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Areas of Improvement in FRAPCON and FRAPTRAN Codes for Applications to Fuels with Cladding Material Change

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1. Introduction

Since 2021, Korea Institute of Nuclear Safety (KINS) has been conducting a long-term regulatory research and one of objectives of the research is to improve the prediction capabilities of the fuel analysis codes, FRAPCON and FRAPTRAN [1] when applying to fuels with cladding material change. The primary target fuel of this research is the HANA fuel employing HANA-6 cladding but any new fuels with cladding changes from the conventional Zircaloy alloys (For example, an Accident Tolerance Fuel with chrome coated on the cladding) are also subject to the current research scope.

Through comprehensive researches, primary models and material property correlations of FRAPCON and FRAPTRAN codes, which need modifications due to any cladding change were identified. [1-4] In these previous researches, two different approaches were adopted. A rigorous criterion that any models and material property correlations linked with cladding changes should be modified was employed in the first approach [1,2] and expert panels judgement backed by partial experimental data on HANA-6 cladding was employed in the second approach [3,4]. However, since these two approaches were conducted at their basic level, the results are far from complete and even showed some differences between them. Therefore, as a further study, it is highly advisable to consolidate these results from two approaches with a rigorous manner.

Therefore, in the present study, specific evaluations for each of the pre-identified models and material property correlations from the two approaches are conducted based on further in-depth discussion and using proper references [5-8] first and then precise areas of improvement in FRAPCON and FRAPTRAN codes for cladding change application are drawn.

In conclusion, a new list of models and material property correlations for modifications narrowed down by the present study is suggested and their impact on overall models of FRAPCON and FRAPTRAN codes is identified. Further considerations regarding several material property correlations are indicated from a regulatory perspective as well.

2. Specific Evaluations of the pre-identified Models and Material Property Correlations in FRAPCON/FRAPTRAN with Cladding Changes

Table 1 shows that models and material property correlations from FRAPCON and FRAPTRAN codes primarily identified to be modified for their applications to fuels with cladding material changes. Each of item appeared in the second column of Table 1 are identified by the first or the second approach or from both [1-4]. Specific evaluation on the each of models and material property correlations is given as follows.

Table 1. Pre-identified Models and material property correlations from FRAPCON and FRAPTRAN codes which need modifications for cladding change

No.	Models or Material Property Correlations	Note
①	Cladding density	MPC (Thermal)
②	Cladding specific heat	MPC (Thermal)
③	Cladding thermal conductivity	MPC (Thermal)
④	Cladding oxide thermal conductivity	MPC (Thermal)
⑤	Cladding surface emissivity	MPC (Thermal)
⑥	Cladding thermal expansion	MPC (Thermal)
⑦	Cladding elastic modulus/shear modulus	MPC (Mechanical)
⑧	Cladding axial growth	MPC (Mechanical)
⑨	Creep rate	MPC (Mechanical)
⑩	Cladding Meyer Hardness	MPC (Mechanical)
⑪	Stress-strain curve	MPC (Mechanical)

[1] FRAPCON-4.0 and FRAPTRAN-2.0 versions are considered in the present study

⑫	Instability strain	MPC (Mechanical)
⑬	Waterside corrosion	Model (Thermal)
⑭	Hydrogen pickup fraction	MPC (Thermal)
⑮	Uniform plastic elongation at failure	MPC (Mechanical)
⑯	Plastic strain at failure	MPC (Mechanical)
⑰	Burst stress	MPC (Mechanical)
⑱	High-temperature corrosion	Model (Thermal)

MPC: Material Property Correlation

① *Cladding density*

Not FRAPCON but FRAPTRAN only needs cladding density in its calculation process. Although HANA-6 cladding density varies depending on temperature (See, Table 2), its variation is relatively small over wide range of temperature. In FRAPTRAN, cladding density is always used in conjunction with cladding specific heat which varies a lot compared to cladding density. Furthermore, it is well known that small addition of different metallic components in Zircaloy alloy will not create any substantial density variation and this may apply to HANA-6 cladding with small metallic additives (Nb (1.1%) and Cu (0.07%)). Consequently, it is concluded that an existing practice of FRAPTRAN code, application of a constant cladding density (6,520kg/m^3 from Zircaloy-4 @ 300℃) is adopted for HANA-6 cladding density but a sensitivity study to evaluate impact of cladding density variation on typical accident analysis results should be conducted as well.

Table 2. HANA-6 cladding density variation depending on temperature [4]

Temperature (℃)	Density (kg/m^3)
20	6.552
200	6.528
400	6.500
600	6.474
800	6.456
1,000	6.456
1,200	6.418

② *Cladding specific heat*

Like cladding density, only FRAPTRAN needs cladding specific heat in its calculation process. Measurement shows cladding specific heat of HANA-6 displays a substantial difference due to change of phase transition temperatures (12℃ lower) in comparison with Zircaloy-2 whose value is uniformly applied to all Zircaloy alloys in FRANPTRAN code. However, since a shift of existing Zircaloy-2 curve based on newly confirmed phase transition temperatures of HANA-6 (750℃, 960℃) gives a best fit, it is concluded that this transformed Zircaloy-2 curve (See, black dotted line in Figure 1) is chosen for HANA-6 cladding specific heat value.

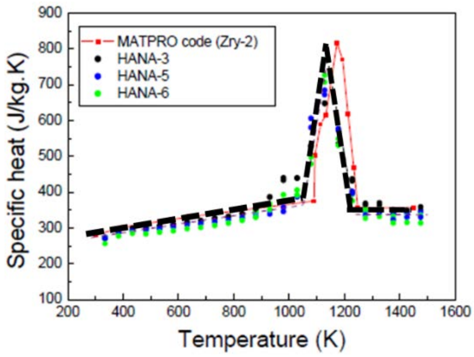

Fig. 1. HANA-6 cladding specific heat variation depending on temperature [4]

③ *Cladding thermal conductivity*

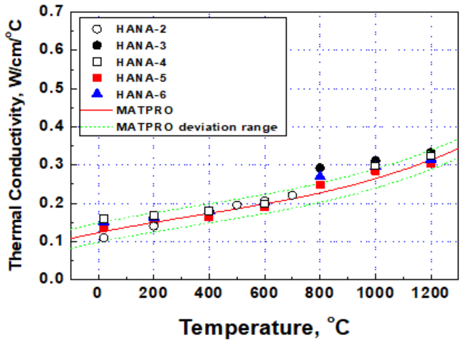

Fig. 2. HANA-6 cladding thermal conductivity variation depending on temperature [4]

Measurement of HANA-6 cladding thermal conductivity shows overall trend is similar to MATPRO model used for FRAPCON and FRAPTRAN codes but a discrepancy beyond normal deviation range was observed near 800℃. Therefore, it is concluded that applicability of existing cladding thermal conductivity in FRAPCON and FRAPTRAN codes to that of HANA-6 cladding should be further investigated with additional experiment data if possible.

④ *Cladding oxide thermal conductivity*

Cladding oxide thermal conductivity is formulated in terms of temperature in FRAPCON and FRAPTRAN codes. It is a practice to apply the same cladding oxide thermal conductivity for all Zircaloy alloys. However, in a rigorous sense, cladding oxide thermal conductivity of HANA-6 is different from that of Zircaloy alloys. This is also independently verified through a regulatory review for fuel. Therefore, it is concluded that an existing value for cladding oxide thermal conductivity in FRAPCON and FRAPTRAN codes is applied to HANA-6 unless the impact of precision of cladding oxide thermal conductivity is substantial to affect typical accident analysis results.

⑤ *Cladding surface emissivity*

In FRAPCON and FRAPTRAN codes, cladding surface emissivity is formulated in terms of temperature and cladding oxide thickness (See, Figure 3), and the same cladding surface emissivity is used for various zircaloy alloys. This is because cladding surface emissivity is mostly dependent on surface condition of cladding oxide rather than cladding material itself.

Therefore, with the same logic, an existing value for cladding surface emissivity in FRAPCON and FRAPTRAN codes can be applied to HANA-6 cladding as well.

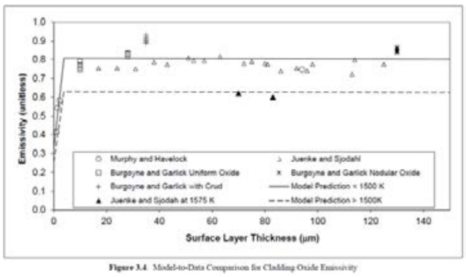

Fig. 3. Cladding oxide emissivity in FRAPCON and FRAPTRAN codes [7]

⑥ *Cladding thermal expansion*

Since cladding material is anisotropic, axial and radial thermal expansions are different in general. Measurements of HANA-6 cladding thermal expansion for axial and radial directions depending on temperature show that axial cladding thermal expansion is well agreed with MATPRO but radial thermal expansion is lower than MATPRO which is very close to cladding thermal expansions for axial and radial in FRAPCON and FRAPTRAN codes. (See, Figure 4) Therefore, it is concluded that an existing radial cladding thermal expansion model should be changed while keeping axial cladding thermal expansion for HANA-6 application with FRAPCON and FRAPTRAN codes.

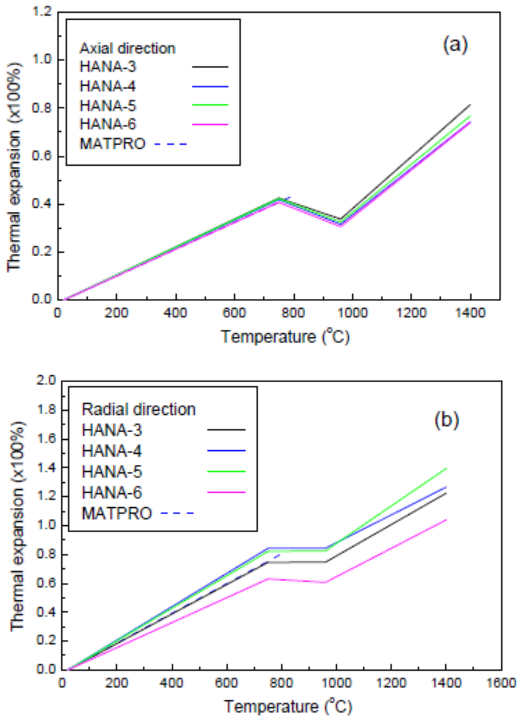

Fig. 4. HANA-6 cladding thermal expansion variation depending on temperature [4]

⑦ *Cladding elastic modulus, shear modulus*

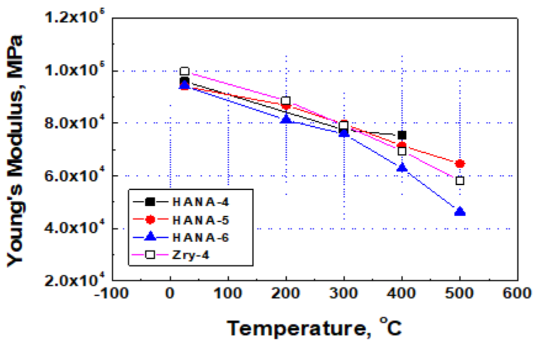

Fig. 5. HANA-6 Young's Modulus variation depending on temperature [4]

Table 3. Comparison of Poisson's ratio between HANA-6 and Zircaloy-4 claddings [4]

No. of Measurement	HANA-6	Zircaloy-4
1	0.374	0.366
2	0.397	
Average	0.386	0.366

Measurements clearly show that elastic modulus and shear modulus of HANA-6 cladding are different from those of Zircaloy-4 included in FRAPCON and FRAPTRAN codes. (Table 3 and Figure 5). Therefore, it is concluded that an existing elastic and shear moduli of FRAPCON and FRAPTRAN codes should be updated in case of HANA-6 cladding applications.

⑧ *Cladding axial growth*

FRAPCON code uses a uniform correlation functional form with different correlation coefficients for various zircaloy alloys and the same goes for HANA-6. Therefore, it is concluded that HANA-6 specific correlation coefficients should be used for cladding axial growth analysis.

⑨ *Creep rate*

It is known that HANA-6 cladding has low creep resistance compared to Zircaloy and ZIRLO because it has small contents of metallic alloy elements such as Sn and Nb. Measurements substantiates this statement. (See, Figure 6 and 7) Therefore, it is concluded that HANA-6 specific creep rate model should be developed for HANA-6 cladding application in FRAPCON and FRAPTRAN codes based on HANA-6 creep data under a specific thermal treatment condition.

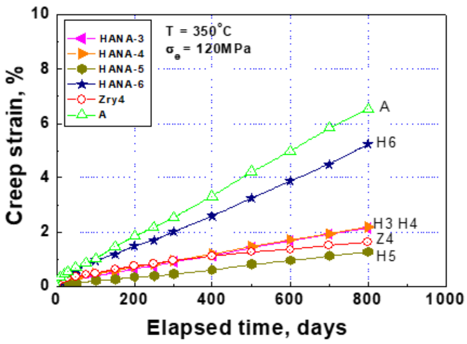

Fig. 6. Measurement of creep for HANA-6 cladding at 350°C and 120MPa [4]

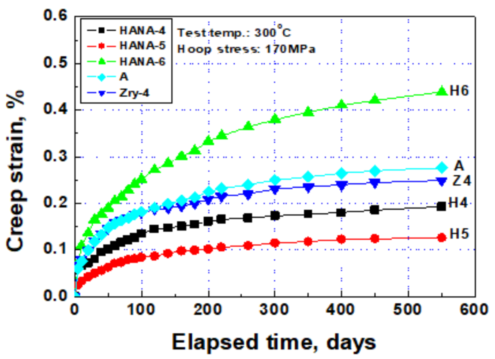

Fig. 7. Measurement of creep for HANA-6 cladding at 300°C and 170MPa [4]

⑩ *Cladding Meyer hardness*

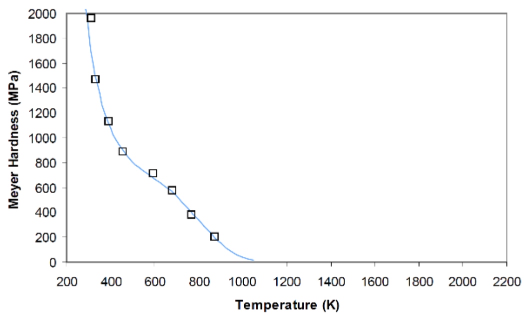

Fig. 8. Meyer hardness model in FRAPCON and FRAPTRAN [7]

It is believed that Meyer hardness changes depending on cladding material and affects heat conduction by way of changing fuel-to-cladding contact conductance. Currently, a uniform Meyer hardness is applied for all zircaloy alloys in FRAPCON and FRAPTRAN codes (See, Figure 8). Although it is highly likely that the same is true for HANA-6 cladding, an indirect method using Vickers hardness test combined with a theory regarding a relation between yield strength and Meyer hardness may be adopted to verify this statement [9].

⑪ *Stress-strain curve,* ⑮ *Uniform plastic elongation at failure and* ⑯ *Plastic strain at failure*

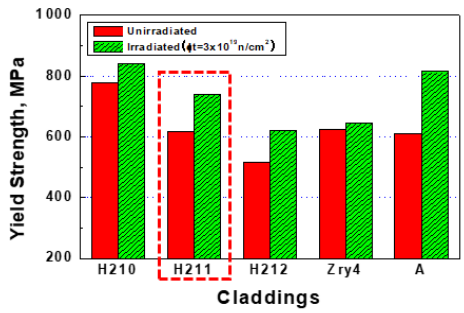

Fig. 9. Measurement of yield strength of HANA-6 (dotted red) cladding before/after irradiation [4]

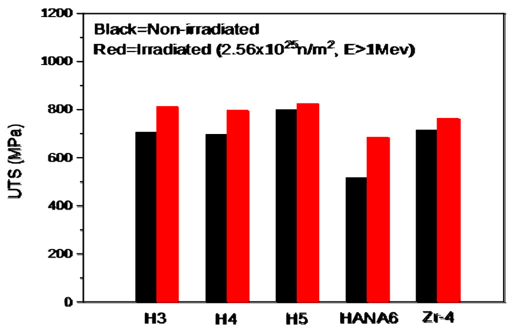

Fig. 10. Measurement of ultimate tensile strength of HANA-6 cladding [4]

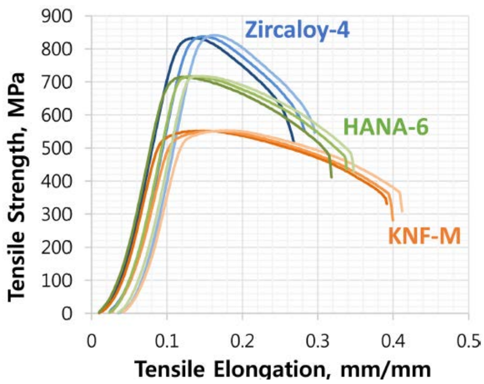

Fig. 11. Measurement of stress-strain curve of HANA-6 cladding at 25℃ [4]

After irradiation, yield stress of HANA-6 cladding increases in comparison with zircaloy-4 (See, Figure 9). Ultimate tensile strength of HANA-6 cladding is rather small than zircaloy-4 (See, Figure 10). Stress-strain curve of HANA-6 cladding at low temperature (25℃) shows a clearly different shape to zircaloy-4 (See, Figure 11). These evidences ensure that typical mechanical properties such as stress-strain curve, uniform plastic elongation at failure, and plastic strain at failure are to be uniquely determined depending on cladding material types.

Therefore, it is concluded that stress-strain curve, uniform plastic elongation at failure, and plastic strain at failure for FRAPCON and FRAPTRAN codes should be updated in case of HANA-6 cladding applications.

⑫ *Instability strain*

Instability strain depends on cladding material in a strict sense but FRAPTRAN adopts zircaloy-4 instability strain value from MATPRO. When cladding strain exceeds its instability strain, ballooning is assumed and BALON2 model is called in FRAPTRAN code. Unfortunately, BALON2 model has a lot of inaccuracies, so KINS developed a new ballooning model based on high temperature creep to replace BALON2 and it was already incorporated in the regulatory audit code called FAMILY [10]. All things considered, it is highly unlikely that BALON2 model would give improved accuracy even if very precise instability strain for HANA-6 cladding is applied. Therefore, it is concluded that an existing instability strain value in FRAPTRAN remain untouched and FAMILY would be updated for HANA-6 application if necessary.

⑬ *Waterside corrosion*

In FRAPCON, waterside corrosion has different models for before transition thickness and after transition thickness because different corrosion mechanisms apply with the transition thickness as a boundary. Measurements on before transition and after transition clearly reveal that HANA-6 cladding has different but superior waterside corrosion characteristics compared to zircaloy-4. (See, Figures 12 and 13). By the way, it is well known that FRAPCON's waterside corrosion model badly predicts accelerated corrosion phenomenon at upper part of fuel due to local boiling. (See, Figure 14) All things considered, it is concluded that an existing waterside corrosion model in FRAPCON code is to be updated with new model coefficients based on HANA-6 corrosion experiments or a whole new corrosion model may be developed taking accelerating corrosion at fuel into account.

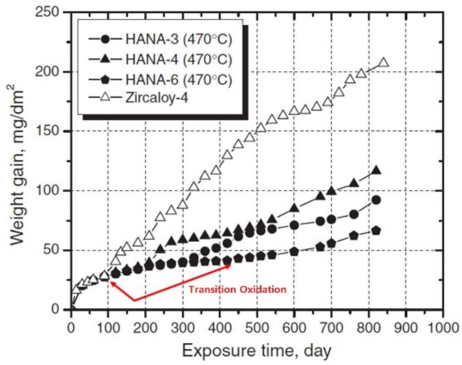

Fig. 12. Measurement of waterside corrosion of HANA-6 cladding before transition thickness [4]

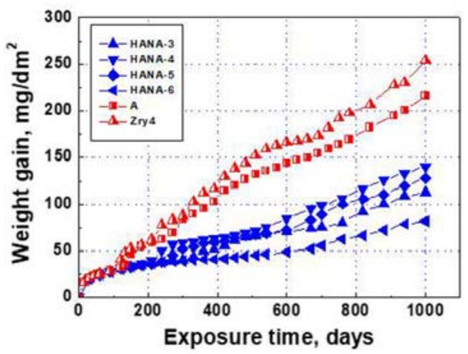

Fig. 13. Measurement of waterside corrosion of HANA-6 cladding after transition thickness [4]

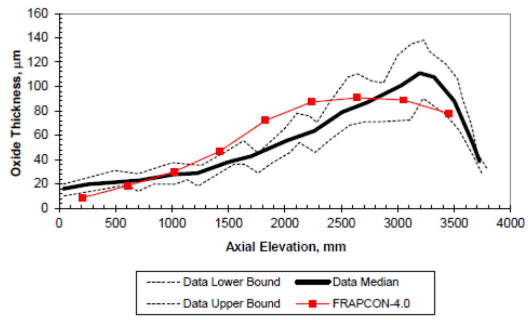

Fig. 14. Verification of FRAPCON waterside corrosion model for ZIRLO at 65.9MWd/KgU [4]

⑭ *Hydrogen pickup fraction*

Hydrogen produced by cladding oxidation process is absorbed into cladding material and gives rise to embrittlement of cladding material. Therefore, cladding dependent hydrogen pickup fraction in relation to cladding oxidation is used in FRAPCON code. KINS acquired primary information on hydrogen pickup fraction for HANA-6 cladding through a license application review process. Therefore, this information will be incorporated into FRAPCON code for HANA-6 application.

⑰ *Burst stress*

In FRAPTRAN code, cladding burst is differentiated based on burst strain or burst stress. That is to say, in case of ballooning, FRAPTRAN assumes that burst happens when calculated stress reaches critical burst stress. Zircaloy alloys such as zircaloy-4, ZIRLO etc. use a correlation from NUREG-0630 [11] to determine their critical burst stresses. Measurement shows that the NUREG-0630 correlation for burst stress is also applicable to HANA-6 cladding. (See, Figure 15) Since FRAPTRAN code has a more conservative criterion for burst stress than NUREG-0630 correlation, it is concluded that an existing FRAPTRAN burst stress criterion can be conservatively applicable to HANA-6 cladding.

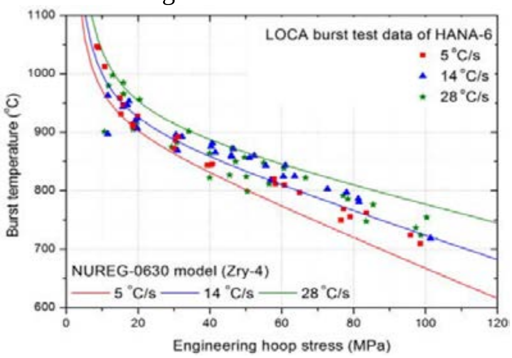

Fig. 15. Measurement of burst stress of HANA-6 cladding depending on temperature [4]

⑱ *High-temperature corrosion*

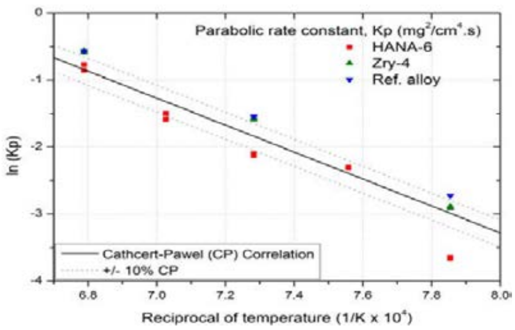

Fig. 16. Measurement of high-temperature corrosion of HANA-6 cladding [4]

Cladding corrosion at a high temperature condition such as Loss of Coolant Accident (LOCA) is conducted by FRAPTRAN code. FRAPTRAN code has two models, Cathcart-Pawel (CP) and Baker-Just (BJ) with the same functional form but with different model coefficients. CP model is widely used these days. Measurement shows that HANA-6 cladding has different high-temperature corrosion characteristics from zircaloy-4 and it gives about 5% increase in corrosion resistance compared to CP model. (See, Figure 16) Therefore, it is concluded that an existing CP model in FRAPTRAN can be used with adjustment of model coefficients for HANA-6 cladding application.

3. Confirmed Models and Material Property Correlations for Further Improvement in FRAPCON/FRAPTRAN codes with Cladding Changes

Table 4 shows status of confirmed models and material property correlations of FRAPCON and FRAPTRAN codes which need modifications based on specific evaluations on pre-identified models and material property correlations. Total 12 out of 18 models and material property correlations are re-identified as the items needs modifications for HANA-6 cladding application.

Table 4. Status of Confirmed Models and material property correlations from FRAPCON and FRAPTRAN codes which need modifications for cladding change

No.	Models or Material Property Correlations	Confirm	Note
①	Cladding density	No	Sensitivity
②	Cladding specific heat	Yes	
③	Cladding thermal conductivity	Yes	Sensitivity Data
④	Cladding oxide thermal conductivity	No	Sensitivity
⑤	Cladding surface emissivity	No	
⑥	Cladding thermal expansion	Yes	R-direction
⑦	Cladding elastic modulus/shear modulus	Yes	
⑧	Cladding axial growth	Yes	Data
⑨	Creep rate	Yes	Data
⑩	Cladding Meyer Hardness	No	Further verification
⑪	Stress-strain curve	Yes	Data
⑫	Instability strain	No	
⑬	Waterside corrosion	Yes	Data
⑭	Hydrogen pickup fraction	Yes	
⑮	Uniform plastic elongation at failure	Yes	Data
⑯	Plastic strain at failure	Yes	Data

⑰	Burst stress	No	
⑱	High-temperature corrosion	Yes	Data

In this table, "Sensitivity" in the "Note" column indicates that any sensitivity study for an impact of the model or the material property correlation to typical fuel analysis cases is required. Depending on the sensitivity evaluation, confirmation status of each model or material property correlation may be reversed. "Data" shown in "Note" column means additional experimental data is required to develop accurate models or material property correlations for HANA-6 cladding. "R-direction" implies radial direction thermal expansion only needs to be changed. "Further verification" means that an additional verification may need to ensure the conclusion regarding cladding Meyer hardness. It is worth paying attention to those models or material property correlations noted in Table 4 because they may be subject to intense regulatory review during an application review process for new fuels.

Since models and material property correlations of FRAPCON and FRAPTRAN codes needed to be modified under cladding material change identified precisely, how they impact overall analysis models in FRAPCON and FRAPTRAN codes is summarized in Table 5 to give an idea that which part of the codes needs to be changed. Here, each number shown in second column is identical to the number shown in "No." column in Table 1.

Table 5. Impact of Models and Material Property Correlations Changes on Overall Analysis Models in FRAPCON and FRAPTRAN Codes

Overall Analysis Models	Modes and Material Property Correlations	Codes
Thermal Analysis Model	①,②,③,④,⑤ ⑥,⑩	FRAPCON FRAPTRAN
Creep Model	⑦,⑨	FRAPCON
Elastic Deformation Model	⑦	FRAPCON FRAPTRAN
Plastic Deformation Model	⑪	FRAPCON FRAPTRAN
Waterside Corrosion Model	③,④,⑬	FRAPCON
Hydrogen Pickup Model	⑭	FRAPCON
High-Temperature Corrosion Model	⑱	FRAPTRAN
Pellet-Cladding Mechanical Interaction Model	⑦,⑭,⑮	FRAPTRAN
Ballooning Model	⑫,⑯,⑰	FRAPTRAN
Rod Internal Pressure Model	⑥	FRAPCON

4. Conclusions

Specific evaluations for each of the pre-identified models and material property correlations from FRAPCON and FRAPTRAN codes with cladding change application by primary researches [1-4] are conducted based on in-depth expert panel discussion and using proper references including experimental data for HANA-6 cladding [5-8].

Total 12 out of 18 models and material property correlations from the previous studies are re-identified as the critical items needs clear modifications for HANA-6 cladding application of FRAPCON and FRAPTRAN codes. Also couples of follow-up items which need special attention during any potential regulatory review process on new fuels are identified. Finally, impact of models and material property correlation changes on overall analysis models in FRAPCON and FRAPTRAN codes is suggested to facilitate the codes modifications to follow.

Acknowledgements

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