*2017 International Nuclear Atlantic Conference - INAC 2017*
*Belo Horizonte, MG, Brazil, October 22-27, 2017*
*ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR – ABEN*

Agência Brasileira do ISBN
ISBN 978-85-99141-07-6

# SENSITIVITY ASSESSMENT OF FUEL PERFORMANCE CODES FOR LOCA ACCIDENT SCENARIO

**Alfredo Abe[1], Claudia Giovedi[2], Daniel Gomes[1], Antonio Teixeira e Silva[1], Rafael O. R. Muniz[1], Marcelo Martins[2]**

[1] Instituto de Pesquisas Energéticas e Nucleares (IPEN / CNEN - SP)
Av. Professor Lineu Prestes 2242
05508-000 São Paulo, SP
ayabe@ipen.br

[2]Laboratório de Análise, Avaliação e Gerenciamento de Risco –LABRISCO
Escola Politécnica – USP
Av. Prof. Mello de Moraes, 2231
05508-030 São Paulo, SP
claudia.giovedi@labrisco.usp.br

## ABSTRACT

FRAPCON code predicts fuel rod performance in LWR (Light Water Reactor) by modeling fuel responses under normal operating conditions and anticipated operational occurrences; FRAPTRAN code is applied for fuel transient under fast transient and accident conditions. The codes are well known and applied for different purposes and one of the use is to address sensitivity analysis considering fuel design parameters associated to fabrication, moreover can address the effect of physical models bias. The objective of this work was to perform an assessment of fuel manufacturing parameters tolerances and fuel models bias using FRAPCON and FRAPTRAN codes for Loss of Coolant Accident (LOCA) scenario. The preliminary analysis considered direct approach taken into account most relevant manufacturing tolerances (lower and upper bounds) related to design parameters and physical models bias without considering their statistical distribution. The simulations were carried out using the data available in the open literature related to the series of LOCA experiment performed at the Halden reactor (specifically IFA-650.5). The manufacturing tolerances associated to design parameters considered in this paper were: enrichment, cladding thickness, pellet diameter, pellet density, and filling gas pressure. The physical models considered were: fuel thermal expansion, fission gas release, fuel swelling, irradiation creep, cladding thermal expansion, cladding corrosion, and cladding hydrogen pickup. The results obtained from sensitivity analysis addressed the impact of manufacturing tolerances and physical models in the fuel cladding burst time observed for the IFA-650.5 experiment.

## 1. INTRODUCTION

One of the most challenging design basis accident for water cooled reactors is the LOCA caused by double-ended guillotine break of the one large coolant pipe. The license acceptance criteria led necessity of the emergency core cooling systems capability to keep the fuel cooled and maintain a coolable geometry during whole LOCA sequence [1]. The fuel rods during the LOCA accident are subjected to a sequence of various types of stresses, including thermal stress, thermal-hydraulic stress associated to quenching phase and residual mechanical stress due to ballooning. Currently, there is a good understanding in terms of major phenomena that

occurs to fuel and cladding during irradiation such as: pellet densification, fission gas formation, bubble development, swelling, cracking, oxidation, hydrogen pickup (hydriding), hardening, and embrittlement. This understanding is based on several experiments performed during last decades and moreover information and data obtained from experiments related to accident conditions such as LOCA and Reactivity Initiated Accident (RIA) [2].
Specifically related to LOCA condition [3], the transient starts with the fuel under normal operating condition (steady state) when cladding temperature is nearly 350 °C, the pellet temperature is about 420 °C with parabolic distribution and fuel centerline temperature can reach up to 2000 °C depending on the power. As LOCA starts, the fission reaction starts to decrease due to loss of neutron moderation condition and, after some few seconds, the fission reaction ends due to control and safety banks insertion. At first initial seconds of LOCA, due to increase of flowrate, the fuel cladding experiences a decrease of temperature but, later as consequence of stored energy in the fuel pellet and loss of heat removal condition, the cladding temperature will start to quickly increase heat up. Consequently, internal fuel rod pressure increases, the strength of the cladding is reduced and, eventually, the cladding will start to deform plastically. The cladding deformation can be non-uniform as consequence of temperature distribution along of fuel rod length. As cladding temperature increases, zirconium-based alloys start the phase transformation (nearly around 800 °C), additionally oxidation reaction and creep contribute to cladding degradation up to experience failure [4][5]. Moreover, the initial condition of fuel cladding such as existing oxide thickness and hydriding condition can affect the way of failure [6][7]. On the other side, computer code simulation to model and perform LOCA evaluation can be addressed in different approaches, starting with reactor physics and thermal hydraulics codes, which give the boundary condition for the fuel simulation codes. The fuel simulation codes normally are divided in two separated calculations, the first is a steady state condition (ex: FRAPCON code), which supplies the information for subsequent transient calculation (ex: FRAPTRAN code).
This work address the FRAPCON/FRAPTRAN [8][9] codes model uncertainties [10] and fuel manufacturing tolerances (upper and lower bounds) in the LOCA accident condition considering the IFA-650-5 experiment.

## 2. METHODOLOGY

The work performed is essentially based on fuel performance codes simulation using data obtained from open literature related to the well know series of LOCA experiments performed in the framework of the HALDEN Reactor Project.

### 2.1. IFA-650.5 Experiment Description

A series of experiment was conducted at HALDEN reactor to simulate de LOCA accident condition, in these experiments the segments of test rods were placed into the instrumented irradiation rig IFA-650 [11]. Prior to the LOCA condition, the reactor power was properly adjusted in specific level in order to reach steady state condition to start the LOCA transient initiation (blowdown phase). The blowdown starts with opening a sequence of valves to the dump tanks. The coolant pressure of the rig is rapidly decreased as result of blowdown and cladding temperature starts to increase immediately due to lack of cooling condition. The cladding burst will happen due to temperature increases. The associated instrumentation to rig were: 3 thermocouples, fuel pressure transducer and cladding elongation detector. Those instrumentations give all necessary information regarding the fuel rod condition, even when the fuel rod experiences failure.

The fifth experiment, named IFA-650.5 is a refabricated fuel rod segment from a standard PWR with zircaloy cladding irradiated up to average burnup of 83 MWd/kgU. The refabricated fuel rod segment is filled with a gas mixture of 90 % argon and 10 % helium at 40 bar. Argon was used to simulate the fission gas. The properties of the IFA-650.5 [12] fuel rod are summarized in Table 1 below.

**Table 1. 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 |

## 2.2. Simulation Codes and Modelling Conditions

The FRAPCON code [8] was designed to simulate the fuel rod burnup under steady state condition considering different interrelated phenomena that occurs during the fuel irradiation. The main phenomena modeled in the code includes heat conduction through the fuel and cladding to the coolant, fission gas release, fuel swelling, fuel cladding creep, cladding elastic and plastic mechanical deformation (strain and stress), fuel-cladding mechanical interaction, and cladding reaction (oxidation and corrosion). The code has material properties, water properties, and heat-transfer correlations associated to fuel normal operation condition. The material properties and model are built from experimental data, experimental correlations and some are based on analytical equations.

The FRAPTRAN code [9] was designed for transient performance of Light Water Reactor (LWR) fuel rods during reactor transients and postulated accidents such as LOCA, Anticipated Transients Without Scram (ATWS), and RIA. The code can calculate the temperature and deformation of the fuel rod as a function of time-dependent fuel rod power and coolant boundary conditions. The main phenomena modeled in the code include: heat conduction, heat transfer from cladding to coolant, elastic-plastic fuel and cladding

deformation, cladding oxidation, fission gas release, and fuel rod gas pressure. Moreover, the code can run in standalone mode or in conjunction with FRAPCON code.
The sensitivity assessment analysis was carried out using FRAPCON and FRAPTRAN codes in a coupled mode, initially steady state simulations were performed to initialize the FRAPTRAN code for the LOCA simulation.
The input data and experiment modelling for FRAPCON code were prepared properly according to data presented in the Table 1 and others data obtained from literature [12], the input for transient using FRAPTRAN code considered the experimental data (cladding temperature profile and evolution of rig pressure) as boundary condition and others required data were feed from previous FRAPCON code calculations.

### 2.3. Sensitivity Analysis Methodology

Initially, the direct approach was considered to perform the sensitivity analysis under LOCA considering steady state and transient condition using FRAPCON and FRAPTRAN codes. The methodology adopted was: initial simulations considering only the fuel manufacturing parameters (upper and lower bounds), followed by simulations taking into account the fuel model bias analysis, and finally combining all previous simulations. Although, normally the most of sensitivity analysis requires a sampling of the relevant parameters from the statistical distribution, in this work the direct approach without sampling from the statistical distribution was considered as a preliminary analysis.
The first round of simulations considering the fuel manufacturing parameters were taken each individual parameter with lower and upper bound in order to verify the fuel performance under burnup evolution. The results from individual parameter simulation with associated bounds (lower and upper) assist to identify the worst accident condition (LOCA) for given manufacturing parameter. The criteria adopted as worst condition was the time after the blowdown when fuel rod experiences failure (burst time) obtained from FRAPTRAN code. Then, the earlier the failure occurs; the greater is the influence of the evaluated parameter.
The results obtained from steady state simulation (FRAPCON) utilized to identify as candidate for a worst condition were based on some understanding and insight from the experiments devoted to simulate LOCA condition, which provide the fuel condition that more likely could experience failure. The fuel rod cladding condition (hydrogen pickup, corrosion layer) due to burnup associated to loads from internal pressure due to the fission gas release might contribute to the fuel rod failure. Moreover, the temperature and energy stored in the fuel shall contribute as worst initial condition before starting LOCA. The results taken from FRAPCON code were: fission gas release, maximum fuel center temperature, and maximum internal fuel rod pressure.
After completion of each individual fuel manufacturing parameter simulation and identification of which parameter gives worst condition, the second round of simulations were conducted combining those previous selected parameters. The simulation gives the worst condition associated only to the fuel manufacturing parameters.
The fuel model bias analysis was addressed in order to verify existing and in built model of the FRAPCON code. The recent version of FRAPCON code has capabilities [10] to evaluate the bias related to fuel model, for this the user can select the following models: fuel thermal conductivity, fuel thermal expansion, fission gas release, fuel swelling, irradiation creep, cladding thermal expansion, cladding corrosion, and cladding hydrogen pickup. Initially, simulation was performed considering only individual fuel model to identify the worst condition. Subsequently, the combination of the fuel model was simulated in order to

identify the overall contribution of each fuel model. All simulations for fuel models bias were conducted considering +1σ for upper bound and -1σ for lower bound under steady state condition with nominal fuel manufacturing parameters.
Finally, all the information obtained from previous simulations (fuel manufacturing parameters and fuel simulation models) was properly combined to perform the simulation of worst condition of fuel rod for LOCA.

## 3. RESULTS AND DISCUSSION

### 3.1Fuel Manufacturing Parameters Sensitivity Evaluation

Table 2 presents the main fuel manufacturing considered in this work, the parameter was selected based on well-known manufacturing experience, where some fabrication parameters cannot be tightly controlled during the process, such as: blending, sintering and grinding for the pellet; cladding tube dimensions, and fuel rod pressurization during the assembling. Only the bounds (lower and upper) were taken to perform the analysis, the statistical distribution of the parameters was not considered at this moment.

**Table 2: Fuel fabrication parameters considered in the sensitivity analysis.**

| Parameter | Lower bound | Nominal value | Upper Bound |
|---|---|---|---|
| U235 enrichment (%) | 3.45 | 3.5 | 3.55 |
| Cladding outside diameter (mm) | 10.725 | 10.735 | 10.745 |
| Cladding thickness (mm) | 0.716 | 0.721 | 0.726 |
| Fuel gap thickness (mm) | 0.0755 | 0.0805 | 0.0855 |
| Fuel theoretical density (%) | 94.6 | 94.8 | 95.0 |
| Filling gas pressure (MPa) | 3.8 | 4.0 | 4.2 |

FRAPCON code does not require fuel pellet as input data, the fuel pellet ($UO_2$) diameter is obtained by calculation from cladding outer radius minus cladding thickness and gap thickness. The combination of cladding outer radius, cladding thickness and gap thickness gives the current fuel pellet radius. The steady state simulations (FRAPCON code) were performed using the data presented in Table 2, resulting in 12 (twelve) different runs. Table 3 presents the results obtained from fuel enrichment variation within the given bounds and all others parameters were kept as pre-defined nominal values.

**Table 3: Fuel enrichment sensitivity results.**

| Fuel enrichment (enrch) | | | |
|---|---|---|---|
| **Parameter** | **Lower Bound (3.45%)** | **Nominal (3.5 %)** | **Upper Bound (3.55%)** |
| Fission gas release | 7.99 % | 8.62 % | 8.60 % |
| Maximum Fuel Rod Internal Pressure | 50.01 | 50.67 bar | 50.65 bar |
| Maximum Fuel Centerline Temp. | 1544 °C | 1547 °C | 1547 °C |

Table 4 presents the results obtained from simulations considering fuel theoretical density variation within the given bounds. All others parameters were kept as pre-defined nominal values.

**Table 4: Fuel theoretical density sensitivity results.**

| Fuel theoretical density (den) | | | |
|---|---|---|---|
| **Parameter** | **Lower Bound (94.6 %)** | **Nominal (94.8%)** | **Upper Bound (95.0%)** |
| Fission gas release | 8.88 % | 8.62 % | 8.04 % |
| Maximum Fuel Rod Internal Pressure | 50.95 bar | 50.67 bar | 50.06 bar |
| Maximum Fuel Centerline Temp. | 1550 °C | 1547 °C | 1543 °C |

Table 5 presents the results obtained from simulations considering fuel rod filling gas pressure variation within the given bounds. All others parameters were kept as pre-defined nominal values.

**Table 5: Fuel rod filling gas pressure sensitivity results.**

| Filling Gas Pressure (fgpav) | | | |
|---|---|---|---|
| **Parameter** | **Lower Bound 1.8 MPa (260 psi)** | **Nominal 2.0 MPa (290 psi)** | **Upper Bound 2.2 MPa (320 psi)** |
| Fission gas release | 8.86 % | 8.62 % | 8.14 % |
| Maximum Fuel Rod Internal Pressure | 46.61 bar | 50.67 bar | 55.00 bar |
| Maximum Fuel Centerline Temperature | 1543 °C | 1547 °C | 1545 °C |

Table 6 presents the results obtained from simulations considering fuel clad outer diameter variation within the given bounds. All others parameters were kept as pre-defined nominal values.

**Table 6: Fuel clad outer diameter sensitivity results.**

| Clad Outer Diameter (dco)* | | | |
|---|---|---|---|
| **Parameter** | **Lower Bound (10.725 mm)** | **Nominal (10.735mm)** | **Upper Bound (10.745 mm)** |
| Fission gas release | 8.49 % | 8.62 % | 8.33 % |
| Maximum Fuel Rod Internal Pressure | 50.56 bar | 50.67 bar | 50.35 bar |
| Maximum Fuel Centerline Temperature | 1548 °C | 1547 °C | 1546 °C |

*the fuel cladding and gap thickness were kept nominal values, consequently the changes of clad outer diameter will change the $UO_2$ pellet diameter.

Table 7 presents the results obtained from simulations considering fuel clad thickness variation within the given bounds and all others parameters were kept as pre-defined nominal values.

**Table 7: Fuel clad thickness sensitivity results.**

| Clad Thickness (thkcld) | | | |
|---|---|---|---|
| **Parameter** | **Lower Bound (0.7160 mm)** | **Nominal (0.7210 mm)** | **Upper Bound (0.726 mm)** |
| Fission gas release | 8.23 % | 8.62 % | 8.58 % |
| Maximum Fuel Rod Internal Pressure | 50.24 bar | 50.67 bar | 50.65 bar |
| Maximum Fuel Centerline Temp. | 1546 °C | 1547 °C | 1548 °C |

*the fuel cladding outer diameter and gap thickness were kept nominal values, consequently the changes of clad thickness will change the $UO_2$ pellet diameter.

Table 8 presents the results obtained from simulations considering fuel gap thickness variation within the given bounds and all others parameters were kept as pre-defined nominal values.

**Table 8: Fuel gap thickness sensitivity results.**

| Gap Thickness (thkgap) | | | |
|---|---|---|---|
| **Parameter** | **Lower Bound (0.0755 mm)** | **Nominal (0.0805 mm)** | **Upper Bound (0.0855 mm)** |
| Fission gas release | 8.19 % | 8.62 % | 8.64 % |
| Maximum Fuel Rod Internal Pressure | 50.04 bar | 50.67 bar | 50.92 bar |
| Maximum Fuel Centerline Temp. | 1518 °C | 1547 °C | 1575 °C |

*the fuel cladding outer diameter and cladding thickness were kept nominal values, consequently the changes of gap thickness will change the $UO_2$ pellet diameter.

After steady state simulations, the transient simulations were performed in order to obtain the time of fuel rod failure due to the burst for each manufacturing parameter (considering lower and upper bounds). The burst time obtained by means of FRAPTRAN code simulations considering the fuel manufacturing parameters with lower and upper bounds are presented in Table 9.

**Table 9 – FRAPTRAN simulation results considering the fuel manufacturing parameters**

| **Parameter** | **Burst time (reference t= 189 sec)** | |
|---|---|---|
| | **Lower bound** | **Upper Bound** |
| U235 enrichment (%) | 190 | 189 |
| Cladding outer diameter (mm) | 189 | 189 |
| Cladding thickness (mm) | 189 | 189 |
| Gap thickness (mm) | 190 | 189 |
| Fuel theoretical density (%) | 188 | 189 |
| Filling gas pressure (MPa) | 194 | 189 |

The $UO_2$ fuel pellet diameter variation was evaluated considering combination of cladding outer diameter, cladding thickness and gap thickness due to the FRAPCON code constrain, which does not require fuel pellet diameter as input. Moreover, the fuel manufacturing parameters (cladding outer diameter, cladding thickness and gap thickness) present the upper and lower bounds that was also taken into account considering the combination of lower and upper bounds. Table 10 presents all possible combinations for cladding outer diameter, cladding thickness and gap thickness considering the bounds (lower and upper). The results obtained from simulations carried out with FRAPCON code are presented in Tables 11 and 12.

**Table 10 - Combination of parameters applied to perform simulation of different $UO_2$ pellet diameter.**

| Case description | Adopted Nomenclature | $UO_2$ diameter (cm) |
|---|---|---|
| **Upper** cladding outer diameter and **upper** cladding thickness and **upper** gap thickness | UCD + UCT + UGT (UUU) | 9.12E-01 |
| **Upper** cladding outer diameter and **upper** cladding thickness and **lower** gap thickness | UCD + UCT +LGT (UUL) | 9.14E-01 |
| **Upper** cladding outer diameter and **lower** cladding thickness and **lower** gap thickness | UCD + LCT +LGT (ULL) | 9.16E-01 |
| **Upper** cladding outer diameter and **lower** cladding thickness and **upper** gap thickness | UCD + LCT + UGT (ULU) | 9.14E-01 |
| **Lower** cladding outer diameter and **lower** cladding thickness and **lower** gap thickness | LCD + LCT + LGT (LLL) | 9.14E-01 |
| **Lower** cladding outer diameter and **lower** cladding thickness and **upper** gap thickness | LCD + LCT + UGT (LLU) | 9.12E-01 |
| **Lower** cladding outer diameter and **upper** cladding thickness and **upper** gap thickness | LCD + UCT + UGT (LUU) | 9.10E-01 |
| **Lower** cladding outer diameter and **upper** cladding thickness and **lower** gap thickness | LCD + UCT + LGT (LUL) | 9.12E-01 |

**Table 11 – Results obtained from FRAPCON simulation for different $UO_2$ pellet diameter.**

| Parameter | Case (see Table 10 for nomenclature) | | | | |
|---|---|---|---|---|---|
| | **Reference** | **UUU** | **UUL** | **ULL** | **ULU** |
| Fission gas release | 8.62 % | 8.74 % | 8.18 % | 7.88 % | 8.36 % |
| Maximum Fuel Rod Internal Pressure (bar) | 50.67 | 51.02 | 50.02 | 49.67 | 50.58 |
| Maximum Fuel Centerline Temperature (°C) | 1547 | 1576 | 1519 | 1516 | 1573 |

**Table 12 – Results obtained from FRAPCON simulation for different $UO_2$ pellet diameter .**

| Parameter | Case (see Table 10 for nomenclature) | | | | |
|---|---|---|---|---|---|
| | **Reference** | **LLL** | **LLU** | **LUU** | **LUL** |
| Fission gas release | 8.62 % | 8.28 % | 8.64 % | 9.17 % | 8.82 % |
| Maximum Fuel Rod Internal Pressure (bar) | 50.67 | 50.13 | 50.92 | 51.52 | 50.73 |
| Maximum Fuel Centerline Temperature (°C) | 1547 | 1518 | 1575 | 1577 | 1520 |

There are no remarkable results (Table 11 and 12) compared to reference result, the highest fission gas release was 9.17% and lowest 7.88%; the highest fuel centerline was 1577 °C and the lowest 1516 °C; the highest internal fuel rod pressure was 51.52 bar and the lowest 49.67 bar. The conditions for highest values were observed at LUU (**Lower** cladding outer diameter and **upper** cladding thickness and **upper** gap thickness). The lowest values were observed at ULL (**Upper** cladding outer diameter and **lower** cladding thickness and **lower** gap thickness).

The FRAPTRAN simulations were performed in order to verify how the combination of the parameters could affect the fuel rod failure (burst time). The results obtained are present in Table 13. There are no remarkable results. The burst time variation is about ± 1 sec compared to reference case (189 sec.)

**Table 13: FRAPTRAN results for simulation for different $UO_2$ pellet diameter.**

| Case | Burst time (sec.) |
|---|---|
| (UUU) | 188 |
| (UUL) | 190 |
| (ULL) | 190 |
| (ULU) | 189 |
| (LLL) | 190 |
| (LLU) | 188 |
| (LUU) | 188 |
| (LUL) | 189 |

Then, combining the previous results (Table 9 and 13) for fuel rod failure time (burst time), the worst condition for LOCA , considering only fuel manufacturing parameters, shall be the combination which gives the lowest failure time, i.e, anticipated fuel rod failure during LOCA. From Table 9 results, the lowest failure time is obtained for fuel density parameter, and from Table 13 results, it is observed that at least three conditions (UUU, LLU, and LUU) give the lowest failure time. For the highest failure time, it was observed three conditions (UUL, ULL, and LLL) for $UO_2$ pellet diameter and lower bound of filling gas pressure parameters (Table 9).

The following FRAPCON and FRAPTRAN simulations were performed to verify how the combination affects the fuel rod burst failure time.

**Table 14: Coupled FRAPCON and FRAPTRAN considering the lowest failure time obtained from previous evaluation.**

| Case | Burst time (sec.) |
|---|---|
| Reference case (all parameters with nominal values) | 189 |
| (UUL) + Lower bound of fuel density + others parameters with nominal values | 188 |
| (LLU) + Lower bound of fuel density + others parameters with nominal values | 187 |
| (LUU) + Lower bound of fuel density + others parameters with nominal values | 188 |

**Table 15: Coupled FRAPCON and FRAPTRAN considering the highest failure time obtained from previous evaluation.**

| Case | Burst time (sec.) |
|---|---|
| Reference case (all parameters with nominal values) | 189 |
| (UUL) + Lower filling gas pressure + others parameters with nominal values | 194 |
| (ULL) + Lower filling gas pressure + others parameters with nominal values | 194 |
| (LLL) + Lower filling gas pressure + others parameters with nominal values | 194 |

The influence of the fuel rod manufacturing parameters considering upper and lower bounds in the fuel rod failure (burst time) is not significant. The reference condition gives 189 seconds, the lowest failure time was observed at 187 seconds and the highest time was 194 seconds (see Table 14 and 15). The fuel manufacturing parameters considering upper and lower bounds does not play an important role for the IFA-650.5 fuel rod failure during LOCA.

It should be worthwhile that the sensitivity analysis results could change based on power history during the irradiation and/or specific fuel rod design characteristics. In this work, the irradiation conditions is not taken as parameters, the condition was already defined condition.

### 3.2 Fuel Model Sensitivity Evaluation

FRAPCON code has capabilities to address the bias due to fuel model utilized internally [10]. Some fuel models can be addressed by means of code input options, such as: fuel thermal conductivity, fuel thermal expansion, fission gas release, fuel swelling, irradiation creep, cladding thermal expansion, cladding corrosion, and cladding hydrogen pickup. This work addressed all the models in order to verify their contribution in LOCA simulation.

The approach adopted was similar to the previous evaluation, firstly the fuel models bias were evaluated in the steady state and transient (LOCA) conditions in order to identify the individual contribution of each fuel model in specific fuel performance results: fission gas release fraction, maximum internal fuel pressure, maximum fuel centerline temperature, and fuel rod burst time.

The results obtained from each individual model bias evaluation give some indication about how the combination of the fuel models could affect the fuel rod failure.

The following tables (Table 16 up to 23) present the results obtained from FRAPCON simulations considering sensitivity analysis of each individual fuel model. All simulations were performed considering the nominal values for fuel manufacturing parameters.

**Table 16: FRAPCON results considering fuel thermal conductivity model.**

| Bias on fuel thermal conductivity model ±1σ (SIGFTC) | | | |
|---|---|---|---|
| **Parameter** | **- 1 σ** | **Nominal (reference)** | **+ 1 σ** |
| Fission Gas Release | 14.08 % | 8.62 % | 7.91 % |
| Maximum Fuel Rod Internal Pressure | 56.50 bar | 50.67 bar | 49.90 bar |
| Maximum Fuel Centerline Temp. | 1642 °C | 1547 °C | 1460 °C |

**Table 17: FRAPCON results considering fuel thermal expansion model .**

| Bias on fuel thermal expansion model ±1σ (SIGFTEX) | | | |
|---|---|---|---|
| **Parameter** | **- 1 σ** | **Nominal (reference)** | **+ 1 σ** |
| Fission Gas Release | 8.61 % | 8.62 % | 8.31 % |
| Maximum Fuel Rod Internal Pressure | 50.66 bar | 50.67 bar | 50.39 bar |
| Maximum Fuel Centerline Temp. | 1578 °C | 1547 °C | 1515 °C |

**Table 18: FRAPCON results considering fission gas release model.**

| Bias on fission gas release model ±1σ (SIGFGR) | | | |
|---|---|---|---|
| **Parameter** | **- 1 σ** | **Nominal (reference)** | **+ 1 σ** |
| Fission Gas Release | 7.80 % | 8.62 % | 15.77 % |
| Maximum Fuel Rod Internal Pressure | 49.81 bar | 50.67 bar | 58.20 bar |
| Maximum Fuel Centerline Temp. | 1547 °C | 1547 °C | 1547 °C |

**Table 19: FRAPCON results considering fuel swelling model.**

| Bias on fuel swelling model ±1σ (SIGSWELL) | | | |
|---|---|---|---|
| **Parameter** | **- 1 σ** | **Nominal (reference)** | **+ 1 σ** |
| Fission Gas Release | 8.62 % | 8.62 % | 8.62 % |
| Maximum Fuel Rod Internal Pressure | 50.67 bar | 50.67 bar | 50.69 |
| Maximum Fuel Centerline Temp. | 1547 °C | 1547 °C | 1547 °C |

**Table 20: FRAPCON results considering cladding creep model.**

| Bias on cladding creep model ±1σ (SIGCREEP) | | | |
|---|---|---|---|
| **Parameter** | **- 1 σ** | **Nominal (reference)** | **+ 1 σ** |
| Fission Gas Release | 8.62 % | 8.62 % | 8.62 % |
| Maximum Fuel Rod Internal Pressure | 50.67 bar | 50.67 bar | 50.67 bar |
| Maximum Fuel Centerline Temp. | 1547 °C | 1547 °C | 1547 °C |

**Table 21: FRAPCON results considering cladding axial growth model.**

| Bias on cladding axial growth model ±1σ (SIGGRO) | | | |
|---|---|---|---|
| **Parameter** | **- 1 σ** | **Nominal (reference)** | **+ 1 σ** |
| Fission Gas Release | 8.29 % | 8.62 % | 8.52 % |
| Maximum Fuel Rod Internal Pressure | 50.63 | 50.67 bar | 50.21 |
| Maximum Fuel Centerline Temp. | 1547 °C | 1547 °C | 1547 °C |

**Table 22: FRAPCON results considering cladding corrosion model.**

| Bias on cladding corrosion model ±1σ (SIGCOR) | | | |
|---|---|---|---|
| **Parameter** | **-1 σ** | **Nominal (reference)** | **+ 1 σ** |
| Fission Gas Release | 7.84 % | 8.62 % | 9.61 % |
| Maximum Fuel Rod Internal Pressure | 49.85 bar | 50.67 bar | 51.67 bar |
| Maximum Fuel Centerline Temp. | 1547 °C | 1547 °C | 1557 °C |
| $ZrO_2$ weight gain (gm/m**2) | 89.31 | 111.62 | 133.93 |

Although the cladding hydrogen pickup may not affect substantially and directly the parameters listed in Table 23 below, the hydrogen pickup can brittle the cladding and consequently it will affect the burst phenomena during LOCA simulation.

The highest and the lowest values obtained from each fuel performance results considering the fuel model assessment are presented in Table 24.

Initially, taking into account overall results obtained from the fuel model bias evaluation, as a preliminary analysis, it was possible to verify that fuel model bias gives more spread results compared to the fuel manufacturing parameters. However, the fuel rod failure time due to burst does not varies significantly.

Table 25 presents the FRAPTRAN results associated to each fuel model evaluation. The results obtained from all simulations show that there is no effect at all for following models: fuel thermal conductivity, fuel thermal expansion, cladding hydrogen pickup, fuel swelling, cladding creep and clad axial growth. The burst time was slightly affected in the following simulations: cladding corrosion, and fission gas release.

**Table 23: FRAPCON results considering cladding hydrogen pickup model.**

| Bias on cladding hydrogen pickup model 1σ (SIGH2) | | | |
|---|---|---|---|
| **Parameter** | **-1 σ** | **Nominal (reference)** | **+ 1 σ** |
| Fission Gas Release | 8.62 % | 8.62 % | 8.62 % |
| Maximum Fuel Rod Internal Pressure | 50.67 bar | 50.67 bar | 50.67 bar |
| Maximum Fuel Centerline Temp. | 1547 °C | 1547 °C | 1547 °C |
| $ZrO_2$ weight gain (gm/m**2) | 111.62 | 111.62 | 111.62 |
| $H_2$ (ppm) | 394.1 | 488.1 | 582.1 |

**Table 24: The lowest and the highest values obtained from fuel models bias assessment.**

| **Parameter** | **Nominal** (reference) | **Lowest Value** | **Highest Value** |
|---|---|---|---|
| Fission Gas Release | 8.62 % | 7.80 % (-1σ of SIGFGR) | 15.77 % (+1σ of SIGFTEX) |
| Maximum Fuel Rod Internal Pressure | 50.67 bar | 49.81 bar (-1σ of SIGFGR) | 58.20 bar (+1σ of SIGFTEX) |
| Maximum Fuel Centerline Temperature | 1547 °C | 1460 °C (+1σ of SIGFTC) | 1642 °C (-1σ of SIGFTC) |
| $ZrO_2$ weight gain (gm/m**2) | 111.62 | 89.31 (-1σ of SIGCOR) | 133.93 (+1σ of SIGCOR) |
| $H_2$ (ppm) | 488.1 | 394.1 (-1σ of SIGH2) | 582.1 (+1σ of SIGH2) |

**Table 25: Fuel rod failure time at burst obtained from different fuel model evaluation.**

| **Model Sensitivity** | **Burst time** (reference t= 189 sec) | |
|---|---|---|
| | Lower bound | Upper Bound |
| fuel thermal conductivity (SIGFTC) | 189 | 189 |
| fuel thermal expansion (SIGFTEX) | 189 | 189 |
| fission gas release (SIGFGR) | 190 | 181 |
| fuel swelling (SIGSWELL) | 189 | 189 |
| cladding creep (SIGCREEP) | 189 | 189 |
| cladding axial growth (SIGGRO) | 189 | 189 |
| cladding corrosion (SIGCOR) | 190 | 188 |

| | | |
|---|---|---|
| cladding hydrogen pickup (SIGH2) | 189 | 189 |

Considering the results from each individual fuel model assessment, the evaluation of combined fuel models was performed in order to verify the lowest and the highest burst time. Table 26 presents results combining the fuel models.

**Table 26: Fuel rod failure time (burst) obtained combining fuel models.**

| **Model Sensitivity** | **Burst time** (reference t= 189 sec) |
|---|---|
| Combining all models with upper bound | 186 |
| Combining all models with lower bound | 189 |
| Combining all models which give the highest burst time (sigftc=1.sigftex=1.sigfgr=-1.sigswell=1 sigcreep=1.siggro=1.sigcor=-1.sigh2=1) | 194 |
| Combining all models which give the lowest burst time (sigftc=-1.sigftex=-1.sigfgr=1.sigswell=-1 sigcreep=-1.siggro=-1.sigcor=1.sigh2=-1) | 176 |

Finally, the combination of the two main results was verified performing the simulations considering fuel manufacturing parameters and fuel models bias.

The combination of fuel manufacturing parameters which gives the lowest burst time was: lower bound of cladding outer diameter and lower bound of cladding thickness, and upper bound of gap thickness and lower bound of fuel density and others fuel parameters with nominal values.

The combination of fuel models which gives the lowest burst time was: lower bound of fuel thermal conductivity and lower bound of fuel thermal expansion and upper bound of fission gas release and lower bound of fuel swelling, and lower bound of cladding creep and lower bound of cladding axial growth and upper bound of cladding corrosion and lower bound of cladding hydrogen pickup.

There are three conditions which give the highest burst time for the combination of fuel manufacturing parameters:

a) Case a: Upper bound of cladding outer diameter and upper bound of cladding thickness, and lower bound of gap thickness and lower bound of filling gas pressure and others fuel parameters with nominal values.
b) Case b: Upper bound of cladding outer diameter and lower bound of cladding thickness, and lower bound of gap thickness and lower bound of filling gas pressure and others fuel parameters with nominal values.
c) Case c: Lower bound of cladding outer diameter and lower bound of cladding thickness, and lower bound of gap thickness and lower bound of filling gas pressure and others fuel parameters with nominal values.

The combination of fuel models which gives the highest burst time was: upper bound of fuel thermal conductivity and upper bound of fuel thermal expansion, and lower bound of fission gas release and upper bound of fuel swelling, and upper bound of cladding creep and upper bound of cladding axial growth, and lower bound of cladding corrosion and upper bound of cladding hydrogen pickup. Table 26 presents the results obtained combining fuel manufacturing parameters and fuel models.

**Table 27: Fuel rod failure time at burst obtained combining fuel manufacturing parameters and fuel models.**

| **Model Sensitivity** | **Burst time** (reference t= 189 sec) |
|---|---|
| Combining all fuel manufacturing parameters (case a) and all fuel models which give the highest burst time | 200.0 |
| Combining all fuel manufacturing parameters (case b) and all fuel models which give the highest burst time | 198.0 |
| Combining all fuel manufacturing parameters (case c) and all fuel models which give the highest burst time | 198.0 |
| Combining all fuel manufacturing parameters and all fuel models which give the lowest burst time | 175.0 |

As can be seen in Table 27, the highest burst time increases slightly (about 6 seconds) compared to previous results obtained considering only the fuel models combination, and for the slowest burst time no significant variation was observed (only 1 second).

## 4. 4. CONCLUSION

A series of simulations using FRAPCON and FRAPTRAN codes were performed for IFA-650.5 experiment in order to verify the influence of the tolerances of some fuel manufacturing parameters (upper and lower bounds) and fuel models bias in the fuel cladding failure time. The simulations showed that fission gas release fuel models bias plays a very important role , presenting the largest variation (about 83%) compared to the reference value and, the lowest variation was observed for fuel centerline temperature (about 6%) compared to reference value. The fuel manufacturing parameters with upper and lower bounds does not shown any remarkable difference compared to the reference result: the highest fission gas release was 9.17%, and the lowest 7.88%; the highest fuel centerline was 1577 °C, and the lowest 1516 °C. the highest internal fuel rod pressure was 51.52 bar, and the lowest 49.67 bar. When combining the fuel models and fuel manufacturing parameters, the obtained results have shown some differences, which give an indication of the conservative condition for this specific fuel data. In summary, the assessment have shown a simplified methodology which shall contribute to identify the conservative scenario for the fuel safety analysis under LOCA condition without very burden and exhaustive simulation. As future investigation, the statistical distribution of the parameters will be taken into account properly in order to confirm the methodology adopted in this paper.

## REFERENCE


1. 10 CFR 50.46. "Acceptance Criteria for Emergency Core Cooling Systems For Light-Water Nuclear Power Reactors", NRC – Nuclear Regulatory Commission (USA).
2. P.D. Parsons, , E.D. Hindle, , C.A. Mann, , "PWR Fuel Behaviour in Design Basis Accident Conditions. A State-of-the-Art Report by the Task Group on Fuel Behaviour Of CSNI Principal Working Group No 2", Committee on the Safety of Nuclear Installations, OECD Nuclear Energy Agency, CSNI Report 129.
3. H.M. Chung, "Fuel Behavior Under Loss-of-Coolant-Accident Situations", *Nuclear Engineering and Technology*, **37**, pp. 327 (2005).
4. J.C.Hesson, *et al.*, "Laboratory Simulations of Cladding-Steam Reactions Following Loss-of-Coolant Accidents in Water-Cooled Power Reactors", Argonne National Laboratory, ANL-7609 (1970).
5. A.R. Massih, "Transformation Kinetics of Zirconium Alloys under Non-Isothermal Conditions", *Journal of Nuclear Materials*, **384**, pp. 330-335 (2009).
6. F. Nagase, T. Fuketa, "Investigation of Hydride Rim Effect on Failure of Zircaloy-4 Cladding with Tube Burst Test". *Journal of Nuclear Science and Technology*, **42**,pp. 58 (2005).
7. Y. Udagawa, F. Nagase, T. Fuketa, "Effect of Cooling History on Cladding Ductility under LOCA Conditions", *Journal of Nuclear Science and Technology*, **43**, pp. 844 (2006).
8. K. J. Geelhood, W.G. Luscher, "FRAPCON-3.5: A Computer Code for the Calculation of Steady-State, Thermal-Mechanical Behavior of Oxide Fuel Rods for High Burnup", NUREG/CR-7022. Vol. 1 Rev.1 (2014).
9. K. J. Geelhood, W.G. Luscher, J. M. Cuta , "FRAPTRAN-1.5: A Computer Code for the Transient Analysis of Oxide Fuel Rods", NUREG/CR-7023. Vol. 1 Rev.1. (2014).
10. K. J. Geelhood, W. G. Luscher, C. E. Beyer, D. J. Senor, M. E. Cunningham, D. D. Lanning,H. E. Adkins, "Predictive Bias and Sensitivity in NRC Fuel Performance Codes", NUREG/CR-7001 (2009).
11. M. Ek, , "LOCA Testing at Halden, the Third Experiment IFA-650.3", OECD Halden Reactor Project, HWR-785, (2005).
12. T. Manngard, J. Stengard, "Evaluation of the Halden IFA-650 Loss-of-Coolant Accident Experiments 5, 6 and 7", Swedish Radiation Safety Authority, Sweden (2014).