Advanced Cladding Materials for Accident Tolerant Fuels

Janne Heikinheimo, Caitlin Huotilainen, Rami Pohja, Mykola Ivanchenko and Henri Loukusa

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ATF overview

- Nuclear fuel cladding is one of the main barriers in preventing the release of radioactive materials to the environment
- The integrity of the fuel cladding is essential in operation, accident conditions and during long-term storage of spent nuclear fuel
- The traditional UO_2-zirconium alloy fuel system has a well-proven safety and operational record that meet current safety requirements from the regulator
- ATF designs should endure severe accident conditions longer than the traditional fuel and cladding systems, as well as offer the same or better fuel performance during normal operation
- Currently ATF cladding consider numerous types of materials from metallic to ceramic

List of criteria for ATF

- The cladding of nuclear fuel has two major roles:
  - Confine fissile material, while maintaining a good neutron transparency
  - Enable efficient thermal conductivity between the fuel and the coolant
  - Maintain appropriate corrosion and mechanical properties under operation and accident condition
- ***Design basis event*** *(DBE) or* ***design basis accident*** *(DBA) is a postulated event/accident used to establish performance requirements of the structures, systems, and components to withstand the event without endangering the health or safety of the plant operators or the wider public.*

- Currently accepted DBA scenario allow:
  - no incipient melting of the UO_2 fuel
  - cladding temperature should not exceed 1200°C
  - reactor core should be able to accept emergency cooling

Cr and Cr/Al coated zirconium alloys

- Probably the most promising strategy up-to-date is to improve the Zr-alloy's behaviour under working and accident conditions via coating cladding surface with Cr or Cr/Al coating
- Less then 20 μm coating in order to have minimal increase in neutron cross-section can benefit with
  - reduced oxidation kinetics
  - reduced hydrogen pick-up fraction
  - increased wear resistance
  - provide similar mechanical properties as uncoated claddings under normal operational conditions
  - reduce high-temperature steam oxidation and hydrogen production under accident conditions
  - improve post-quench ductility and reduce creep and ballooning effects

FeCrAl alloys

- FeCrAl alloy cladding is fully compatible with both the current boiling water reactor (BWR) and pressurized water reactor (PWR) coolant chemistries and shows excellent corrosion resistance
- Disadvantages:
  - higher neutron cross-section compared to zirconium and its alloys
  - may introduce an increased tritium release into the reactor coolant
  - lack of available experimental data especially under neutron irradiation
- Experimental work is ongoing (ORNL, USA)

42HNM

- Bochalloy 42HNM (in Cyrillic 42XHM) is a Ni-base alloy with Cr and Mo as its primary alloying elements (41-43 wt.% Cr and 1-1.5 wt.% Mo). Developed in the late 90's in the A.A. Bochvar Research Institute of Inorganic Materials (SSC RF-VNIINM) as a radiation and corrosion resistant Ni-Cr alloy to replace austenitic stainless steels used as a cladding material for control rods.
- Presents good mechanical properties, in terms of plasticity and elongation after irradiation to very high fluences at 350°C
- Excellent resistance to IGSCC in Cl-containing environment up to high doses (>30 dpa)
- Disadvantages:
  - Above 550°C mechanical properties are significantly degraded
  - Highest neutron cross-section in comparison to other considered ATF materials

MODELLING AND MATERIAL BEHAVIOUR

Fuel performance overview

- Standard evaluation of ATF performance include:
  - neutronics
  - thermal-hydraulics
  - fuel performance
  - detailed system analysis
- Codes have been modified for ATF characteristics already, but more experimental data needed for proper modelling.
- A large-scale analysis and code coupling is required to get the full picture of the reactor's safety and performance characteristics under accident conditions.
- Accident scenarios, such as loss of coolant accidents (LOCA), simulated with the fuel performance codes (FRAPTRAN) via coupling it with the thermal-hydraulic and thermomechanical codes: TRACE and GENFLO (a Finnish thermal-hydraulics code).
- Modelling of ATF homogeneous cladding material (FeCrAl) can been done with FRAPCON/FRAPTRAN, FUPAC, FALCON and TRANSURANUS.
- More complex structures, such as coated claddings, can be modelled with finite element (FEM) codes, such as BISON (INL, USA), COMSOL, ADINA, and ABAQUS.
- Multi-scale modelling can play a significant role in the ATF design by reducing the need for in-pile testing and thereby accelerating the safety review process. For example, irradiation degradation has recently been evaluated with molecular dynamics and phase field methods for U-Mo fuel and SiC composite cladding.

Oxidation and hydrogen pick-up

- Thermal conductivity of the fuel rod is depended on the thickness of the oxide layer
- One product of the oxidation reaction is hydrogen. When hydrogen pick-up during oxidation is combined with stress, it leads to the formation of brittle hydrides, which reduce the cladding's ductility.
- ATF offer corrosion resistance in nominal conditions provide significant enhancement of the resistance of the material to oxidation in steam at high temperatures (up to 1300°C), with a drastic decrease of hydrogen pick-up
- Coating spallation during high temperature transients, due to interphase transformation will expose the unprotected underlying material to extremely volatile oxidizing conditions

Mechanical behaviour

- Oxide dispersion strengthened (ODS) FeCrAl steels exhibit excellent high temperature strength, creep resistance and improved corrosion resistance
- The drawback for ODS FeCrAl-alloys:
  - due to the fabrication process strongly directional microstructure, leading to anisotropic mechanical properties
  - fusion welding causes agglomeration of fine oxide particles, which results in a loss of strength and creep properties of ODS joints
- In the case of coated claddings cracking or delamination of the Cr-coating may occur at a certain level of strain during high temperature accidental conditions
- Further research is needed to validate the equivalent or better mechanical properties, such as strength and creep resistance under irradiation and in their irradiated state, as compared to traditional Zr-based claddings

Summary

Accident tolerant cladding material concepts Cr-Cr/Al coated cladding, FeCrAl alloy, and 42HNM show improved behaviour at higher temperatures compared to the traditional Zr-alloy.

However, they have some drawbacks or additional limitations when applied in the operational conditions.

Fuel performance modelling, oxidation, hydrogen pick-up and mechanical behaviour should be addressed when these materials are considered

Acknowledgements

The authors would like to thank the Finnish Research Programme on Nuclear Power Plant Safety 2019 – 2022 (SAFIR2022) for their financial support of the Interdisciplinary Fuels and Materials (INFLAME) project

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Corresponding author: janne.heikinheimo@vtt.fi
Presentation by: mykola.ivanchenko@vtt.fi