Modelling of LOCA Fuel Rod Behaviors Using Code FRAPTRAN 1.5

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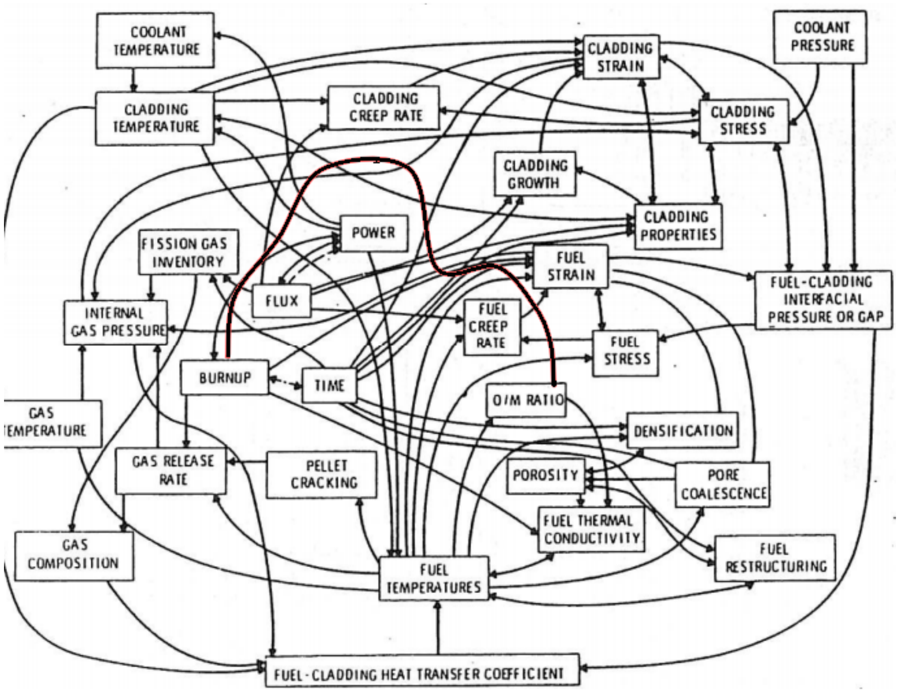
INTRODUCTION

- Fuel rod is the first barrier of protection in nuclear safety
  - — Dedicated fuel rod codes needed in safety analysis
    - Fuel rod design: Normal conditions and Condition II transients
    - Accident analyses: Condition III and IV accidental conditions
  - — Need accurate and reliable simulation of fuel rod behaviours, but…
    - Multiplicity of strong/weak interactions between physicals and thermo-mechanical phenomena



INTRODUCTION

- In particular, fuel rod behaviour in LOCA is an active research subject:
  - — LOCA is a postulated design basis accident which is "dimensioning" for numerous components.
    - Its safety demonstration is an essential part of the plant safety analysis report
  - — Numerous tests have been performed in the past decades
    - With high burnup fuel rods.
  - — Complex physical phenomena observed
    - Ballooning, burst, two-sided oxidation, fragmentation, relocation, dispersal, oxidation and hydriding…
    - Some are not explicitly addressed in original regulation.
    - Nuclear safety authorities consider revisions to the current LOCA safety criteria
  - — The nuclear industry is acting by improving its modelling capacities
    - Fuel rod codes and safety analysis methods

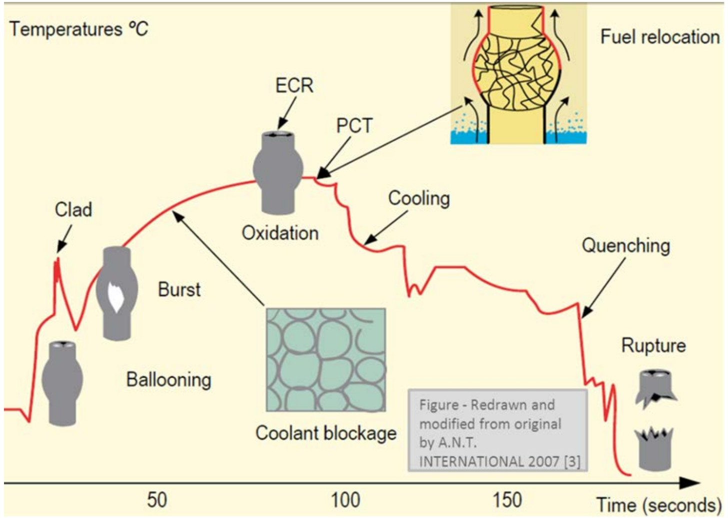


Figure - Redrawn and modified from original by A.N.T. INTERNATIONAL 2007 [3]

INTRODUCTION

- Objectives of Tractebel (owner's engineer for Belgian Utility):
  - Own methods for independent verification of vendors' studies (fuel rod design or LOCA/RIA safety analyses)
    - Review of fuel vendors' methods and results
    - Margin assessment for different plants.
    - Sensitivity analyses.
  - Capacity development
    - Qualification of the fuel rod codes FRAPCON and FRAPTRAN (developed by PNNL and distributed under the NRC's Code Applications and Maintenance Program (CAMP)).
    - Methods for analyzing the uncertainties in multi-physics modelling and safety analyses.
      - With DAKOTA optimization and uncertainty analysis code.
      - Monte-Carlo sampling on the inputs parameters to perform state of the art uncertainty analyses.
  - **This work: Use those codes/methods on an experimental case in order to test and improve them.**

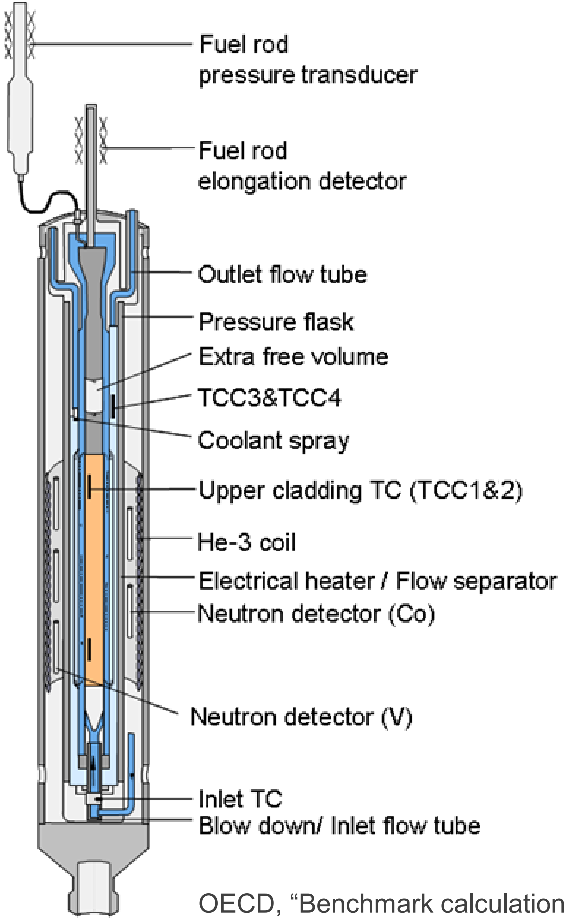
OECD Halden LOCA TESTS

- Different benchmarks used to improve and validate the codes and methods.
  - Exercises based on the Halden LOCA tests have been chosen.
- LOCA tests at Halden reactor (in Norway):
  - Integral in-pile single rod tests.
  - Address various LOCA issues for high and medium burnup fuel rods.
  - Tested rods have been irradiated in commercial reactors.
- Work presented here:
  - To simulate the chosen tests with the fuel rod codes FRAPCON/FRAPTRAN and perform uncertainty analyses.

→ to improve and validate our fuel rod safety evaluation methods.

OECD Halden LOCA TESTS

- Experimental set-up
  - — Fuel rod installed in test rig
  - — LOCA activated by blowdown valve
  - — Measurements of interest:
    - Cladding temperature (TCC1) → Boundary condition
    - Inner flow channel temperature (TCC3) → Boundary condition
    - Fuel rod pressure (PF1) → Result testing
- Test of interest
  - — IFA650.4: 92 GWd/t, ~10μm oxide, 800°C
  - — Covers **ballooning/burst** and **relocation** and allows to challenge code **modelling capacities**



OECD, "Benchmark calculations on HALDEN IFA-650 LOCA test results", NEA/CSNI/R(2010)6, 15 November 2010

Modelling with fuel rod codes FRAPCON/FRAPTRAN

- Simulation of the LOCA transient with FRAPCON/FRAPTRAN
  - Pre-irradiation with FRAPCON given a power history of the fuel rod
  - Transient simulation by FRAPTRAN with imposed cladding outside temperature.
  - Focus on the fuel rod responses of interest: ballooning, burst, ECR.
- Assumptions
  - FRAPCON simulation of the refabricated rodlet at normal operation conditions.
  - Modification of the FRAPCON restart file used for initialization of FRAPTRAN model.
    - Refabricated rodlet pressure and gas content.
  - Use of FRAPTRAN “heat” option for thermal hydraulic (TH) boundary conditions.
    - Cladding temperature history imposed on the base of TCC1 measurements (Specifed coolant temperature with very high HTC).

FRAPCON/FRAPTRAN modelling

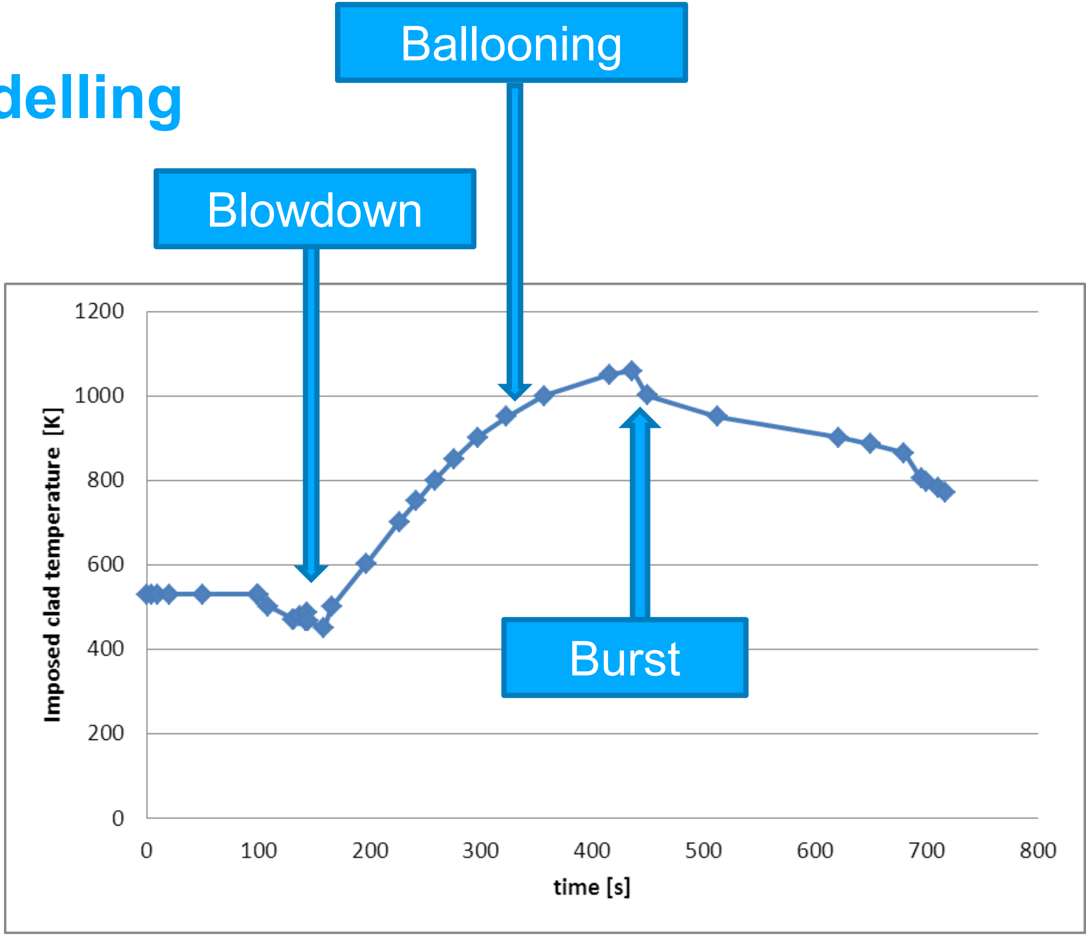
- Modifications in the FRAPTRAN1.5 code
  - The original rod gas plenum temperature model gave unsatisfactory results: too high temperature and rod internal pressure.
  - Modifications made to allow specification of an external plenum volume held at a defined gas temperature.
  - Added variables:
    - explenumv –Volume of external plenum
    - explenumt – temperature of gas in external plenum
      - Used for simulation of IFA650.4 fuel rod
- This modification was asked to PNNL by TE based on our previous works.

FRAPCON/FRAPTRAN modelling

- Use of external plenum model:
  - First version: A constant average value => Not sufficiently good.
  - Second version: Possible to insert a plenum temperature time history.
  - Need to define such plenum temperature time history.
    - The history of TCC3 does not correspond to this parameter, but to the temperature outside of the fuel rod.
    - A correlation has been found at TE and calibrated with one of the IFA650 tests.
    - This correlation was further validated with the other IFA650 tests and proved appropriate.

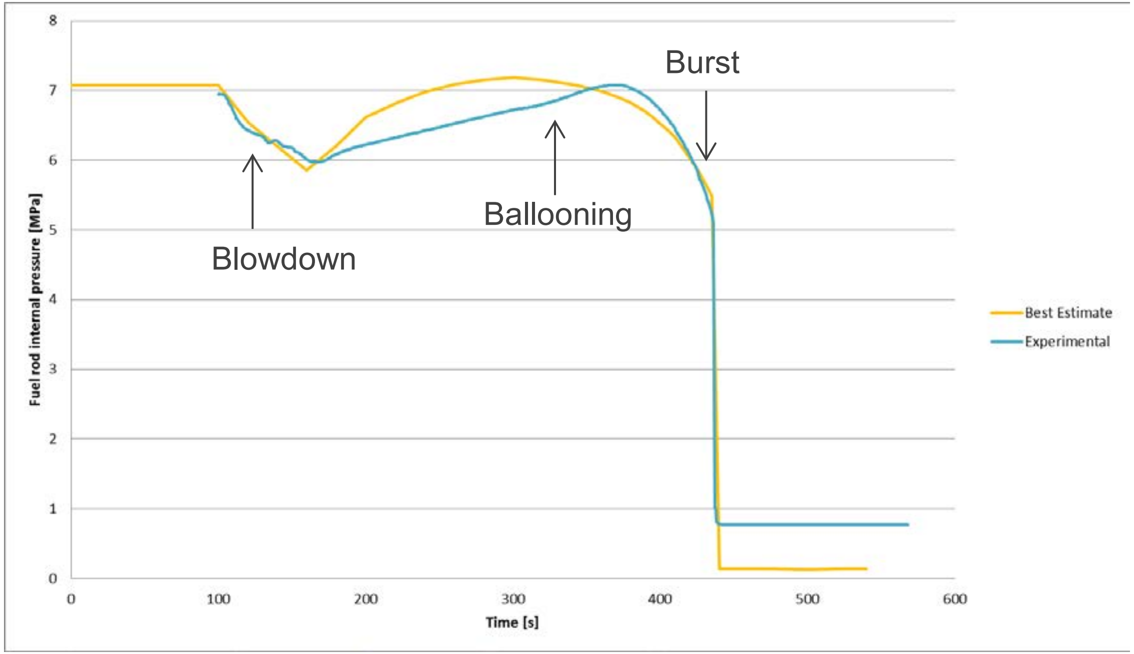
FRAPCON/FRAPTRAN modelling

- Test IFA650.4
  - Imposed plenum gas temperature
  - Imposed cladding temperature
  - Specificities:
    - High burnup
    - Medium temperature
    - Some relocation (important for further developments)
  - Has been studied as well as other IFA650 cases.



FRAPCON/FRAPTRAN modelling

- Test IFA650.4
  - Evolution of best-estimate fuel rod pressure: the pressure is slightly different.
  - Burst at correct time: Very good.
  - Importance of good burst simulation:
    - Burst instant is start of double-sided oxidation.



Uncertainty/Sensitivity Analysis

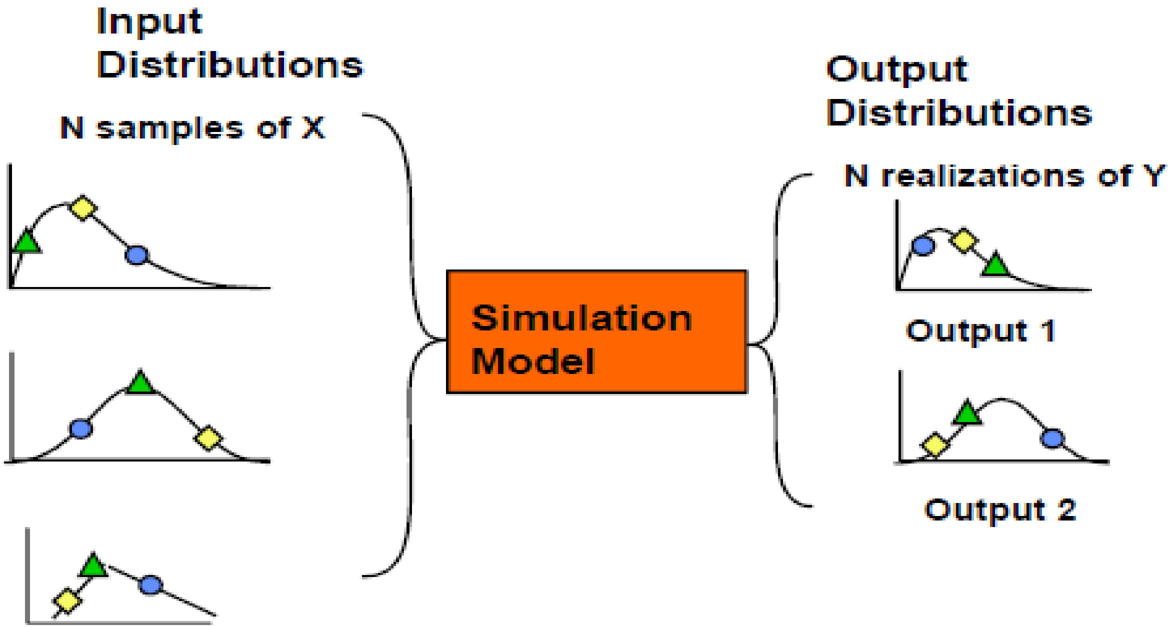
Method

- Objectives
  - — Identify the most important parameters influencing the result of interest.
  - — Evaluate the impact of the fuel rod data, model and test uncertainties on the uncertainties of the calculation results.
- Method: Non-parametric order statistics
  - — Establishment of sampled parameters, uncertainty range and distributions.
  - — Use of DAKOTA code from Sandia National Laboratory for uncertainty analysis:
    - Monte-Carlo sampling of all parameters with 93 FRAPCON/FRAPTRAN runs.
    - Min/Max are the lower and upper bounds (5/95 and 95/95, double-sided, according to Wilk's formula).
  - — Use of Pearson's and Spearman's correlation coefficients for sensitivity analysis.
    - Identification of the most influential parameters on the results of interest.
- Those methods were implemented and tested during various benchmarks.

Uncertainty/Sensitivity Analysis

Method

- Propagation of input uncertainties



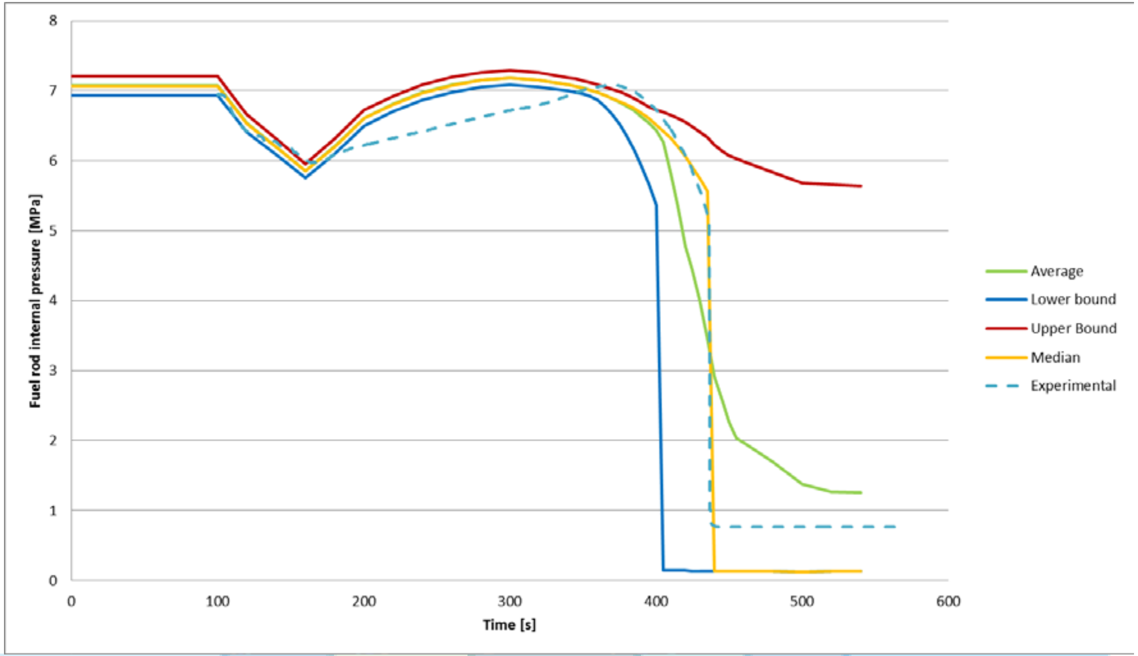
Sandia National Laboratories, “DAKOTA Uncertainty Quantification,” SAND 2009-0511P, (2009)

UNCERTAINTY/SENSITIVITY analysis method

- Sampled parameters: ranges and distributions for test IFA650.4
  - Based on literature and previous study
    - Selection of important uncertainty parameters:
      - Some parameters added for confirmation of non-importance
      - Distributions and ranges taken as usually present in literature
      - Material properties were not included in this study
    - Identification of uncertainty parameters in three categories:
      - Manufacturing
      - Model (including in Fraptran)
      - Operational (or test)

Uncertainty/Sensitivity Analysis
Uncertainty Analysis Results

- Test IFA650.4 : Evolution of fuel rod pressure
  - The uncertain bounds cover the burst instant and pressure value before burst.
  - Uncertainty on measured data would be very helpful.
  - Difference median/average: Response distribution is not symmetric.
  - Lower bound: Estimator covering the 5/95 limit (less than 5% of the values are below the line, with more than 95% confidence).
  - Upper bound: Estimator covering the 95/95 limit (more than 95% of the values are below the line, confidence over 95%).

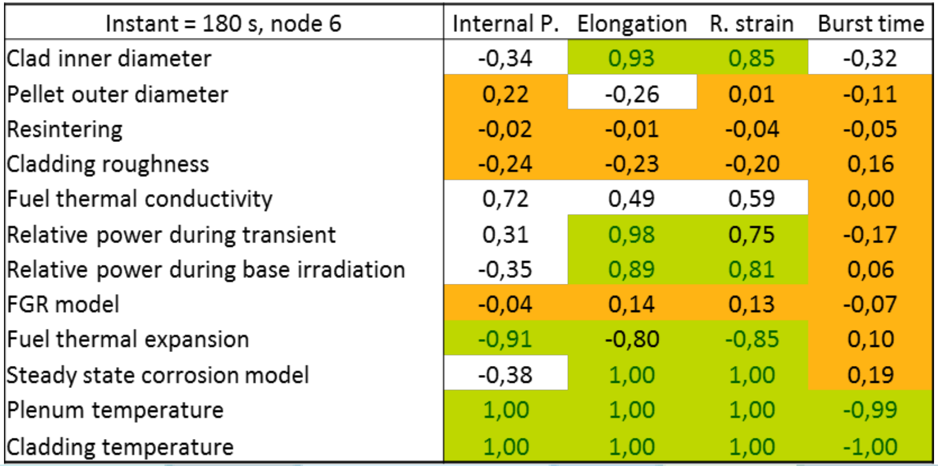


Uncertainty/Sensitivity Analysis

Sensitivity Analysis Results

- Pearson’s linear correlation coefficient
  - Designate the linear correlation between one input and one output.
  - Absolute values below 0.25 indicates weak correlation and are in yellow.
  - Absolute values above 0.75 indicates clear correlation and are in green.

Example (node 6 taken because close to burst position):



Instant = 180 s, node 6	Internal P.	Elongation	R. strain	Burst time
Clad inner diameter	-0,34	0,93	0,85	-0,32
Pellet outer diameter	0,22	-0,26	0,01	-0,11
Resintering	-0,02	-0,01	-0,04	-0,05
Cladding roughness	-0,24	-0,23	-0,20	0,16
Fuel thermal conductivity	0,72	0,49	0,59	0,00
Relative power during transient	0,31	0,98	0,75	-0,17
Relative power during base irradiation	-0,35	0,89	0,81	0,06
FGR model	-0,04	0,14	0,13	-0,07
Fuel thermal expansion	-0,91	-0,80	-0,85	0,10
Steady state corrosion model	-0,38	1,00	1,00	0,19
Plenum temperature	1,00	1,00	1,00	-0,99
Cladding temperature	1,00	1,00	1,00	-1,00

Conclusions and Perspectives

- With the measured cladding temperature and imposed plenum gas temperature as boundary conditions, FRAPTRAN is able to coherently simulate the Halden LOCA tests IFA650.4, in particular:
  - Fuel pellet temperature;
  - Rod internal pressure;
  - The ballooning and burst.
- The important parameters influencing the calculation results of interests are identified:
  - Plenum gas temperature;
  - Cladding temperature;
  - Cladding inner diameter;
  - Initial power and steady-state corrosion for oxide quantities.

Conclusions and Perspectives

- The uncertainties of the important fuel rod data, model and operation uncertainty parameters have significant impacts on the calculation results of interests.
  - Moderate uncertainties on centerline temperature and internal pressure.
  - High uncertainties on strains, burst time and ECR.
- The development of the methods is continuing and the improvement made will be used in the future.
  - Participation in the IAEA FUMAC project
  - Also, several recommendations (measurements uncertainty, parameters of importance) were made to the Halden reactor project.
- Since this work, several tasks were performed:
  - Margin assessment for the Belgian plants
  - Subsequent improvement of the codes, in particular to introduce more model uncertainties

Thank you for your attention !

Any questions ?

- Acknowledgement: Special thanks to Zeynab Umidova, Thomas Drieu, Charles Dupuit, Dou Dou and Thibaut Helman.