ANALYSIS OF THE COMBINED EFFECTS ON THE FUEL PERFORMANCE OF UO_2-BeO AS FUEL AND IRON-BASED ALLOY AS CLADDING

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ABSTRACT: *Iron-based alloys have been considered as promising candidate material to replace zirconium-based alloys as fuel cladding based on the previous experience of the first generation of pressurized water reactors (PWR). Moreover, the safety margins of nuclear fuels can be improved by means of additives in the fuel pellet, as beryllium oxide (BeO), due to the increase of the fuel thermal conductivity. These efforts are part of the accident tolerant fuel (ATF) program which aims to develop nuclear fuel systems with enhanced performance under normal operation, design-basis accident and severe-accident conditions. This paper addresses the combined effects on the fuel performance considering the BeO additive in the fuel pellet and stainless steel 348 as cladding material under steady-state and loss-of-coolant-accident (LOCA) scenario. The fuel performance simulation and assessment are conducted using modified versions of well-known fuel performance codes (FRAPCON/FRAPTRAN). The obtained results have shown that the studied fuel system (stainless steel cladding and UO_2-BeO) enables an improvement in the main parameters associated to the fuel safety margins under steady-state irradiation as well as LOCA scenario.*

KEYWORDS: *Fuel performance, ATF, beryllium oxide, iron-based alloy.*

I. INTRODUCTION

In the framework of the accident tolerant fuels[1] (ATF) program applied to pressurized water reactors (PWR), primarily different cladding materials have been investigated, moreover changes in the uranium dioxide pellet can contribute to enhance the fuel performance.

Concerning to the cladding material, the research is mostly focused on the development of new materials which can keep their integrity under accident scenarios longer than the zirconium-based alloys applied as cladding in the last decades. The iron-based alloys arise as a good candidate to be used as cladding based on the previous existing experience of stainless steel in the first generation of PWR.

Besides new cladding materials, the fuel performance can be enhanced promoting some modifications in the uranium dioxide fuel pellet. One of the changes that significantly can promote an improvement in the fuel performance is associated to the thermal conductivity of the fuel pellet. In this sense, several investigations have shown that beryllium oxide (BeO) can be used as an addictive to increase the fuel thermal conductivity and support extended cycle, with an acceptable fuel cost.

The aim of this paper is to carry out the fuel performance analysis under steady-state and LOCA condition considering UO_2 pellet with BeO as additive combined with iron-based alloy as cladding material, specifically stainless steel (AISI) 348.

I.A. Zircaloy-4/UO_2 Fuel System

The vast majority of nuclear fuel used nowadays all around the world is composed by UO_2 pellets encapsulated in a sealed tube of zirconium-based alloy forming a fuel rod. This fuel system has been applied in the last decades in PWR reactors with well-known performance under steady-state irradiation. Nevertheless, zirconium-based alloys under accident scenarios, as observed in the Fukushima Daiichi accident[2], react with water producing a large amount of hydrogen which combined with the volatile radioactive materials, leak out of the containment vessels and enter into the reactor buildings, resulting in explosions. During the Fukushima Daiichi accident, this reaction caused the release of large amounts of hydrogen and major structural damage to the reactor core structure.

I.B. AISI 348/UO_2-BeO Fuel System

Iron-based alloys cladding present the advantage of not presenting the violent oxidation reaction that occurs with zirconium-based alloys at high temperatures, especially under LOCA accident. Among existing iron-based alloys, the austenitic stainless steels, specifically the types 304, 347, and 348, were already used as cladding in the first generation of PWR presenting a reliable performance under steady-state irradiation and operational transients[3].

For nuclear applications, the intergranular corrosion resistant stainless steels, such as AISI 321, 347, and 348 are more suitable. The AISI 348, studied in this paper, presents in its composition, in percent by weight, the following elements[4]: Fe-balance, C-0.08%, Mn-2.00%, Si-1%, Cr-17 to 19%, Ni-9 to 13%, P-0.045%, S-0.03%, Cu-0.2%, Nb-0.7%, Ta-0.1%, Co-0.2%. The low carbon content associated with the addition of tantalum and niobium prevent corrosion and intergranular precipitation of metallic carbide.

The fuel rod performance also can be improved considering the fuel pellet itself, specially enhancing the thermal conductivity and reducing fission gas release. This can be achieved doping the UO_2 pellet with a high conductivity additive, as BeO. It is well-known that BeO presents high thermal conductivity compared to other oxides, as well as high melting point, reasonable low neutron thermal absorption cross section, and chemical compatibility with UO_2 at high temperatures. Moreover, the BeO addition to the UO_2 fuel pellet does not introduce significant changes in the conventional manufacturing process[5-11]. The thermal conductivity enhancing due to the BeO addition can reach five times or even more compared to UO_2 pellet depending on BeO concentration and fuel system temperature.

I.C. IFA-650.5 Test Case

The modified and original versions of the fuel performance codes (FRAPCON and FRATRAN) were utilized to perform a preliminary assessment of the test case IFA-650.5 conducted in the framework of Halden Reactor Project to study the behavior of Zircaloy/UO_2 fuel rod under LOCA scenario[12].

II. METHODOLOGY

II.A. Fuel Performance Codes Modification

The well-known FRAPCON and FRAPTRAN codes[13], sponsored by the United States Nuclear Regulatory Commission (U.S.NRC) for the licensing of PWR and BWR nuclear power plants, were conveniently modified to support the evaluation of AISI 348 as cladding and UO_2-BeO containing 10 wt% of BeO as fuel.

II.A.1. Steady-State Analysis

The fuel performance under steady-state irradiation for the Zircaloy-4/UO_2 fuel system was simulated using the original version of the FRAPCON-3.4 code.

The steady-state analysis of the AISI 348/UO_2-BeO fuel system was carried out using modified version of the FRAPCON-3.4. Concerning to the cladding, the FRAPCON-3.4 was properly modified into the source code to introduce the mechanical and physical properties of AISI 348, moreover the MATRO[14] was updated with new data. Specifically, a new set of correlations for AISI 348 related to thermal expansion, thermal conductivity, elasticity modulus, Poisson´s ratio, irradiation creep, and swelling were properly implemented into the source code. The modified code version, named IPEN-CNEN/SS, was used to compare the irradiation performance of AISI 348 and Zircaloy-4 under a common steady-state irradiation and the results were presented in a previous paper[15]. Concerning to the fuel pellet, the thermal conductivity of the mixed oxide UO_2-BeO was changed, then the subroutines related to thermal properties of the fuel pellet in the FRAPCON-3.4 source code were properly modified using the Halden correlation[16] for the UO_2 pellet containing 10 wt% of BeO.

II.A.2. Transient Analysis

The analysis of the fuel performance for Zircaloy-4/UO_2 fuel system during the LOCA transient was carried out using the original version of FRAPTRAN-1.4.

The transient analysis of AISI 348/UO_2-BeO fuel system was carried out using modified version of the FRAPTRAN-1.4. Concerning to the cladding, the modifications were primarily focused on the mechanical properties related to the behavior of the cladding under LOCA conditions. In this sense, the subroutine *CKMN* was modified in order to introduce strain rate parameters associated to stainless steel. Due to difficult to find the proper parameters for AISI 348, the data for *k* and *n* parameters were taken from AISI 316L obtained from literature[17]. Moreover, the parameter *m* was kept the same of the original code version for Zircaloy-4. The subroutine *CMLIMT* associated to burst evaluation was modified including the true hoop stress at burst as function of temperature for AISI 304 obtained from literature[18]. These assumptions, which were adopted due to the lack of information related to AISI 348, will not affect the main outcome of simulation due to the similarity among the properties of the stainless steel alloys (304, 316L, and 348). Regarding the fuel pellet, the subroutine FTHCON was modified introducing the Halden correlation[16] for the UO_2 pellet containing 10 wt% of BeO.

II.B. Fuel Rod Analysis

The IFA-650.5 test fuel rod was re-fabricated from an irradiated PWR Zircaloy-4/UO_2 fuel rod. The fuel rod experienced a high average burnup of 83 MWd/kgU. The base irradiation of the full-length rod comprised 6 reactor cycles corresponding about 2000 effective full power days. The properties of the IFA-650.5 fuel rod are summarized in Table 1 below[12].

TABLE I. Fuel Rod Properties of IFA-650.5 Test Fuel Rod

Fuel Rod Property	IFA-650.5 Fuel Rod
Fuel material	UO_2
Fuel pellet diameter (mm)	9.132
Fuel pellet length (mm)	11
Fuel dish depth (mm)	0.28
Fuel dish width (mm)	1.2
Fuel density (% TD)	94.8
Fuel enrichment (w/o %)	3.5
Cladding material	DX ELS0.8b
Cladding outer diameter (mm)	10.735
Cladding wall thickness (mm)	0.721
Fuel rod burnup (MWd/kgU)	83
Fuel rod total length (mm)	480
Fuel rod gap (mm)	0.0805
Fuel rod plenum volume (cm^3)	15
Fuel rod fill gas	90% Ar +10%He
Fill pressure (MPa)	4.0

The data presented in Table I, as well as the power profile, pressure and temperature evolution during the LOCA transient obtained from literature[12] were considered to prepare the input data for the simulation with the original and modified versions of the codes (FRAPCON/FRATRAN) in order to analyze the fuel performance of Zircaloy-4/UO_2 and AISI 348/UO_2-BeO fuel systems, respectively.

II. RESULTS AND DISCUSSION

II.A. Steady-State Irradiation

The fuel centerline temperature evolution as function of time presented in Figure 1 shows that the temperatures reached by the UO_2-BeO pellet are about 300^{o}C lower than those observed for the reference UO_2 fuel pellet. The results clearly show that thermal conductivity plays a very important role in the fuel centerline temperature profile.

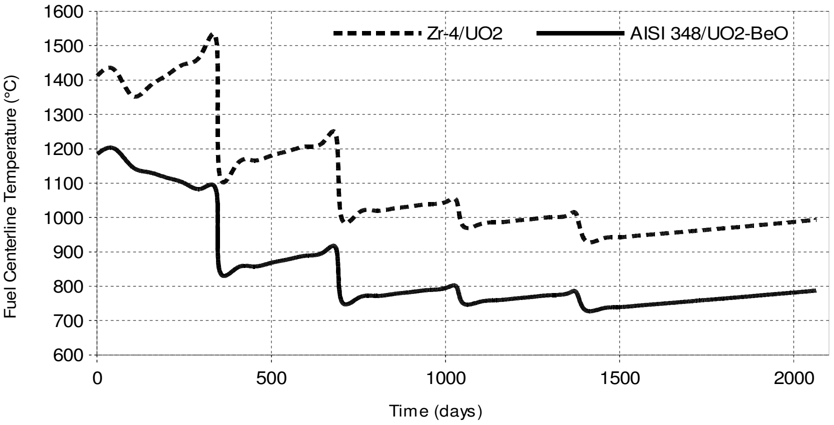

Fig. 1. Fuel centerline temperature evolution under steady-state irradiation as function of time for IFA-650.5 test case considering Zr-4/UO_2 fuel system and AISI 348/UO_2-BeO fuel system.

The lower fuel centerline temperatures observed for the UO_2-BeO pellet impacts other important parameters for the fuel performance, such as cladding inside temperature, internal pressure, and fission gas release. The evolution of these parameters as function of time is presented in Figures 2, 3, and 4, respectively.

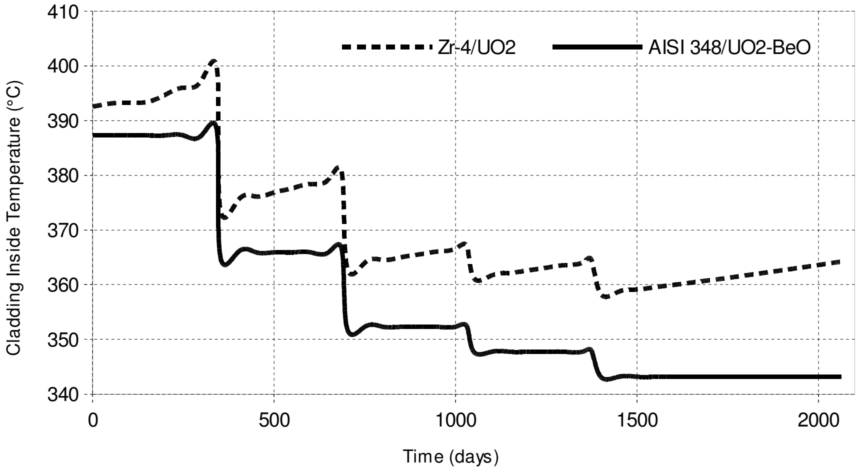

Fig. 2. Cladding inside temperature evolution under steady-state irradiation as function of time for IFA-650.5 test case considering Zr-4/UO_2 fuel system and AISI 348/UO_2-BeO fuel system.

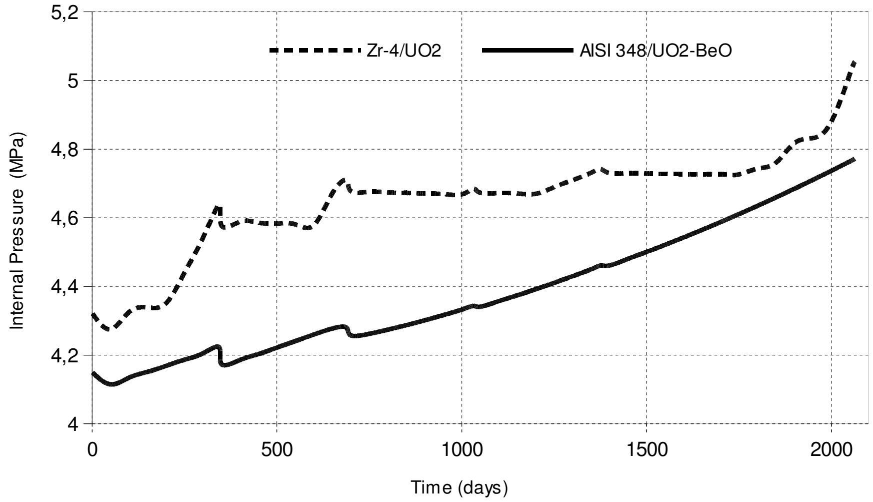

Fig. 3. Internal pressure evolution under steady-state irradiation as function of time for IFA-650.5 test case considering Zr-4/UO_2 fuel system and AISI 348/UO_2-BeO fuel system.

The lower fuel centerline temperature experienced by the UO_2-BeO fuel pellet during the entire irradiation period does not exceed the Vitanza threshold[19], consequently the fission gas release as function of burnup presented in Figure 4 is significantly lower for UO_2-BeO fuel pellet compared to the reference UO_2 fuel pellet.

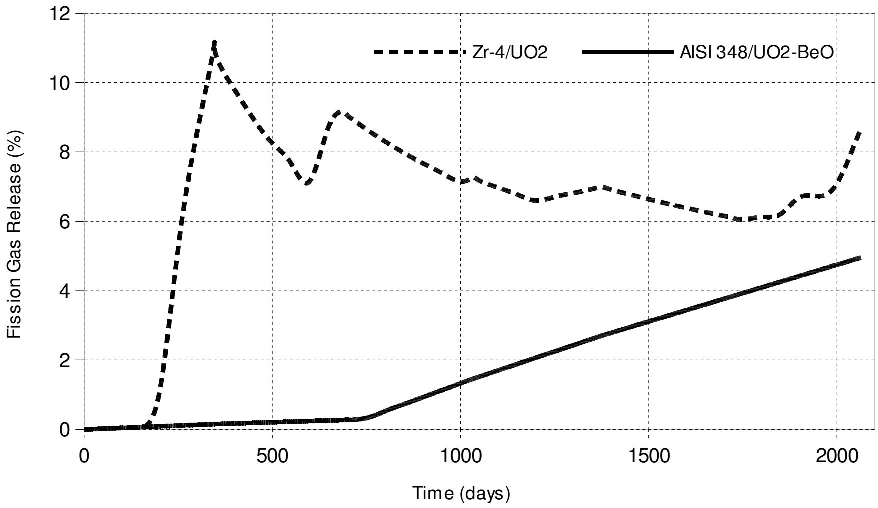

Fig. 4. Fission gas release evolution under steady-state irradiation as function of time for IFA-650.5 test case considering Zr-4/UO_2 fuel system and AISI 348/UO_2-BeO fuel system.

The analysis of the obtained results for the AISI 348/UO_2-BeO fuel system also shows advantages considering the cladding material modification. This can be observed in the curves presented in Figures 5 and 6, which show, respectively, the gap and cladding hoop stress evolution as function of time.

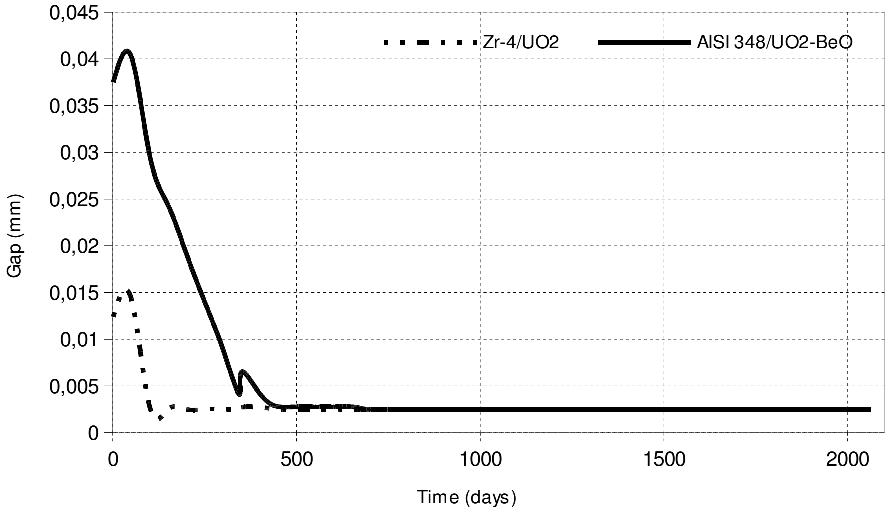

Fig. 5. Gap evolution under steady-state irradiation as function of time for IFA-650.5 test case considering Zr-4/UO_2 fuel system and AISI 348/UO_2-BeO fuel system.

The higher thermal expansion experienced under irradiation by AISI 348 compared to Zircaloy-4 cladding enables that wider gaps be maintained for a longer time in the AISI 348/UO_2-BeO fuel system compared to the conventional Zircaloy-4/UO_2 fuel system.

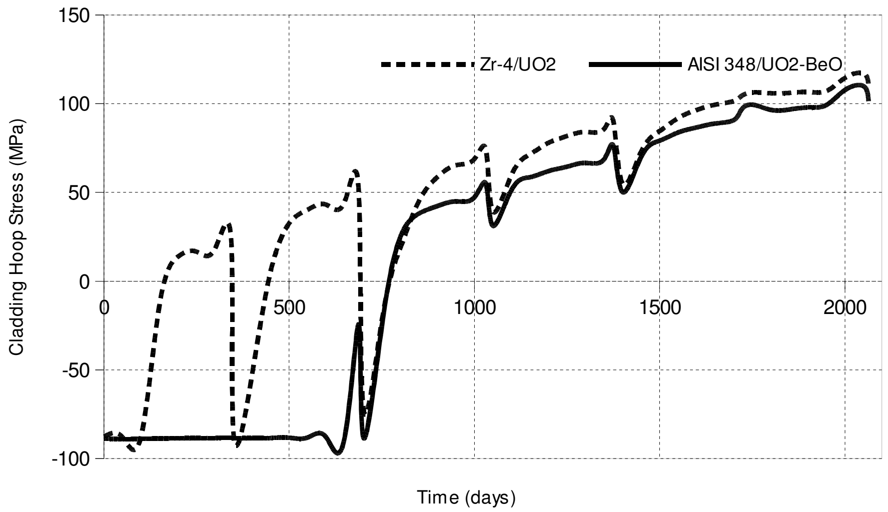

Fig. 6. Cladding hoop stress evolution under steady-state irradiation as function of time for IFA-650.5 test case considering Zr-4/UO_2 fuel system and AISI 348/UO_2-BeO fuel system.

The initial state of compressive stress in the two cladding types (Figure 6) is due to the external coolant pressure. Due to the early gap closure associated to the power profile, the hoop stresses start to alternate between compressive and tensile states at the beginning of the irradiation time for the Zircaloy-4/UO_2 fuel system while for the AISI 348/UO_2-BeO fuel system this behavior is observed later. This phenomenon plays an important role in the occurrence of PCMI failures in PWR fuel rods.

II.A. LOCA Scenario

The IFA-650.5 experiment performed to simulate LOCA conditions used refabricated fuel rod with three thermocouples located at different axial position on the cladding surface. The experimental data from the thermocouples and pressure transducer were utilized as input data for FRAPTRAN code, specifically as thermohydraulic boundary conditions. Although the experimental data is specific to the Zircaloy-4/UO_2 fuel system, the simulation for AISI 348/UO_2-BeO fuel system was performed using the same experimental data. Regardless of the fact that this experimental data is not well suitable to AISI 348/UO_2-BeO fuel system, imposing this data for the simulation of this fuel system will certainly be a conservative condition.

The conservatism can be verified from the previous results obtained in the steady-state simulation, where the fuel centerline temperature and internal pressure for AISI 348/UO_2-BeO fuel system are lower compared to the Zircaloy-4/UO_2 fuel system. The simulation of the accident considered not only conservative boundary condition, as well as initial condition, as presented above. Taking into account the condition adopted to perform the simulation using the code FRAPTRAN, the results and findings, specially associated to the fuel failure shall be conservative. It is worthwhile to perform such assessment in the future to verify the safety margins associated to AISI 348/UO_2-BeO fuel system.

The analysis of the LOCA scenario for the reference Zircaloy-4/UO_2 fuel system shows that the cladding rupture occurs 189 seconds after the blowdown, as presented in Figure 7. The time of cladding rupture obtained by means of the simulation using the original version of FRAPTRAN-1.4 code is about 10 s later than that observed in the experiment, showing a good and consistent agreement between simulation and experimental data.

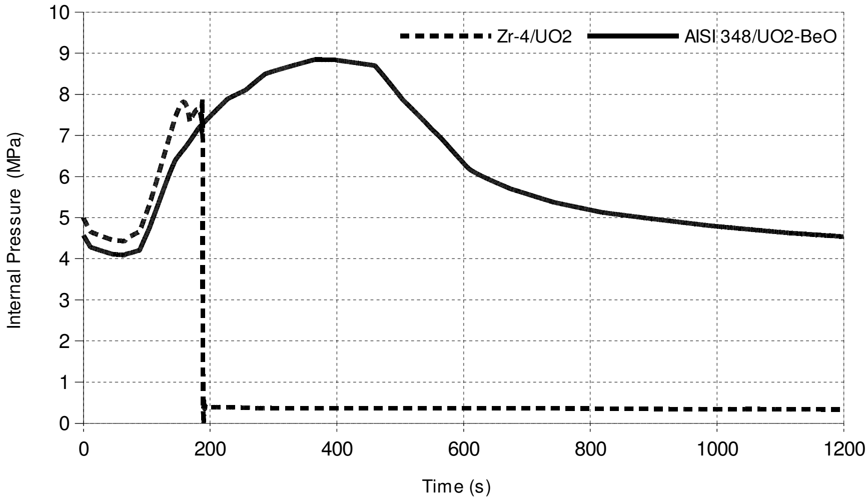

Fig. 7. Fuel rod internal pressure evolution under LOCA as function of time for IFA-650.5 test case considering Zr-4/UO_2 fuel system and AISI 348/UO_2-BeO fuel system.

While for Zircaloy-4/UO_2 fuel system the cladding rupture is observed at 189 s after blowdown, the results obtained for AISI 348/UO_2-BeO fuel system using the modified version of FRAPTRAN-1.4 code, as presented in Figure 7, show that the cladding rupture does not occur under the studied conditions. This behavior can be explained based on the mechanical properties of stainless steel, such as its lower ductility as compared to zirconium-based alloys, resulting in reduced cladding ballooning, and its higher mechanical strength at temperatures below the melting point, as those observed during LOCA test[12]. The evolution of the cladding hoop stress as function of time during LOCA presented in Figure 8 confirms this behavior.

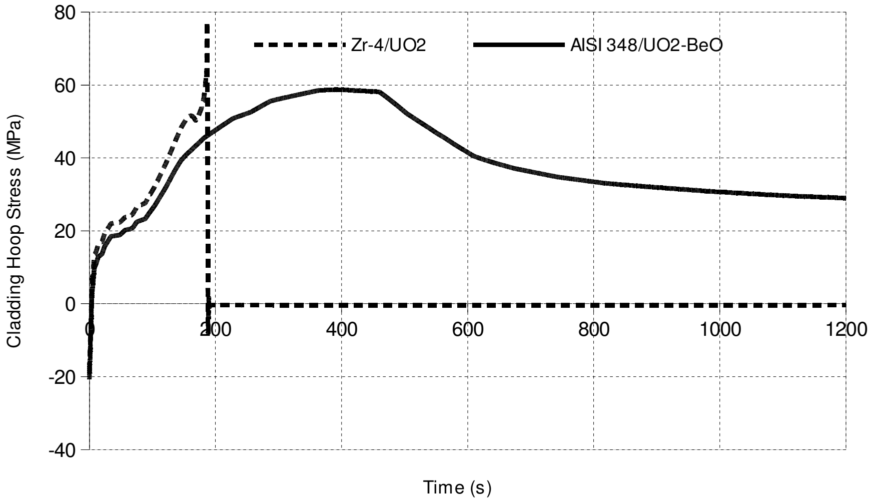

Fig. 8. Cladding hoop stress evolution under LOCA as function of time for IFA-650.5 test case considering Zr-4/UO_2 fuel system and AISI 348/UO_2-BeO fuel system.

The obtained results confirm that the cladding mechanical properties under high temperature are determinant to define the occurrence of cladding failure under LOCA scenario.

IV. CONCLUSIONS

The fuel centerline temperature along of the irradiation plays a very important role, especially concerning to the gas release phenomena due to the Vitanza threshold[19]; moreover the fuel pellet thermal expansion, swelling and fragmentation can contribute directly to PCMI effect. The improvement of thermal properties of the fuel pellet can mitigate and/or reduce significantly all undesired thermal effect, consequently improving the fuel performance under normal operation. The thermal conductivity changes in the pellet due to addition of BeO promotes significant improvement of the fuel safety margins, especially under accident condition as shown in the simulation results obtained in this paper.

At very beginning of LOCA accident, the UO_2-BeO fuel pellet has less thermal energy stored due to lower central temperature and heat output; moreover the fission gas release is lower, reducing consequently the internal pressure, which reduces the internal mechanical loading to the cladding. Additionally, combining with the good mechanical properties of the stainless steel cladding, the fuel rod will not experience failure under LOCA scenario.

Comparing to others existing research related to ATF and UO_2-BeO, unfortunately due to the lack of similar simulation, the results obtained in this work could not be directly compared. Similar analysis[9] was performed but the test case for simulation was different (LOCA simulation using MIT-1 exercise). Although, the results obtained could not be directly comparable to others, the main outcome of this work is quite consistent and qualitatively agrees with expected results. Moreover, in the future different simulations will be conducted in order to obtain more conclusive results.

This work presents a preliminary assessment of alternative and very promising ATF fuel which has shown a significant improvement of safety margins.

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