Study and assessment of (FeCrAl) and (SiC) as candidate materials for accident tolerant fuel cladding in LWRs

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Abstract. Iron-chromium-aluminum (FeCrAl) alloys and Silicon-carbide (SiC) are considered the best choice proposed as alternative cladding materials to replace Zirconium (Zr) alloys to improve the accidents tolerance in light water reactor (LWR) cladding which have much highly oxidation resistance in high-temperature steam than Zr alloys, which lead to maintaining high performance under normal operations and enhancing safety margins during severe accidents. In this work great results were showed in the thermo-physical properties for the candidate materials compared with zirconium.

1. Introduction

After the Fukushima-Daiichi accident in 2011, the demand of increasing the safety margin in nuclear industry by proposed Accident Tolerant Fuels (ATF) for fuel and cladding materials, the main goal of ATF philosophy is increasing the controlling time during accidents in Light Water Reactors (LWRs) and improving the performance of reactors during normal operations and operational transients [1]. Figure. 1 Describes the core degradation processes under loss of coolant conditions during accidents condition which lead to elevated temperature in LWRs core, the blue curve show how the ATFs cladding mitigation the degradation processes inside the reactor core [2].

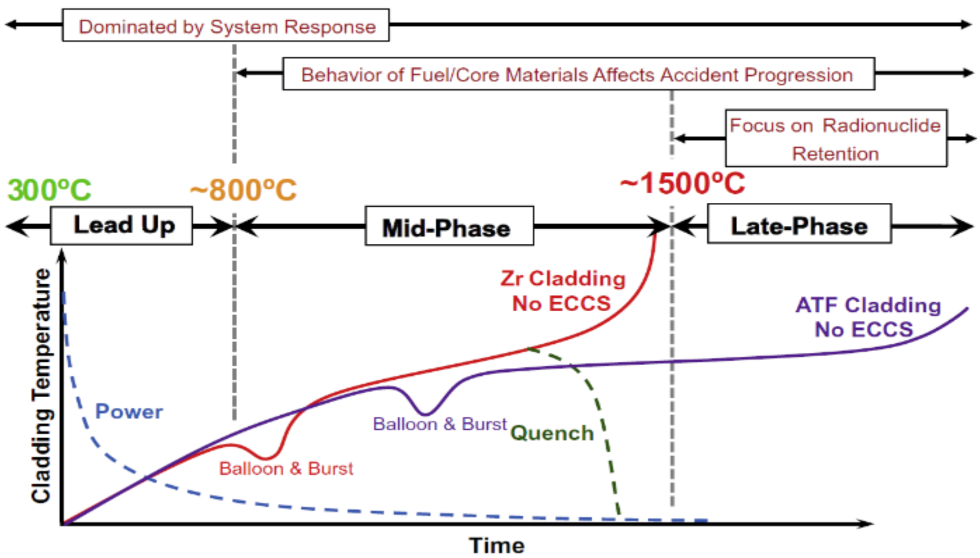

Figure 1. degradation processes inside LWRs core during coolant-limited

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The efforts of development ATFs were focused to a main three issues: a) Eliminate the hydrogen production by reducing the oxidation rate of cladding with high-temperature steam; b) improve the thermal, mechanical and chemical properties of cladding materials to withstand the failure; c) modify the current fuel-cladding systems for lower operation temperatures [3]. Figure. 2 shows the different concepts of accident tolerant fuel under research now which include the fuel design and cladding materials [4]. For fuels, focused on advanced UO2 formulations, high density U fuels (nitride and silicide) compositions and fully ceramic microencapsulated (FCM) fuels [5]. for cladding research and development is focused on improved composition of current Zr alloys [6], coated Zr alloys like MAX phase coatings [7], FeCrAl alloys as replacement or coating on Zr alloys [8][9], Cr coatings [10], Mo coatings [11], Polycrystalline diamond coatings [12], and ceramic (SiC/SiC composite) cladding materials [13]. In this paper the thermo-physical behavior of two types of materials FeCrAl and SiC compared with zirconium were discussed including the advantages and the challenges.

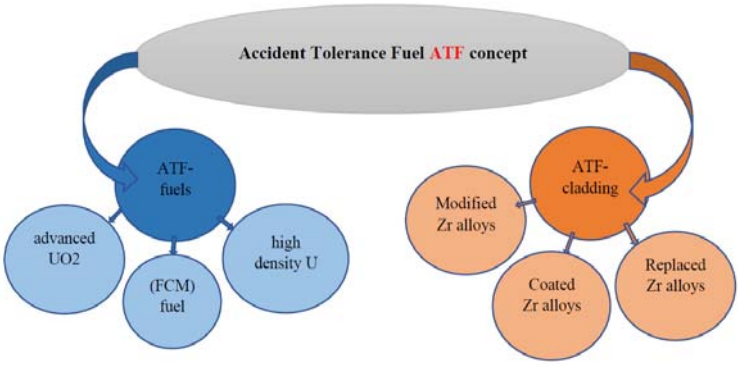

Figure 2. Clarified sketch of current Accident Tolerant Fuel concepts

2. Desirable Properties of fuel and Cladding:

As show in Table 1. The desirable properties for both fuel pellet and cladding always together for lower and higher under the normal or transient operations, however, sometime a property is desirable under normal condition but not desirable under other operation conditions and vice versa. High thermal conductivity is desired to limit the fuel centerline temperature, slow oxidation rate and high strength are desirable in cladding materials at all operation scenarios to limit the rapid degradation in the cladding, for LOCA and SBO, high heat capacity and low creep rate of cladding are desired but insensitive in the fuel pellet [14].

Table 1. Desirable properties of the fuel pellet and cladding materials under NO: normal operation, LOCA: loss-of-coolant accident and SBO: station blackout, (H & L) indicates for high, low respectively and (-) indicates insensitivity [14].

Fuel Cladding				Fuel Pellet		
	NO	LOCA	SBO	NO	LOCA	SBO
Thermal Conductivity	H	H	-	H	H	-
Strength	H	H	H	-	-	-
Oxidation Rate	L	L	L	-	L	L
Creep Rate	H	L	L	H	-	-
Heat Capacity	-	H	H	-	H	H

3. Properties of ATF candidate cladding materials

To create accident tolerant fuel in LWRs fuel cladding, many alternative materials to Zr alloys are being investigated which have >100X improvement in oxidation resistance at high temperature compared to current Zr-based cladding [2]. Figure 3. showed highly results in some thermo-physical properties of two types of candidate materials FeCrAl and SiC compared with zirconium which were amply discussed in references [15][16].

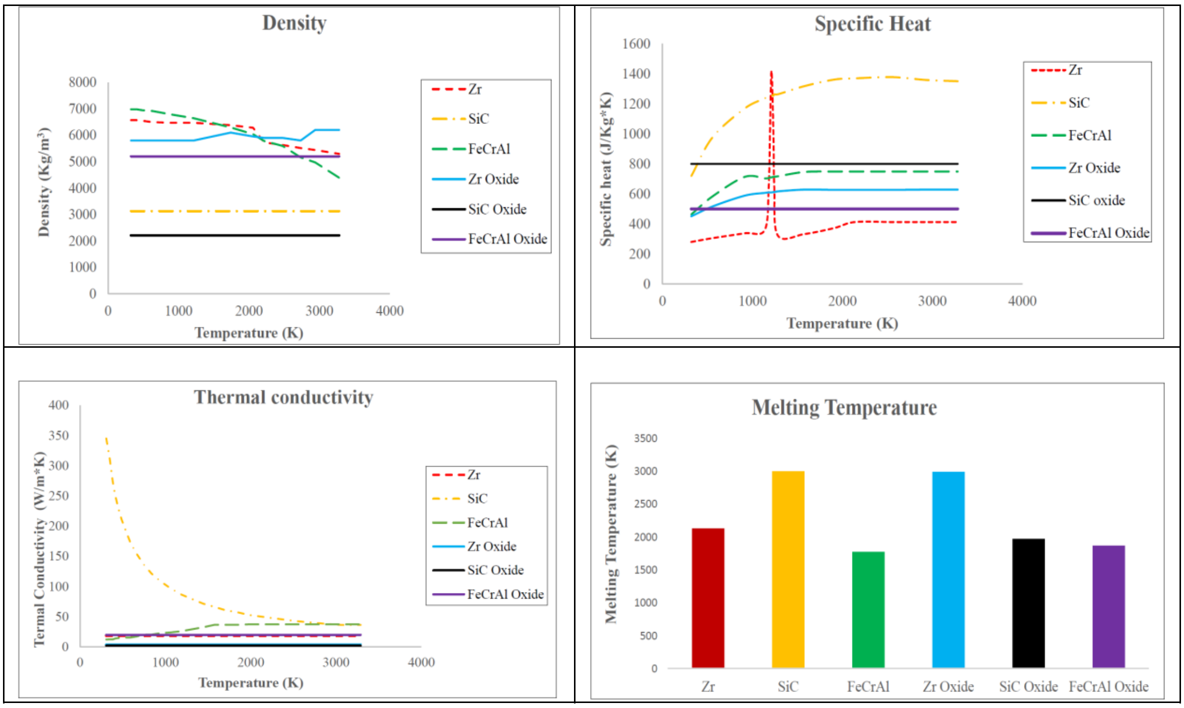

Figure 3. thermo-physical properties of candidate materials compared with zirconium

Table 2. Described some properties of candidate alternate cladding materials and cladding currently uses zircaloy, all candidate materials have significantly slower oxidation kinetic in high-temperature steam than zircaloy according to parabolic oxidation rate constant (POR) at 1200 °C. For SiC has the lower thermal absorption cross-section than Zircaloy, also SiC have chemically inaction, a high radiation resistance, reduced hydrogen generation under off-normal conditions, ability to withstand higher temperatures and considered to be generally stable in nuclear waste. For metallic candidate FeCrAl show macroscopic neutron thermal cross section (Σthermal abs) nearly ~22× greater than Zircaloy [17]. To withstand this neutronic penalty it will be necessary reduces the cladding walls thickness to nearly (~300μm) half the thickness of Zr alloys (~600μm) which current uses to have similar neutron absorption [18], also higher enrichment fuel with slightly larger pellets will be necessary [19].

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Table 2. Summary of relevant data for cladding material options [17].

Clad Material	Density [g/cm^3]	Composition [wt.%]	$\Sigma^{\text{thermal abs}}$ [cm^{-1}]	POR constant in 1200 °C steam [mg]
Zircaloy	6.56	98.26 Zr, 1.49 Sn, 0.15 Fe, 0.1 Cr	0.0028	6.5×10^{-4}
FeCrAl	7.1	75 Fe, 20 Cr, 5 Al	0.0634	1.8×10^{-6}
SiC	2.58	70.08 Si, 29.92 C	0.0021	3.7×10^{-7}

Figure 4. described two types of candidate cladding materials when tested in flowing steam with elevated temperature and pressure at different experiments, in figure 4. a, both alumina formers and silica formers candidate claddings produced oxides outperformed zircaloy, which assumed to be suitable materials to withstand the degradation under abnormal operations condition in LWRs [20], also Pint et al. from ORNL their found the significantly reduced in the hydrogen production from candidate materials compared with zircaloy used as current cladding material, showed in figure 4. b [21].

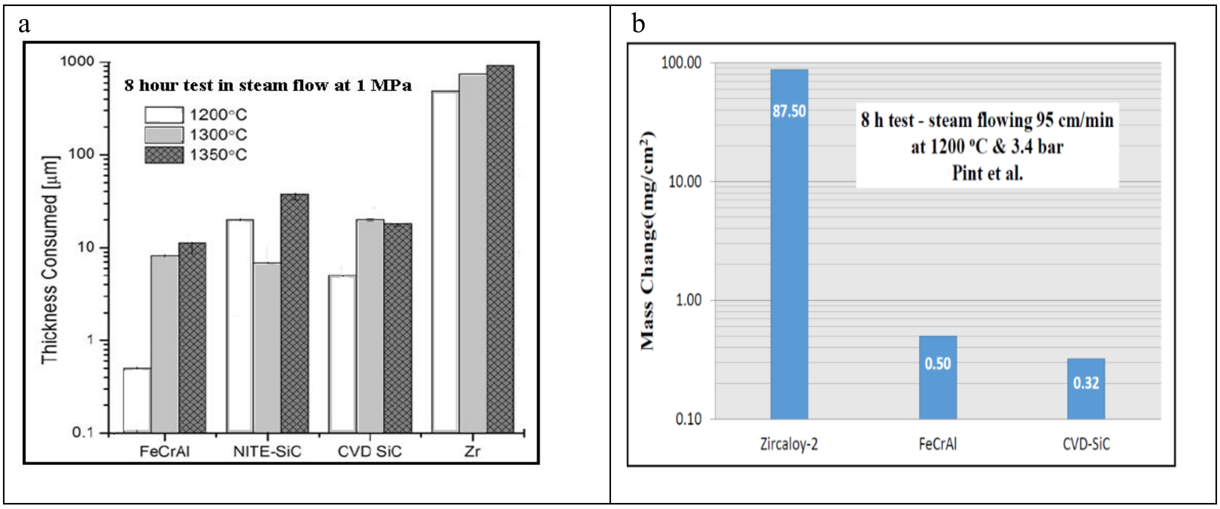

Figure 4. (a) Thickness loss and (b) Oxidation mass change of candidate materials

4. The challenges of candidate materials

As previously discussed, there are some challenges showed when compared the new materials with Zircaloy must solved before goes on to be used as a cladding material in commercial reactors, for FeCrAl material:

- FeCrAl alloys show a thermal neutron cross-section much greater than Zr alloys, this decreases the reactivity of the core, subsequently decreasing the potential cycle length for operation[22].
- FeCrAl cladding may release more tritium to the coolant than Zirconium alloys one solution for this problem might be coating inside part of the tube with alumina [23].
- Also the alpha prime precipitation in FeCrAl after neutron irradiation which is still under investigation [24].

For SiC there are two challenges requiring further examination before approved SiC as cladding materials:

- Water cooling caused aqueous corrosion.
- Microcracking during normal operating conditions.

5. Conclusion

One of approach of developing ATFs cladding LWRs is replace Zr alloys by new materials have highly oxidation resistance to delay and reduce the heat and hydrogen generated during accidents conditions. FeCrAl & SiC claddings, is most important materials will be uses to improving the performance of normal operation and withstand the rapid degradation at accident conditions in LWRs, which increase the safety margin during sever accidents which lead to high progress in nuclear industry. Some challenges meet FeCrAl such as neutronic penalty which overcoming by high enrichment and increased fuel, also decreasing the thickness of cladding might be effective to reduce this neutronic penalty.

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