FUEL PERFORMANCE ASSESSMENT OF ENHANCED ACCIDENT TOLERANT FUEL USING IRON-BASED ALLOYS AS CLADDING

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ABSTRACT

In the framework of the Enhanced Accident Tolerant Fuel (EATF) program, one important tool to assess the behaviour of new materials under irradiation is the use of fuel performance codes. For this, it is necessary to modify conventional fuel performance codes to introduce the properties of the materials to be studied. The aim of this paper is to present some preliminary results obtained using modified versions of the FRAPCON code adapted to evaluate the performance as cladding of two different types of iron-based alloys as cladding: stainless steel (AISI 348), and FeCrAl alloy, including a preliminary sensitivity analysis. The results obtained using the modified versions of the codes were compared to those obtained for zirconium-based alloys using the original code version. The results have shown and confirmed that iron-based alloys are one of the promising candidates to be used as EATF cladding in PWR.

1. Introduction

Enhanced Accident Tolerant Fuel (EATF) has been studied since the Fukushima Daiichi accident aiming to improve the safety of Light Water Reactors (LWR) under steady-state irradiation as well as accident scenarios. Concerning to the fuel cladding, the EATF program aims to address and study new materials to replace the conventional zirconium-based alloys currently used. In this sense, iron-based alloys and ceramic materials, as silicon carbide, have presented good potentiality to be used as cladding material.

In the framework of the EATF program, one important tool to assess the behaviour of new materials under irradiation is the use of fuel performance codes. For this, it is necessary to modify existing conventional fuel performance codes to introduce the properties of the materials to be studied.

This paper presents some preliminary results obtained using modified versions of the well-known FRAPCON code obtained from the introduction of the properties related to two different cladding materials: stainless steel (AISI 348), and FeCrAl alloy. The results obtained using the modified versions of the codes were compared to those obtained for zirconium-based alloys using the original code version. Additionally, a preliminary sensitivity analysis considering different cladding thickness to compensate the neutronic penalty for AISI 348 and FeCrAl alloy was carried out considering manufacturing/design uncertainties which might affect the fuel rod performance response.

1.1 AISI 348 and FeCrAl alloy as cladding

Iron-based alloys, specifically AISI 304, 347, and 348, were the first materials applied as cladding in early LWR. The overall performance of iron-based alloys under irradiation was considered reliable [1]; however due to the high neutron absorption cross section of this material, it was replaced by zirconium-based alloys during the lifetime of the first LWR.

After the Fukushima Daiichi accident, the worldwide research effort aiming to develop new cladding materials with low oxidation rate compared to existing zirconium-based alloys has shown iron-based alloys as very promising candidates to fulfil the EATF requirements. These materials present low oxidation rates, good mechanical properties, and corrosion resistance in the conditions of LWR operation.

The AISI 348, studied in this paper, presents better corrosion resistance compared to other austenitic stainless steel of series 300 due to the low carbon content associated with the addition of tantalum and niobium that prevent corrosion and intergranular precipitation of metallic carbide, $M_{26}C_6$ type, in the region of grain boundaries, avoiding depletion of chromium. Some investigations of AISI 348 performance under irradiation using modified fuel performance codes were already carried out showing good performance under steady-state [2, 3, 4] as well as LOCA scenario [5, 6].

Another iron-based alloy candidate with good potentiality to be used as EATF is the iron-chromium-aluminum (FeCrAl) alloy which presents oxidation rates of 1-3 orders of magnitude lower than oxidation rates of zirconium-based alloys [7]. Data from literature [7] based on computational simulations indicate that FeCrAl alloy maintains acceptable thermo-mechanical properties, and fuel-clad interactions under LWR conditions.

1.2 Fuel Performance Code Uncertainties

Present experience shows that some results obtained by means of computational simulations present discrepancies when compared to experimental evidence indicating that part of the physical phenomena under irradiation cannot be exactly modeled into the codes. Moreover, the manufacturing process of fuel rods involves a set of parameters with tolerances which can affect the fuel rod performance under irradiation. Therefore, for a better understanding of the uncertainties contribution and their consequences in the fuel performance, the influence of manufacturing/design parameters in the codes can be assessed by means of a sensitivity analysis approach. The sensitivity analysis enables the identification of relevant parameters that might affect the fuel behavior in normal operation conditions.

2. Methodology

The methodology applied in this work can be divided in the following steps: modification of FRAPCON code to introduce properties of AISI 348, and FeCrAl alloy; simulations of fuel performance using data available in the open literature [8] for a zircaloy-4 experimental fuel rod, considering the original version of FRAPCON code for zircaloy, and the modified versions for AISI 348, and FeCrAl alloy; analysis of the results obtained under steady-state irradiation comparing the three cladding materials; and, finally, sensitivity analysis evaluation considering some manufacturing/design parameters and thinner cladding thickness for AISI 348 and FeCrAl alloy in order to compensate the neutonic penalty.

2.1 Fuel Performance Code Modification

The basis for the code modification was the well-known FRAPCON-3.4 code [9] sponsored by U.S.NRC (the United States Nuclear Regulatory Commission) for the licensing of nuclear power plants.

The main subroutines related to the cladding in the FRAPCON code modified to introduce the properties in MATPRO [10] of AISI 348, and FeCrAl alloy were: CELMOD, CORROS, CSHEAR, and CTHCON. The material properties concerning to each one of these subroutines are: CELMOD defines the correlation for the cladding Young´s modulus; CORROS is related to the cladding waterside corrosion; CSHEAR calculates shear modulus of cladding based on type and conditions; and CTHCON defines the correlation for the cladding thermal conductivity.

For AISI 348, also the following subroutines were properly modified: CAGROW, CHUPTK, CKMN, CMHARD, CTHEXP, PHYPRP, ZOEMIS, and ZOTCON. The properties related to these subroutines are: cladding axial growth (CAGROW); cladding hydrogen uptake (CHUPTK); strength coefficient and exponent (CKMN); cladding Meyer hardness as a function of temperature (CMHARD); cladding axial and radial thermal expansion (CTHEXP); cladding melting point and heat of fusion (PHYPRP); cladding oxide emissivity (ZOEMIS); and cladding oxide layer thermal conductivity (ZOTCON).

AISI 348 properties implemented in the code are described in [2, 3], and FeCrAl alloy properties were obtained from [7].

2.2 Test Case

The assessment was carried out using experimental data available in the open literature [9] related to a zircaloy/UO_2 fuel rod identified as TSQ002. This fuel rod was part of a program to develop more efficient fuel management concepts and an increase in the burnup of discharged fuel.

The fuel rod TSQ002 was part of a standard 16 x 16 Pressurized Water Reactor (PWR) fuel assembly. It accumulated an end-of-life (EOL) rod-average burnup of 56.1 GWd/MTU. The rod-average LHGR varied from 2.75 to 6.95 kW/ft with the higher values near beginning-of-life (BOL).

2.3 Sensitivity Analysis

A preliminary sensitivity analysis was carried out in order to evaluate the effects of manufacturing/design parameters applied in the FRAPCON code. For this, a set of parameters has been identified together with their appropriate distribution function and range of variation. The statistical distribution (normal), using EXCEL spreadsheet, was applied for each one of the fuel manufacturing/design parameters considering variation within ±σ (one standard deviation). The simulations were performed by means of script (GNU-OCTAVE), where all inputs files were generated automatically and the selected results from outputs files were automatically extracted. The obtained data were compiled and the Pearson Correlation was calculated using GNU-OCTAVE. FRAPCON version codes applied to perform the sensitivity analysis were original version (as released by NRC) for zircaloy-4, and modified versions for AISI 348 and FeCrAl alloy; however the existing fuel models were not directly modified.

Initially, a set of simulations was performed considering nominal value plus 200 (two hundred) runs in the FRAPCON code taking into account fuel manufacturing/design parameters and their respective tolerances as presented in Table 1, such as: cladding thickness, gap thickness, fuel pellet outside diameter, ^{235}U enrichment, fuel theoretical density, and rod filling gas pressure. The cladding outside diameter and fuel-to-cladding gap were kept the same for the three studied materials. However, the cladding thickness for AISI 348 and FeCrAl alloy was thinner in order to compensate the neutronic penalty due to the increased neutron absorption cross-section of these materials. This allows using slightly larger pellet outside diameter to give the same cold gap width in the fuel rod. The statistical distribution (normal) and tolerance interval (upper and lower bounds) for each fuel manufacturing/design parameter were considered based on typical data of LWR fuel rods.

Tab 1. Manufacturing/design parameters, range of variation and distribution function applied in the sensitivity analysis for zircaloy-4, AISI 348, and FeCrAl alloy cladding

Parameter	Nominal value	Upper tolerance	Lower tolerance	Distribution
Cladding outside diameter (mm)	9.70	9.72	9.68	Normal
Cladding inside diameter (mm)	8.43 (Zrloy-4) 8.84 (AISI 348/FeCrAl)	8.46 8.85	8.41 8.82	Normal
Pellet outside diameter (mm)	8.25 (Zrloy-4) 8.66 (AISI 348/FeCrAl)	8.27 8.67	8.22 8.62	Normal
Fuel theoretical density (g cm^{-3})	10.41	10.52	10.33	Normal
^{235}U enrichment (%)	3.48	3.55	3.40	Normal
Filling gas pressure (MPa)	2.62	2.69	2.56	Normal

After all simulations, the main outcomes were Pearson Correlation and some specific results comparing the three studied cladding materials.

3. Results and Discussion

The results obtained under steady-state irradiation have shown that the studied iron-based alloys, AISI 348 and FeCrAl alloy, present fuel centerline temperatures slightly higher than those experienced by zirconium-based alloys (Figure 1). This is a consequence of the higher thermal expansion experienced by iron-based alloys compared to zircaloy-4 under LWR irradiation conditions.

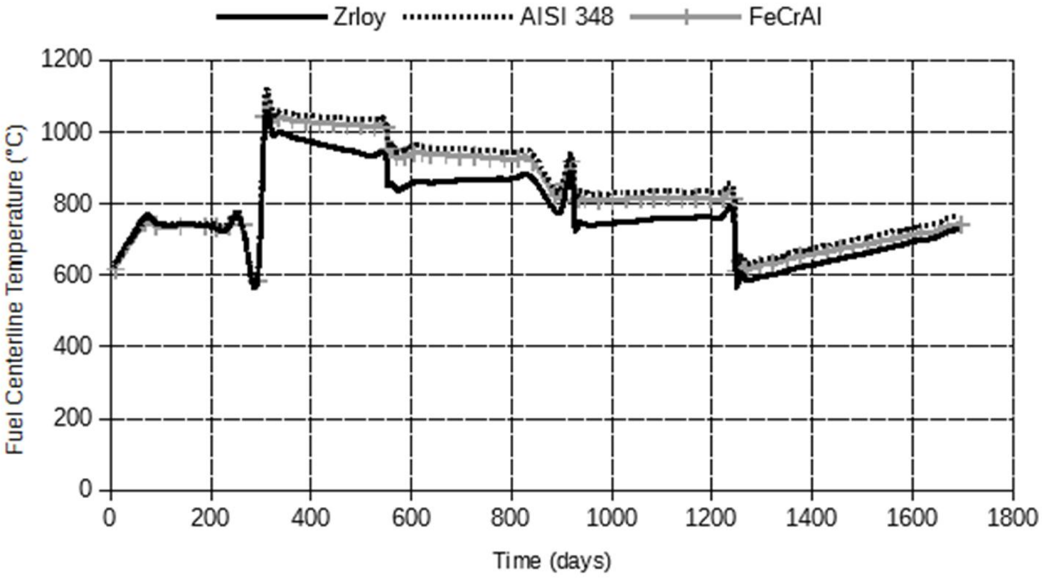

Fig 1. Fuel centerline temperature evolution under steady-state irradiation as function of time considering as cladding: zircaloy-4, AISI 348, and FeCrAl alloy

Despite of the higher fuel centerline temperatures observed for iron-based alloys, the cladding inside temperature is slightly higher for zircaloy-4 (Figure 2), which can be explained based on the higher thermal conductivity of AISI 348 and FeCrAl alloy compared to zircaloy-4.

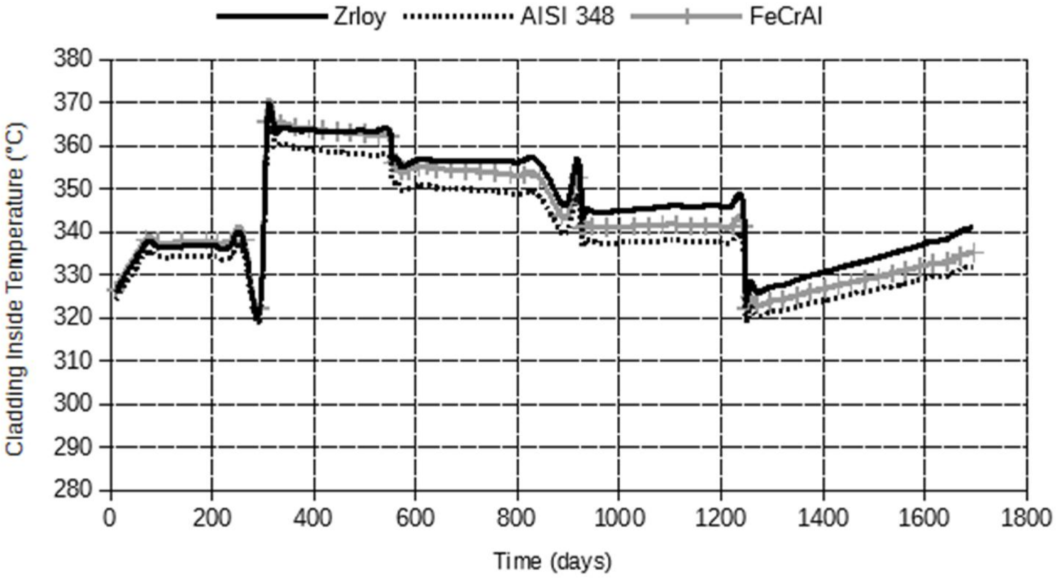

Fig 2. Cladding inside temperature evolution under steady-state irradiation as function of time considering as cladding: zircaloy-4, AISI 348, and FeCrAl alloy

As a consequence of the higher thermal expansion of the iron-based alloys under LWR irradiation conditions, the internal free volume in these rods is higher, and consequently, the internal fuel rod pressure is higher for the fuel rod using zircaloy-4 as cladding material, as can be seen in Figure 3.

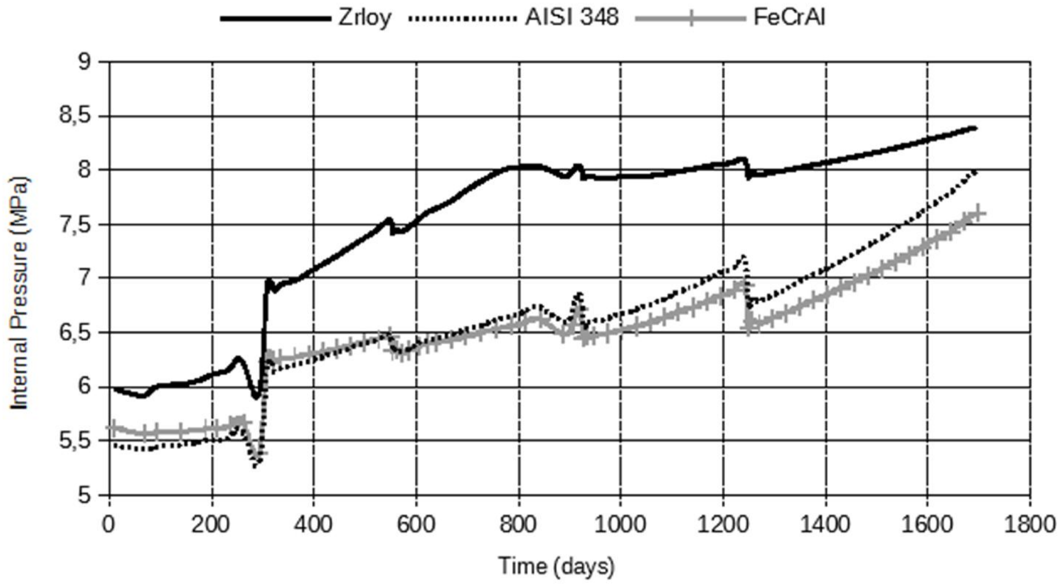

Fig 3. Internal pressure evolution under steady-state irradiation as function of time considering as cladding: zircaloy-4, AISI 348, and FeCrAl alloy

Even considering the slight differences observed in the fuel centerline temperatures in the iron-based alloys fuel rods compared to zircaloy-4, the fission gas release evolution is the same for the three studied cladding materials (Figure 4).

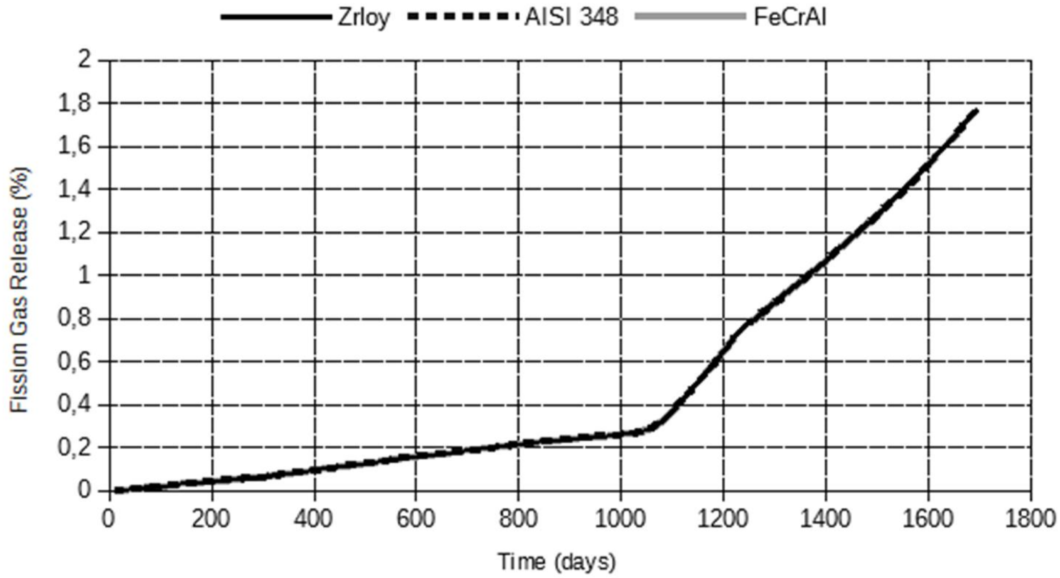

Fig 4. Fission gas release evolution under steady-state irradiation as function of time considering as cladding: zircaloy-4, AISI 348, and FeCrAl alloy

The results also have shown that the gap remains open longer for AISI 348 and FeCrAl alloy fuel rods due to the higher thermal expansion of these materials compared to zirconium-based alloys (Figure 5), this consequently affects the cladding hoop stress (Figure 6).

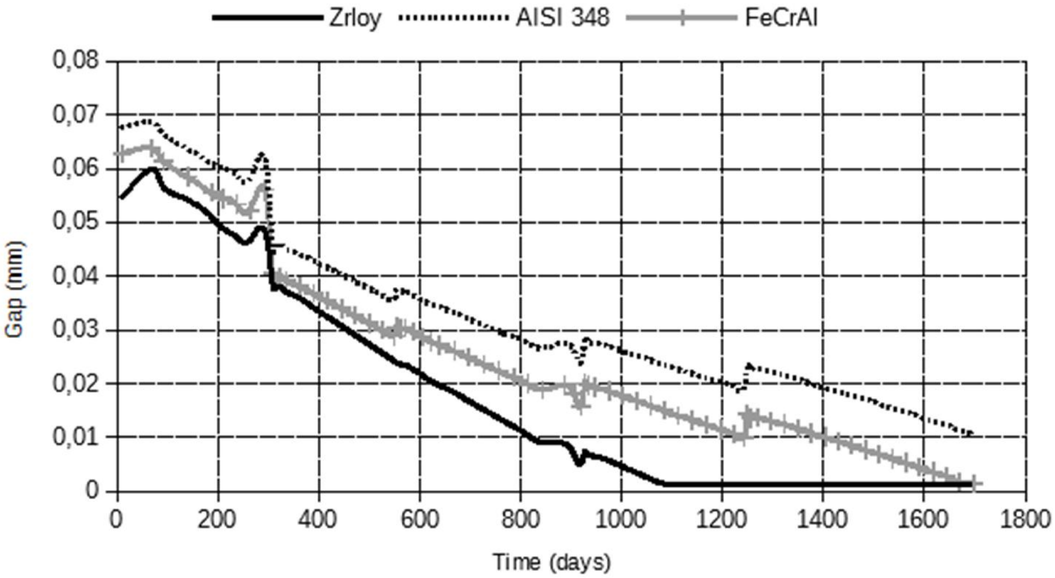

Fig 5. Gap evolution under steady-state irradiation as function of time considering as cladding: zircaloy-4, AISI 348, and FeCrAl alloy

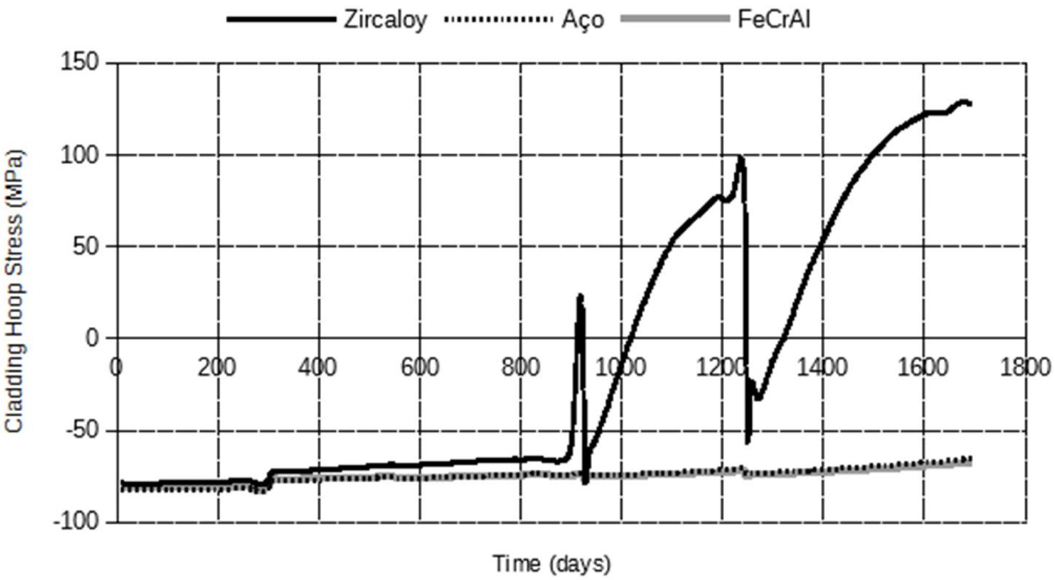

Fig 6. Cladding hoop stress evolution under steady-state irradiation as function of time considering as cladding: zircaloy-4, AISI 348, and FeCrAl alloy

Concerning to the sensitivity analysis carried out for the three studied cladding material, Table 2 shows the results obtained for zircaloy-4, AISI 348, and FeCrAl alloy considering the following fuel manufacturing/design parameters: cladding thickness (thkclad), initial gap thickness (thkgap), fuel pellet outside diameter (dco), ^{235}U enrichment (enrch), fuel theoretical density (den), and initial internal pressure (fgpav). The obtained results were statistically treated using EXCEL spreadsheet (Pearson Correlation) and the following parameters associated to the fuel response were compiled: maximum plenum internal pressure (pinp), maximum cladding hoop stress (chstrs), minimum gap thickness (gap), maximum fuel centerline temperature (fct), and maximum cladding temperature (ct).

The highlighted (gray color) positions in Table 2 present the correlation factor PR≥0.5 (strong correlation); as can be seen there are at least nine identical strong correlation related to fuel manufacturing/design parameters, only FeCrAl presented slightly different results compared to other two cladding material (zircaloy-4 and AISI 348) for cladding thickness, but the difference is almost negligible.

Tab 2. Pearson correlation for each fuel manufacturing/design parameter evaluated for zircaloy-4, AISI 348, and FeCrAl alloy cladding

Cladding material	Manufacturing /design parameter	Pearson correlation (PR)				
		pinp	chstrs	gap	fct	ct
Zircaloy-4	dco	0,05	0,65	-0,09	-0,05	0,67
	thkcld	-0,01	0,81	-0,51	-0,43	0,98
	thkgap	0,15	-0,21	0,96	0,89	-0,51
	enrch	0,07	0,00	-0,03	0,02	-0,04
	den	-0,24	-0,09	-0,01	-0,21	0,01
	fgpav	0,75	0,54	-0,15	-0,10	0,16
AISI 348	dco	0,01	0,67	-0,06	-0,06	0,69
	thkcld	-0,09	0,83	-0,50	-0,48	1,00
	thkgap	0,28	-0,19	1,00	0,95	-0,53
	enrch	0,09	0,00	-0,03	0,02	-0,04
	den	-0,27	-0,09	0,03	-0,27	0,00
	fgpav	0,89	0,57	-0,15	-0,11	0,17
FeCrAl alloy	dco	0,00	0,66	-0,07	-0,06	0,69
	thkcld	-0,10	0,83	-0,47	-0,48	1,00
	thkgap	0,26	-0,20	0,91	0,96	-0,53
	enrch	0,09	0,00	-0,04	0,01	-0,04
	den	-0,25	-0,09	-0,03	-0,26	0,00
	fgpav	0,90	0,58	-0,13	-0,10	0,17

The most influential correlation can be seen between fission gas release and fuel rod fill gas pressure and maximum cladding hoop stress, the gap thickness, and fuel centerline temperature and maximum cladding temperature. Most of correlation outcome agrees with the expected results, as gap thickness increases, the heat transfer from fuel surface to cladding surface will be degraded, consequently the fuel centerline temperature will increase, as well as the higher initial fill rod gas pressure will produce higher final plenum pressure. Moreover, as expected, there is a strong correlation between the gap evolution during irradiation and the initial gap thickness.

4. Conclusions

Based on actual existing experiments and ongoing R&D activities related to ATF, the iron-based alloys are one of the eligible candidates to be used as cladding. The fuel performance code FRAPCON was modified properly in order to implement some material data and properties of iron-based alloys (AISI 348 and FeCrAl alloy) and sensitivity analysis simulations were performed in order to assess the influence of fuel manufacturer/design parameters considering thinner cladding thickness for AISI 348 and FeCrAl alloy.

The initial assessment shown as each set of parameters (fuel manufacturing/design) are correlated taking into account isolated contribution and combination. Some of the fuel manufacturing/design parameters are more strong correlated to final results in the steady-state simulation. As steady-state condition at the end of irradiation somehow will propagate to transient simulation, it can be expected that, existing correlation can contribute to the results obtained in transient scenarios. Although irradiation experiments data were not fully available for FeCrAl alloy, and considering that some drawbacks (hydrogen permeation, neutronic penalty) are still under investigation, this work can contribute to increase knowledge of EATF fuel performance.

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