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ANGRA 1 HIGH BURNUP FUEL BEHAVIOUR UNDER REACTIVITY INITIATED ACCIDENT CONDITIONS

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ABSTRACT

The 16x16 NGF (Next Generation Fuel) fuel assembly, comprising of highly corrosive-resistant ZIRLO clad fuel rods, been replacing the current 16x16 Standard (16STD) fuel assembly in the Angra 1, a pressurized water reactor**,** with a net output of 626 MWe. The 16x16 NGF fuel assemblies are designed for a peak rod average burnup of up to 75 GWd/MTU, thus improving fuel utilization and reducing spent fuel storage issues. A design basis accident, the Reactivity Initiated Accident (RIA), became a concern for a further increase in burnup as the simulated RIA tests revealed a lower enthalpy threshold for fuel failure. Two fuel performance codes, FRAPCON and FRAPTRAN, were used to predict high burnup behavior of Angra 1, during an RIA. The maximum average linear fuel rating used was 17.62 KW/m. The FRAPCON 3.4 code was applied to simulate the steady-state performance of the 16 NGF fuel rods up to a burnup of 55 GWd/MTU. With FRAPTRAN-1.4 the fuel behavior was simulated for an RIA power pulse of 4.5 ms (FHWH), and enthalpy peak of 130 Cal/g. With FRAPCON-3.4, the corrosion and hydrogen pickup characteristics of the advanced ZIRLO clad fuel rods were added to the code by modifying the actual corrosion model for Zircaloy-4 through the multiplication of empirical factors, which were appropriate to each alloy, and by means of reducing the current hydrogen pickup fraction.

Key words: *FRAPCON, FRAPTRAN, reactivity initiated accident, transient analysis*.

1. INTRODUCTION

Reliably predicting the behavior of irradiated fuel rods in Light Water Reactors (LWR) has been a major objective of the research programs in the area of reactor safety. In order to achieve these objectives, extensive development of computer programs (codes) and "in-pile" and "out-pile" test have been carried out in order to validate the analytical capacity of simulations of real cases scenarios, such as those involving Zirlo based next generation fuel.

An updated version of the FRAPCON fuel performance code was used in the simulation of reactivity-initiated accident (RIA). Next generation fuel (NGF), in use in Angra 1; in the form of four 16NGF fuel elements, was used in the simulation test.

The advantage of the simulation suggested here is to analyze the behavior of different fuel bundles in the 16x16 Pressurized Water Reactor (PWR), at the 626 MWe Angra 1 (Brazil) nuclear power plant (NPP). The core reactor is loaded with 121 fuel elements containing 235 fuel rods in each assembly, totaling 28.435 fuel rods. In the particular case, there are four new assemblies of 16NGF together with the older 16STD, under the same burnup cycle in the core.

In the simulation, the FRAPCON-3.4 code was used to model steady-state fuel behavior, in which the burnup averaged up 55 GWd/MTU, thus generating the output data, for both Zirlo and Zircaloy cladding. The levels of oxide formed the hydride uptake and the temperature in the fuel cladding, and the fission gas released were ascertained for, both cases. In the second stage of the simulation, the Zirlo clad test rods were irradiated for about 584 effective full power days (EFPD), corresponding to about 35 GWd/MTU. In addition, an enthalpy pulse width of 4.5 ms, with an enthalpy peak in the 70 to 130 cal/g range was subsequently applied, whose FRAPTRAN code was partially employed in the RIA test.

1.1. Fuel Performance Codes

However, an accurate description of the fuel rod behavior, involves several aspects, such as nuclear and solid state physics, metallurgy, ceramics, the mechanics of plastic deformation, thermal heat transfer, and the effects of radiation on crystal substructures. This interrelationship is the basis for the development of computer codes, which describe the general fuel behavior applied in FRAPCON [2] and FRAPTRAN [4] under continuous development.

1.2. Fuel Modelling

The two main sources for studies on fuel performance are the Fuel Modelling at Extended Burnup (FUMEX), international cooperation programs promoted by the International Atomic Energy Agency (AIEA), and Nuclear Fuel Performance Experiments (IFPE). The IFPE is public database, which contains datasets about 1445 sample rods, for the purpose of code development and code validation, such as in the case of FRAPCON and FRAPTRAN.

The benefits of the IFPE and FUMEX international cooperation programs is include the availability of information, such as clad diameters, oxide thickness, hydrogen content, fuel grain size and porosity. Research is focuses on modeling global fuel performance by means of studies in thermal evolution, fission gas release, fuel swelling, clad deformation, fatigue, and plastic and elastic behavior under irradiation.

1.2.1. FRAPCON

The FRAPCON code is an analytical tool that analyses the behavior of an LWR fuel rod under irradiation, when power variations and boundary conditions are sufficiently slow for the term steady-state apply. FRAPCON has been performed for the U.S. Nuclear Regulatory Commission (USNRC), in conjunction with Pacific Northwest National Laboratory (PNLL).

This code includes situations, such as long periods of constant power and slow power ramps, which are typical of normal operations of a nuclear reactor. FRAPCON designed to burnup at levels of 65 GWd/MTU. The FRAPCON code calculates all the significant variables of the fuel rod by the time variation method, including fuel and cladding temperatures, gas and pressure release in from the fuel rod, cladding deformation and oxidation of the fuel densification, swelling, releases of gases and pressure in the fuel rod. In addition, the code is designed to generate initial conditions for a transient analysis code simulated by the FRAPTRAN code for the performance of transient-state.

1.2.2. FRAPTRAN

The Fuel Rod Transient Analysis Program (FRAPTRAN) is a computer code developed to calculate both the thermal and mechanical behavior under of transitory LWR fuel rods. The code models all the thermal, structural, and chemical phenomena necessary for a complete performance evaluation of light water reactor fuel rods. FRAPTRAN code is used to evaluate the behaviour of fuel rods during transient power and reactor accident cooling, such as reactivity and loss of coolant accidents during burnup at 65 GWd/MTU. The code was developed using rigorous quality assurance procedures and a large assessment database available and validated by FUMEX and IFPE programs, programs, knowledge base about fuel rods under operation.

1.3. Pulse Width and Shape

In order to simulate the transient-state of the amount of heat added to fuel, the FRAPTRAN, code was used, which was supplied with data from FRAPCON output files. In a hypothetical accident, the process consists a failure simulation involving the withdrawal of control rods. The characteristics of the power pulse depend on the accident scenario, but also on the core and fuel rod design, the operational state of the reactor, and the time point during the fuel cycle at which the accident occurs.

The transient-state is simulated by means of the FRAPTRAN code. The material property correlations for fuel cladding describe correlations applicable to Zircaloy-2, Zircaloy-4, Zirlo, and M5. Additionally, several FRAPTRAN subroutines include supplementary correlations that describe zirconium alloy (Zr-1%Nb), [4]. The Niobium reduced oxidation rate, as well as the hydrogen pickup rate. Oxide thickness and hydride concentration limits are usually in the range 100 microns and 500-600 ppm, respectively.

RIA type accidents are characterized by reactivity insertion, in the short time, caused by the rapid ejection of controls rods. For a prompt reactivity insertion, an upper reactor power excursion occurs [5]. The transient-state is so fast that the heat increase of the fuel pins is close to adiabatic thermal process. Heat losses are due to both gamma and neutron transports out of the fuel, but also, to a certain degree, to heat conduction at the fuel periphery.

The power pulse can induce clad deformation, proportional to the strain energy density, for pulse energies around or below 130 cal/g. The deformation is driven mainly by the thermal expansion of the fuel rods, while very energetic level pulses causes considerable increase in the amount of Xenon and Krypton gas released.

Swelling starts playing a significant role, is especially of concern at high-burnup due to the formation of high-burnup structures at the pellet rim. The adiabatic correlation between the pulse width and enthalpy results in a simple point-kinetics approach to describe this transient-state.

The Nordheim-Fuchs model, where a step reactivity insertion, ρ_0 is constant, and Cp is the fuel-specific heat capacity, β is the delayed neutron fraction, Λ is the prompt neutron life time, and γ is the Doppler reactivity. The approximate average power is given by the Equation (1):

$$P_m = \frac{(\rho_0 - \beta)^2 Cp}{2\Lambda\gamma} \tag{1.0}$$

The Nordheim-Fuchs adiabatic model also gives us a simple approximation of the total energy deposition in the fuel subject to the power pulse, described by Equation (2).

$$E = \frac{2(\rho_0 - \beta)C_p}{\gamma} \tag{2.0}$$

For a constant step insertion of pulse reactivity, full width at half maximum (FWHM) is employed, described by Equation (3).

$$FWHM = \frac{3.5255\Lambda}{\Delta\rho - \beta} \tag{3.0}$$

1.4. Next Generation Fuel (16NGF)

In last decade was decided to implement a new fuel assembly design for the class reactor 16X16, two loops, power gross of 650 MWe, PWR (Westinghouse). The 16NGF program planned change fuel elements from 16STD to 16NGF. The program was initiated in 2001 when it was decided to implement new fuel assembly design. The same strategy was used in several nuclear power plants, around the world: Kori-2 (Korea), Angra 1 (Brazil), Krsko (Slovenia).

Next generation fuel was jointly designed by Indústrias Nucleares Brasileiras (INB), the Westinghouse Electric Company (Westinghouse), and Korea Nuclear Fuel Company, Ltd. (KNFC). Essentially, the currently used 16STD does not have optimized characteristics, such as Zirlo cladding and your its structural elements. In the 16STD fuel assembly, Inconel alloy for middle grids and spacer grids is used, and there is no Intermediate Flow Mixer (IFM). Debris filters, and guide thimbles with inefficient components from a neutron economy standpoint are also used. In the 16NGF fuel assembly, mechanical design characteristics have been improved for extended burnup.

In seventeenth discharge burnup, four 16NGF fuel bundles were inserted into the core at Angra 1, as planned for the burnup cycle. The main objective was to assure the compatibility with current technology of Westinghouse. 16NGF is defined for burnup peaks of up to 75 GWd/MTU, and average of 55 GWd/MTU. In general, the new designs have been improved to low wear, high corrosion resistance and fretting, quality improved to Departure Nucleate Boiling Rate (DNBR), and filtering debris. Below find summarized the main features of 16NGF:

- The use of optimized zirconium alloys Zirlo improves corrosion margin for heavier duty use. 16NGF fuel rod cladding, thimbles tubes, mid grids, and IFM grids are all manufactured by optimized Zirlo. Grids and vanes provide enhanced thermal-hydraulic performance and neutron economy;
- The increase of contact area between the grid and the rod significantly improves the grid for rod fretting rates, compared to 16STD designs. Zirlo is used in middle grids, new spring/dimple and mixing vane, enhancement DNB margin and neutron economy;

- Enhanced debris mitigation and heat transfer improvements. The Westinghouse Integral Nozzle (WIN), in which the top nozzle, bottom nozzle and protective grid improved filter of debris. The Debris Filter Bottom Nozzle (DFBN) has been designed to mitigate fretting failures, and protective grids have been implemented.

1.4.1. Economic advantages for extended burnup

The most important advantage of extended burnup is the potential economy from the improved fuel cycle. The economics benefits depend in part on the fact that fewer decrease fresh fuel bundles need to be purchased. In addition, occurs a decrease in fuel bundles result in reduced handling and storage spent fuel. The fuel assemblies for the advanced Westinghouse 16x16 PWR design for the 16NGF designed for Angra 1, can optimize fuel cycle management, by aggregating the design intents, which can be summarized as follows:

- Annual fuel cycles extended from 12 to 18 months;
- Economy uranium, it’s possible used 373 Kg in each element instead of 411 Kg;
- Average burnup greater than 55 GWd/MTU;
- The new fuel rods are more enriched than the current fuel rods, from 3.4% to 3.8%;
- Departure nucleating boiling rate optimized by 20%;
- Structural elements, grids and mixer vanes changed from Inconel to Zirlo;
- Power output extended at rates ranging from 5% to 20% in PWRs;
- Compatibility between updated and older fuel assemblies (16STD and 16NGF).

New approaches to fuel projects are researched topics, with the purpose of optimizing economic operation, and extended fuel cycles have led to a significant decrease in the specific consumption of uranium. The current 16STD fuel assembly employs an outer rod outer diameter of 9.5 mm, which was decreased to 9.144 mm, and fuel pitch of 12.319 mm, at the same pellet height, with an increase in enrichment to 3.8% ,Uranium-235. The economy of uranium was implemented. The intermediate Inconel grids were replaced with Zirlo.

1.4.2. Zirconium alloys

The characteristics of nuclear fuel cladding, generally manufactured from zirconium alloys, include low neutrons absorption, excellent resistance to corrosion, and high quality mechanical properties. These alloys have been used in LWRs since the 1950s.

The properties of oxides that form on the surfaces of clad have an especial influence on their lifetimes. Further structural elements made from this material include spacer grids, guide tubes in PWRs and in fuel assembly channels in Boiling Water Reactors (BWRs). The Zircaloy-2 has been used in BWR. Zircaloy-4 has been used in PWR, [1].

In the advanced Zr-alloys Sn content was decreased below limits 1.2%. The oxidation and hydrogen uptake of Zr alloys are important limiting phenomena for extending the burnup cycle [1]. The main types of zirconium alloys: with wt 1% Nb, (Zr-1%Nb), named Zirlo (Zr-1Nb-1Sn-0.1Fe-0.12O), such as ZIRLO^{TM} (Westinghouse), or M5^{TM} (Framatone ANP), MDA (Mitsubishi), and HANA (Korea). Other types of zirconium alloys, such as, E-635 and E-110, are the materials for cladding and structures used in Western-type reactor VVERs and RBMKs. The many types of zirconium alloys are shown in Table 1.

Table 1. Nominal composition of major zirconium alloys

Cladding Alloy	Nominal Composition (in wt%)
Zircaloy-2	Zr-(1.2-1.7)Sn-(0.7-0.2)Fe-(0.5-0.15)Cr-(0.03-0.08)Ni-(0.1-0.14)O
Zircaloy-4	Zr-(1.2-1.7)Sn-(0.18-0.24)Fe-(0.7-0.13)Cr-(0.1-0.14)O
Zirlo	Zr-1Nb-0.1Fe-0.12O
M5	Zr-1Nb-(0.8-0.12)O-(0.015-0.08)Fe-(0.09-0.12)O
MDA	Zr-0.5Nb-0.8Sn-0.2Fe-0.1Cr-0.12
NDA	Zr-0.1Nb-1.0Sn-0.27Fe-0.16Cr-0.01Ni-0.12O
E-110	Zr-1Nb(0.05-0.07)O
E-635	Zr-1Nb-1.2Sn-0.1Fe (0.05-0.10)O
HANA-4	Zr-1.5Nb-0.4Sn-0.2Fe-0.1Cr

2. FUEL BEHAVIOR UNDER RIA

2.1. Safety Criteria

The temperature limits of thermal cladding in the steady-state is of 982 °C, when exceeds to 1204 °C or (2200 °F) are characteristics of the loss of coolant accident (LOCA). The threshold, Equivalent Cladding Reacted (ECR) or maximum oxidation cannot exceed 1204 °C and 17% of its level, the respective the oxygen generated reacts with the zirconium dioxide, and forms the stoichiometric ZrO_2 [5], summarized:

- DNB: Critical heat flux describes the thermal limit of a phenomenon, which the phase change occurs during heating. The heat flux occurs in an interval of 95%, limits energy is deposited in the fuel rods in case of RIA, and also limits temperature and oxidation in the case of LOCA. DNBR safety limit is derived from statistical analysis;
- CRUD: Deposition as a criterion is derived by limiting the oxidation phenomena and pellet clad interaction (PCI). The crud layer can induce localized corrosion, but limits vary among suppliers;
- Strain: Generally conservative design limits are taken for the stress; around 1% yield or tensile strength at operating temperature, or strain, and circumferential elastic and plastic strain 2.5 %, for permanent axial and tangential strain. These limits, together with other such as PCMI, are used to define thermal mechanics limits;
- Fission Gas Release: The generation of fission product gases increases considerably when the burn rate reaches 40 to 45 GWd/MTU;
- Pulse Heat: The first RIA tests validated a pulse of heat of 280 cal/g. Electric Power Research Institute (EPRI) suggests limits of 240 cal/g, in the CABRI reactor, 70 cal/g.

The main fuel safety criteria have been developed over the last forty years. The various aspects of the safety criteria in the hypothesized RIA have been researched, such as fuel fragmentation, fuel failure, due to hydride concentration and, oxidation and strain levels.

3. SIMULATION AND RESULTS

In this simulation, the fuel rod, exhibits the best rate of corrosion and hydriding. The relative performance between oxide thicknesses in Zirlo is 30%, of that formed on conventional. When compared to Zircaloy-4. Zirlo cladding exhibited better dimensional stability, lower hydrogen uptake, and lower axial growth than Zircaloy-4. The gap formed between fuel and pellet takes contact after Zircaloy-4 under irradiation. The pellet cladding interaction occurs at 234, effective full-power days (EFPD), for Zircaloy-4, and 351 EFPD for Zirlo, as detailed in Table 2.

Table 2. 16NGF and 16STD results comparisons

Burnup (GWd/MTU)	EFPD (days)	Zirlo - 16NGF			Zircaloy - 16STD		
		Hydride (ppm)	ZrO_2 (mils)	Gap (mils)	Hydride (ppm)	ZrO_2 (mils)	Gap (mils)
5	117	20	0.06	0.79	21.9	0.06	0.69
10	234	22.6	0.08	0.23	25.1	0.08	0.13
15	351	31.6	0.13	0.13	40.5	0.15	0.13
20	467	45.8	0.21	0.13	66.4	0.28	0.13
25	584	61.7	0.31	0.13	94.5	0.42	0.13
30	702	78.8	0.41	0.13	123.8	0.57	0.13
35	818	97.8	0.52	0.13	155.6	0.72	0.13
40	935	119.3	0.65	0.13	189.9	0.89	0.13
45	1052	144	0.8	0.13	227.8	1.07	0.13
50	1169	173.7	0.97	0.13	270.9	1.28	0.13
55	1286	209.5	1.18	0.13	318	1.51	0.13

In Table 2, simulation was summarized results about 16NGF. It presents lower hydrogen uptake than 16STD does, and oxidation thickness. For optimized performance and ability to withstand high burnup is recommended the change 16STD to 16NGF.

Table 3. Burnup comparisons at 55 GWd/MTU

Output Summary	16NGF	16STD
Peak Burnup (GWd/MTU)	79.00	85.91
Time (days)	1286	1286
Maximum strain increment (elastic + plastic)	0.042146	0.049427
Fission gas release (%)	18.44	22.63
ZrO_2 weight gain, (g/m^2)	2.91	2.92
Maximum fuel rod pressure (psi)	988.88	970.18
Cladding axial strain	0.015264	0.016287
Cladding hoop strain	0.004366	0.004351
Cladding axial stress (psia)	12607	13719
Cladding hoop stress (psia)	11510	12547

16NGF simulation test performed using FRAPCON-3.4 codes. Initially, the fuel rod was irradiated, with a burnup average of 55 GWd/MTU. The maximum local burnup was respectively 79 and 85 GWd/MTU for 16NGF and 16STD. The mean zirconia thickness was 29.9 µm for 16NGF the mean value 38.8 µm for 16STD. Table 3.

3.1. A Comparative Analysis

In high temperature, zirconium alloys absorb considerable amounts of hydrogen, which solved in coolant or set free by oxidation process. At the beginning of the cycle, the difference was low, and by the end cycle, was considerable. This is described in Fig. 1.

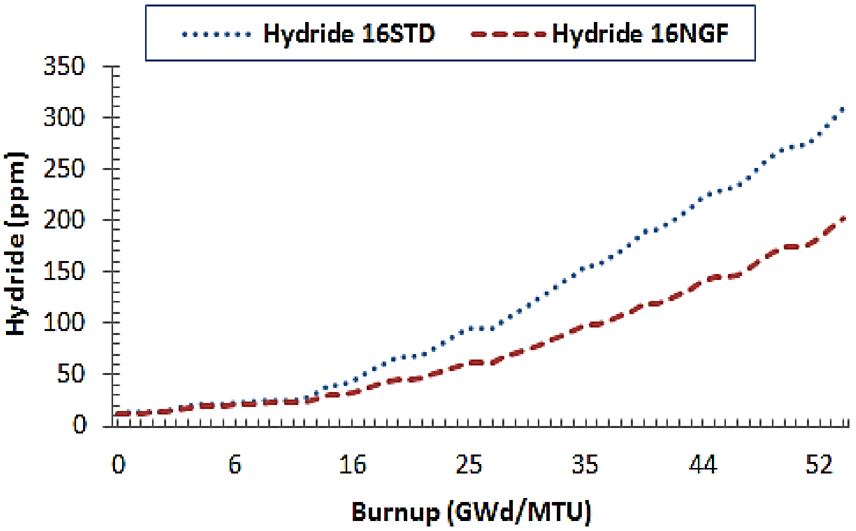

Figure 1. Hydrogen uptake comparisons between 16STD and 16NGF.

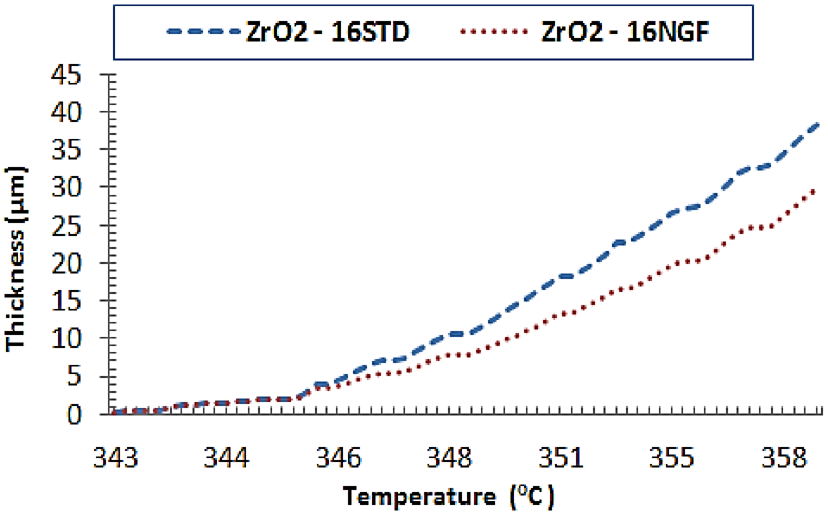

Figure 2. Zirconia between 16STD and 16NGF.

At first it is solved in alpha-phase metal; a higher concentration, hydride precipitated in zirconium matrix, hydrogen pickup. Is useful the temperature at which hydride precipitates for estimating when hydriding will begin to embrittle the cladding. This is described in Fig. 2.

The relative diameters change in claddings is a function of hydrogen content, average hydrogen uptake in the Zirlo is lower than the average of Zircaloy-4, which displays 65% of Zircaloy-4. Fuel 16NGF claddings, growth is approximately 57% of Zircaloy-4, along with lower plastic or elastic strain. Consequently, low hoop, axial and radial strain, as indicate in Fig.3, and complemented in the Fig. 4.

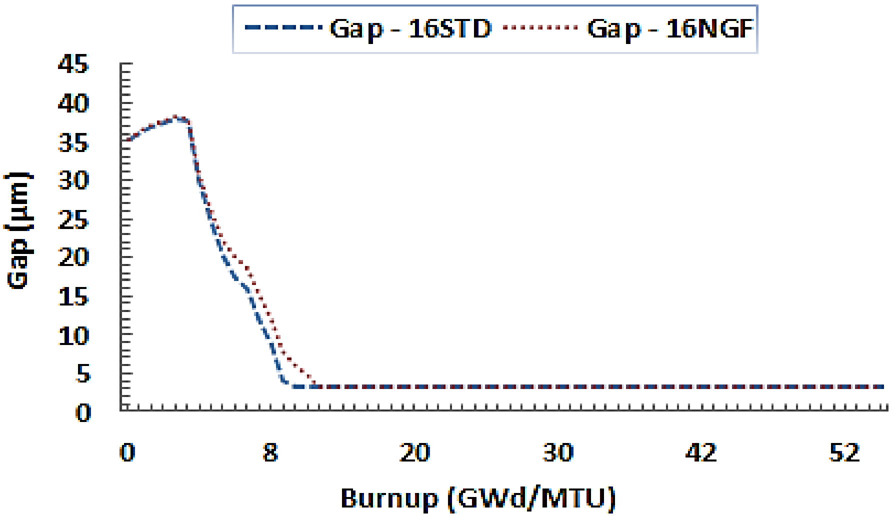

Figure 3. Gap between Fuel pellet and clad thickness, 16NGF and 16STD.

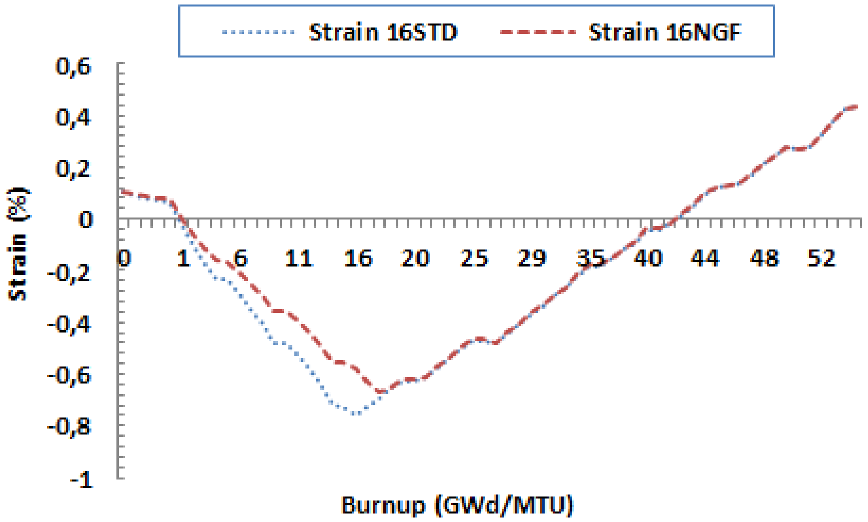

Figure 4. Axial and strain comparisons between 16NGF and 16STD.

Test simulation test by means of FRAPTRAN1-4, where some guidelines were applied. FWHM is equal 4.5 ms and enthalpy range peak from 70 cal/g, to 130 cal/g is applied to the 16NGF fuel element, with a pre-irradiated average burnup of 35 GWd/MTU [6]. Power pulse of 4.5 ms FHWH and enthalpy peak of 130 cal/g. In simulation, the corrosion and hydrogen pickup characteristics of the advanced Zirlo fuel cladding failure at a burnup of 35 GWd/MTU under an enthalpy pulse of 130 cal/g.

The failure fuel rods and cladding an empirical limit proposed by Korea Atomic Energy Research Institute (KAERI), which is a statistical regression model, and has been employed to predict the failure enthalpy for fuel elements. First 16NGF was irradiated at 35 GWd/MTU. The failure at the limits is accurate in function of fuel burnup, oxide thickness, and pulse width [6]. Applied KAERI correlation for 16NGF, oxide layer 38 microns, burnup of 35 GWd/MTU. Power pulse of 4.5 ms, the given value by KAERI correlation happening 108 cal/g; Equation 4, [3].

$$H_f = 156.6 - 0.774Ox - 1.076Bu + 29.41\log(\Delta\tau) \tag{4}$$

The correlation indicated the decrease of failure enthalpy with fuel burnup and layer oxide formed, for 16NGF. The effect of pulse width has been confirmed. The failure occurs at 130 cal/g and not failure was observed at 70 cal/g, with pulse width, 4.5 ms and 16NGF average burnup at 35 GWd/MTU, Fig. 5.

In the simulation, pulse irradiation causes the reactivity-initiated accident type RIA. The RIA condition can be seen by time and temperature. The pulse irradiation expands the fuel forcing cladding deformation simultaneously as show in Fig. 4. The cladding surface temperature increased as well to reach the peak. The rod internal pressure in simulation increased promptly during the pulse irradiation. The fuel temperature was estimated 1770 °C, large amount fission gases, mainly Xe and Kr in the gap where the inner pressure increase. The rate Xe/Kr rising during the pulse.

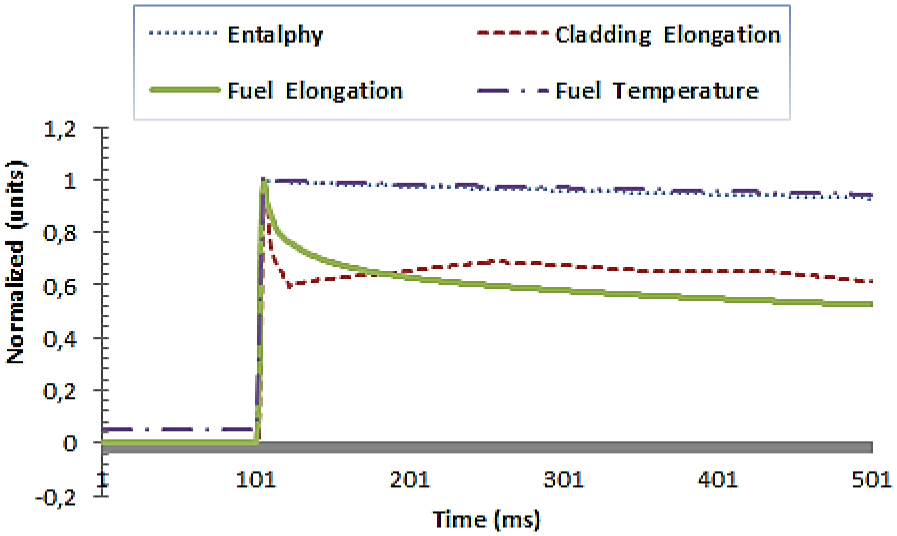

Figure 5. Behavior under pulse enthalpy 70 cal/g.

4. CONCLUSIONS

The cladding absorbs a fraction of the hydrogen that follows the (Zr-1%Nb) reaction in LWRs. The Hydrogen absorption is known to enhance cladding embrittlement, the first step to failure of the mechanism. The major conclusions are as follows:

- In the transient-state, the heat pulse occurs in the transition phase region, α phase to β phase transition of zirconium takes place principally in the 800°C-1000°C temperature range, which is typical in the enthalpy peak. The phase transformation is not temperature dependent only on temperature alone;
- The fuel does not fail under 70 cal/g under pre-irradiation of 35 GWd/MTU, but it shows exhibits failure behavior under 130 cal/g with FWHM equal to 4.5 ms;
- These simulations and considerations on a potential contribution of the materials properties of zirconium alloys lead to the conclusion that cladding materials with substantially reduced oxide layer thicknesses on the cladding and hydrides in the cladding will contribute to the mitigation of fuel rod defects caused by RIA accidents;
- Definitively Zirlo alloy of zirconium material with niobium, tin and iron is the result an extensive look for a successor of Zircaloy-4. 16NGF perform better than 16STD.

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