21S-005

Oxidation, hydriding, and the buildup of corrosion products (crud) for Zr–based cladding

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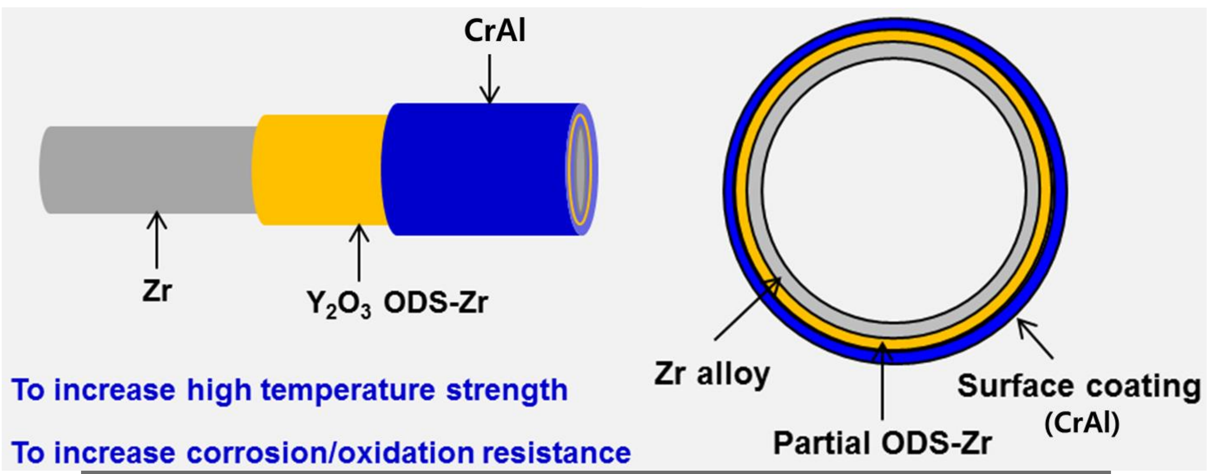
KNS 사단법인 한국원자력학회 KOREAN NUCLEAR SOCIETY

춘계 학술대회
May 13-14, 2021
On-line

Introduction

- Oxidation, hydriding, and the buildup of CRUD
  - Degrade cladding ductility, decreases in thermal conductivity and load–bearing thickness, Oxide spallation, etc.
  - Act as a heat transfer barrier => CILC / AOA
  - Acceptance criteria in regulatory SRP 4.2 [1,2]
    - Limited based on mechanical testing to demonstrate that each component maintains acceptable strength and ductility
    - Allowable levels and demonstration of acceptability on SAR
    - Effects in the thermal and mechanical fuel analyses
    - Effect of CRUD on T–H / neutronic (AOA) considerations
- Coated ATF cladding
  - Couldn't simply apply existing limits due to limited relevant knowledge & limited data
- In this study, those of ATF cladding (CrAl–ODS–Zr alloy) is qualitatively studied and its effect on fuel in–reactor behavior is discussed for PIRT development study
  - CrAl–ODS–Zr alloy ATF cladding [3,4]
    - CWSR Zry–4 cladding + Partial ODS treatment (Y_2O_3) by laser beam scanning (LBS) + CrAl coating by arc ion plating (AIP)



Structure of CrAl-ODS-Zr alloy cladding [3,4]

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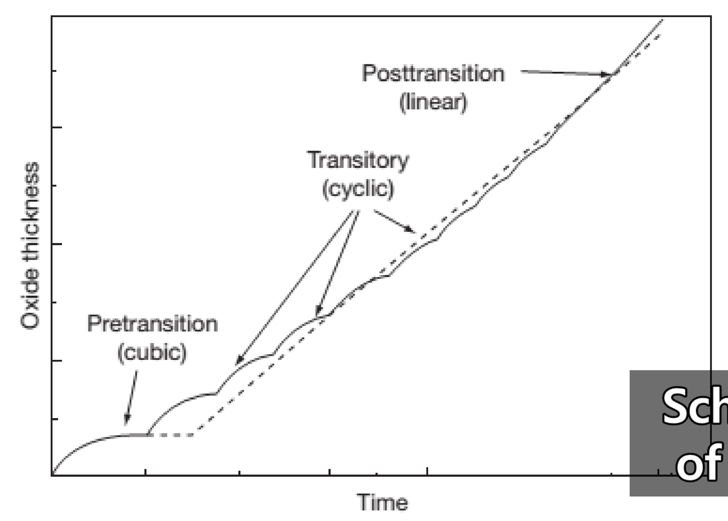
- Oxidation & Hydriding
  - Dependent on the various parameters (e.g. temperature, $Zr(Fe,Cr)_2$, hydrogen segregation at oxide/matrix interface, dissolved oxygen, irradiation, Li concentration)
  - Design limit at EOL [5]
    : 100 ㎛ (Oxide) and 500–600 ppm (Hydrogen)
  - Limiting parameter the length of time that fuel rod can safely be left in reactors
  - Garzarolli's model : Approximated pre–transition region (cubic rate law) and post–transition region (linear rate law)
    - Most of models on the fuel performance codes (e.g. FRAPCON, EPRI/KWU/CE, ESCORE, EPRI SLI, NE PLC etc.)
  - Hydriding : constant HPUF (hydrogen pickup fraction)
    - On FRAPCON, they depend on the material type (e.g. 0.15 for Zry–4, 0.1 for M5, 0.175 for ZIRLO/Opt. ZIRLO) [8]

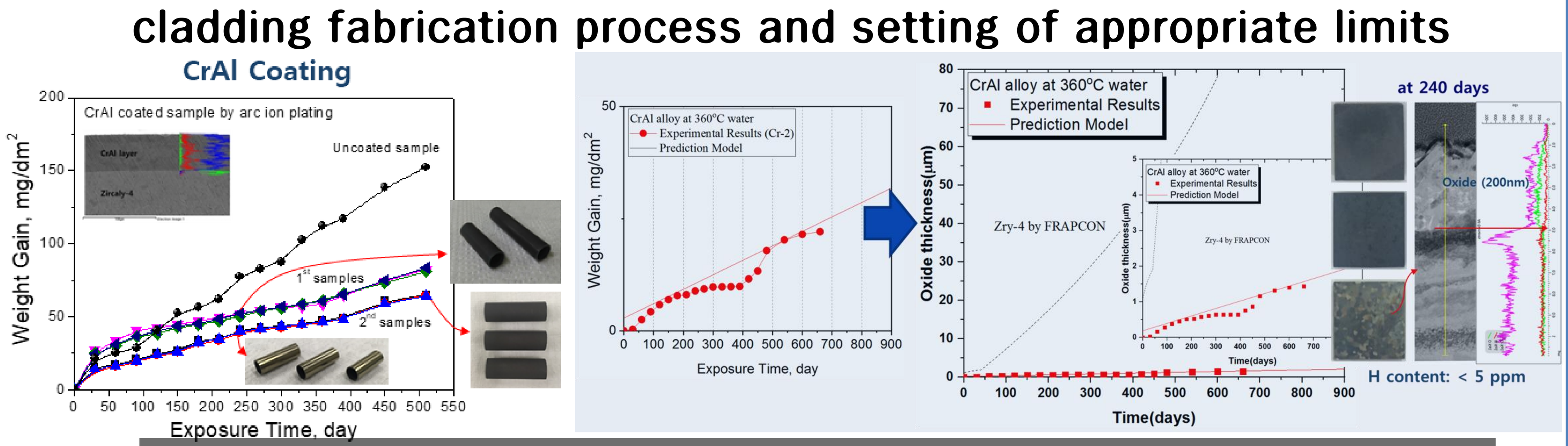


Schematic diagram of the oxidation rate of Zr-alloy during normal operation [7]

- CRUD
  - No relevant design limit
  - On FRAPCON, reflect CRUD effect on temperature analysis (no deposition model)

Oxidation, hydriding, and the buildup of corrosion products (crud) for CrAl–ODS–Zr alloy ATF cladding

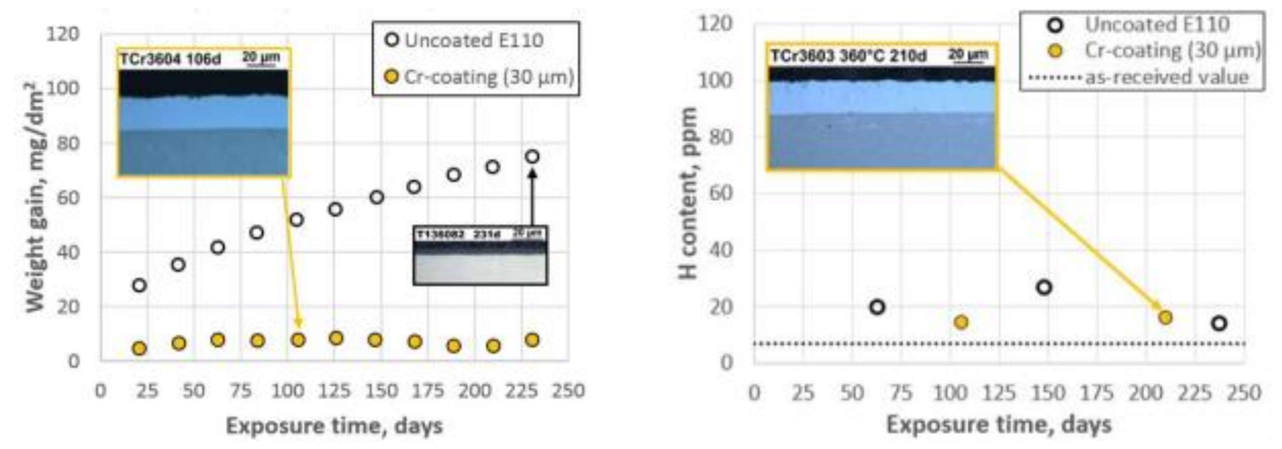
- Oxidation & Hydriding
  - Only outermost layer (CrAl) exposed to primary water need to be considered as long as coating layer maintains intact
    - Highly improved oxidation resistance without local flaking and galvanic corrosion
    - Prediction model : Considering only uniform corrosion
  - Most of Cr/CrAl data based on ex–reactor test (need to confirm by PIE of LTRs & evaluated based on in–reactor data)
  - Coating cracking and defects can be solved by optimization of cladding fabrication process and setting of appropriate limits



Oxidation properties of CrAl coated cladding (a) Autoclave test under 360°C simulated PWR environment, (b) Prediction model [10,11]

  - Hydriding : protective Cr_2O_3 prevent to diffuse hydrogen into Zr matrix and very low hydrogen pickup is anticipated
    - (M. Ševeček et al) high hydrogen pickup fraction for Cr–coated
    - Scatter? Need further examinations and in–reactor tests

Ex-reactor oxidation and hydriding properties of Cr-coated E110 cladding (360°C, 197 bar, simulated WWER env.) [12]



- CRUD
  - Significantly decreases the deposition rate for CrAl coated Zry–4 cladding using static autoclave at 360° C for 200 days)
  - Need additional ex–reactor and in–reactor test
- Limits for CrAl–ODS–Zr alloy ATF cladding
  - Zr–thickness is maintained => Existing design limits could be similarly applicable to Zr matrix with additional margin
    + limits for preventing coating cracking/delamination
  - Or separate limits based on the oxidation/mechanical test
  - No necessity for specific limit of CRUD buildup, but should be evaluated by PIE of LTRs and monitored in plants

Conclusion

- Superior resistance for oxidation and hydriding (need to confirm by PIE of LTRs and evaluated based on in–reactor data)
- Existing design limits could be similarly applicable to Zr matrix, with additional margin & coating cracking/delamination consideration
- Or separate limits based on the oxidation/mechanical test
- No necessity for specific limit of CRUD buildup, and CRUD deposition rates should be evaluated and monitored in plants

Acknowledgments & References

- This work has been carried out under the Nuclear R&D Program supported by the Ministry of Science and ICT. (NRF–2017M2A8A5015064)

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