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The FeCrAl Cladding Assessment under Accident Condition Using TRANSURANUS Fuel Performance Code

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1.Introduction

The Fukushima Daiichi accident exhibited one of the main drawback of zirconium alloy cladding under accident condition, because of this, worldwide efforts are concentrated toward to obtain accident tolerant fuels (ATF), which the main scope resides in the replacement of existing fuel system based on zirconium alloys and conventional uranium dioxide (UO_2) fuel pellet. In this sense, ATF claddings shall enhance the performance and improve safety, considering reduced rate of heat generated from steam oxidation at high temperatures in the event of accident, which will in turn reduce the rate of temperature rise and the hydrogen generation, delay core degradation, and hence provide additional coping time for accident mitigation[1].

A different and alternative fuel system (cladding and fuel) has been investigated in the framework of ATF program conducted by several institutions, including major fuel vendors, national laboratories, and universities around the world. Nowadays, ATF research has seen many different strategies considering availability and existing technology, material data readiness application for near, mid, and long term. The strategy for near term considers the existing cladding technology that can be applied without much modifications in order to make easier the license process, as well as validation, and verification activities. The chromium coated zirconium-based alloys and iron-based alloy (FeCrAl) claddings options were considered to be most promising for near term application. Recently, the Cr-coated cladding using a cold spray process developed by Westinghouse considering ZIRLO® and Optimized ZIRLO™ claddings had been submitted to irradiation at MIT research reactor and as lead test fuel rods in the Byron (PWR) reactor in April of 2019[2]. Additionally, as part of the DOE's ATF program, the FeCrAl lead test fuel rods developed by GNF (Global Nuclear Fuels) fuel vendor company was loaded in the Hatch nuclear power plant during the 2018 refueling outage[3].

The aim of this work is to address and contribute to the assessment of new cladding material properties and correlation using the well-known TRANSURANUS code[4] for iron alloy (FeCrAl) cladding using the separate effect experiment named PUZRY from AEKI[5], which consists of an experimental test series to investigate ballooning and burst phenomena for zirconium-based alloy cladding.

2. Methodology

In order to perform the preliminary assessment of the FeCrAl alloy as ATF cladding, the material data, thermal-mechanical properties and correlations were taken from available open literature (mainly from ORNL FeCrAl Databook[6]), as well as commercial FeCrAl alloy datasheet. In a previous work, the AISI-348 was implemented as cladding material in the TRANSURANUS 2017 version (v1m1j17) [7] as part of preliminary ATF cladding assessment. As starting point, a similar approach adopted for AISI-348 implementation was considered to implement FeCrAl as a cladding option in the newest version of TRANSURANUS (2019-v1m3j19). Initially, the modifications were mainly limited to thermal and mechanical properties data, therefore the kinetic model of water side cladding corrosion, and correlations associated to corrosion, such as hydrogen uptake and others chemical reactions were not considered.

The modifications in the TRANSURANUS code comprise the following data, correlations, and models: modulus of elasticity, Poisson ratio, swelling, thermal strain, thermal conductivity, creep rate, yield stress, fracture strain, true tangential stress at rupture of cladding as a function of temperature and oxygen concentration (burst stress), specific heat, heat of melting, emissivity, solidus, and liquidus melting temperatures, and density.

The preliminary assessment of modified TRANSURANUS code (version 2019-v1m3j19) was performed simulating PUZRY experiment, which consist of a series of isothermal ballooning and burst experiments with Zircalloy-4 unirradiated, and unoxided single rod. The experiment was performed at AEKI/Hungary, aiming to investigate mechanical behavior (separate effects) under well-controlled environment: temperature range between 973 and 1473 K, pressurization rates from $7\times10{-4}$ to $2.6\times10{-2}$ MPa/s, and constant inert gas concentration.

Initially, the zircalloy cladding was replaced by FeCrAl alloy in order to investigate the mechanical strength as function of cladding thickness comparing the time of burst with experimental data. The simulation was performed considering a segment of fuel rod with the experimental pressure rate and temperature as boundary conditions. The input data were the cladding material (FeCrAl) and geometry (inner and outer diameter) taken from AP-1000 reactor fuel as reference. Moreover, it is well known that there is one important challenge for FeCrAl alloy cladding: its increased thermal neutron absorption cross-section compared to the current Zr-based cladding, resulting in neutronic penalty consequently reduction fuel cycle length. In order to compensate the neutron absorption penalty, it may require an increase in the pellet enrichment and/or a reduction of cladding thickness and/or increase of pellet radius to obtain an equivalent fuel cycle length to those of the current fuel systems in LWRs. Therefore, the FeCrAl neutronic evaluation with different cladding thickness was performed using Serpent Monte Carlo code[8] in order to verify the reactivity change due to thickness change. The neutronic evaluation was performed for single fuel pin (enrichment 4.45%) of AP-1000 reactor.

3. Results and Discussion

The simulations results obtained with modified version of TRANSURANUS code are presented in Table 1.

Table 1: Results obtained from modified version o TRANSURANUS code

Case	dP/dt (bar/s)	Temp (°C)	Exp. T_{burst}(sec)	T_{burst}(sec)			
				Thickness (0.50mm)	Thickness (0.40mm)	Thickness (0.45mm)	Thickness (0.50mm)
1	0.0064	1201.3	531.90	998.12	1139.27	1281.25	1422.21
2	0.0065	1154.4	566.00	1269.74	1449.36	1629.68	1810.01
3	0.0063	1102.1	607.80	1739.85	1985.50	2230.35	2473.87
4	0.0062	1053.2	705.30	2294.30	2613.44	2930.22	3243.94
5	0.0062	997.9	810.70	3020.76	3426.73	3824.93	4217.58
6	0.0048	950.5	1805.40	4740.45	5345.23	5936.53	6514.33
7	0.0759	952.9	208.20	329.11	375.55	421.33	466.81
8	0.0763	1001.0	116.70	252.81	288.52	323.79	359.44
9	0.0712	1051.6	104.70	204.77	233.97	263.27	292.18
10	0.0710	1102.6	92.00	156.75	178.49	200.50	221.19
11	0.0717	1149.8	84.10	121.01	138.16	153.17	170.59
12	0.0723	1197.7	80.00	90.64	103.74	115.49	129.74
13	0.0314	698.8	2828.00	2664.42	2991.38	3310.28	3621.69
14	0.1190	702.2	892.40	773.90	873.50	970.68	1065.95
15	0.1173	802.1	538.40	469.93	532.32	593.65	653.84
16	0.1224	750.3	678.50	586.90	663.39	738.21	811.74
17	0.1162	850.1	342.30	371.55	422.16	471.98	521.04
18	0.1151	900.2	233.70	289.048	329.23	369.04	408.29
19	0.0243	900.6	801.30	1296.745	1467.51	1635.14	1799.56
20	0.0225	849.7	1211.10	1760.195	1984.07	2202.43	2416.23
21	0.0168	800.8	2693.30	2859.815	3212.2	3555.80	3891.64
22	0.0148	749.9	4105.10	4052.566	4545.02	5025.27	5493.92
23	0.0717	748.6	1011.80	974.78	1098.97	1220.30	1338.93
24	0.0179	698.8	4522.20	4408.203	4943.01	5464.15	5973.07
25	0.0173	698.3	4623.50	4555.33	5107.75	5646.09	6171.61
26	0.1193	698.4	888.80	787.799	888.99	988.10	1085.06
27	0.0248	801.4	1946.00	2003.569	2253.51	2497.24	2735.58
28	0.0425	800.0	1244.70	1230.717	1387.26	1540.03	1689.51
29	0.0720	799.9	804.50	753.789	851.67	947.51	1041.52
30	0.2630	800.4	275.70	217.867	247.66	277.14	306.17
31	0.1961	800.4	346.20	289.532	328.67	367.34	405.41

In Table 1., the first three columns are related to experimental data: pressure rate, temperature and burst time, respectively. All remain columns are the burst time obtained from modified TRANSURANUS simulation considering different FeCrAl cladding thickness. The fields filled with yellow color in Table 1 present lower burst times compared to experimental burst times, therefore the cladding thickness higher than 0.45 mm has superior burst time when compared to experimental data obtained for zircalloy cladding with 0.725 mm. From the results, it can be seen that FeCrAl cladding thickness can be reduced in order to mitigate the neutronic penalty without losing the equivalent mechanical strength of zircalloy cladding.

Regarding the neutronic evaluation, results present in Table 2, the cladding thickness reduction could be an alternative to overcome the neutronic penalty. Initially, reactivity loss due to changing zircalloy to FeCrAl cladding represent a penalty of 9.305 pcms, whereas the gain of reactivity is at least 1500 pcms.

Table 2: Reactivity change due to reduction of cladding thickness

Cladding thickness (mm)	**$K_{infinity}$**	**Cladding thickness (mm)**	**$K_{infinity}$**
0.3500	1.33462 ± 0.00008	0.5715 (AP-1000-Zry)	1.38468 ± 0.00007
0.4000	1.32079 ± 0.00008	0.6000	1.26469 ± 0.00009
0.4500	1.30664 ± 0.00007	0.7000	1.23631 ± 0.00009
0.5000	1.29285 ± 0.00008	0.725 (PUZRY-FeCrAl)	1.22233 ± 0.00009
0.5715 (AP-1000-FeCrAl)	1.29163 ± 0.00007	0.725 (PUZRY-Zry)	1.36652 ± 0.00009

4. Conclusions

The modification implemented into the recent version of TRANSURANUS fuel performance code was evaluated by means of PUZRY experiment and the obtained results are coherent with the FeCrAl material properties when compared to zircalloy. Moreover, the neutronic penalty imposed by FeCrAl cladding can the mitigated by reduction of cladding thickness. Nevertheless the obtained results. it is important to highlight the need of carrying out similar experiments, as PUZRY test case, for FeCrAl alloys to perform validation and verification of the burst correlation applied in the fuel performance codes.

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