



IMPACT OF FeCrAl CLADDING MATERIAL ON THE PROGRESSION OF A SEVERE ACCIDENT IN A GENERIC BWR4 MARK-1 NPP: ANALYSIS OF A SBO SCENARIO WITH THE ASTEC CODE

Onur Murat¹, Eddy Gazzola^{1,2}, Mauricio Exequiel Cazado¹, Michela Angelucci², Sandro Paci², Fabrizio Gabrielli¹, Victor Hugo Sánchez-Espinoza¹

¹Karlsruhe Institute of Technology (KIT), Institute for Neutron Physics and Reactor Technology, Germany

²University of Pisa (UNIP), Department of Civil and Industrial Engineering, Italy

1. MOTIVATION

- A **Station Blackout (SBO)** event can lead to severe accident if electrical power is not restored within the coping time.
- Conventional **Zr-based alloys** cladding has limitations under severe accident (SA) conditions, specifically rapid oxidation and massive hydrogen release.
- This study uses the ASTEC code to assess the potential of **Advanced Technology Fuels (ATF)** concepts. Particularly, **FeCrAl** cladding, to mitigate or limit the accident progression.

2. ASTEC MODEL AND ATF IMPLEMENTATION

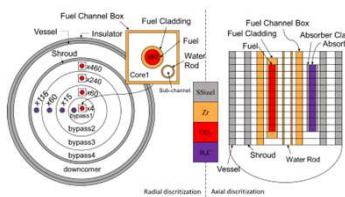


Figure 1. Reactor Core radial mesh (left) and axial mesh (right) loaded with GE14 10x10 fuel assembly [1]

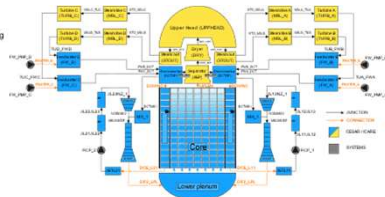


Figure 2. BWR Reactor Pressure Vessel and water circulation system [1]

- The reactor concept analyzed is [1] is a generic BWR-4 Mark-I with loaded 764 GE10x10 fuel assemblies.
- The active core discretized radially into 5 rings and axially 10 uniform meshes.

FeCrAl Implementation

- FeCrAl thermal properties were assessed and defined for both solid and liquid phases.
- These properties are critical for accurately calculating the core's heat capacity and thermal response during the SBO transient.
- The oxidation model follows a Parabolic Rate Law where the oxygen mass gain:

$$K_p = A_{\text{Gain}} \cdot \left(e^{\frac{B_{\text{Gain}}}{R \cdot T}} \right) \left[\frac{\text{Kg}^2}{\text{m}^4 \cdot \text{s}} \right]$$

Temperature [K]	$A_{\text{Gain}} \left[\frac{\text{Kg}^2}{\text{m}^4 \cdot \text{s}} \right]$	$B_{\text{Gain}} \left[\frac{\text{J}}{\text{mol}} \right]$	Comments
$873 \leq T < 1173$	$5.376 \cdot 10^{-3}$	$1.847 \cdot 10^5$	θ -alumina
$1173 \leq T < 1273$	$4.692 \cdot 10^{-12}$	0.0	-
$1273 \leq T < 1648$	5.018	$2.877 \cdot 10^5$	α -alumina
$T \geq 1648$	$2.4 \cdot 10^9$	$3.527 \cdot 10^5$	Fe-oxide

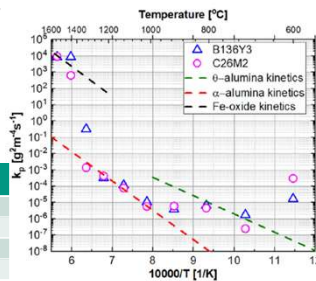


Figure 3. Parabolic rate constants of B136Y3 and C26M2 as a function of the temperature with the parabolic constants of Fe-oxide, θ -alumina and α -alumina [2]

- Strong oxidation rate occurs at 1648 K from α -Al₂O₃ to Fe-oxide formation.

3. BEST ESTIMATE CASE RESULTS

- Simulations indicate that substituting Zircaloy with FeCrAl significantly delays cladding failure and temperature escalation.
- FeCrAl cladding demonstrates a strong reduction in oxidation rates, leading to a significant decrease in total hydrogen production, in particular before the cladding failure.
- After extensive cladding failure and core degradation, the late-phase models still rely on Zr-based assumptions; therefore, late in-vessel results should be interpreted with caution.

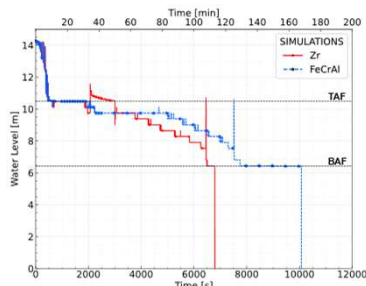


Figure 4. Water level in the vessel during accident progression

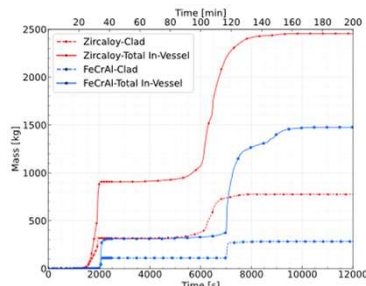
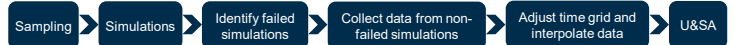


Figure 5. Hydrogen production resulted by the oxidation reaction

4. UNCERTAINTY AND SENSITIVITY ANALYSIS

- An Uncertainty and Sensitivity Analysis (U&S) was conducted using the KIT in-house **KATUSA** tool [3]. Flow chart of the tool for uncertainty analysis is given below:



- The analysis quantified the impact of uncertain inputs on Figures of Merit, specifically the cumulative hydrogen mass and total activity in containment.
- Two primary parameters were evaluated: an absolute temperature shift (T_{usa} between -50 and +50) and a kinetic multiplier (A_{usa} between 0.85 and 1.15).

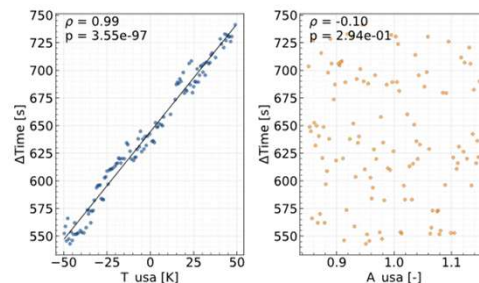


Figure 6. Spearman correlation analysis for hydrogen production delay

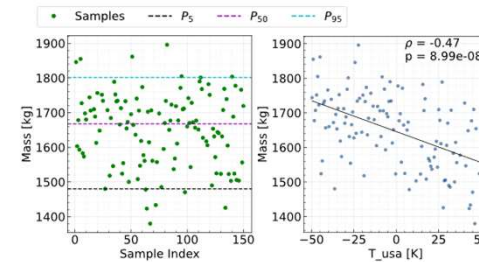


Figure 7. Uncertainty distribution and sensitivity of total RPV hydrogen generation to transition temperature T_{usa}

The very high Spearman correlation coefficient ($\rho = 0.99$) and negligible p-value ($3.55e-97$) indicate an almost perfect linear relationship between the temperature shift and the timing of hydrogen production.

Time delay is directly proportional to how long the protective α -alumina layer remains stable.

Even with uncertainties, the maximum hydrogen produced in the vessel (~ 1900 kg) is still significantly lower than the Zircaloy baseline (~ 2460 kg), confirming benefit of the FeCrAl material in terms of reactor safety.

The spearman coefficient indicates a moderate negative relationship between switching temperature and produces total hydrogen mass.

Increasing the transition temperature keeps the material in the α -alumina regime (slow oxidation) for a longer duration. Consequently, the core spends less time in the Fe-oxide regime (rapid oxidation) before the simulation ends or the geometry fails, leading to less hydrogen production.

5. CONCLUSION

- In an unmitigated SBO scenario, a generic BWR-4 Mark-I experiences rapid core degradation when utilizing standard Zircaloy cladding.
- The implementation of **FeCrAl ATF concepts successfully delays** the accident progression and massively decreases hydrogen generation.
- While oxidation kinetics strongly drive the accident progression, dedicated model for FeCrAl are still required to assess late-phase phenomena.

ACKNOWLEDGEMENTS



The work has been performed in the framework of the mobility program of the EU SEAKNOT project, which has received funding under the Grant Agreement No. 101060327. The content of this work reflects only the authors' view. The European Commission is not responsible for any use that may be made of the information it contains.

The authors gratefully acknowledge Dr. -Ing. Anastasia Stakhanova for her continuous support and expert feedback during the uncertainty analysis with the KATUSA tool.

REFERENCES

- [1] Murat, O., Sanchez-Espinoza, V., Gabrielli, Wang, S. F., Stieglitz, R., and Queral, C., "Improved Analysis of the Short-Term Station Blackout Accidents of the Peach Bottom Unit-2 Reactor with ASTEC Including Radiological Impact and Statistical Analysis with JRODOS", Nuclear Engineering and Design, Vol. 420, pages 113012, 2024. DOI: 10.1016/j.nucengdes.2024.113012
- [2] C. Kim, et al., "Oxidation mechanism and kinetics of nuclear-grade FeCrAl alloys in the temperature range of 500-1500°C in steam," Journal of Nuclear Materials, vol. 564, p. 153696, 2022.
- [3] Stakhanova, A., Gabrielli, F., Sanchez-Espinoza, V. H., Hofer, A., & Pauli, E. M. (2023). Uncertainty and sensitivity analysis of the ASTEC simulations results of a MBLOCA scenario in a generic KONVOI plant using the FSTC tool. Annals of Nuclear Energy, 192, 109964. <https://doi.org/10.1016/j.anucene.2023.109964>