transition boiling are expected altered.

The individual effects of geometric difference, surface, and heat transfer difference induced by Cr coating on LOCA PCT are evaluated, respectively.

Additional considerations for review due to the Cr coating and additional considerations for KINS-REM are presented. The above results can be used in the review and regulatory audit calculation of Cr-coated ATF core loading.

The additional considerations in regulatory audit methodology due to the introduction of Cr-coating have been reviewed. The introduction of Cr coating has led to an examination of further considerations within the regulatory verification methodology. A summary of the additional considerations that need to be taken into account is as follows:

- Effect on CHF and PDO
- Effect on LOCA PCT
- Surface condition such as crack or delamination
- Heat transfer coefficient for two-phase flow

Acknowledgement

This work was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KoFONS) using the financial resource granted by the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea. (No. 2103051).

REFERENCES

[1] H. Jang, Development of Accident Tolerant Fuel in Korea and commercialization plan, Nuclear Safety & Security Information Conference 2023, Jun 20-21, Daejeon

[2] S.J. Hong, J.H. Bae, T.S. Ro, T.K. Park, and S.K. Zee, “NSTAR-21NS22-186, Establishment of Audit Code System and Methodology of Thermal-hydraulic Accident Analyses for Chromium Coated Accident Tolerant Fuel Loaded Reactor”, FNC tech. 2021.

[3] S.J Hong, T.S. Ro, B.D. Chung, and D.Y. Lee, “NSTAR-22NS22-186, Development of MARS-KS Cladding Oxidation Model for Chromium Coated Accident Tolerant Fuel”, FNC tech. 2022.

[4] S.J Hong, T.S. Ro, B.D. Chung, and D.Y. Lee, “NSTAR-22NS22-186, Development of MARS-KS Cladding Multi-Layer Model for Chromium Coated Accident Tolerant Fuel”, FNC tech. 2022.

[5] J.H. Bae, S.J. Hong, T.S. Ro, Effect of chromium coated zircaloy cladding of accident tolerant fuel on the best estimate LOCA methodology. Progress in Nuclear Energy, Vol. 151, 104330, 2022.

[6] D.Y. Lee, T.S. Ro, B.D. Chung, and S.J. Hong Implementation of chrome oxidation model into best-estimate system code for accident tolerant fuel, Annals of Nuclear Energy, Vol. 192, 110002, 2023.

[7] USNRC, “ATF-ISG-2020-01, Supplemental Guidance Regarding the Chromium-Coated Zirconium Alloy Fuel Cladding Accident Tolerant Fuel Concept, Interim Staff Guidance. U. S. Nuclear Regulatory Commission”, 2020.

[8] INL, “INL-EXT-19-56455, Investigations on the Thermal hydraulic Behavior of Accident Tolerant Fuel Cladding Materials” Idaho National Laboratory, 2020.

[9] A. Gurgen, and K. Shirvan, Estimation of coping time in pressurized water reactors for near term accident tolerant fuel claddings. Nuclear Engineering and Design, Vol. 337, pp. 38-50, 2018.

[10] D.Y. Lee, T.S. Ro, B.D. Chung, and S.J. Hong, Evaluation the Effect of Cr-coated Cladding Surface Roughness on Large Break-Loss of Coolant Accident using MARS-KS 1.5 with Multi-layer Model, Transactions of the Korean Nuclear Society Spring Meeting, May 18-19, 2023, Jeju.

[11] X. Wu, and K. Shirvan, System code evaluation of near-term accident tolerant claddings during boiling water reactor short-term and long-term station blackout accidents. Nuclear Engineering and Design, Vol. 356, 110362, 2020.

[12] A. Seshadri, B. Phillips, K. Shirvan, Towards understanding the effects of irradiation on quenching heat transfer. International Journal of Heat and Mass Transfer, Vol. 127, pp. 1087–1095, 2018.

[13] Y.S. Bang, B.G. Huh, A.J. Cheong, and S.W. Woo, “NEA-CSNI-R--2013-8, Experience in KINS on Best Estimate Calculation with Uncertainty Evaluation”, Nuclear Energy Agency of the OECD (NEA)