IPEN/CNEN-Brazil

Preliminary Assessment of Iron Alloy Cladding as Accident Tolerant Fuel Cladding

Contributors

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SUMMARY

- Brazilian Nuclear Policy
- IPEN/CNEN
- IAEA FUMAC CRP
- Stainless Steel as Cladding
- Conclusions

BRAZILIAN NUCLEAR POLICY

- Nuclear energy should be used only for peaceful purposes (Constitutional Articles n° 21 and 177).

- All nuclear activities shall be solely carried out for peaceful uses and always under the approval of the National Congress.

- Nuclear material production is monopoly of the federal government.

BRAZILIAN NUCLEAR POLICY

- Currently, Brazil has two nuclear power plants in operation and one under construction:

Angra 1 unit, 640 Mwe, 2-loop PWR, first criticality was reached in March 1982, and the plant was connected to the grid in April 1982.

Angra 2 unit, 1345 Mwe, 4-loop PWR, first criticality was reached in 17 July, 2000, and plant was connected to the grid on 21 July 2000.

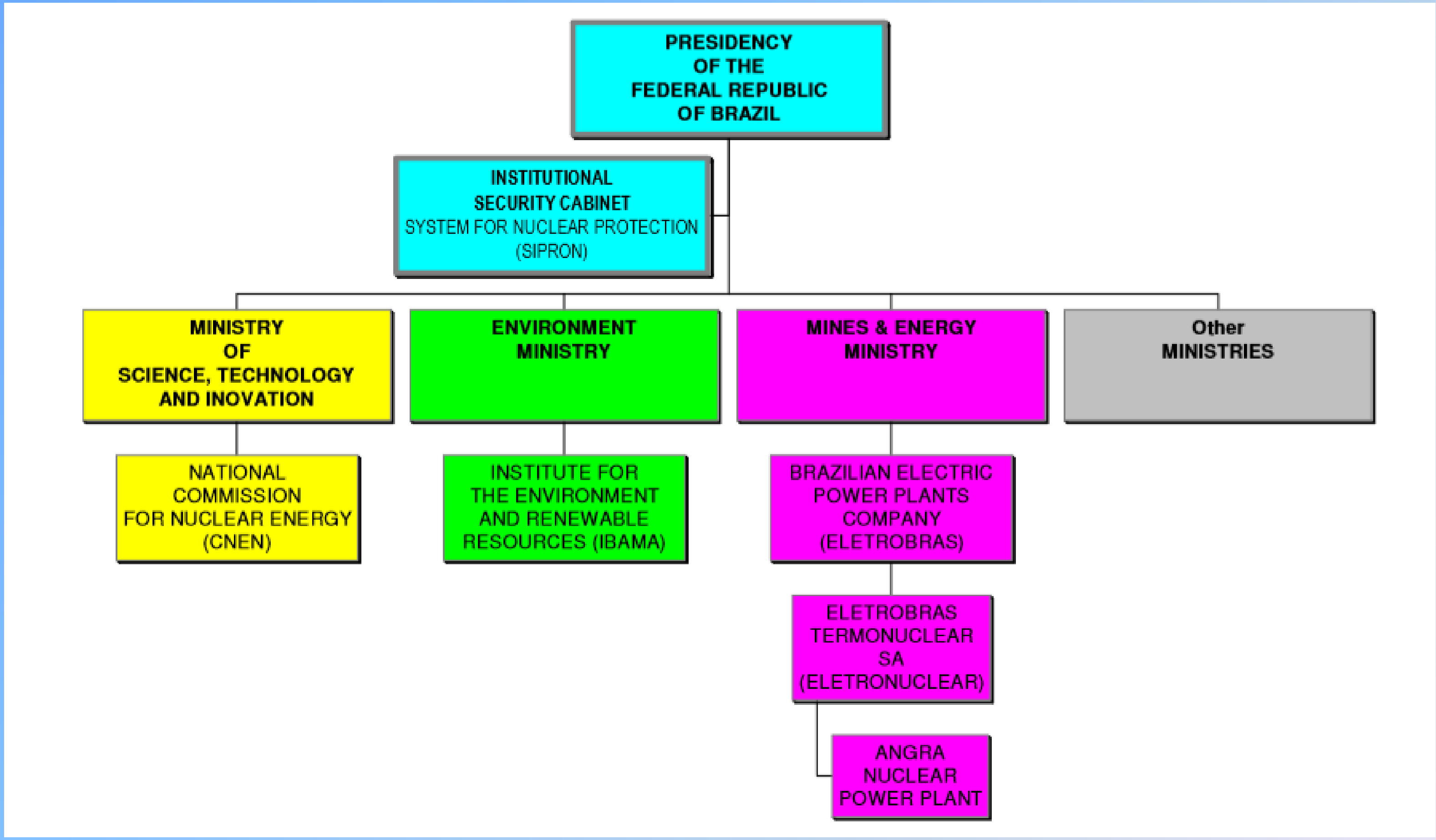
Angra 3 unit, 1351 MWe, 4-loop PWR under construction

BRAZILIAN NUCLEAR POLICY

- CNEN is license authority in BRAZIL according Brazilian Federal Laws 4118/62, 6189/74 and 7781/89.

These laws established that CNEN has the authority "to issue regulations, licences and authorizations related to nuclear installations", "to inspect licensed installations" and "to enforce the laws and its own regulations".

BRAZILIAN NUCLEAR POLICY



IPEN/CNEN-Brazil

The IPEN/CNEN is supported and operated technical and administratively by the Brazilian Nuclear License Authority – CNEN (it is the biggest of the CNEN's Institutes).

The IPEN/CNEN has different and multidisciplinary research activities and contributes to specific license issues for Brazilian License Authority – CNEN.

IPEN/CNEN-Brazil

FUMAC CRP

- The IPEN/CNEN presented a proposal to participate in IAEA CRP FUMAC (Fuel Modeling under Accident Condition).

- Perform an assessment of iron alloy as cladding for accident tolerant fuel under FUMAC framework and comparing the performance with zircaloy cladding.

FUMAC CRP

- The IAEA FUMAC CRP 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.

FUMAC CRP

- 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 a separate 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.

FUMAC – IPEN/CNEN-Brazil

- The proposal 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.

Activities performed

- FRAPCON & FRAPTRAN codes modifications in order to implement AISI-348 as cladding material
- Assessment and simulation of IFA-650 experiments using original version of FRAPCON&FRAPTRAN
- Assessment and simulation of IFA-650 experiments using modified version of FRAPCON&FRAPTRAN (stainless steel as cladding)
- Sensitivity and Uncertainties Analysis

Stainless Steel as Cladding

Stainless Steel as cladding

- Steel alloys as candidate for ATF cladding, especially FeCrAl
- Good and well known thermo-mechanical properties
- Previous operational experience (304 and 316) as fuel cladding
- Some constraint (neutron absorption, tritium)
- Safety performance

Stainless Steel as Cladding

Table 1 Zircaloy-4 [5, 6] and type 348 austenitic stainless steel properties [7-9].

Property	Zircaloy-4	AISI 348
Crystalline structure	HCP(α)/CCC(β)	CFC
Density (10^3 kg/m^3)	6.56	7.84
Rockwell-B hardness	89	85
Ultimate strength (MPa)	413	655
Tensile strength at yield (MPa)	241	275
Maximum elongation (%)	20	45
Elastic modulus (GPa)	99.3	195
Poisson's ratio	0.37	0.27
Shear modulus (GPa)	36	77
Resistivity μ(Ohm.cm)	74	79
Specific heat (J/g·°C)	0.285	0.5
Thermal conductivity (W/mK)	16.8	19.1
Thermal expansion coefficient (10^{-6}/K)	6.7	18.5
Melting point (°C)	1,825	1,400
Under irradiation creep (%) (φ_t = 3.1021 n/cm^2)	0.3	0.045

Stainless Steel as Cladding

The AISI-348 stainless steel displays a higher thermal conductivity. Also, it presents a thermal expansion coefficient approximately three times higher than that of Zircaloy-4.

Due to this last aspect, stainless steel rods maintain a wider pellet-cladding gap and it is necessary longer irradiation times to verify gap closure than Zircaloy-4 rods.

Stainless Steel as Cladding

Alloying Elements Features

➢**Chromium** forms a surface film of chromium oxide to make the stainless steel corrosion resistant. It also increases the scaling resistance at elevated temperatures.

➢**Carbon** strengthens stainless steel but promotes the formation of precipitates harmful to corrosion resistance.

Stainless Steel as Cladding

Alloying Elements Features

- **Nickel** stabilizes the austenitic structure and increases ductility, making stainless steel easier to form. It increases high temperature strength and corrosion
Resistance.

- **Molybdenum** increases corrosion
resistance, strength
at elevated temperatures, and creep resistance.

Stainless Steel as Cladding

Recently, the IPEN/CNEN have been doing some preliminary studies related to stainless steel.

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DAVID PUBLISHING

Revisiting Stainless Steel as PWR Fuel Rod Cladding after Fukushima Daiichi Accident

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Stainless Steel as Cladding

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REGULAR ARTICLE OPEN ACCESS

Evaluation of corrosion on the fuel performance of stainless steel cladding

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Stainless Steel as Cladding

- 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 code are gathered in MATPRO data libraries and some others are specifically considered in modular subroutines where the material properties (thermal and mechanical) as function of temperatures and for burnup are explicitely considered.

Stainless Steel as Cladding

- Initially, the subroutines and data related to material properties were identified, specially 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.

Stainless Steel as Cladding

Table 2 Zircaloy cladding material properties modified in MATPRO for the construction of IPEN-CNEN/SS.

Material properties	Modification and reference
Thermal expansion	New model [7, 8]
Thermal conductivity	New model [7, 8]
Elastic modulus	New model [7, 8]
Poison's ratio	New model [7, 8]
Thermal creep	Deleted
Irradiation creep	New model [10, 11]
Axial growth	Deleted
Swelling	New model [10]
Oxidation	Deleted
Pellet-cladding gap Conductance	New emissivity factor [8] and new meyer hardness correlation [12]

FUMAC – IPEN/CNEN-Brasil

- Preliminary modified subroutines in the FRAPCON code and MATPRO for stainless steel

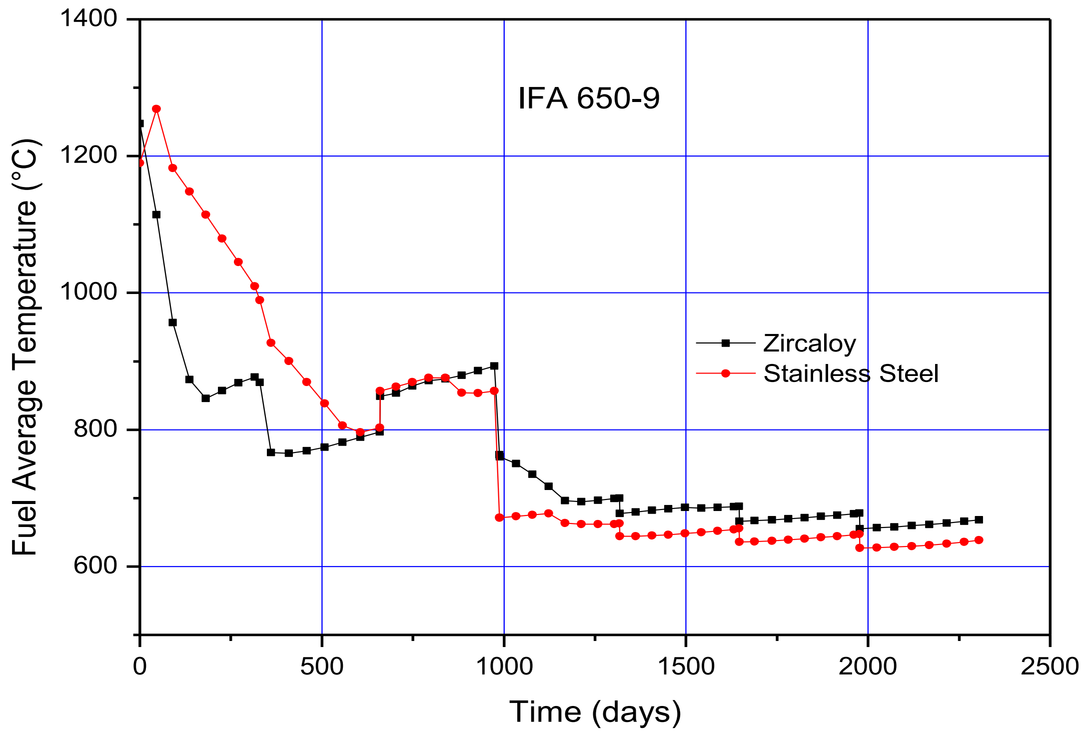
crepr2	cmhard	emcton
cagrow	cobild	emctxp
caneal	corros	phyprp
caniso	cshear	zoemis
cbrttl	csigma	zotcon
cclaps	cstran	
ccp	cstres	
celast	cstrni	
celmod	cthcon	
chscp	cthexp	
chuptk	emccp	
ckmn	emcpir	

Stainless Steel as Cladding

- 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.
- 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

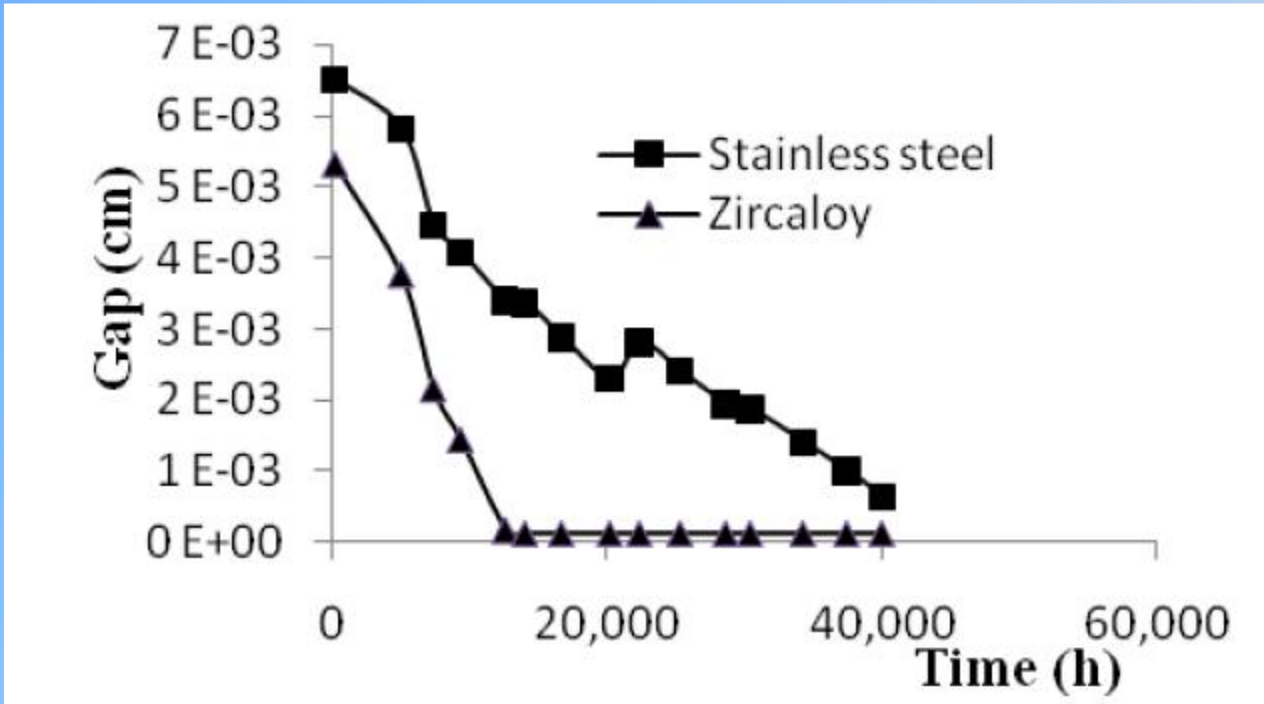
Stainless Steel as Cladding

Comparison of Fuel Average Temperature for IFA 650-9 for Zircaloy-4 and AISI 348 cladding (steady state)



Stainless Steel as Cladding

Comparison of gap evolution for Zircaloy-4 and AISI 348 cladding.



Stainless Steel as Cladding

- 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.

Stainless Steel as Cladding

- 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.

Stainless Steel as Cladding

- Preliminary modified subroutines in the FRAPTRAN code for stainless steel

CCP / CCPINT
CELMOD
CSHEAR
CMHARD
CTHEXP
CTHCON
ZOEMIS
ZOTCON
CMLIMT
CKMN

Stainless Steel as Cladding

- The cladding deformation is calculated and result of effective plastic strain is compared to instability strain, if the effective plastic strain is greater than instability strain, the ballooning model is used to calculated nonuniform deformation.

- Fuel cladding failure will occurs when the cladding true hoop stress exceeds an empirical limit that is a function of temperature.

Stainless Steel as Cladding

- Preliminary, the empirical limit was taken from AISI-304 due to lack of burst data for AISI-348, specially at high temperature (above 900 Kelvin).

- This assumption will be main limitation associated to FRAPTRAN code modification to consider stainless steel as cladding.

Stainless Steel as Cladding

FRAPTRAN code : Elasto-plastic deformation

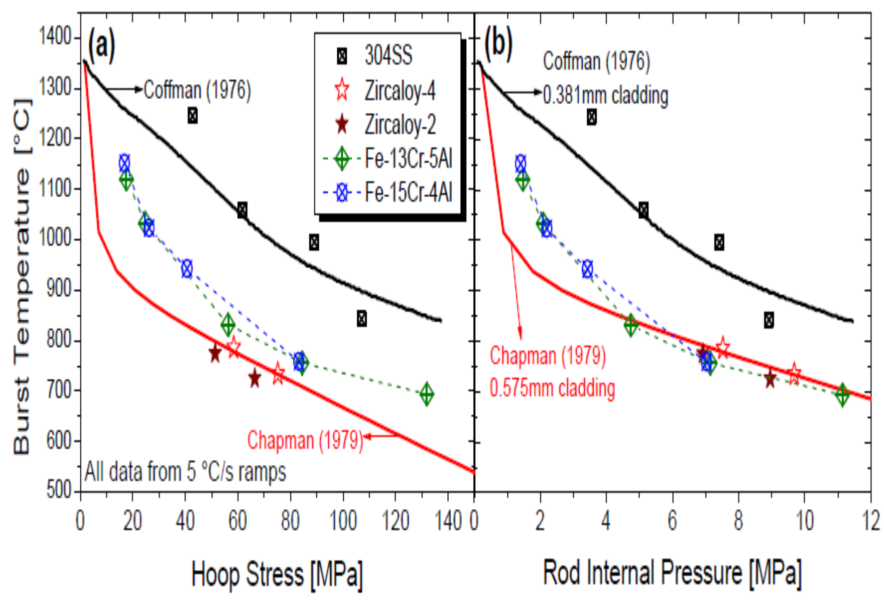


Fig. 4. Burst temperature as a function of a) engineering hoop stress and b) rod internal pressure for various cladding materials examined in this study (scatter data) alongside empirical correlations from prior literature for Zr-alloys [49] and 304SS [46] (lines).

Stainless Steel as Cladding

Comissão Nacional de Energia Nuclear

FRAPTRAN code : Elasto-plastic deformation

The preliminary modification was performed introducing into the code data related to the burst stress as function of temperature for AISI-304 (stainless steel) obtained from the literature.

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ELSEVIER

Cladding burst behavior of Fe-based alloys under LOCA☆

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Burst experiment shall be performed in the future specifically for AISI-348.

Stainless Steel as Cladding

IFA Experiment : Experimental Data Assessment, Modelling and Calculations

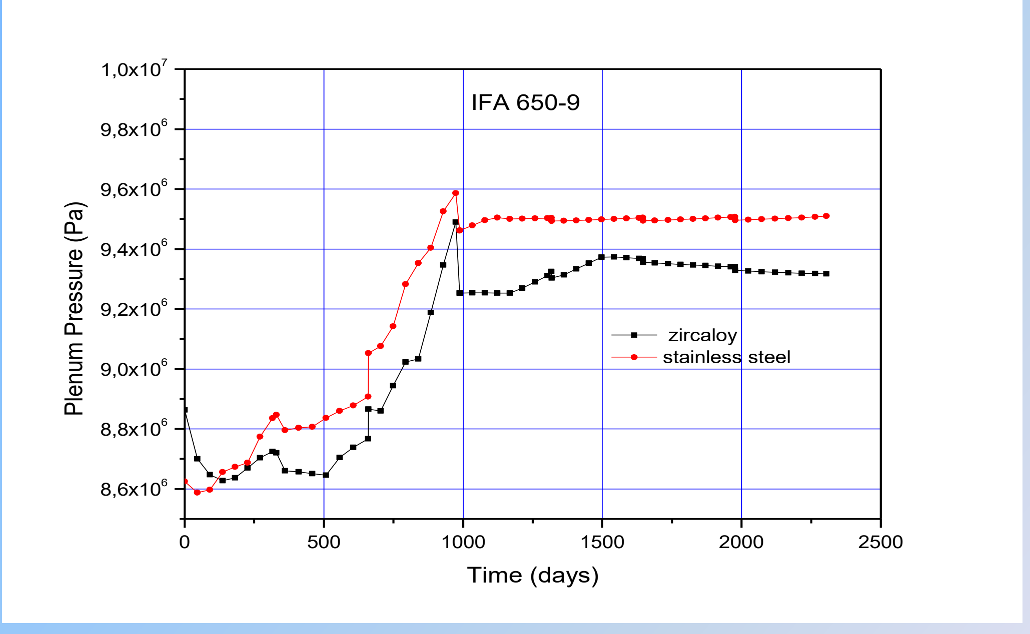
- The FRAPCON and FRAPTRAN input data were taken from HWR reports (Halden Technical Report) and Data Sheet Description.

- The temperature profile at fuel cladding surface and loop pressure (external pressure) data as function of time were properly selected in order to prepare FRAPTRAN input data (boundary data block input).

Stainless Steel as Cladding

FRAPCON Simulations (IFA-650.9, IFA-650.10 and IFA-650.11)

➢ The simulations results using FRAPCON code (original and modified version) for IFA-650 series.



Stainless Steel as Cladding

FRAPCON Results (Steady State)

Base irradiation results from FRAPCON original version and modified version for AISI 348.

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

Stainless Steel as Cladding

FRAPTRAN Simulations (IFA-650.9, IFA-650.10 and IFA-650.11)

The simulations results using FRAPTRAN code (original and modified version) for IFA-650 series.

Parameters	IFA-650.09		IFA-650.10		IFA-650.11	
	Zircaloy	Stainless Steel	Zircaloy	Stainless Steel	E110	Stainless Steel
Burst (sec)	99	134	109	-----	258	267
Rod burst at elevation (ft)	0.787	0.787	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

Stainless Steel as Cladding

Uncertainty and Sensitivity

The uncertainty and sensitivity assessment can assist and contributes to :

- Safety analysis (Best Estimate plus Uncertainties – BEPU approach).
- Obtain relationship between input and output.
- Analysis of model and model development.

Stainless Steel as Cladding

Uncertainties and Sensitivity Assessment using FRAPCON – FRAPTRAN codes (original and modified version)

- The uncertainty and sensitivity assessment was conducted mostly according to Technical Specification prepared by CRP organizer.

- The statistical distribution (normal) was applied for each one of the fuel fabrication/design parameters and for fuel models (physical properties) utilized in the fuel performance code (FRAPCON) models.

Stainless Steel as Cladding

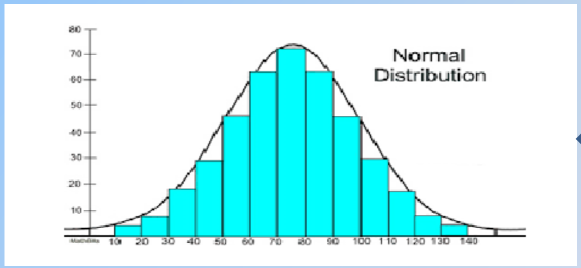
Uncertainties and Sensitivity Assessment using FRAPCON – FRAPTRAN codes (original and modified version)

Fuel fabrication parameters

cladding thickness
gap thickness
fuel pellet outside diameter
^{235}U enrichment,
fuel theoretical density
rod gas-gap fill pressure

Fuel models

fuel thermal conductivity
fuel thermal expansion coefficient
cladding axial growth model
cladding creep model,
fuel swelling model
fission gas release model,
cladding corrosion
cladding hydrogen pickup

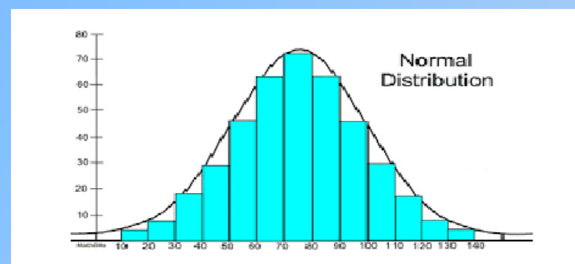


Stainless Steel as Cladding

Uncertainties and Sensitivity Assessment using FRAPCON – FRAPTRAN codes (original and modified version)

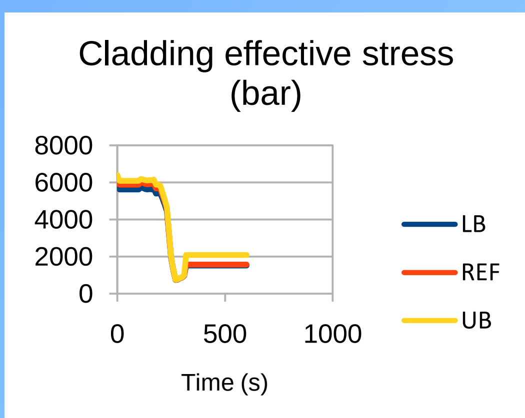
Fuel fabrication parameters

Fuel models



FRAPCON

FRAPTRAN



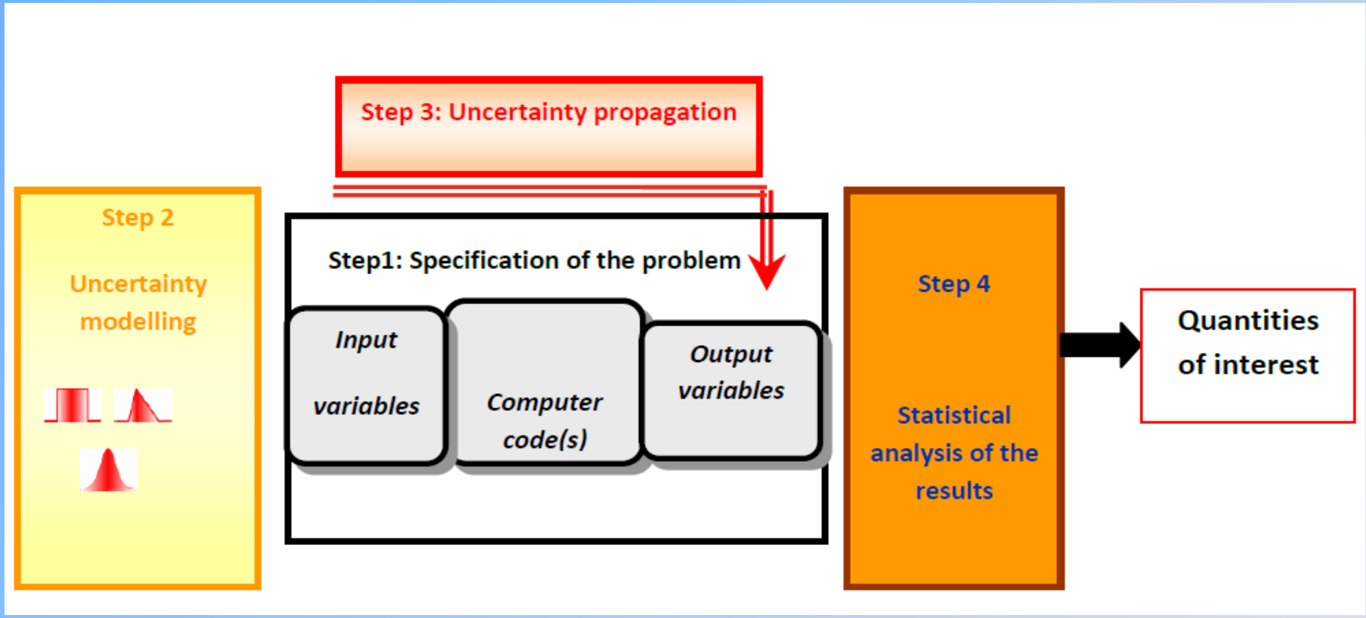
Uncertainties Analysis

Person correlation

Sensitivity Analysis

Stainless Steel as Cladding

Uncertainty analysis: input uncertainty propagation method



The fuel codes are treated as “black boxes”, and the input uncertainties are propagated to the simulation model output uncertainties via the code calculations with sampled input data from the known distributions

Stainless Steel as Cladding

Uncertainty analysis: input uncertainty propagation method

- Initially, a set of simulations was performed considering 200 (two hundred) runs (FRAPCON and FRAPTRAN), where fuel fabrication/design parameters were considered, 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.

Stainless Steel as Cladding

Uncertainty analysis: input uncertainty propagation method

- Additionally, following fuel models (physical properties) embedded in the FRAPCON code were addressed: fuel thermal conductivity, fuel thermal expansion coefficient, cladding axial growth model, cladding creep model, fuel swelling model, fission gas release model, cladding corrosion and, cladding hydrogen pickup.
- The statistical distribution (normal) was considered as well as correspondent standard deviation for each fuel model (physical properties) as suggested in the Technical Specification.

Stainless Steel as Cladding

Pearson correlation (FRAPCON Results – ZRY cladding)

Fabrication/design tolerance	Fission gas release	Maximum Plenum pressure	Peak fuel centerline temperature
dco	-0.02	0.10	-0.07
thkcld	0.01	0.01	**-0.50**
thkgap	0.28	0.13	**0.99**
enrch	0.05	0.08	-0.02
den	**-0.87**	-0.19	-0.04
fgpav	0.12	**0.94**	-0.15

cladding thickness (**thkclad**), gap thickness (**thkgap**), fuel pellet outside diameter (**dco**), ^{235}U enrichment (**enrch**), fuel theoretical density (**den**), rod gas-gap fill pressure (**fgpav**).

Stainless Steel as Cladding

Pearson correlation (FRAPCON Results – SS cladding)

Fuel model and fuel fabrication tolerance	Fission gas release	Maximum plenum pressure	Peak fuel centerline temperature
dco	-0.10	-0.01	-0.08
thkcld	**-0.52**	-0.35	**-0.50**
thkgap	**0.98**	**0.78**	**0.97**
enrch	-0.02	0.04	-0.02
den	-0.03	-0.15	-0.08
fgpav	-0.18	0.45	-0.14

Stainless Steel as Cladding

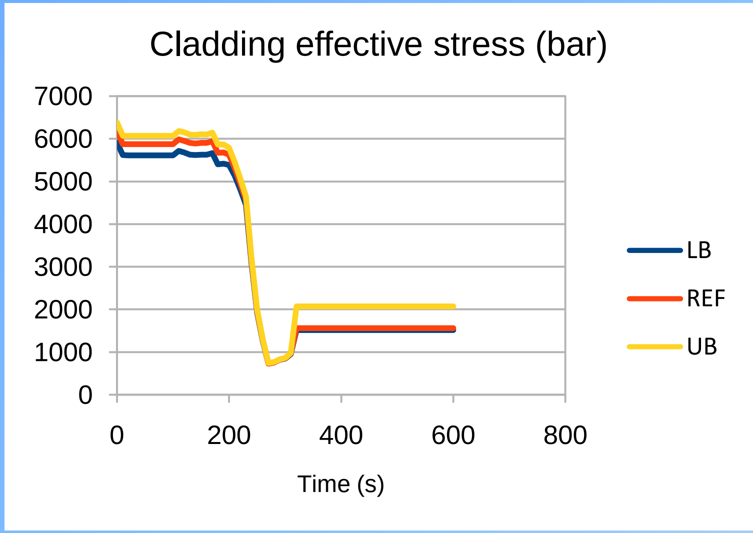
Pearson correlation (During the transient)

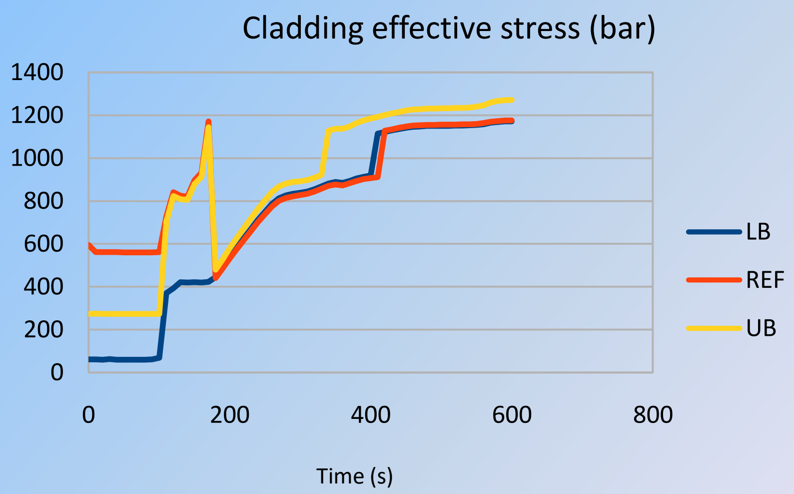
Time parameters	t_1	t_2	t_3	t_4	t_5
Definition	End of natural circulation	Beginning of blowdown	End of cooldown	Burst	**End of calculation**
Value	**100.0s**	**110s**	**170s**	**350s**	**600 s**

Results considered : Plenum Pressure, Fuel Center Temperature, Fuel Surface Temperature, Clad Inner Temperature , Cladding Outer Temperature, Cladding Hoop Strain, Cladding Effective Stress, Cladding radial Strain, Cladding Axial Elongation, Fuel Stack Elongation, Fuel energy and Fuel Surface Displacement

Stainless Steel as Cladding

Uncertainty analysis results



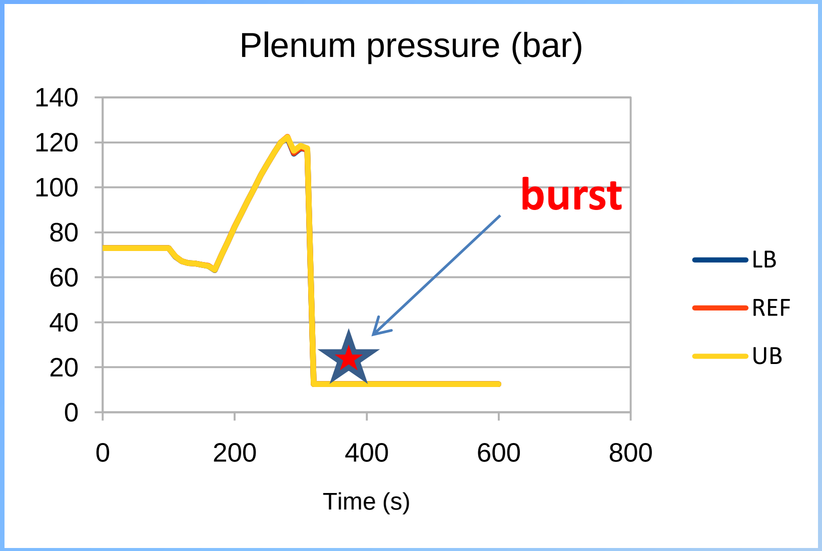


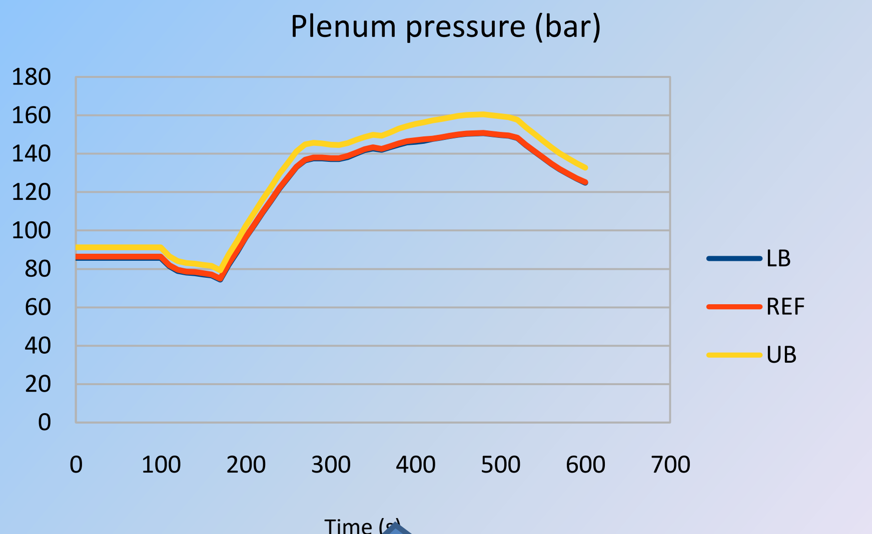
Zircaloy Cladding

Stainless Steel Cladding

Stainless Steel as Cladding

Uncertainty analysis results





Zircaloy Cladding

Stainless Steel Cladding

No burst

Preliminary Conclusions

There are some gap of information in order to confirm the potential of iron based alloys cladding as ATF:

- *Burst data (high temperature)*
- *Behavior under irradiation (mechanical properties)*
- *Metal vapour reaction (hydrogen generation)*

ipen

CNEN Comissão Nacional de Energia Nuclear

Thank you for your kind attention!