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Areas of improvement in FRAPCON and FRAPTRAN codes for applications to fuel with cladding material change

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국민에게 신뢰받는 안전 최우선의 KINS

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KINS is a Cornerstone for a Safe Korea

Contents

I. Introduction [1 of 2]

- In order to achieve efficient operations of nuclear power plants, Korean nuclear utility is planning to use a new fuel with HANA-6 cladding including the extension of averaged burnup from 60 MWd/KgU to 62 MWd/KgU

- After the Fukushima accident, Accident Tolerance Fuel (ATF) has been actively developed worldwide and Korean nuclear utility is planning to submit technical report (TR) once it's ATF is ready by adopting new cladding or pellet designs

- In light of the introduction of new fuels with cladding or pellet changes, KINS needs to update analysis codes for regulatory audit calculations

- Since a safety assessment on the fuel is being implemented by fuel performance analysis codes such as **FRAPCON-4.0 and FRAPTRAN-2.0 these days, it is necessary to identify required areas of change in these codes rigorously in line with the introduction of the new fuels**

I. Introduction [2 of 2]

(SRG: Safety Review Guidelines for light water reactors, KINS/GE-N001, 2022)

Acceptance Criteria

- **SRG 4.2**

- Fuel system design

FRAPCON FRAPTRAN

- **Thermal analysis**
- **Mechanical analysis**
- **Corrosion analysis**
- **Failure analysis**

Available data

- **Comparing HANA data with MATPRO or others**

(Further work)

Sensitivity analysis

- **Critical items need clear modification for HANA-6 cladding are re-identified**

II. Models and material property correlations in FRAPCON/FRAPTRAN with cladding change

Acceptance Criteria

SRG 4.2 Fuel system design

(SRG: Safety Review Guidelines for light water reactors, 2022)

(1) The fuel system is not damaged as a result of normal operation and AOOs
(2) Fuel system damage is never so severe as to prevent control rod insertion when it is required
(3) The number of fuel rod failures is not underestimated for postulated accidents
(4) Coolability is always maintained

Category	Fuel system damage	Fuel rod failure	Fuel coolability
Design Bases	Stress & Strain Fatigue Fretting wear Cladding oxidation, hydriding, crud Rod bow & Irradiation growth Rod internal pressure Hydraulic lift loads Control rod reactivity & insertability	Cladding collapse Overheating of cladding Overheating of fuel pellet Excessive fuel enthalpy Pellet/cladding interaction - PCI or PCMI Bursting Mechanical fracture	Cladding embrittlement Violent expulsion of fuel Generalized cladding melting Fuel rod ballooning
Conditions	Normal operation	Normal operation / AOOs / PAs	PAs (Postulated accidents)

II. Models and material property correlations in FRAPCON/FRAPTRAN with cladding change

Acceptance Criteria for cladding | **FRPACON / FRAPTRAN**

(SRG: Safety Review Guidelines for light water reactors, 2022)

- Not applicable to cladding : Control rod reactivity & insertability, violent expulsion of fuel
- Criteria not implemented by FRAPCON/FRAPTRAN : Fatigue, fretting wear, hydraulic lift loads, PCI and so on

Category	Fuel system damage	Fuel rod failure	Fuel coolability
Design Bases	Stress & Strain Fatigue Fretting wear Cladding oxidation, hydriding, crud Rod bow & Irradiation growth Rod internal pressure Hydraulic lift loads Control rod reactivity & insertability	Cladding collapse Overheating of cladding Overheating of fuel pellet Excessive fuel enthalpy Pellet/cladding interaction - PCI or PCMI Bursting Mechanical fracture	Cladding embrittlement Violent expulsion of fuel Generalized cladding melting Fuel rod ballooning
Conditions	Normal operation	Normal operation / AOOs / PAs	PAs

II. Models and material property correlations in FRAPCON/FRAPTRAN with cladding change

Acceptance Criteria for cladding

FRPACON / FRAPTRAN

01 Thermal analysis	02 Mechanical analysis
▪ Rod internal pressure ▪ Overheating of fuel pellets & cladding	▪ Stress & Strain ▪ Irradiation growth
03 Corrosion analysis	**04 Failure analysis**
▪ Oxidation, hydriding, crud ▪ Cladding embrittlement	▪ PCMI ▪ Ballooning ▪ Bursting

II. Models and material property correlations in FRAPCON/FRAPTRAN with cladding change

Acceptance Criteria for cladding | **FRPACON / FRAPTRAN**

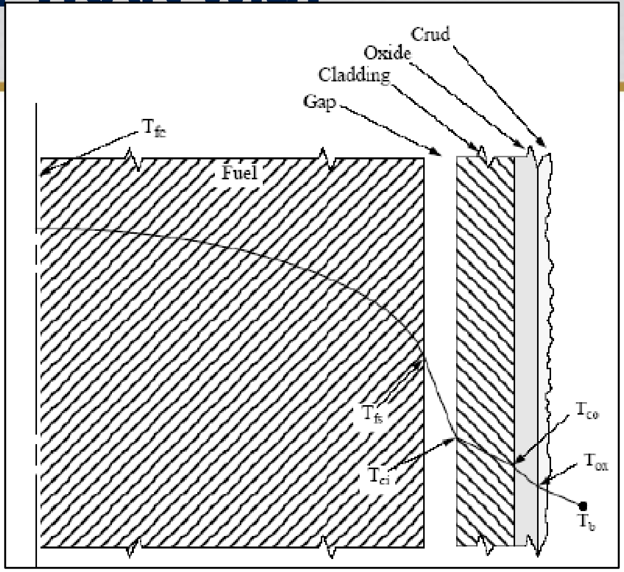

Fig. 1 Schematic of the fuel rod temperature distribution

Thermal analysis

- **Overheating of fuel pellets**

  - Calculation of fuel rod surface temperature
  - Calculation of cladding temperature gradient
  - Calculation of fuel-cladding gap temperature gradient

  → Thermal conductivity, Oxide thermal conductivity, Emissivity, Meyer hardness

- **Rod internal pressure**

  - Calculation of the fuel rod internal gas pressure include the temperatures assigned to the various volumes such as plenum temperature → Thermal expansion, Thermal conductivity

Density

Specific heat

II. Models and material property correlations in FRAPCON/FRAPTRAN with cladding change

Acceptance Criteria for cladding | **FRPACON / FRAPTRAN** | **Available data**

(Y.S. Yang et al., KINS/HR-1835, 2022)

(Yong Jun Oh et al., KNS, 2005)

Thermal conductivity

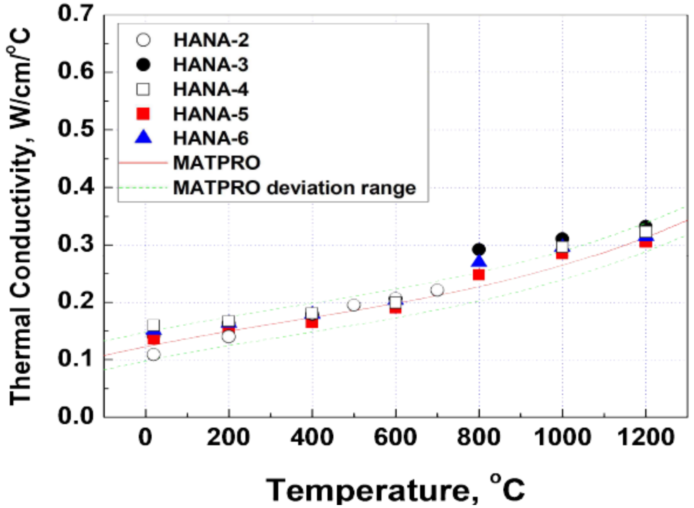

Fig.2 HANA thermal conductivity variation depending on temperature

Thermal expansion

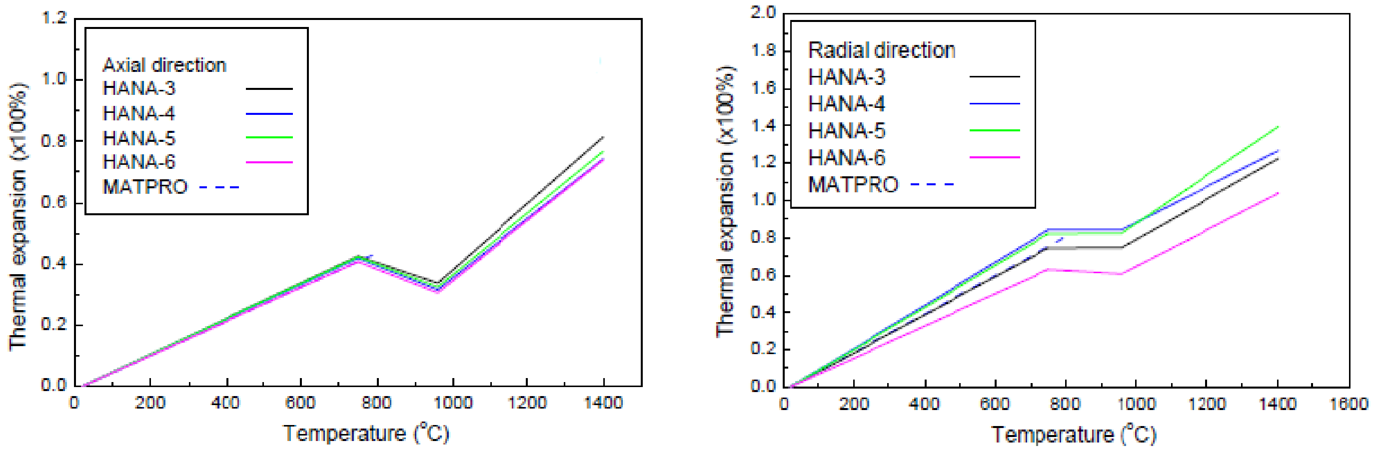

Fig. 3 HANA thermal expansion variation depending on temperature

- Measurement of HANA thermal conductivity shows overall trend is similar to MATPRO but a discrepancy beyond normal deviation range was observed near 800 °C
  → It will be further investigated with additional experimental data if possible

- Measurement of HANA axial thermal expansion is well agreed with MATPRO but radial thermal expansion is lower than MATPRO
  → It should be changed using additional experimental data

II. Models and material property correlations in FRAPCON/FRAPTRAN with cladding change

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Acceptance Criteria for cladding | FRPACON / FRAPTRAN | Available data

(PNNL-19417, rev.2)

(I.D. Peggs and D.P. Godin, Journal of nuclear materials 57, 1975)

Oxide thermal conductivity → Since the oxidation product of HANA-6 is also ZrO_2 equal to other zirconium alloys,

The model in FRAPCON/FRAPTRAN can be used without modification

Emissivity

→ In FRAPCON/FRAPTRAN, same surface emissivity is used for various Zircaloy alloys and therefore, an existing value can be applied to HANA-6 as well

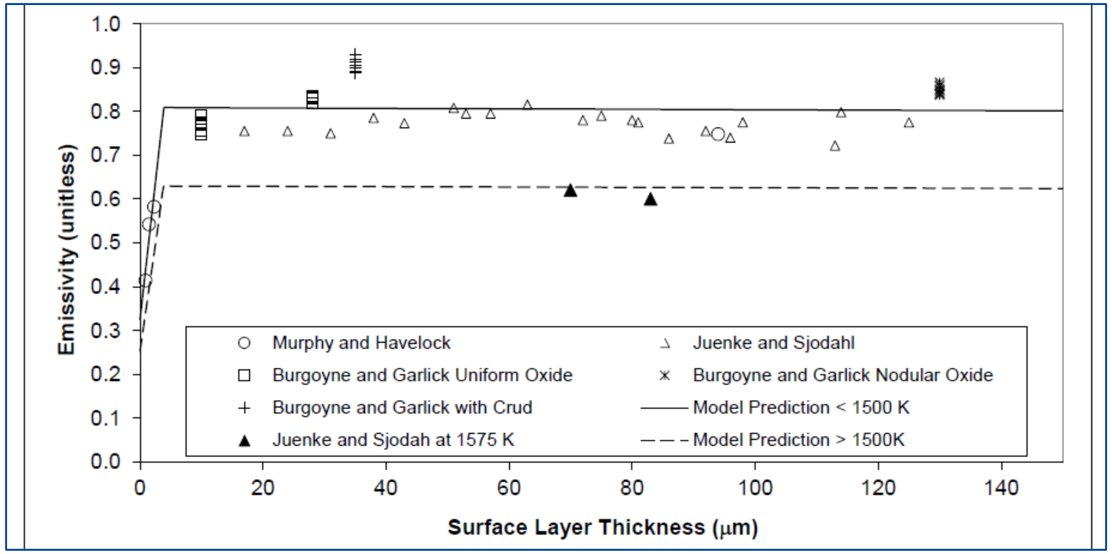

Fig. 4 Model-to data comparison for cladding oxide emissivity

Meyer hardness(MH)

→ In FRAPCON/FRAPTRAN, MH numbers for temperatures from 298 to 877 K were taken from Peggs and Godin (1975)

It will be further investigated with additional experimental data if possible

Acceptance Criteria for cladding | FRPACON / FRAPTRAN | Available data

(Y.S. Yang et al., KINS/HR-1835, 2022)

Density

Table 1. HANA-6 cladding density variation depending on temperature

Temperature [℃]	Density [kg/m³]
20	6,552
200	6,528
400	6,500
600	6,474
800	6,456
1,000	6,456
1,200	6,418

- In FRAPTRAN, a constant cladding density (6,550 kg/m^3, Zr-4) is adopted

- Sensitivity study to evaluate impact of cladding density variation will be conducted

Specific heat

- Measurement of HANA specific heat shows good agreement with MATPRO

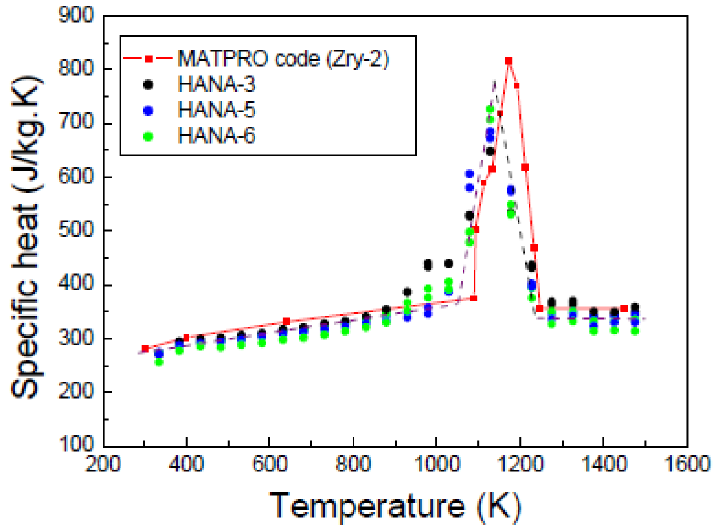

Fig. 5 HANA cladding specific heat variation depending on temperature

II. Models and material property correlations in FRAPCON/FRAPTRAN with cladding change

Acceptance Criteria for cladding | **FRPACON / FRAPTRAN**

(PNNL-19418, vol.1, rev.2)
(PNNL-19400, vol.1, rev.2)

Mechanical analysis

- **Stress & Strain**

  - The deformation analysis in FRAPCON consists of a small deformation analysis that includes stresses, strains, and displacements in the fuel and cladding for the entire fuel rod

  → Stress-strain curve; Elastic modulus; Shear modulus; Creep rate

- **Irradiation growth**

  - FRAPCON uses a uniform correlation with different coefficients for various Zircaloy alloys. Therefore, coefficients for HANA-6 should be needed for axial growth analysis

  → Axial growth

Acceptance Criteria for cladding | FRPACON / FRAPTRAN | **Available data**

(Y.S. Yang et al., KINS/HR-1835, 2022)

(Yong Hwan Jeong et al., JNST, 2006)

Stress-strain curve

- Stress-strain curve of HANA-6 at low temperature (25 °C) shows a clearly different shape to Zircaloy-4
- Ultimate tensile strength of HANA-6 is smaller than Zircaloy-4

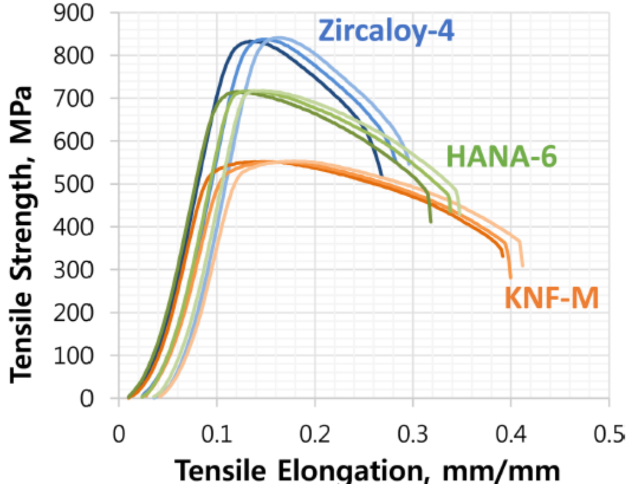

Fig. 6 Measurement of stress-strain curve of HANA-6 at 25 °C (unirradiated)

Elastic / Shear modulus

- Measurements clearly show that elastic and shear modulus of HANA-6 are different from those of Zircaloy-4 included in FRAPCON and FRAPTRAN

Table. 2 Comparison of Poisson's ratio of HANA-6 with Zr-4

No. of measurement	HANA-6	Zr-4
1	0.374	0.366
2	0.397	-
Average	0.386	0.366

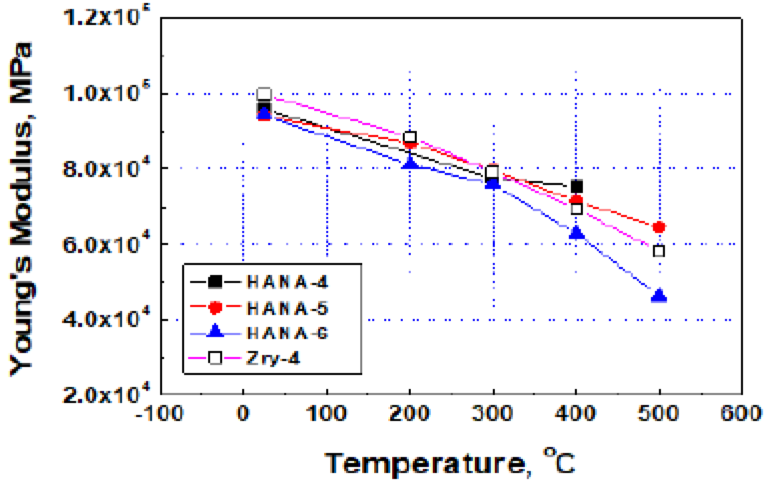

Fig. 7 HANA Young's modulus variation depending on temperature

II. Models and material property correlations in FRAPCON/FRAPTRAN with cladding change

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Acceptance Criteria for cladding | FRPACON / FRAPTRAN | Available data

(Y.S. Yang et al., KINS/HR-1835, 2022)

(H.G. Kim et al., J. of the Korean Society for Heat treatment, 2005)

Axial growth

$$ax = A \cdot \Phi^B$$

- FRAPCON uses a uniform correlation with different coefficients (A, B) for various Zircaloy alloys and the same goes for HANA-6

- Therefore, HANA-6 specific correlation coefficients should be used for cladding axial growth analysis

Creep rate

- It's known that HANA-6 has low creep resistance compared to Zircaloy and ZIRLO

- HANA-6 specific creep rate model should be developed for application in FRAPCON

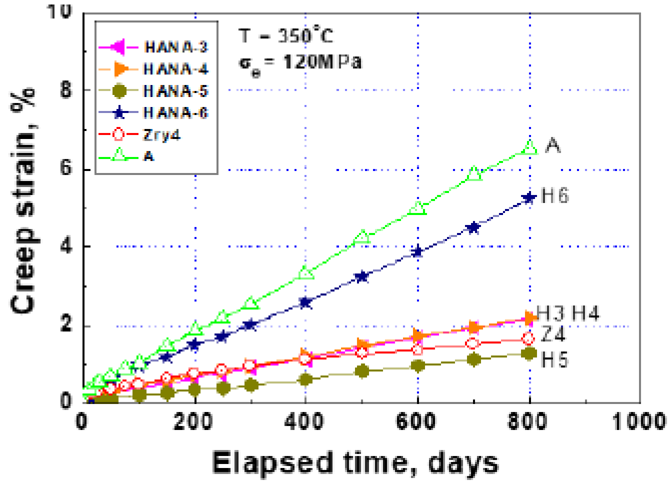

Fig. 8 Measurement of creep for HANA at 350 °C and 120 MPa

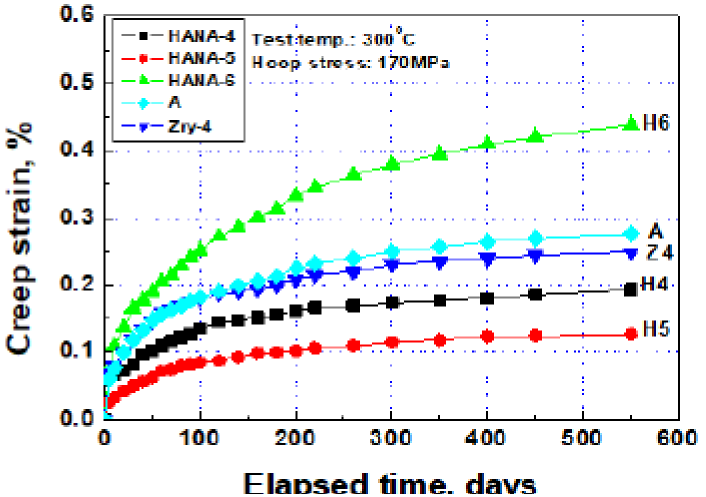

Fig. 9 Measurement of creep for HANA at 300 °C and 170 MPa

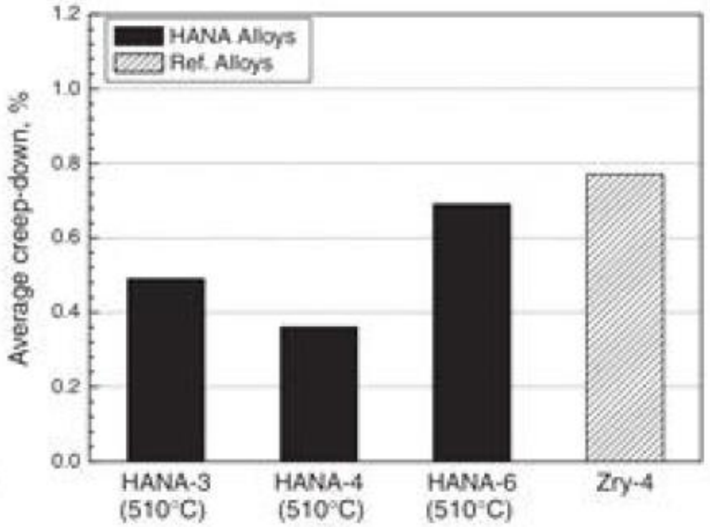

Fig. 10 Measurement of creep for HANA from Halden

(PNNL-19418, vol.1, rev.2)

Acceptance Criteria for cladding

FRPACON / FRAPTRAN

Corrosion analysis

- **Oxidation, hydriding, crud and cladding embrittlement**

- Oxidation, hydriding and buildup of corrosion products (Crud) should be limited

- In FRAPCON, waterside corrosion has different models before and after the transition

- Hydrogen produced by cladding oxidation process is absorbed into cladding material and gives rise to embrittlement of cladding

→

Waterside corrosion

High-temperature corrosion

Hydrogen pickup

II. Models and material property correlations in FRAPCON/FRAPTRAN with cladding change

(Y.S. Yang et al., KINS/HR-1835, 2022)

Waterside corrosion

- Measurements on before and after transition clearly reveal that HANA-6 has different but superior corrosion characteristics compared to Zircaloy-4

- The existing corrosion model in FRAPCON is to be updated with new model coefficients based on HANA-6 corrosion experiments

Hydrogen pickup

- In FRAPCON, constant hydrogen pickup fractions for PWR conditions has been used depending cladding materials such as Zircaloy-4, M5, ZIRLO & Optimized ZIRLO

- Therefore, the hydrogen pickup fraction for HANA-6 should be updated

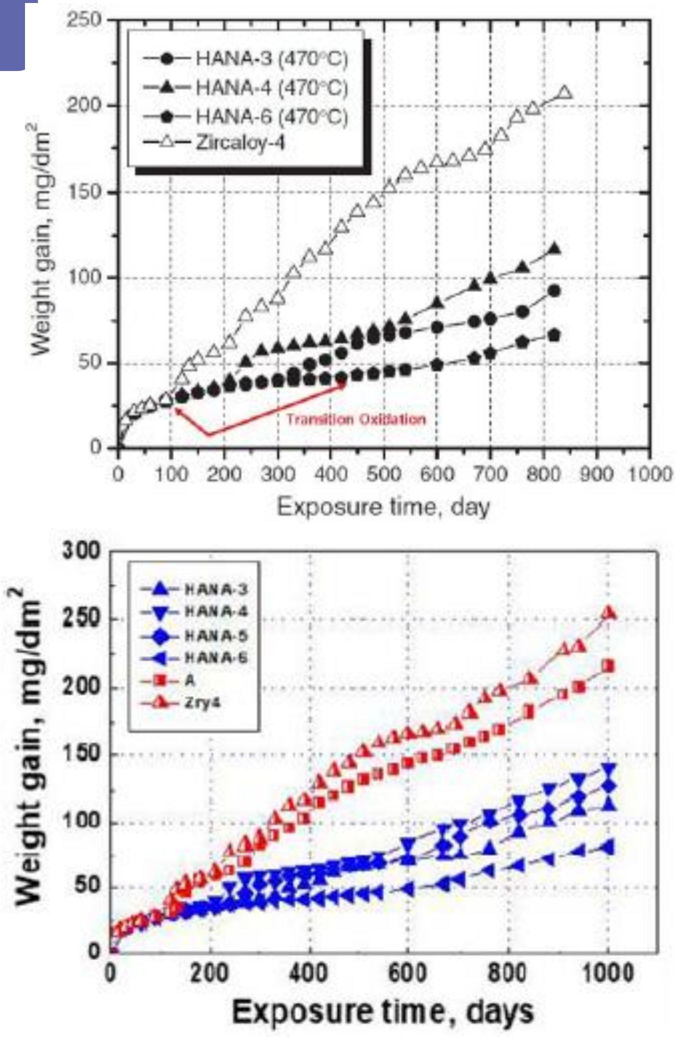

Fig. 11 Measurement of waterside corrosion of HANA

Acceptance Criteria for cladding | FRPACON / FRAPTRAN | Available data

(Y.S. Yang et al., KINS/HR-1835, 2022)

(Hun Jang et al., KNS, 2016)

(PNNL-19400, vol.1, rev.2)

High-temperature corrosion

- Cladding corrosion at high temperature condition such as Loss of Coolant Accident (LOCA) is conducted by FRAPTRAN

- FRAPTRAN has two models, Cathcart-Pawel (CP) and Baker-Just(BJ) with the same functional form but with different model coefficients

- Measurement shows that HANA-6 has different high-temperature corrosion characteristics from Zircaloy-4 and it gives about 5% increase in corrosion resistance compared to CP model

- Therefore, FRAPTRAN should be used with high temperature corrosion model coefficients for HANA-6

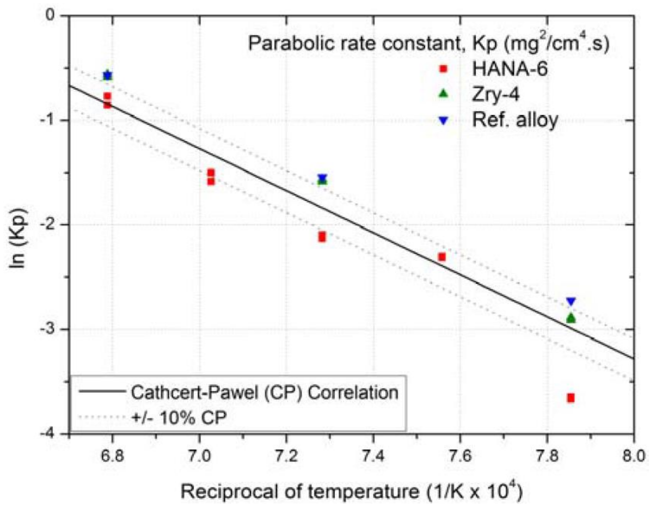

Fig. 12 Measurement of high-temperature corrosion of HANA-6

Acceptance Criteria for cladding

FRPACON / FRAPTRAN

(PNNL-19400, vol.1, rev.2)

Failure analysis

- **PCMI**

  - FRAPTRAN has two principal models that are used to predict when cladding failure happens. PCMI is the driving force for cladding deformation, a model based in uniform plastic elongation from irradiated cladding is used as the failure criteria

  → Uniform plastic elongation

- **Ballooning & Bursting**

  - If the cladding effective plastic strain is greater than the cladding instability strain, the ballooning model, BALON2 is used to calculate the localized, nonuniform straining of the cladding

  - In case of ballooning, the BALON2 model in FRAPTRAN predicts failure in the ballooning node when the cladding true hoop stress exceeds an empirical limit that is a function of temperature

  → Burst stress

  → Instability strain

Acceptance Criteria for cladding | FRPACON / FRAPTRAN | Available data

(Y.S. Yang et al., KINS/HR-1835, 2022)
(Hun Jang et al., spring KNS, 2017)

Uniform plastic elongation

- This model is a function of temperature and hydrogen concentration for irradiated Zircaloy
- It will be further investigated with additional experimental data if possible

Instability strain

- BALON2 model has a lot of inaccuracies, so KINS developed a new ballooning model based on high temperature creep and it was already incorporated in FAMILY code

Burst stress

- Measurement shows that the NUREG-0630 correlation for burst stress is applicable to HANA-6 and therefore an existing FRATRAN burst stress criterion can be conservatively applicable to HANA-6

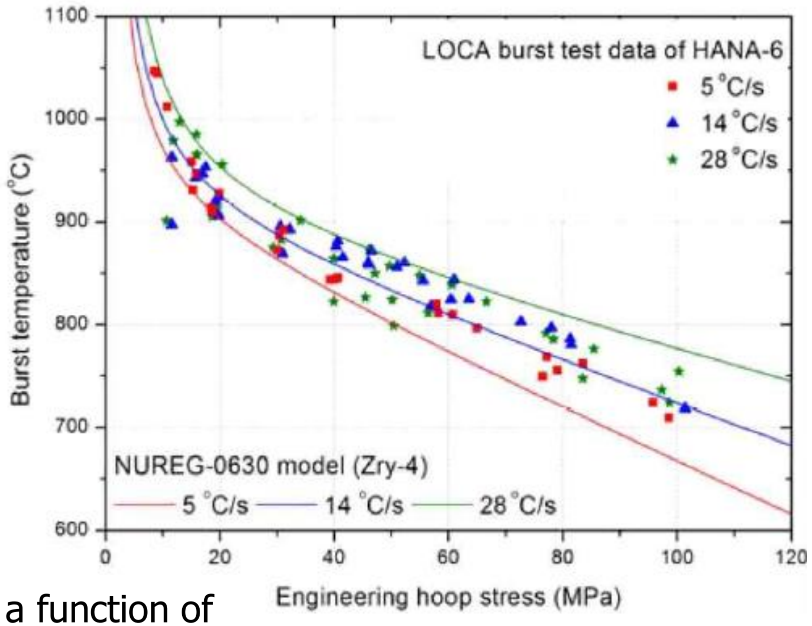

Fig. 13 Measurement of burst stress of HANA-6 as a function of engineering hoop stress and temperature-ramp rate

II. Models and material property correlations in FRAPCON/FRAPTRAN with cladding change

- **Status of confirmed models and material property correlations from FRAPCON/FRAPTRAN which need modifications for cladding change**

	Models or material property correlations for cladding	Need
1	Density	Sensitivity
2	Specific heat	-
3	Thermal conductivity	Sensitivity Data
4	Oxide thermal conductivity	Sensitivity
5	Surface emissivity	-
6	Thermal expansion	R-direction sensitivity
7	Elastic modulus/Shear modulus	Data
8	Axial growth	Data
9	Creep rate	Data

	Models or material property correlations for cladding	Need
10	Meyer Hardness	Further verification
11	Stress-strain curve	Data
12	Instability strain	-
13	Waterside corrosion	Data
14	Hydrogen pickup fraction	Data
15	Uniform plastic elongation at failure	Data
16	Plastic strain at failure	Data
17	Burst stress	-
18	High-temperature corrosion	Data

III. Conclusions

- Through rigorous analysis on acceptance criteria for cladding models and material property correlations attend by cladding changes are identified

- Specific evaluations for each of the models and material property correlations from FRAPCON and FRAPTRAN with cladding change application are conducted based on in-depth expert panel discussion and using proper references including experimental data for HANA cladding.

- Total 14 out of 18 models and material property correlations are re-identified as the critical items needs clear modifications for HANA-6 cladding application of FRAPCON and FRAPTRAN.

- Present research results will be applied to improve the fuel performance analysis codes for application of the new fuel with cladding change

감사합니다

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