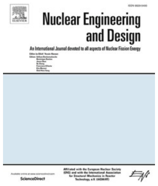
Nuclear Engineering and Design 415 (2023) 112707

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes



Assessment of minimum allowable thickness of advanced steel (FeCrAl) cladding for accident tolerant fuel

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ABSTRACT

The ferritic iron-chromium-aluminum (FeCrAl) alloy cladding is considered to be the most promising for near-term application in the ATF framework to replace existing zirconium alloy cladding. Although FeCrAl cladding presents several advantages, it is well known that there are at least two main drawbacks, one is the increased thermal neutron absorption cross-section compared to the current Zr-based cladding resulting in a neutronic penalty and another is tritium higher permeation. In the present study, the minimum allowable thickness of cladding is addressed considering neutronic penalty reduction and the mechanical-structural behavior under the LOCA accident condition. The neutronic penalty assessment was performed using the Monte Carlo code and mechanical-structural performance of the FeCrAl cladding using the TRANSURANUS fuel code, which was modified to consider properly the FeCrAl cladding.

1. Introduction

The Fukushima Daiichi accident exhibited one of the main drawbacks of zirconium alloy cladding under accident condition, and as consequence worldwide efforts are concentrated toward obtaining accident tolerant fuel (ATF), which the main scope resides in the replacement of existing fuel systems based on zirconium alloys and/or conventional uranium dioxide fuel pellet. In this sense, the ATF claddings shall enhance the performance and improve safety considering the reduced rate of heat generated from steam oxidation at high temperatures in the event of an accident, which will, in turn, reduce the rate of temperature rise, reduce hydrogen generation, delaying core degradation, and hence provide additional coping time for accident mitigation. Moreover, as desirable attributes for the fuel system, it shall present a better thermal conductivity and improved fission gas retention when compared to existing fuel-based on UO_2 ceramic pellet (Terrani, 2018).

A variety of different fuel system (cladding and fuel) are been investigated (Terrani, 2018; Lin,et al., 2018; Hiscox and Shirvan, 2019; Kim,et al., 2018; Chun,et al., 2015; Shah et al., 2017) in the framework of the ATF programs conducted by several institutions, including major fuel vendors, national laboratories, and universities around the world. Nowadays, ATF researches has seen many different strategies considering an availability and existing technology, as well as material data, and readiness application for near, mid, and long term. The strategy for the near term with respect to the time to commercial deployment considers the existing cladding technology, which can be utilized without many modifications to ease the licensing process as well as the validation and verification process. Among the options, the chromium coated and advanced steel alloy (FeCrAl) claddings were considered to be most promising for near-term application. The chromium coating in the zirconium alloy cladding can enhance resistance to corrosion in the LWR coolant and the FeCrAl alloy exhibit an exceptional resistance to steam oxidation, consequently reduction of hydrogen generation by oxidation when compared to zirconium alloy. Conversely, the options which represent a significant deviation from zirconium alloy cladding and ceramic UO_2 fuel are considered as mid and long-term deployment options, such as SiC cladding (Yueh and Terrani, 2014) and metallic or high-density fuels (Brown, et al., 2014).

Recently, Cr coated ZIRLO® and Optimized ZIRLO™ claddings by a cold spray had been submitted to irradiation at MIT research reactor and as lead test fuel rods in the Byron (PWR) reactor in April of 2019(IAEA, 2020). 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 (United States Senate, 2018).

Those two ATF cladding options are considered mature to submit to the licensing process, the fuel vendors or licensees typically prepare and submit licensing topical reports to the license authority, where describe the codes and methods applied to perform safety analyses for a new fuel design compared to currently approved methodologies. The licensee

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https://doi.org/10.1016/j.nucengdes.2023.112707
Received 1 August 2023; Received in revised form 8 October 2023; Accepted 22 October 2023

shall address at least three issues: the new material property correlations to be used in fuel performance codes, the acceptable fuel design limits (SAFDLs) and an assessment of changes in the existing and approved methodology.

Although advanced steel (FeCrAl) cladding presents several advantages(Pint et al.,2013; Field et al., 2017; Yamamoto, et al., 2015; Terrani, et al., 2014), it is well known that there are at least two main drawbacks, the first is the increased thermal neutron absorption cross-section (Pint et al.,2013) compared to the current Zr-based cladding, resulting in neutronic penalty consequently reducing fuel cycle length.

The second is related to the degree tritium of permeability, it can be mitigated by means of coating material into the cladding (Hu et al., 2015).

The neutron absorption penalty will requires an increase in fuel enrichment level to maintain the same cycle length; however it can be minimized by decreasing the cladding thickness and/or increasing the fuel pellet.

In this context, many different studies addressed (Wu et al., 2015; Honghao et al., 2021; Naceur and Marleau, 2018; George et al., 2015; Abe et al., 2015) how thin can be FeCrAl cladding from a neutronic standpoint but a very few assessment of mechanical strength and performance due to reduction under normal operation and accident conditions.

This work will perform an assessment of the minimum cladding thickness of FeCrAl specifically under LOCA accident conditions taking to account mechanical strength and as boundary conditions previous neutronic analysis of cladding thickness reduction. The mechanical performance under normal operational condition is not expected to be lower compared to Zr-alloy cladding due to better mechanical properties.

Initially, neutronic cladding thickness assessment were performed using Serpent Monte Carlo neutronic code (Leppänen, 2013) and TRANSURANUS fuel performance code (Lassmann,1992)to address the FeCrAl cladding thickness under LOCA accident condition and compared to current Zr alloy.

Due to lack of experimental data of FeCrAl mechanical strength, specially under LOCA condition, the well know separate effect experiment named PUZRY from AEKI (Perez-Feró et al., 2007), which consists of an experimental test series with Zircaloy-4 to investigate ballooning and burst phenomena was considered in the evaluation.Experimental data of the PUZRY tests were used for the modeling benchmarks in the framework of the IAEA projects FUMAC (IAEA, 2019) and ACTOF (IAEA, 2020).

2. Methodology

In order to perform the preliminary assessment of minimum cladding thickness of FeCrAl alloy as ATF cladding, the neutronic and fuel performance combined analysis was performed considering fuel rod data from typical PWR and separate effect experiment (PUZRY) dedicated to ballooning and burst phenomena. The neutron absorption penalty can be mitigated by different approaches: increasing fuel enrichment, reduction of cladding thickness, an increase in fuel pellet radius, moderation ratio change, fuel assembly geometry changes, or a combination of changes mentioned. The most common approach envisioned cladding thickness reduction and/or enrichment degree increase. Any increase in fuel enrichment has an economic impact on the fuel cycle that should be minimized impact as much as possible, and cladding thickness reduction shall be limited by structural mechanical constraints associated with performance requirement.

2.1. Neutronic assessment

The initial assessment of a neutronic penalty of FeCrAl exploited parameters, which has less economic impact, starting from reduction of cladding thickness and/or increase of fuel pellet radius, as well as a change in the moderation degree to verify reactivity changes compared to the current fuel system. Complementary, the FeCrAl cladding reactivity as a function of fuel enrichment level and moderation degree was investigated after structural mechanical evaluation of cladding thickness.

Table 1
AP-1000 fuel rod data (Westinghouse, 2011) applied for neutronic analysis.

Parameter	Value
Enrichment (^{235}U%)	4.45 %
Clad Outer radius (cm)	0.47498
Clad Inner radius (cm)	0.41783
Clad thickness (cm)	0.05715
Fuel gap size (cm)	0.008255
Fuel pellet radius (cm)	0.409575
Fuel pitch size (cm)	1.25984

Table 2
Neutronic reactivity change due to cladding thickness.

CASE	Cladding Material	Cladding thickness (mm)	$K_{infinity}$	$\Delta K_{infinity}$
1^{+}	Zircaloy	0.5715	1.38468 ± 0.00007	—
2	FeCrAl	0.5715	1.29163 ± 0.00007	0.09305
3^{a}(see Note)	Zircaloy	0.7250^{++}	1.36652 ± 0.00009	—
4^{a}(see Note)	FeCrAl	0.7250^{++}	1.22233 ± 0.00009	0.14419^{b}(see Note)
5	FeCrAl	0.7000	1.23631 ± 0.00009	0.14837
6	FeCrAl	0.6000	1.26469 ± 0.00009	0.11999
7	FeCrAl	0.5000	1.29285 ± 0.00008	0.09183
8^{c} (see Note)	FeCrAl	0.4500	1.30664 ± 0.00007	0.07804
9^{d}(see Note)	FeCrAl	0.4500	1.29674 ± 0.00008	0.08794
10^{e}(see Note)	FeCrAl	0.4500	1.29201 ± 0.00009	0.09267
11	FeCrAl	0.4000	1.32079 ± 0.00008	0.06389
12	FeCrAl	0.3500	1.33462 ± 0.00008	0.05006

Note:
\+ actual AP-1000 cladding thickness.
++ actual PUZRY cladding thickness.
a - fuel segment adopted from PUZRY experiment (cladding outer diameter: 5.375 mm and inner diameter: 4.65 mm).
b - $\Delta K_{infinity}$ was taken from PUZRY data with zircaloy cladding.
c - reducing the clad outer side, keeping the clad inner radius, fuel diameter constant, and gap size.
d - increasing clad inner radius, keeping outer radius and fuel diameter constant, and increasing fuel gap.
e - increasing clad inner radius and fuel diameter, keeping outer radius and fuel gap constant.

The neutronic analysis with different cladding thicknesses and UO_2 fuel with different ^{235}U enrichment degrees was performed simulations using the well-known Serpent code (Leppänen, 2013) based on the Monte Carlo approach. The simulations mainly comprised of AP-1000 reactoŕs single fuel pin (enrichment 4.45 %) and moderator without boric acid, reflective boundary condition to obtain infinity neutron multiplication factor, which is the usual neutronic parameter to quantify fuel system (cladding and fuel) reactivity at first glance.The SERPENT code simulations were performed at begin of life, with following temperature distribution in the regions: fuel at 900 K, cladding at 600 K and moderator 550 K. All simulations were considered 50 millions of

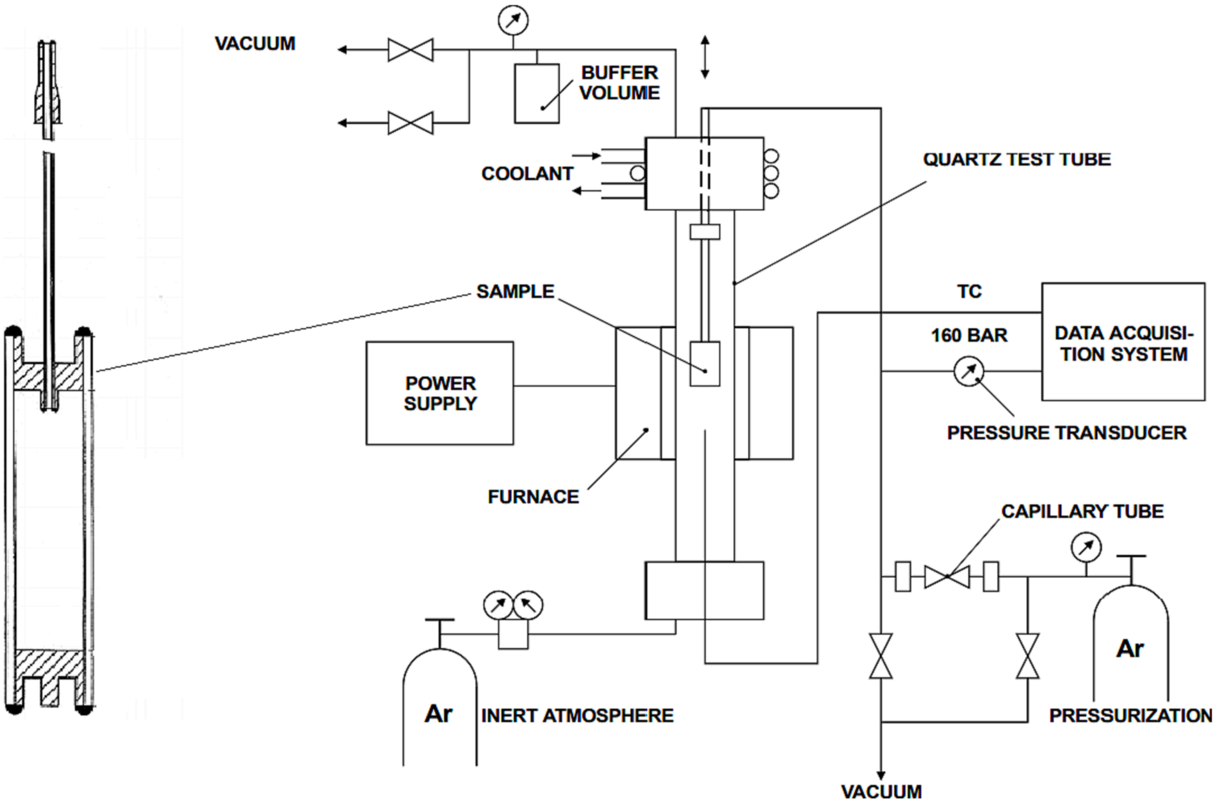

Fig. 1. Schematic diagram of single rod burst facility (adapted from Perez-Feró et al., 2007).

particles enough to give a standard deviation less than 10 pcms of reactivity.

The zircaloy cladding composition was taken ZIRLO, as following: Sn (1,0%), Nb (1,0%), Fe (0,1%) e Zr (balance) and for FeCrAl alloy composition of APMT-KHANTAL from SANDVIK: Cr (22 %), Al (5,0%), Mo (3,0%), Si (0,7%), Mn (0,4%), C (0,05 %) e Fe (balance).Table 1 present the AP-1000 reactor fuel rod data (Westinghouse, 2011) utilized in the neutronic analysis.

The reactivity changes due to the replacement of cladding material, as well as cladding thickness and fuel pellet size changes were addressed and the results are presented in Table 2. The enrichment level was kept constant and different configurations for a given thickness (0.45 mm) were exploited. The cladding thickness varies between 0.350 mm up to 0.7250 mm, which covers the thickness range of ASTM B811-13, Standard Specification for Wrought Zirconium Alloy Seamless Tubes for Nuclear Reactor Fuel Cladding, (ASTM B811-13, 2022) The upper limit cladding thickness was adopted as the same as of fuel rod segment thickness utilized in PUZRY structural mechanical experiment to have meaningful comparison.

The usual neutronic parameter related to reactivity is the infinity or effective neutron multiplication factor (Glasstone and Sesonske, 2012), which indicates the amount of reactivity in the given fuel system (fuel and cladding) and relative reactivity change as $\Delta K = (K_{ref} - Ki)$, where $K_{ref}$is a reference infinity neutron multiplication factor obtained for actual AP-1000 fuel rod (cladding thickness: 0.5715 mm) or actual PUZRY fuel rod (cladding thickness: 0.7250 mm)segment. The Table 2 presents infinity neutron multiplication factor results obtained for reference case (AP-1000 and PUZRY) and different approach for FeCrAl cladding thickness reduction, as well as respective the reactivity change.

The neutronic absorption penalty represented by the difference of infinity neutron multiplication factor was presented in the fifth column of Table 2, where can be observed the penalties due to replacement of cladding material and changes in cladding thickness.

Moreover, as the change of cladding thickness could be applied on the inner or outer side of cladding surface, such change was exploited taking 0.45 mm thickness. In one case cladding thickness changes were considered a reduction in outer radius and kept all other fuel rod dimensions, in another case the inner clad radius was increased and all other dimensions were kept and the last case considers the change in the inner side of cladding and pellet radius was slightly increased to maintain the original gap size.

It can be seen from three different changes applied to the 0.45 mm thickness, the reduction of thickness from the outer side of cladding surface is more effective compared to other changes, even including the slight increases in fuel pellet diameter. The obtained results indicates important role of moderation ratio (H/U) from the neutronic standpoint. Another important outcome from the preliminary assessment indicates clearly that only cladding thickness reduction is not enough to overcome or mitigate the neutron absorption penalty.

2.2. *Cladding mechanical structural assessment*

The assessment structural mechanical of cladding performance with different cladding thickness was performed by numerical simulation of PUZRY experiment using the TRANSURANUS fuel performance code (Lassmann, 1992)aiming to investigate mechanical behavior (separate effects) under accident condition (LOCA).

The PUZRY experiment consists of a single segment of Zircaloy-4 tube, unirradiated and submitted to ballooning and burst conditions under a well-controlled environment, where temperature range between 973 and 1473 K, pressurization rates from 7×10^{-4} to 2.6×10^{-2}MPa/s, and constant inert gas concentration environment.

The experiment comprises of 31 specimens of single segment of fuel rod tubes, each segment was tested under isothermal condition and submitted to constant linear pressure increase using capillary tubes with different diameters to allow the rate pressurization control after ~ 1000 s of heat-up period. In these experiments, tube specimens were placed in a quartz test tube filled with inert atmosphere (argon gas) and externally

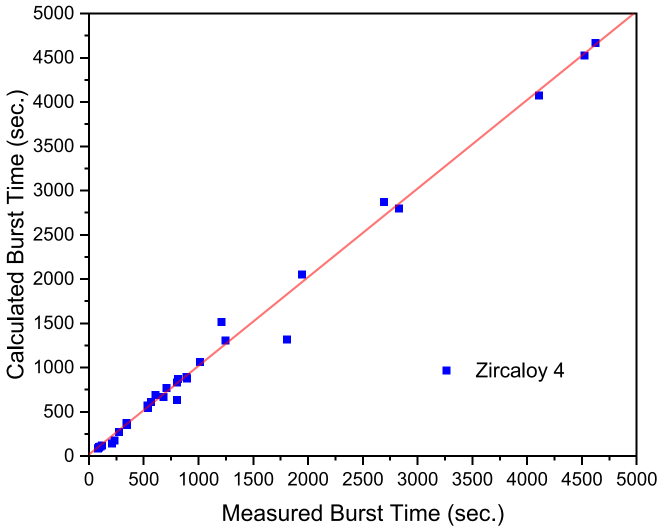

Fig. 2. Comparison between calculated (TRANSURANUS version v1m3j19) and measured timeof burst.

heated using a resistance furnace in order to provide isothermal conditions, without air or steam during the entire test.

The inner pressure of the specimens tubes were increased linearly up to burst failure. The specimen's tube consisted of 50 mm long with 9.3 mm of inner diameter, and 10.75 mm of outer diameter. The Fig. 1. presents a schematic view of PUZRY experimental rig.

The numerical simulation model options adopted comprises essentially with standard TRANSURANUS userś manual recommendations (Lassmann, 1992), where cladding material selection is defined properly for each different material. The geometry model considered a cylindrical geometry with 50 mm of length and external diameter of 10.75 mm and 9.3 mm of inner diameter. For the modeling, the axial length was divided equally into 10 nodes and 10 radial nodes. As boundaries conditions were set the temperatures and pressurization rate according to each case among of 31 cases. A small axial temperature gradient was applied (~4 °C) to force a peak temperature at the center of the rod (Pastore, et al., 2017).

Initially, an assessment of TRANSURANUS (version v1m3j19) was performedto validate the all inputs models, verify the capabilities to reproduce the original PUZRY experiment, and compare the results of 31 cases against experimental data. The results obtained for all 31 cases can be seen in Fig. 2 and Table 3.

The obtained simulation results and relative difference between experimental and calculated results presented in Table 3 show a fair agreement in the majority of cases, only a few cases (about 22 %) presented a relative difference higher than 10 %, somehow there is no any specific trend related to temperature and pressure rate for the higher difference observed. Moreover, the majority of simulation results overpredicted the burst time consequently, the calculated pressures at burst times are higher than experimental values.

As the aim of the this work is an assessment of FeCrAl cladding strength under accident condition, the next step consist of changes in the TRANSURANUS source code in order to consider FeCrAl alloy as cladding material.

The TRANSURANUS source code modification was performed considering the thermo-mechanical data of FeCrAl alloy available in the open literature, specially data from ORNLHandbook on the Material Properties of FeCrAl Alloys for Nuclear Power Production Applications (Kevin, et al., 2017). The approach for TRANSURANUS source code modification was the same adopted previouslyforAISI-348 cladding implemented in the TRANSURANUS code (version v1m1j17) (Giovedi

Table 3
Results for burst time obtained from TRANSURANUS code (version v1m3j19).

Experimental PUZRY Data					
Case	Pressure Rate (bar/s)	Temperature (°C)	Experimental burst time (s)	TRANSURANUS burst time (s)	Difference* (%)
1	0.0064	1201.3	531.90	572.45	7.62
2	0.0065	1154.4	566.90	612.52	8.05
3	0.0063	1102.1	607.80	690.04	**13.53**
4	0.0062	1053.2	705.30	770.29	9.21
5	0.0062	997.9	810.70	874.56	7.88
6	0.0048	950.5	1805.40	1320.41	**26.86**
7	0.0759	952.9	208.20	144.46	**30.61**
8	0.0763	1001.0	116.70	118.92	1.90
9	0.0712	1051.6	104.70	112.08	7.05
10	0.0710	1102.6	92.00	101.61	**10.45**
11	0.0717	1149.8	84.10	92.51	10.00
12	0.0723	1197.7	80.00	84.68	5.85
13	0.0314	698.8	2828.00	2798.50	1.04
14	0.1190	702.2	892.40	879.35	1.46
15	0.1173	802.1	538.40	542.43	0.75
16	0.1224	750.3	678.50	668.14	1.53
17	0.1162	850.1	342.30	375.21	9.61
18	0.1151	900.2	233.70	178.80	**23.49**
19	0.0243	900.6	801.30	633.99	**20.88**
20	0.0225	849.7	1211.10	1515.05	**25.10**
21	0.0168	800.8	2693.30	2872.61	6.66
22	0.0148	749.9	4105.10	4073.80	0.76
23	0.0717	748.6	1011.80	1064.49	5.21
24	0.0179	698.8	4522.20	4524.53	0.05
25	0.0173	698.3	4623.50	4670.54	1.02
26	0.1193	698.4	888.80	895.91	0.80
27	0.0248	801.4	1946.00	2053.72	5.54
28	0.0425	800.0	1244.70	1304.31	4.79
29	0.0720	799.9	804.50	831.50	3.36
30	0.2630	800.4	275.70	274.14	0.57
31	0.1961	800.4	346.20	352.31	1.76

*$[(T_{experimental}\text{-}T_{calculate})/T_{exmperimental}]$x100.

Table 4
Results for burst time obtained from TRANSURANUS code (version v1m3j19 modified).

Experimental PUZRY Data				Calculated Burst time (s)	
Case	Pressure rate (bar/s)	Temperature (°C)	Experimental burst time (s)	Zry-4	FeCrAl
1	0.0064	1201.3	531.90	572.45	1266.72
2	0.0065	1154.4	566.90	612.52	1482.15
3	0.0063	1102.1	607.80	690.04	1856.41
4	0.0062	1053.2	705.30	770.29	2291.90
5	0.0062	997.9	810.70	874.56	2911.99
6	0.0048	950.5	1805.40	1320.41	4515.43
7	0.0759	952.9	208.20	144.46	423.31
8	0.0763	1001.0	116.70	118.92	335.17
9	0.0712	1051.6	104.70	112.08	283.53
10	0.0710	1102.6	92.00	101.61	228.08
11	0.0717	1149.8	84.10	92.51	184.88
12	0.0723	1197.7	80.00	84.68	149.04
13	0.0314	698.8	2828.00	2798.50	4194.64
14	0.1190	702.2	892.40	879.35	1277.76
15	0.1173	802.1	538.40	542.43	666.41
16	0.1224	750.3	678.50	668.14	895.32
17	0.1162	850.1	342.30	375.21	505.12
18	0.1151	900.2	233.70	178.80	386.42
19	0.0243	900.6	801.30	633.99	1465.10
20	0.0225	849.7	1211.10	1515.05	2070.26
21	0.0168	800.8	2693.30	2872.61	3559.71
22	0.0148	749.9	4105.10	4073.80	5538.08
23	0.0717	748.6	1011.80	1064.49	1442.93
24	0.0179	698.8	4522.20	4524.53	6800.77
25	0.0173	698.3	4623.50	4670.54	7028.92
26	0.1193	698.4	888.80	895.91	1309.61
27	0.0248	801.4	1946.00	2053.72	2544.92
28	0.0425	800.0	1244.70	1304.31	1620.02
29	0.0720	799.9	804.50	831.50	1030.56
30	0.2630	800.4	275.70	274.14	331.80
31	0.1961	800.4	346.20	352.31	429.88

et al., 2016) by authors as part of a preliminary ATF cladding assessment during the IAEA ACTOF CRP framework. Due to the flexible feature of TRANSURANUS source code, a new material and their properties were implemented without the need to create new subroutines.

The data, correlations, and models implemented for FeCrAl alloy in the TRANSURANUS source code are: modulus of elasticity (Subroutine ELOC), Poisson ratio (Subroutine NUELOC), swelling (Subroutine SWELOC), thermal strain (Subroutine THSTRN), thermal conductivity (Subroutine LAMBDA), creep rate (Subroutine ETACR), yield stress (Subroutine SIGSS), fracture strain (Subroutine ETAPRR), true tangential stress (Subroutine SIGMAB)at rupture of cladding as a function of temperature and oxygen concentration (burst stress), specific heat (Subroutine CP), the heat of melting (Subroutine FH), emissivity (Subroutine EMISS), solidus and liquidus melting temperatures (Subroutine SOLIMT), and density (Subroutine RO). Moreover, a new version of burst stress correlation (Subroutine SIGMAB) was received separately from ITU (Institute for Transuranium Elements).

The modifications were mainly limited to thermal and mechanical properties data only, therefore the kinetic model of waterside cladding corrosion, and correlations associated with oxidation, such as hydrogen uptake and other chemical reactions were not considered in this version.

It is worthwhile to mention that the UO_2 fuel data and thermo-mechanical data or correlations of cladding were not modified, the data were considered as originally implemented by the TRANSURANUS code developers. Also, the PUZRY simulation model does not require any sort of fuel data, consequently, fuel properties will not affect any results.

The modification implemented in the TRANSURANUS code was assessed considering PUZRY experiment with FeCrAl as cladding material. Although PUZRY experiment was conceived and performed using zircaloy-4 as cladding, this simulation will allow verify the implementation of FeCrAl data and model and compare the performance different cladding material under same conditions. The assessment and verification of new version of TRANSURANUS code with capability to consider FeCrAl as cladding will allow to address main aim of this work, the minimum allowable thickness of FeCrAl.

From Table 4, it can be seen that TRANSURANUS code modification in order to consider FeCrAl as cladding material with the data and models available in the open literature was well succeeded and the results obtained for FeCrAl cladding burst time is higher compared to zircaloy-4, consequently, the cladding will experience failure at higher pressure. The average mechanical performance of FeCrAl as cladding is about 74 % superior compared to zircaloy.

2.3. *Cladding minimum allowable thickness*

The reduction of cladding thickness could be considered as the first approach to overcome the neutron absorption penalty as presented previously but, it cannot, per se, be mitigated entirely and cladding has to have a minimum thickness to prevent buckling and not collapse due external pressure during the normal operation and the performance should be comparable to existing cladding under accident condition.

The minimum allowable thickness assessment was performed using a modified version of the TRANSURANUS code with new FeCrAl models and data, the original input model of the PUZRY experiment was modified taking to account FeCrAl as cladding and changing the thickness of cladding covering the interval presented in Table 2. The structural mechanical performance of FeCrAl cladding with the different thicknesses could be compared to the zircaloy cladding. Table 5 presents the burst times as a function of cladding thickness for all 31 cases.

In Table 5, all values highlighted with red color have a lower burst time when compared to the experimental values (fourth column), therefore the cladding thickness higher than 0.45 mm shall have superior mechanical strength when compared to 0.725 mm of zircaloy cladding thickness.

Moreover, the majority of data (burst time) exceeds by far the experimental burst time, only in a few cases, the difference is somewhat not so high. Therefore, as a preliminary finding, the FeCrAl cladding thickness can be reduced up to 0.45 mm without losing the equivalent mechanical strength of zircaloy cladding and change can play a very important role to mitigate the neutronic absorption.

2.4. *Cladding minimum allowable thickness and fuel enrichment*

Additional neutronic analysis was performed considering 0.450 mm as the minimum thickness obtained from the TRANSURANUS assessment. The influence of two different parameters was investigated: enrichment level and moderation ratio for AP-1000 fuel system considering FeCrAl as cladding. From the results presented previously in Table 2, only a reduction of thickness was not enough to overcome the neutron absorption penalty, moreover, it seems that the moderation ratio plays an important role. The reference pitch was slightly increased by about 4 % to increase the degree of moderation and keep the fuel system under-moderated. The increase of fuel system reactivity due to moderation degree can be combined with an increase in fuel enrichment level.

Thefuel system of AP-1000, which has $K_{inf} = 1.38468 \pm 0.00007$ (reactivity), enrichment level of 4.45 % and pitch 1.2598 is a reference for comparison with the results presented in Table 6 obtained as function of enrichment level for a given moderation degree.

From the second column of Table 6, it can be seen that an enrichment level of 8 % is needed to obtain the same initial reactivity of zircaloy-4 cladding, i.e., an increase of enrichment of about 3.55 %, only due to change cladding for FeCrAl. The enrichment of near 7.0 %, an increase of about 2.55 % is needed due to cladding thickness reduction, and combining it with the change of moderation the increase needed is about 1.55 %. The approach of pitch size change gives another additional 1.0

Table 5
Time of burst results obtained with modified version of the TRANSURANUS code simulation.

Case	dP/dt (bar/s)	Temp (°C)	Exp. T_{burst}(sec)	T_{burst}(sec)				
				Thickness (0.350 mm)	Thickness (0.40 mm)	Thickness (0.45 mm)	Thickness (0.50 mm)	Thickness (0.725 mm)
1	0.0064	1201.3	531.90	998.12	1139.27	1281.25	1422.21	1851.87
2	0.0065	1154.4	566.00	1269.74	1449.36	1629.68	1810.01	2355.01
3	0.0063	1102.1	607.80	1739.85	1985.50	2230.35	2473.87	3211.41
4	0.0062	1053.2	705.30	2294.30	2613.44	2930.22	3243.94	4173.12
5	0.0062	997.9	810.70	3020.76	3426.73	3824.93	4217.58	5362.54
6	0.0048	950.5	1805.40	4740.45	5345.23	5936.53	6514.33	8207.07
7	0.0759	952.9	208.20	329.11	375.55	421.33	466.81	603.07
8	0.0763	1001.0	116.70	252.81	288.52	323.79	359.44	466.37
9	0.0712	1051.6	104.70	204.77	233.97	263.27	292.18	380.33
10	0.0710	1102.6	92.00	156.75	178.49	200.50	221.19	288.50
11	0.0717	1149.8	84.10	121.01	138.16	153.17	170.59	221.61
12	0.0723	1197.7	80.00	90.64	103.74	115.49	129.74	170.09
13	0.0314	698.8	2828.00	**2664.42**	2991.38	3310.28	3621.69	4525.28
14	0.1190	702.2	892.40	**773.90**	**873.50**	970.68	1065.95	1343.21
15	0.1173	802.1	538.40	**469.93**	**532.32**	593.65	653.84	829.93
16	0.1224	750.3	678.50	**586.90**	**663.39**	738.21	811.74	1025.71
17	0.1162	850.1	342.30	371.55	422.16	471.98	521.04	665.52
18	0.1151	900.2	233.70	289.048	329.23	369.04	408.29	525.44
19	0.0243	900.6	801.30	1296.745	1467.51	1635.14	1799.56	2280.26
20	0.0225	849.7	1211.10	1760.195	1984.07	2202.43	2416.23	3037.21
21	0.0168	800.8	2693.30	2859.815	3212.2	3555.80	3891.64	4866.87
22	0.0148	749.9	4105.10	**4052.566**	4545.02	5025.27	5493.92	6856.35
23	0.0717	748.6	1011.80	**974.78**	1098.97	1220.30	1338.93	1683.56
24	0.0179	698.8	4522.20	**4408.203**	4943.01	5464.15	5973.07	7449.00
25	0.0173	698.3	4623.50	**4555.33**	5107.75	5646.09	6171.61	7698.73
26	0.1193	698.4	888.80	**787.799**	**888.99**	988.10	1085.06	1366.96
27	0.0248	801.4	1946.00	**2003.569**	2253.51	2497.24	2735.58	3427.77
28	0.0425	800.0	1244.70	**1230.717**	1387.26	1540.03	1689.51	2123.94
29	0.0720	799.9	804.50	**753.789**	851.67	947.51	1041.52	1315.26
30	0.2630	800.4	275.70	**217.867**	**247.66**	277.14	306.17	391.84
31	0.1961	800.4	346.20	**289.532**	**328.67**	367.34	405.41	517.35

Table 6
Neutronic reactivity as function of ^{235}U enrichment degree and fuel pitch size.

Enrichment (% ^{235}U)	Pitch (1.2598 cm)		Pitch (1.30 cm)
	$K_{infinity}$ (thickness: 0.5715 mm)	$K_{infinity}$ (thickness: 0.450 mm)	$K_{infinity}$ (thickness: 0.450 mm)
5.0	1.29596 ± 0.00012	1.32981 ± 0.00011	1.34979 ± 0.00010
5.5	1.31604 ± 0.00010	1.34830 ± 0.00012	1.36805 ± 0.00013
6.0	1.33271 ± 0.00011	1.36423 ± 0.00011	1.38461 ± 0.00011
6.5	1.34788 ± 0.00012	1.37799 ± 0.00013	1.39889 ± 0.00012
7.0	1.36087 ± 0.00010	1.39038 ± 0.00012	1.41101 ± 0.00013
7.5	1.37252 ± 0.00011	1.40154 ± 0.00012	1.42190 ± 0.00013
8.0	1.38528 ± 0.00012	1.41090 ± 0.00011	1.43218 ± 0.00013
8.5	1.39294 ± 0.00012	1.42001 ± 0.00011	1.44067 ± 0.00012
9.0	1.40122 ± 0.00010	1.42807 ± 0.00012	1.4491 ± 0.00012
9.5	1.40969 ± 0.00011	1.43529 ± 0.00011	1.45653 ± 0.00011
10.0	1.41718 ± 0.00012	1.44277 ± 0.00011	1.46350 ± 0.00011

% of enrichment reduction without significant change in the original fuel assembly design. Moreover, the fuel pin pitch of the AP-1000 reactor is very under moderated, therefore there is a margin to increase the pitch size without compromising safety.

Finally, it is worthwhile to mention that change of pitch size requires additional analysis regarding reactivity behavior as a function of burnup and reactivity coefficient assessment in order to guarantee the safety of reactor operation. Moreover, the fuel assembly analysis is needed in order to address burnable absorber as well as neutronic parameters behavior as a function of burnup, such as conversion ratio, spectral change, and reactivity coefficients.

3. Conclusions

The minimum cladding thickness of FeCrAl was addressed considering combined neutronic and fuel performance analysis under accident conditions. The neutronic evaluation was performed using the Serpent Monte Carlo code focused on the neutron absorption penalty taking AP-1000 reactor as the fuel system. A different cladding thickness, uranium enrichment level, and moderation degree were investigated. The FeCrAl cladding structural mechanical performance analysis was performed using the latest version of the TRANSURANUS fuel performance code simulating the PUZRY separate effect experiment. The PUZRY experiment was originally conceived to address and investigate the zircaloy cladding mechanical behavior under LOCA accident conditions.

The latest version of the TRANSURANUS fuel performance code, which consider FeCrAl as cladding was not simulating properly and modification was required during the assessment. The new FeCrAl material termo-mechanical properties data were implemented taking into account existing FeCrAl thermo-mechanical data in the open literature. The initial verification of new a version with new FeCrAl was performed and results obtained showed expected and coherent behavior according to FeCrAl material properties when compared to zirconium alloy.

The PUZRY separate effect benchmark experiment was simulated changing zircaloy for FeCrAl as cladding and the results are compared to the reference case (zircaloy cladding) showing a better mechanical performance of FeCrAl as cladding. Consequently, the reduction of cladding thickness could be considered one of the options to mitigate the neutron absorption penalty without compromising safety.

As the main preliminary finding of the assessment has shown that the need for enrichment level increase can be minimized considering the reduction of cladding thickness without compromising structural mechanical performance, moreover the moderation change can be implemented depending on the fuel assembly design.

Nevertheless, it is important to highlight the need of carrying out similar experiments, such as PUZRY test cases, for FeCrAl alloys to perform validation and verification of the burst correlation to be implemented in the fuel performance codes.

CRediT authorship contribution statement

Alfredo Abe: Conceptualization, Formal analysis, Methodology, Validation, Visualization, Writing – original draft. **Claudia Giovedi:** Methodology, Supervision, Writing – review & editing. **Caio Melo:** Methodology, Software, Validation, Writing – review & editing. **Antonio Teixeira e Silva:** Formal analysis, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

The authors would like to extend their gratitude to Dr. Paul Uffelen from ITU for providing the newest version of TRANSURANUS code and Dr. Thiago Carluccio for guidance and helping with Serpent Monte Carlo Code.

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