THE IPEN/CNEN CONTRIBUTION TO IAEA FUMAC BENCHMARK USING MODIFIED FUEL PERFORMANCE CODE BASED ON STAINLESS STEEL AS CLADDING UNDER STEADY STATE, TRANSIENT AND ACCIDENT CONDITIONS

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Abstract.

The IPEN/CNEN (Brazil) participated in IAEA Coordinated Research Project on Fuel Modeling in Accident Conditions (FUMAC) among others 18 countries (Argentina, Belgium, Bulgaria, China, Czech Republic, Finland, France, Germany, Hungary, Italy, Japan, Norway, Republic of Korea , Russian Federation , Spain , Sweden , Ukraine and United States of America), which aim was focused in modelling, predicting and improving the understanding of the behaviour of nuclear fuel under accident conditions in order to better understanding and enhanced safety of nuclear fuel. A serie of LOCA (Loss of Coolant Accident) experiments data were made available for the participants to perform simulation using their fuel performance codes and the outcome gives an idea about fuel codes limitation considering LOCA simulation and possible improvement needed in the existing models related to LOCA condition.The IPEN/CNEN (BRAZIL) proposal for FUMAC-CRP was to modify existing fuel performance codes (FRAPCON and FRAPTRAN) considering stainless steel as cladding material and perform a simulation comparing to zircaloy cladding performance under steady state and accident condition. The HALDEN LOCA Experiments (IFA 650-9, IFA-650-10 and IFA-650-11) were selected and modeled to perform the LOCA accident simulation considering the original cladding (zircaloy) and compared to stainless steel cladding.

1. INTRODUCTION

The IAEA FUMAC CRP [1]was focused in LOCA (Design Basis Accident) fuel behaviour at early stage of the scenario of the Fukushima Daiichi accident (Beyond Design Basis Accident) in order to better understanding of fuel behaviour in loss of coolant accident conditions through the computer fuel performance codes considering experiments dedicated to LOCA conditions. A set of LOCA experimental data were made available to the FUMAC participants, such as: HALDEN LOCA in pile experiments (IFA 650-09, IFA 650-10 and IFA-650-11), NRC-Studvisk LOCA out of pile experiment (test 192 and 198), Quench LOCA out of pile fuel bundle experiment (KIT-Germany) and aseparate effect experiment (PUZRY from MTA-EK Hungary) in order to perform simulation using fuel performance codes and compare to the existing experimental results, moreover perform some sensitivity and uncertainties analysis. The participants could select any of experiment and perform simulations considering the data made available, best practices in the modelling and input preparation considering relevant physical models available in their own codes, proper initial and boundary conditions and at end compare the calculated results with existing experimental aiming to verify the capabilities and limitation of the fuel performance code to simulate the LOCA accident condition.The IPEN/CNEN was conducting some investigations of stainless steel as cladding material in the ATF (accident Tolerant Fuel) context after Fukushima Daiichi accident and presented a proposal to investigate the stainless steel cladding performance under same conditions as zircaloy cladding fuel in the FUMAC framework using FRAPCON[2] and FRAPTRAN[3] codes. The participation was an excellent opportunity to access the LOCA experiments (in pile, out of pile and separate effect) data in order to investigated fuel performance capabilities and the modifications implemented in the codes related to stainless steel as cladding.

2. ACTIVITIES

The FUMAC CRP initial activitiesperformed were mostly related to fuel performance (FRAPCON and FRAPTRAN) modification in order to consider stainless steel as cladding material and experimental data evaluation to prepare the input data for simulations.

2.1 Codes Modifications

Originally, the NRC fuel performance codes: FRAPCON/FRAPTRAN consider only zirconium based alloys as cladding material (Zircaloy-2, Zircaloy-4, M5, Zirlo, Improved Zirlo, and E110). Most of material properties considered in the FRAPCON codeare gathered in MATPRO data libraries [4] and some others are specifically consideredin modular subroutines where the material properties (thermal and mechanical) as function of temperatures and for burnup are explicitely considered. Initially, the subroutines and data related to material properties were identified, specialy thermo-mechanical properties of cladding (zircaloy) in order to verify and replace for stainless steel properties. Some material properties for stainless steel were taken from existing metal handbook and others were not available in the open literature, in that case, the approach adopted was not changed the data at all. Some additional details can be found in the reference[5]: *Revisiting Stainless Steel as PWR Fuel Rod Cladding after Fukushima Daiichi Accident*, published in **Journal of Energy and Power.** After modifications, some qualitative and quantitative assessment were performed in order to verify the modifications implemented in both codes. The major modification in the FRAPCON code (steady state) were related to thermal (expansion, conductivity, thermal creep) and mechanical (elastic modulus, Poisson ratio, ultimate tensile strength, shear modulus, irradiation creep) properties and results obtained (gap thickness, internal pressure, fuel temperature) are quite in agreement to expected results compared to zircaloy cladding. It is worthwhile to mention that main difference is associated to thermal properties (thermal expansion and conductivity) of cladding, as stainless steel exhibits higher thermal expansion compared to zircalloy, as consequence gap thickness of stainless steel rod is larger compared to zircaloy fuel rod, moreover the fuel temperature could be slightly high and at end of irradiation fission gas and associated pressure could be high compared to zircaloy fuel rod. The figures 1 and 2 shown the evolution of fuel average temperature and plenum pressure for IFA 650-9[4], respectively. As can be seen, the fuel average temperature considering stainless steel is slightly high compared to zircaloy due to gap thickness and as consequence the plenum pressure is high, too. At end of irradiation, the difference observed in the results are less than 5% in both parameters (temperature and pressure). As main outcome of steady state simulations indicates that modification of FRAPCON was successfully accomplished, moreover temperature and pressure reached by original and modified version of FRAPCON code at end of irradiation for steady state condition could not be influential for transient simulation. Although the pressure and temperature shall not be influential, the sensitivity assessment can identify most influential parameter at end of irradiation that can contributes to fuel cladding failure for LOCA transient.

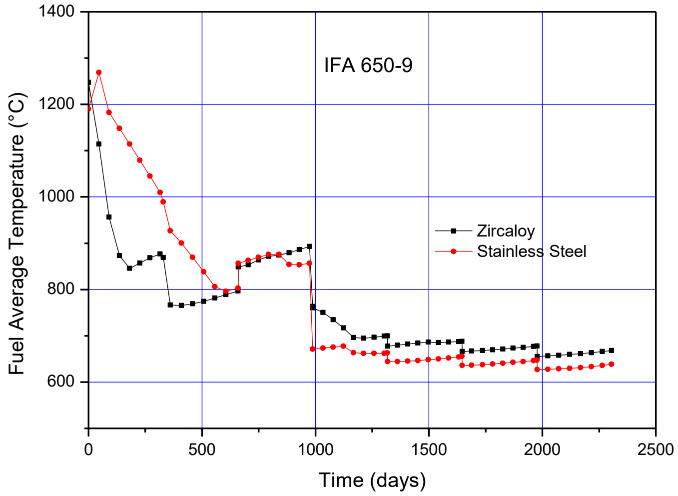

FIG. 1 Fuel average temperature (IFA 650-9) evolution obtained from FRAPCON original version (zircaloy cladding) and modified version (stainless steel).

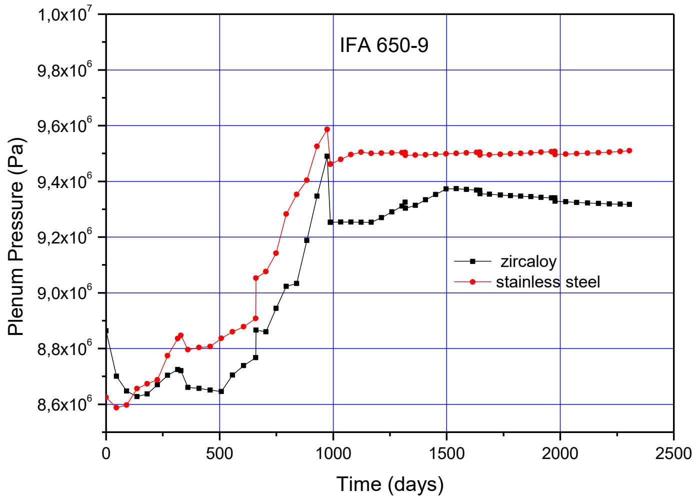

FIG. 2 Plenum pressure (IFA 650-9) evolution obtained from FRAPCON original version (zircaloy cladding) and modified version (stainless steel).

The transient/accident condition wasperformed using FRAPTRAN code (original and modified version) considering coupled simulation with the steady state simulation using FRAPCON code. The FRAPTRAN code deals mostly with the conditions that changes quite fast (LOCA and RIA) to obtain power, fuel and cladding temperatures, cladding elastic and plastic stress and strain, cladding oxidation, and fuel rod gas pressure as function of time. The fuel parameters which change slowly during the irradiation (burnup), such as fuel densification, swelling, cladding creep and irradiation growth are not calculated by FRAPTRAN code. Those parameters are read from a file generated by FRAPCON code at end of steady state simulation.The modification of FRAPTRAN code starts taking to account that some subroutines related to the cladding are same of FRAPCON code, consequently modifications already implemented in FRAPCON code for stainless steel could be harnessed in FRAPTRAN modification. Initially, the approach to perform modification was taken step by step, considering subroutines already implemented in FRAPCON: CCP, CSHEAR, CELMOD, CMHARD, ZOEMIS, CTHCON, ZOTCON and CTHEXP.Moreover, the subroutines related to mechanical properties of cladding (stress and strain) during the transient of cladding were identified in the CMLIMT [6] and CKMN subroutines, which calculate the limits of mechanical strain and the plastic strain for the cladding, respectively. According to FRAPTRAN code documentation (User Manual), the mechanical model used for calculating mechanical response of the fuel and cladding consider the rigid pellet model where does not account for stress induced deformation of the fuel.

The model includes the effect of thermal expansion of the fuel pellet, internal fuel rod pressure, thermal expansion, high temperature creep. The cladding deformation is calculated by FRACAS[7] and result of effective plastic strain is compared to instability strain, which is given by MATPRO, if the effective plastic strain is greater than instability strain, the ballooning model is used to calculated nonuniform deformation. The BALON2 subroutine calculates the extent and shape of the localized large cladding deformation that occurs between the time and predicts failure in the ballooning node when the cladding true hoop stress exceeds an empirical limit that is a function of temperature.

The empirical limit was taken from AISI-304 [8,9] due to lack of burst data for iron based alloys, specially for AISI-348 at high temperature (above 900 Kelvin). This assumption will be main limitation associated to FRAPTRAN code modification to consider stainless steel as cladding in this evaluation.

The modification implemented in the code the data related to the burst stress as function of temperature was obtained from the literature, according to the equation 1, below:

$$CTSTRT = (599{,}98-0.73269.Tc+0{,}0002143.Tc^2).1.0d+06 \text{ (Pa)} \qquad (1)$$

where:
CTSTRT is the tangential component of real stress at burst; and
Tc is the temperature in °C.
The stress-strain correlation used in the FRAPTRAN code is described based on stress [3]. The deformation in the elastic region is based on Hooke´s law, according equation 2, below:

$$\sigma = E.\varepsilon \qquad (2)$$

where:
$\sigma$is the stress;
$E$is the modulus of elasticity; and
$\varepsilon$is the strain.

The elastic strain is described by a power law according to equation 3, below:

$$\sigma = K.\varepsilon^n.\left(\frac{\dot{\varepsilon}}{10^{-3}}\right)^m \qquad (3)$$

where:
$K$is the strength coefficient;
$n$is the strain hardening exponent;
$m$is the strain rate sensitivity constant; and
$\dot{\varepsilon}$is the strain rate.

The stress-strain curve with yield strength (*YS*), ultimate tensile strength (UTS) and uniform elongation (EU) can be obtained from equations 2 and 3.The parameters$K$ and$n$ in equation 3 as function of temperature for stainless steel were obtained fromStainless Steel 304L and 316L[10].

The parameter$m$ was not available for stainless steel, the m value was kept the same of the zircaloy, considering that the open literature shows that m values for metals are about 0.1 to 0.2, such assumption shall be investigated latter. The modifications were implemented according to information above and initial verification of the modified version was performed using another LOCA experiment (IFA 650-5).

2.2 Experimental Dataand Simulation Modelling

The FRAPCON and FRAPTRAN codes were evaluatedconsidering specifically theHALDEN LOCA experiment (IFA 650-9, IFA 650-10 and IFA 650-11), all information of experimentswere made available to the participants of the CRP with additional HWR reports (Halden Technical Report) and Data Sheet Description. The Halden LOCA tests are integral in-pile single rod tests which address different LOCA issues. The test condition were planned to meet considerable cladding ballooning, fuel fragmentation and relocation after the LOCA transient. The fuel rod segment was properly instrumented with thermocouples in cladding surface, a cladding extensometer, fuel pressure transducer and introduced in the centre of rig surrounded by electrical heater. The rig was connected to the loopand LOCA condition was initiated by opening the valves allowing the water flow to the blowdown tank. The development of blowdown was monitored by inlet and outlet pressure of the rig and temperature evolution of cladding surface temperature were monitored by means of three thermocouples located axially. The figure 3 illustrate the experimental temperature evolution obtained for IFA 650-10 and were taken as they are to consider as boundary condition in the FRAPTRAN code. The alternative option to consider the temperature evolution was a calculated temperature using SOCRAT code supplied by one of the participants (Russia) that made available. One of the most important information to perform a LOCA calculation is the temperature evolution during the LOCA phase. As it can be observed in figure 3, the cladding temperature reach nearly 900°C in 300 seconds. Others fuel rod data needed to perform steady state simulation such as material, dimension/geometry were taken from HALDEN Data Sheet and Technical Report made available.

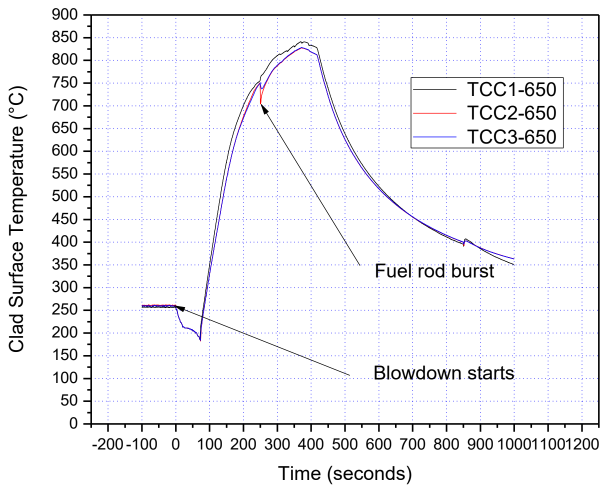

FIG. 3 Experimental Temperature Evolution for IFA 650-10 evolution.

Initially, the steady state condition was simulated using FRAPCON code in both versions (original and modified). The transient/accident simulations were performed using FRAPTRAN code (original and modified version. The time length for LOCA experiment simulation (IFA series) was considered 100 seconds before the blowdown phase and up to reactor SCRAM, so the fuel rod burst time was properly considered, others input data were prepared according to FRAPTRAN User´s Manual recommendation.

2.3 Obtained Results for IFA 650-9, IFA 650-10 and IFA 650-11

2.3.1 - The steady state condition (burnup accumulation) was simulated considering the power profile given in the Halden Technical Report and results were presented in Table 1, below.

TABLE 1: BASE IRRADIATION RESULTS FROM FRAPCON (ORIGINAL AND MODIFIED VERSION) CODE.

Parameters	**IFA 650-9**		**IFA 650-10**		**IFA 650-11**	
	Zircaloy	**Stainless Steel**	**Zircaloy**	**Stainless Steel**	**E110**	**Stainless Steel**
Maximum rod internal pressure (MPa)	9.48	9.58	8.48	8.50	4.45	4.47
Fission gas release(%)	13.81	14.13	0.16	2.35	1.94	1.94
Maximum fuel centerline temperature (°C)	1797	1811	1313	1390	972	1007

The results presented shown clearly that stainless steel as cladding does not promote significant difference in temperature, pressure and fission gas release compared to zircaloy cladding. The stainless steel results are always slightly higher mostly due to thermal conductivity and thermal expansion of stainless steel. The results of stainless steel compared zircaloy cladding due to thermal properties and gap thickness can be verified by means of sensitivity analysis, which was additionally performed in the FUMAC framework in order to get some qualitative insights on the most influential parameters (fuel data and model). This evaluation considered IFA 650-10 experiment simulation with 200 code runs in order to obtain correlation coefficients (Pearson). The fuel models (physical properties) utilized in the FRAPCON code was investigated. The following fuel models were addressed:fuel thermal conductivity (**sigftc**), fuel thermal expansion coefficient (**sigftex**), fuel swelling (**sigswell**) and cladding creep (**sigcreep).** Table 2 shows the results of Pearson Correlation due to the fuel models. Moreover, the sensitivity analysis considered fuel fabrication/design parameters, such as: cladding thickness, gap thickness, fuel pellet outside diameter, ^{235}U enrichment, fuel theoretical density and, rod gas-gap fill pressure. The statistical distribution (normal) and tolerance interval (upper and lower bounds) for each fuel fabrication/design parameter were considered according to CRP organization. It can be seen from Table 2 and Table 3, that there are strong Pearson Correlation (PRC> 5.0) related to gap thickness, fuel thermal expansion coefficient and fuel thermal conductivity for fuel pellet central temperature.

TABLE 2: PEARSON CORRELATION FOR EACH FUEL MODEL FOR IFA 650-10

Fuel model	Fission gas release	Maximum Plenum pressure	Peak fuel centerline temperature
sigftc	NA	0.03	-0.55
sigftex	NA	0.04	-0.84
sigfgr	NA	0.07	-0.04
sigswell	NA	0.02	0.03
sigcreep	NA	-0.11	-0.07

*200 cases (normal distribution)

TABLE 3: PEARSON CORRELATION FOR EACH FUEL FABRICATION PARAMETERS FOR IFA 650-10

Fabrication/design tolerance	Fission gas release	Maximum Plenum pressure	Peak fuel centerline temperature
fuel pellet outside diameter	-0.02	0.10	-0.07
cladding thickness	0.01	0.01	-0.50
gap thickness	0.28	0.13	0.99
^{235}U enrichment	0.05	0.08	-0.02

*****200 cases (normal distribution)

2.3.2 **-** The accident condition (LOCA) was simulated using FRAPTRAN (original and results were presented in Table 4.

The results obtained for LOCA simulation, somehow were not in good agreement due to ballooning (maximum circumferential strain data), the IFA 650-10 results for stainless steel were higher than zirconium alloy, others cases (IFA 650-9 and IFA 650-11) exhibited different trend. The mechanical ballooning model in the FRAPTRAN (BALON2) was not modified for the stainless steel code version due to that, the results are not consistent as expected. The assessment of ballooning model for stainless steel was in progress at that time.

Table 4: LOCA-transient results from FRAPTRAN (original and modified version)

Parameters	**IFA 650-9**		**IFA 650-10**		**IFA 650-11**	
	Zircaloy	**Stainless Steel**	**Zircaloy**	**Stainless Steel**	**E110**	**Stainless Steel**
Burst (sec)	99	318	109	110	258	267
Rod burst at elevation (ft)	0.787	0.787	0.722	0.722	0.787	0.787
Clad ballooning - maximum circumferential strain (%)	31.25	30.58	74.66	87.71	38.83	30.94
Plenum gas temperature (°C)	722	802	695	695	860	870

3. CONCLUSIONS

The loss of coolant (LOCA) caused by the failure of a primary circuit coolant pipe is one of the challenging accidents of the design basis accidentfor lightwater cooled reactors. In order to mitigate the consequences of this event, all reactors must have an emergency core cooling system to keep the fuel efficiently cooled and a cooling geometry at all stages of the accident. For fuel rod with zirconium alloy as cladding, the requirement for cooling geometry and structural integrity is a very challenging problem. During the LOCA accident the coolable geometry of the reactor core could be lost due to fuel clad ballooning, which can lead to partial blockage of the fuel assembly channel and cladding failure during actuation of emergency cooling system actuation (quench and loading associated after quench). The FUMAC-CRP was an excellent opportunity to address, verify and identify existing limitation to simulate the LOCA event in existing fuel performance code. The objective proposed by IPEN/CNEN (Brazil) was to modify FRAPCON and FRATRAN codes in order o implement the stainless steel as cladding and verification was performed using HALDEN LOCA experiment (IFA650-9, IFA 650-10 and IFA-650-11). The proposal was partially accomplished due to lack of experimental data related to burst experiment at high temperature for AISI-348 stainless steel. The FRATRAN code failure criteria is associated to the strain limit, which is compared to calculated strain, such approach require the burst experimental data ranging high temperature. Although FRAPTRAN code modification present limitation, important outcome of the CRP-FUMAC is the difficulty to predict cladding strains for many fuel performance codes and the failure criteria based on hoop stress as function of the temperature need to be reviewed.

ACKNOWLEDGMENTS

The authors are grateful to the technical support of AMAZUL, USP and IPEN-CNEN/SP.

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