Post-Test Calculation and Uncertainty Analysis of the Experiment QUENCH-07 with the System Code ATHLET-CD

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Topics

- Introduction:
  - Short description of the code ATHLET-CD
  - Short description of the QUENCH facility and of test QUENCH-07
- Post-Test Calculation of QUENCH-07
  - Input data
  - Main results of reference calculation
- Sensitivity analysis
  - Methodology
  - Main results
- Conclusions

ATHLET-CD

Analysis of Thermal-Hydraulics of Leaks and Transients with Core Degradation

- Mechanistic code for beyond design basis and severe accidents
- Assessment of accident management systems and procedures
- Simulation of processes in primary and secondary coolant systems:
  - Loss of coolant, core heat-up, degradation, melting, relocation
  - Release and transport of fission products and aerosols
  - Mechanical and thermal loads of reactor pressure vessel
- Calculation of source terms for containment analyses
- Status of development: core damage before gross relocation

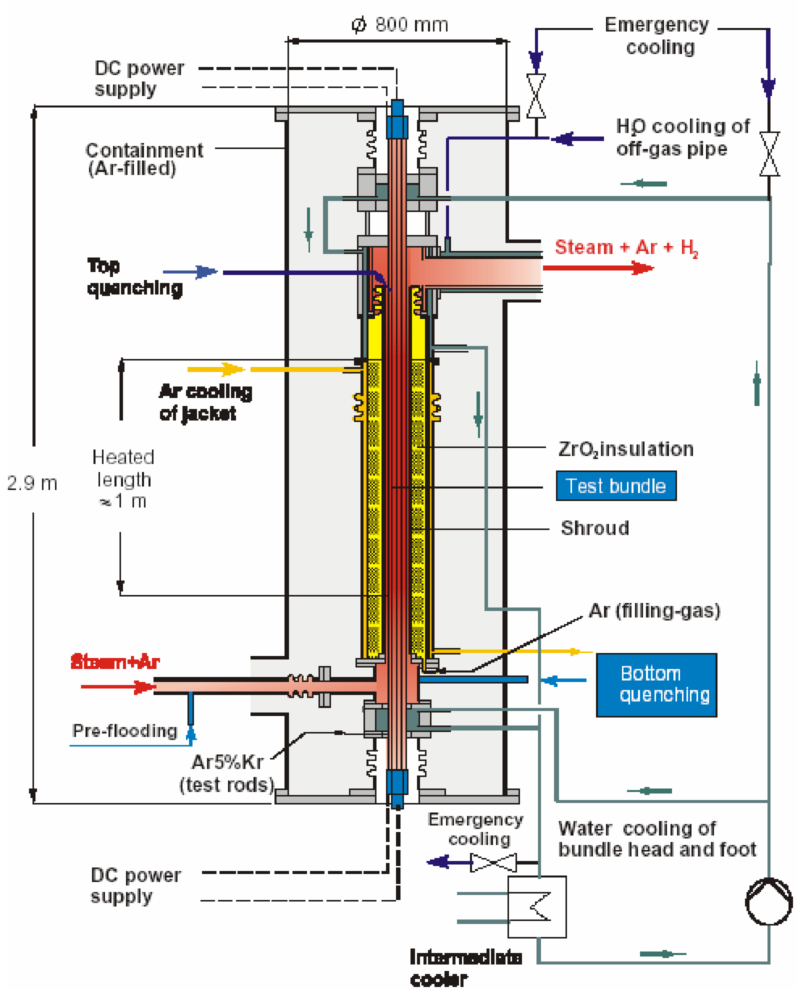
ATHLET-CD: Main Modules (I)

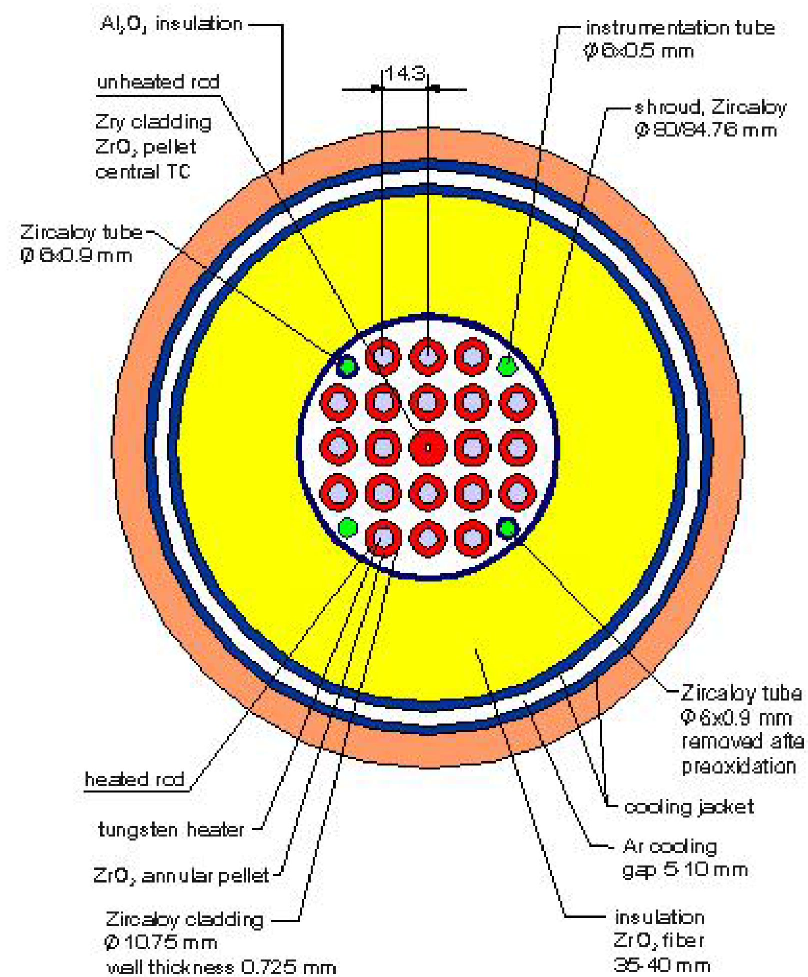
- RCS Thermal-Hydraulics (ATHLET):
  - two-fluid modelling
  - additional balance equations for non-condensable gases
  - one-dimensional heat conduction within structures
  - control simulation module for the description of control, protection and balance-of-plant systems
- Core Degradation (ECORE):
  - simulation of fuel and control rods, as well as BWR core structures
  - mechanical fuel rod behaviour, including thermal expansion, ballooning and cladding rupture
  - cladding oxidation (parabolic rate equations)
  - melting and relocation of cladding Zircaloy, absorber rods and guide tubes, fuel and oxidized cladding

ATHLET-CD: Main Modules (II)

- Fission Products and Aerosol Release (FIPREM):
  - fission products release and diffusion inside the grain
  - up to 24 elements or release groups considered
- Fission Product and Aerosol Transport (SOPHAEROS):
  - deposition, transport and agglomeration processes
  - gas phase chemistry
- Heat-up and Melting within Debris Bed (MESOCO):
  - 2D balance equations with 3 components: particles, melt and gases

QUENCH test section and bundle cross section (FZKA 6412)

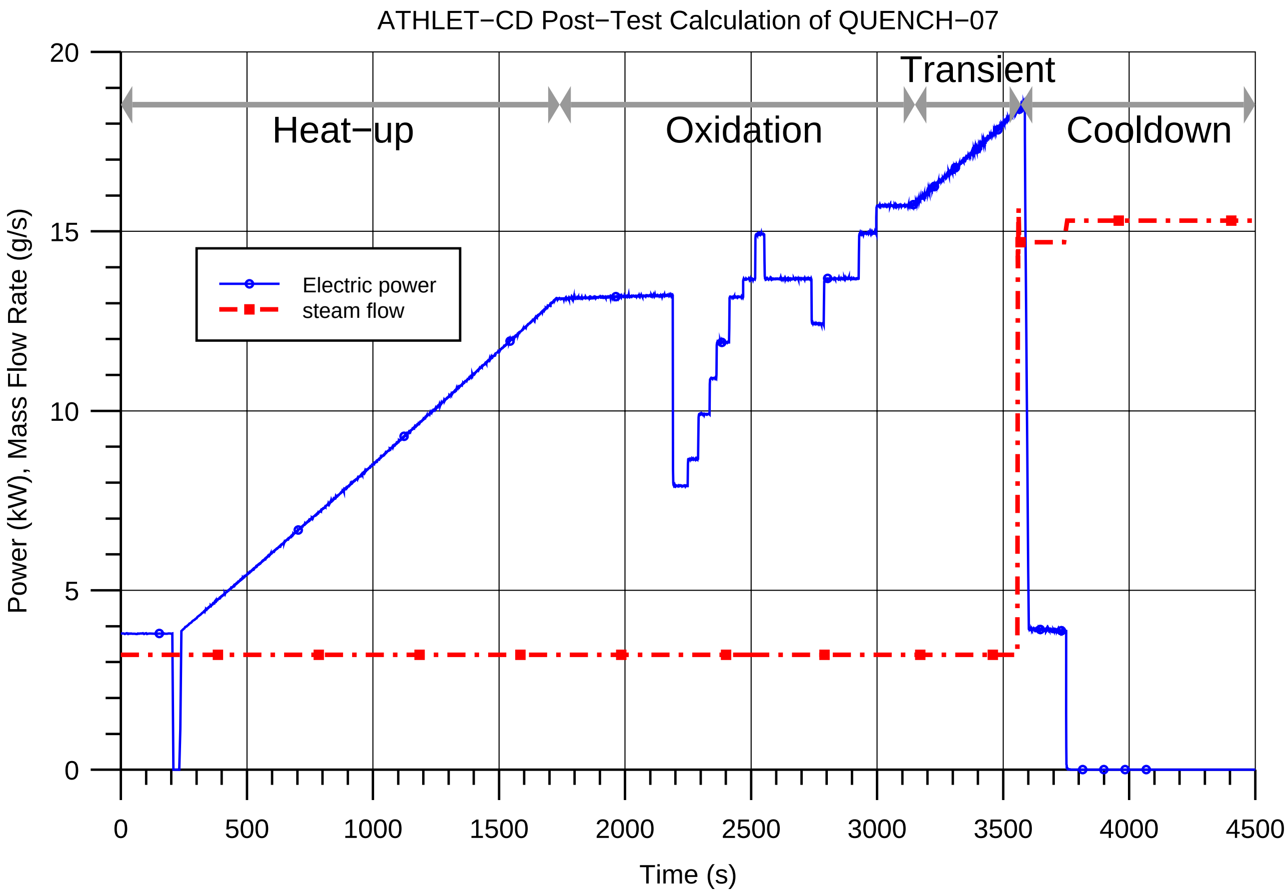




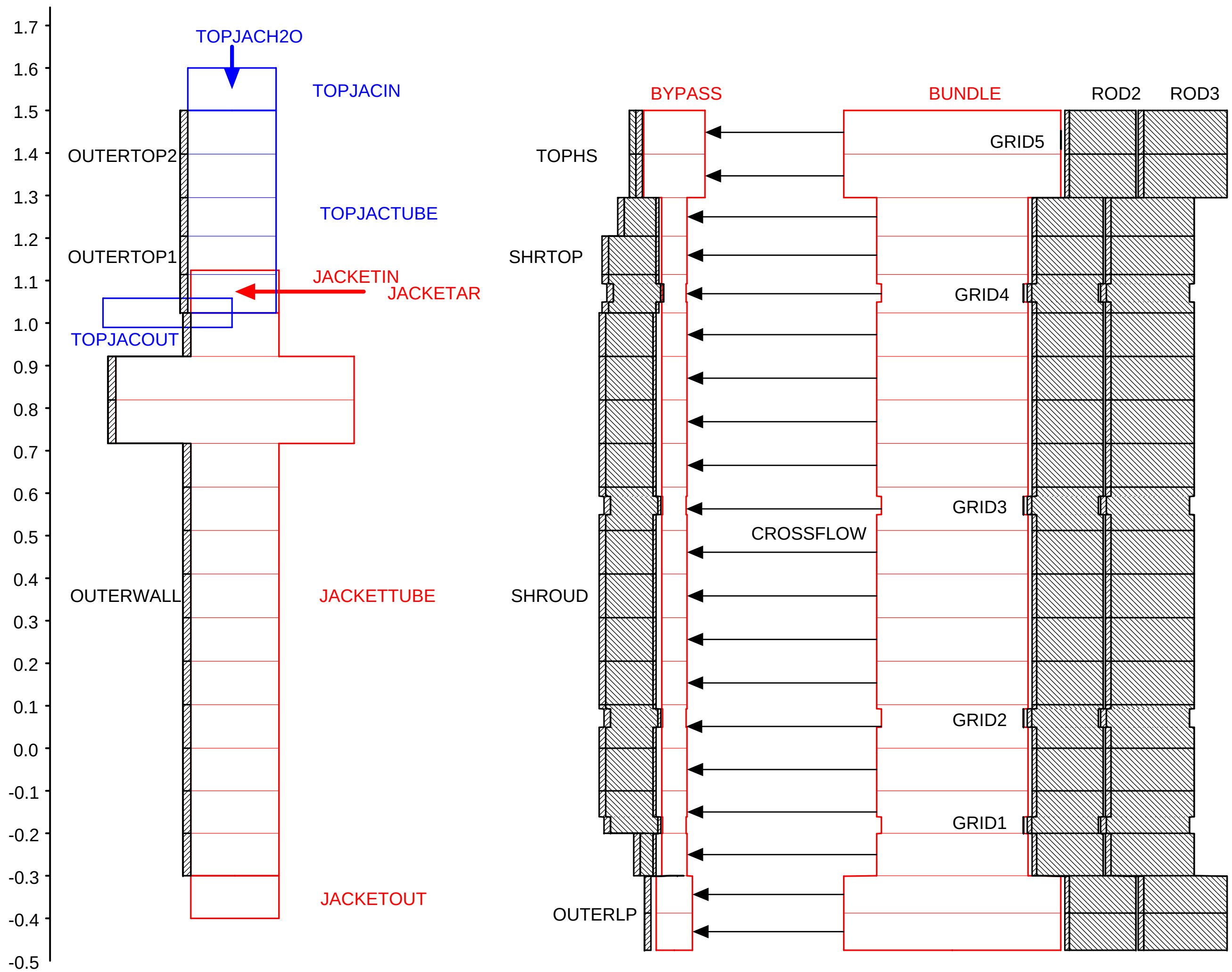
Main Features of Test QUENCH-07

- First experiment with a boron carbide absorber rod in the bundle
- Main objectives:
  - Determination of the impact of a B_4C absorber rod on a pre-oxidized LWR fuel rod bundle at high temperatures:
    - Impact of absorber rod failure on fuel rod degradation
    - Impact of absorber rod on bundle behaviour during cooldown
  - Information on gas generation after failure of absorber rod cladding and guide tube due to oxidation of B_4C , in particular additional H_2 generation and release of CO, CO_2, CH_4.
  - Additional heat-up due to the oxidation of B_4C and its contribution to the temperature escalation of fuel rods
  - Information on the B_4C - stainless steel - Zry interactions

Boundary conditions for QUENCH-07



Nodalization of QUENCH test section for ATHLET-CD



Input Data for ATHLET-CD

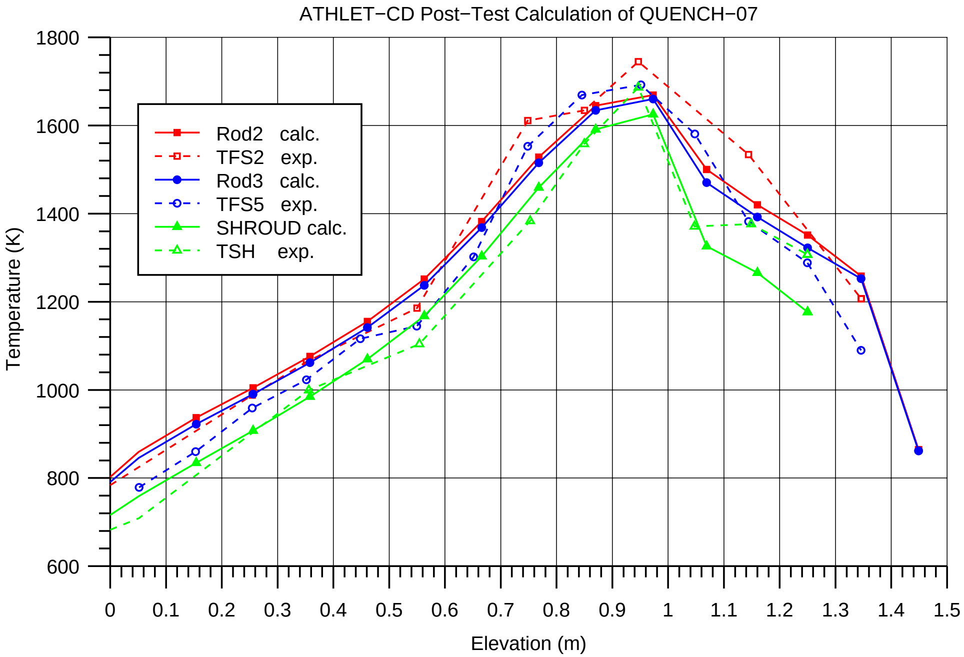
- Basis: standard data sets used for the calculation of previous QUENCH experiments, specially for QUENCH-06 (ISP-45)

- Modelling options as recommended in the code User's Manual, except calculation of Zr oxidation at temperatures above 1773K (correlation of Prater-Courtright instead of Urbanic-Heidrick)

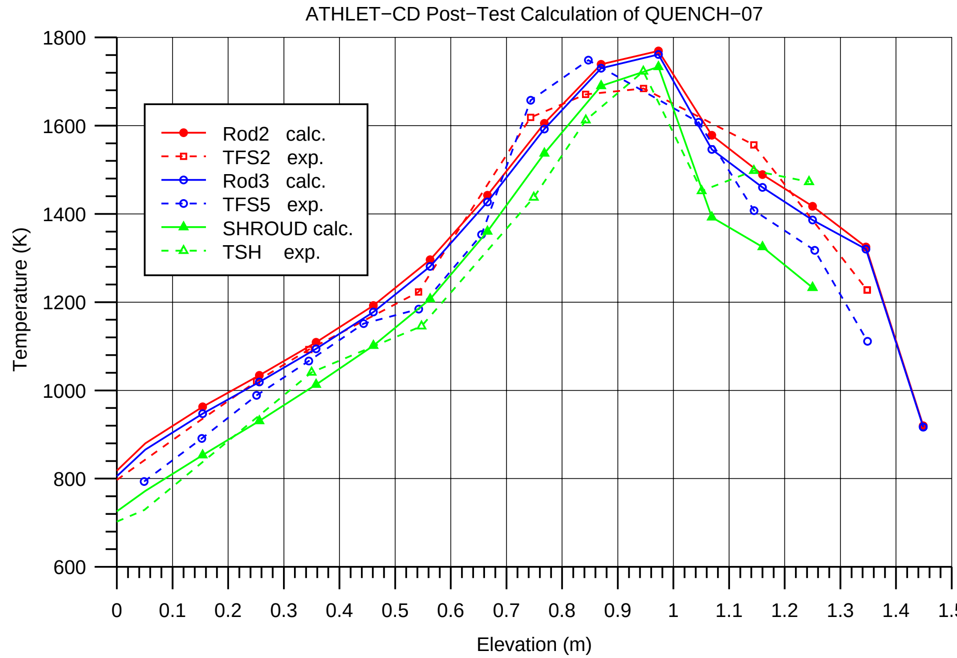
- Steam/argon inlet temperatures:
  Temperatures measured by thermocouple T511 minus 100K

- External resistance per heated rod: 4 mΩ

Calculated and measured axial temperature profiles



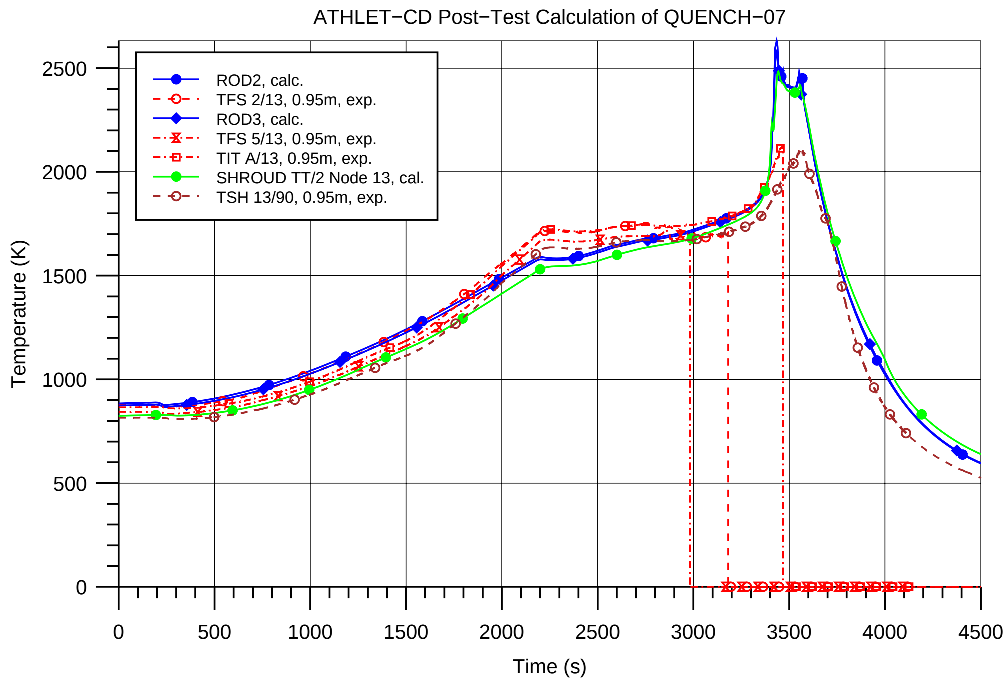
Oxidation phase (t = 2700 s)



Start of transient phase (t = 3150 s)

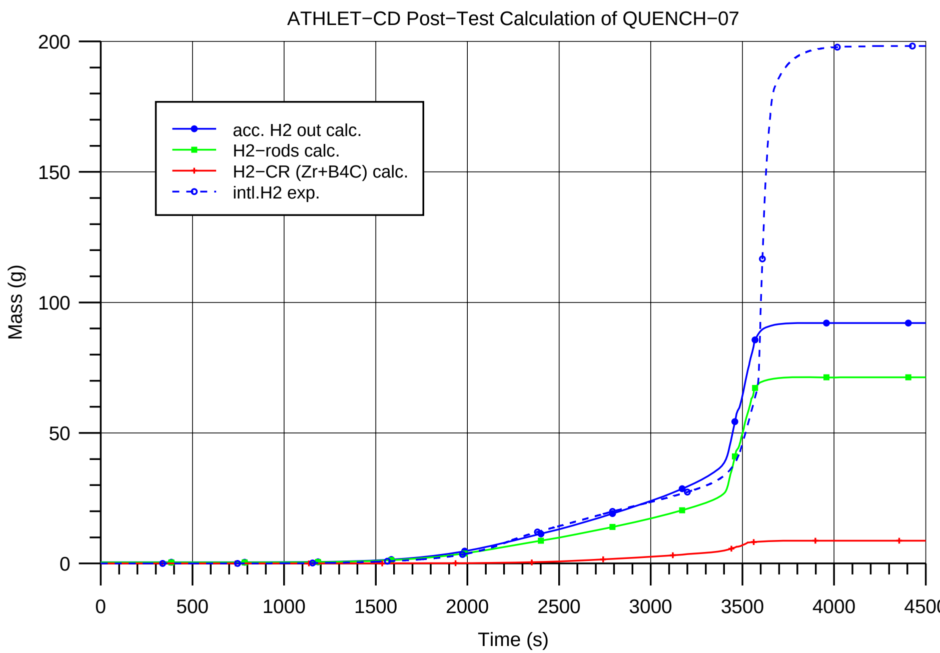
Test section temperatures at elevation 950 mm

- code reproduces satisfactorily thermal behaviour of test bundle
- clad temperatures at the end of first heat-up phase are underestimated
- good agreement with respect to the start of temperature escalation due to oxidation
- code overestimates shroud temperature excursion due to oxidation at the final heat-up phase
- shroud failure was not reproduced by the code



Integral H_2 production

- good agreement up to start of oxidation escalation
- code strongly underestimates H_2 production during quench
- calculation did not consider:
  - oxidation of external shroud surface
  - oxidation of Mo-electrodes (about 22 g H_2)
  - possible cracking of oxide layer due to thermal shock
- total amount of H_2 generation:
  calc. : 92 g
  exp. : 177 g
  (130 g for simulated components)
- H_2 mass due to CR oxidation:
  calc.: 8.7 g
  exp.:   8 g



Combined Sensitivity Analysis

- Application of some features of the GRS methodology for code uncertainty analyses:
  - Simultaneous variation of uncertain parameters
  - Statistical evaluation of the code results
  - Application of the Wilks formula:
    - number of code calculations independent of number of input and output parameters
    - number of code calculations only depends only on the desired statistical tolerance limits (e.g. for a two-sided statistical tolerance, a minimum of 93 calculations are required for a 95% probability and a 95% confidence level)
- Support software SUSA:
  - input of uncertain parameters and probability distributions
  - automatic generation of ATHLET-CD input data sets (total: 100)
  - statistical evaluation of code results

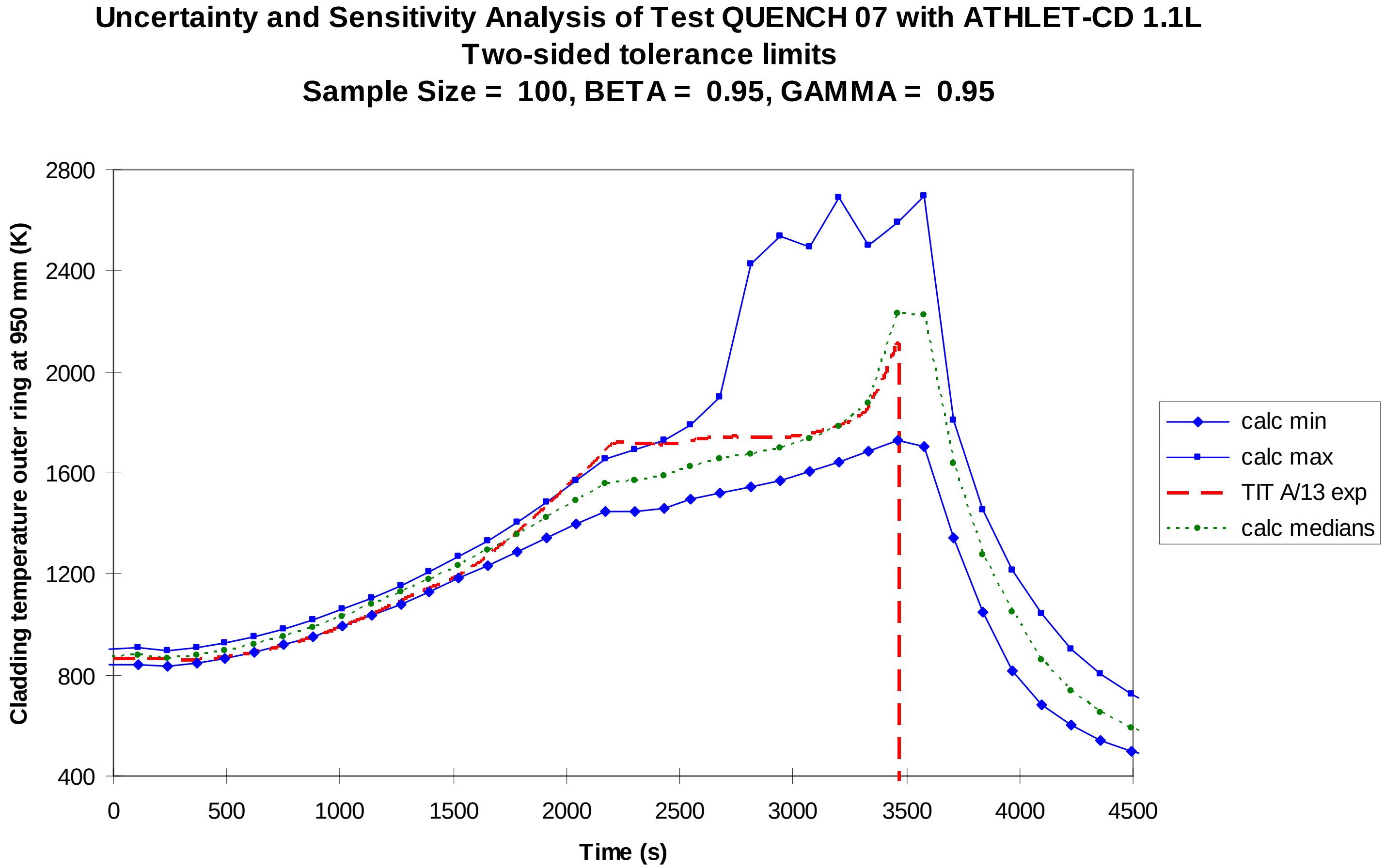
Input parameters for sensitivity analysis (I)

index	parameter	input data	unit	distribution	min. value	max. value	reference calculation	discrete options
1	External heater rod resistance	WHRES0	mΩ	uniform	3.6	4.4	4.0	
2	Deviation of steam inlet temperature to T511	DELTA	K	uniform	-80	-120	-100	
3	Factor for conductivity of shroud insulation	FSUSA1	-	uniform	0.8	1.2	1.0	
4	Factor for heat capacity of shroud insulation	FSUSA2	-	uniform	0.8	1.2	1.0	
5	Factor for conductivity of heater rods	FSUSA3	-	uniform	0.8	1.2	1.0	
6	Factor for heat capacity of heater rods	FSUSA4	-	uniform	0.8	1.2	1.0	
7	Factor for argon conductivity (top of shroud)	FSUSA5	-	uniform	0.5	2.0	1.0	
8	Nodalization at top of bundle	PAR08	-	discrete	1	3	1	1: node length 10 cm 2: node length 5cm 3: node length 3.3cm
9	Correlation for Zr oxidation	IOXMOD	-	discrete	15	19	15	15: Cathcart + Prater/Courtright 16: Cathcart + Urbanic/Heidrick 19:Leistikov + Prater/Courtright
10	Correlation for B_4C –SS interaction	IB4CSS	-	discrete	3	7	7	3:JAERI 5:Belovsky 7:Nagase

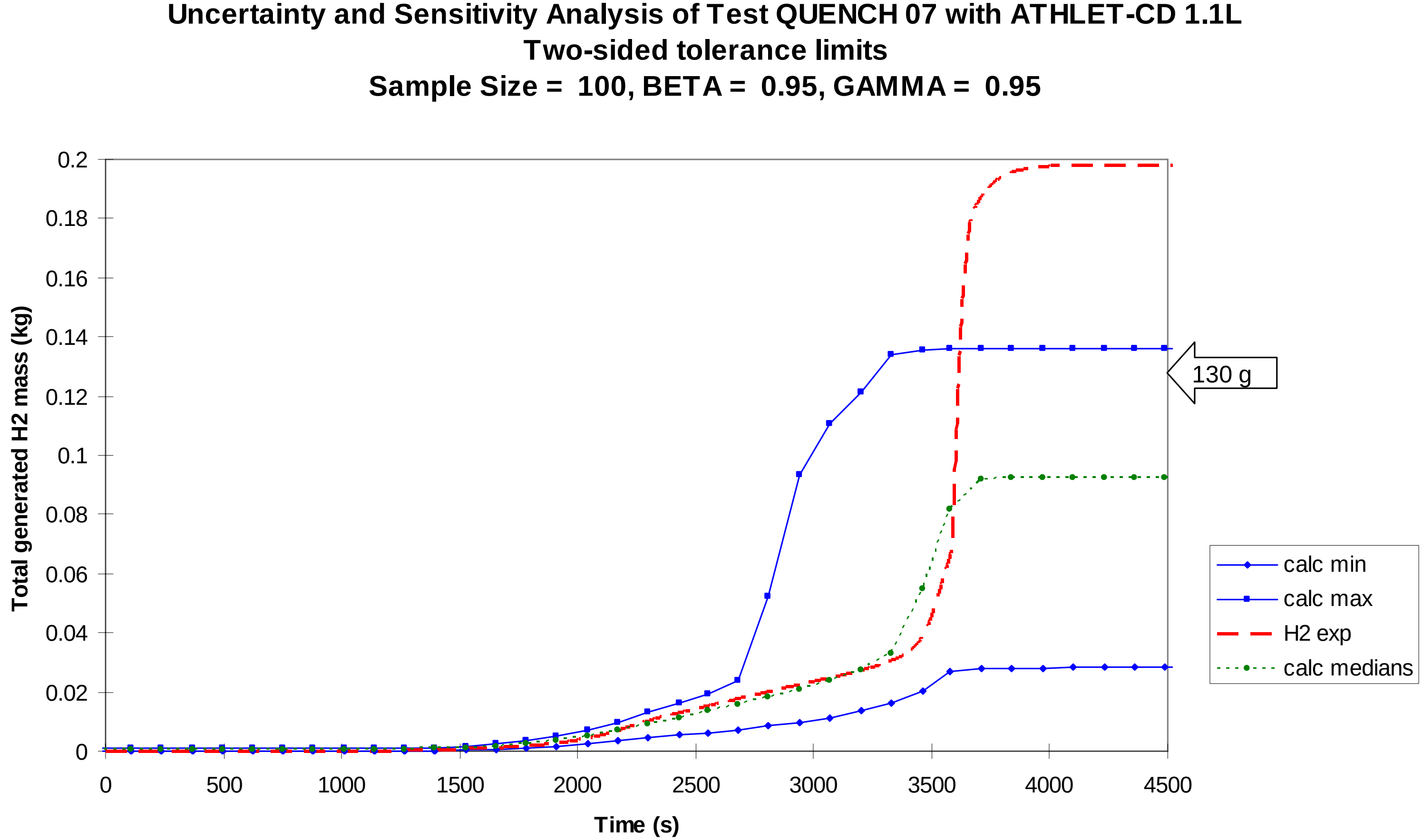
Input parameters for sensitivity analysis (II)

index	parameter	input data	unit	distribution	min. value	max. value	reference calculation	discrete options
11	Correlation for B_4C oxidation	ICRB4C	-	discrete	1	7	7	1:mod Steinbrück 5:Steinbrück 7:VERDI/BOX data
12	Factor for HTC due to convection to vapour	FSUSA6	-	uniform	0.8	1.2	1.0	
13	HTC to argon (jacket tube)	PAR13	W/m^2K	uniform	10	20	15	
14	HTC to air (containment)	PAR14	W/m^2K	uniform	5	20	10	
15	Limit of steam availability for oxidation red.	OXXLIM	-	log. uniform	0.1	0.5	0.1	
16	Limitation of protective oxide layer	HROXLM	mm	uniform	0.1	0.3	0.2	
17	Fraction of bundle area assigned to bypass flow	PAR17	-	uniform	0.01	0.1	0.05	
18	Gap conductivity in the heated rods	HTCGAP	W/m^2K	uniform	500	1500	500	
19	Emissivity of heated rods	EPS	-	normal $\sigma = 0.1$	0.6	1.0	0.8	
20	Factor for surface area due to porosity	FAREA	-	uniform	1.0	3.0	2.0	
21	Melt temperature of absorber guide tube	CRTAM	K	uniform	1423	1523	1473	

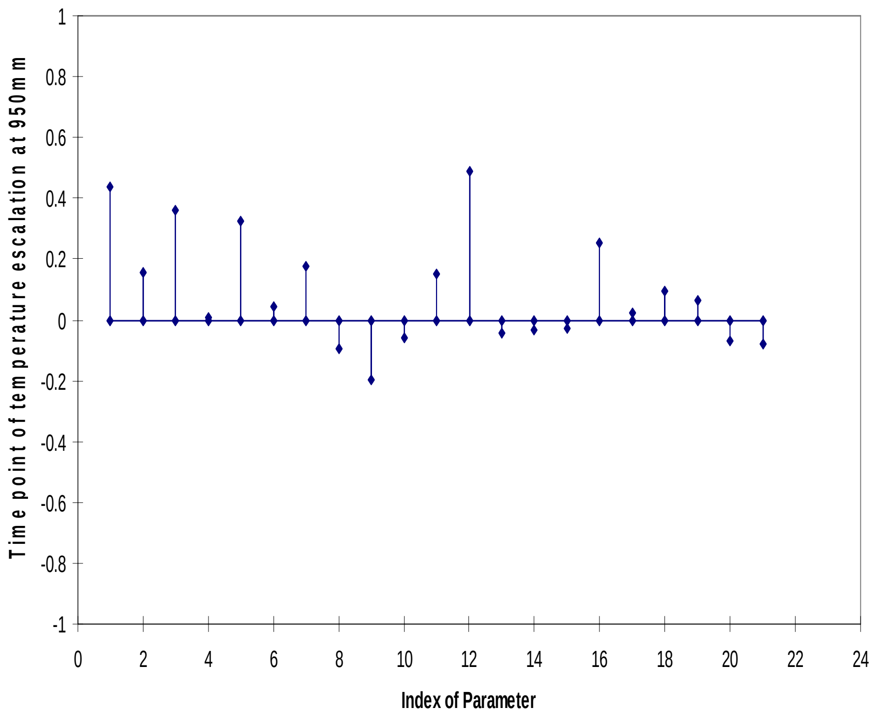
Cladding temperature of outer ring at elevation 950 mm



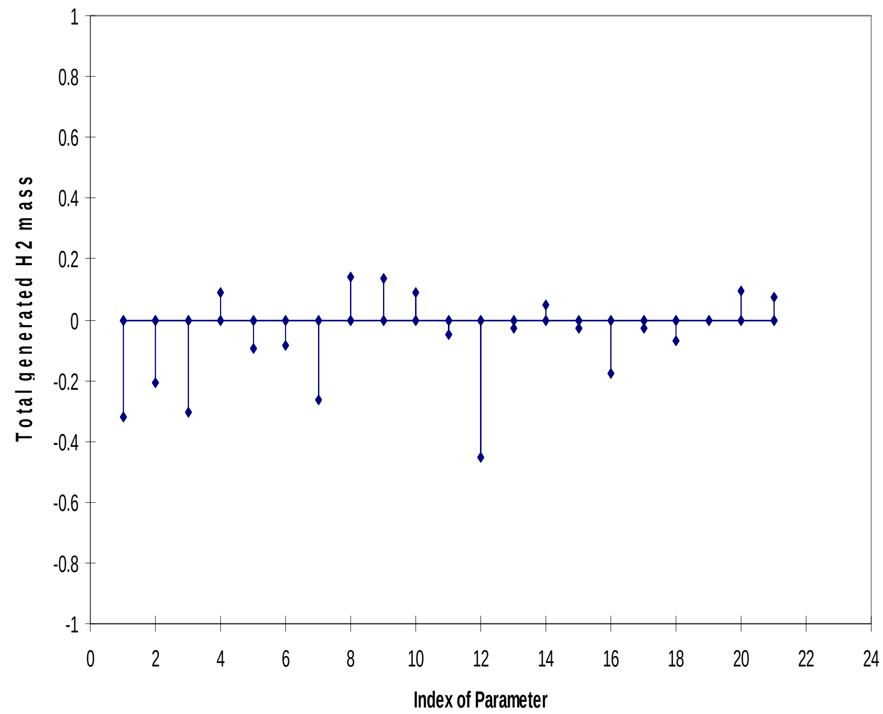
Total generated H_2 mass



Sensitivity Coefficients



Time point of temperature escalation



Total generated H_2 mass

Sensitivity coefficients of main uncertainty parameters

Index	Description	Range of variation	Sensitivity coefficients		
			Temperature escalation	Total H_2 mass	H_2 due to B_4C
1	electrical resistance	± 10%	0.436	-0.322	-0.324
3	conductivity of shroud insulation	± 20%	0.360	-0.304	-0.174
5	conductivity of fuel pellets	± 20%	0.324	-0.093	-0.049
7	Ar conductivity in top of shroud	± 50%	0.178	-0.261	-0.094
8	nodalization upper part of bundle	3.3-10 cm	-0.095	0.139	0.215
9	correlation for Zr oxidation	15,16,19	0.195	0.134	0.005
11	correlation for B_4C oxidation	1,5,7	0.151	-0.051	-0.047
12	HTC convection to cooling gas	± 20%	**0.488**	**-0.453**	**-0.547**

Main findings of the sensitivity analysis (I)

- Main sources of code uncertainties:
  - convective heat transfer between cladding and steam-argon mixture
  - input value for the external electrical resistance (controls the actual power generated within rods)
  - input of material properties, mainly the thermal conductivity of test section components and cooling gases
- Non-prototypic aspects of the test facility have a considerable influence on code results
- Small variations of input parameters can affect considerably the good agreement between experiment and prediction obtained with the reference calculation

Main findings of the sensitivity analysis (II)

- Influence of chosen nodalization not so strong as expected a priori. Finer nodalization in the upper part of test bundle leads to:
  - increased cladding temperatures
  - earlier start of temperature escalation
  - higher hydrogen production
- Choice of correlations for Zr oxidation plays a secondary role on code uncertainties
- Main uncertainty parameters affect mostly the H_2 generation before cooldown. Their influence on H_2 production during quench is considerably reduced.
- Modelling of B_4C-SS interaction and B_4C oxidation does not affect significantly the calculated global thermal behaviour nor total H_2 production

Summary and Conclusions (I)

- Post-test calculation of QUENCH-07 showed a good overall agreement with experimental results concerning thermal-hydraulic behaviour of test bundle
- Combined sensitivity analysis provided additional information about the influence of several code input parameters and modelling options on the simulation of main phenomena observed experimentally
- Results indicate that the main experimental measurements lay within the uncertainty range of the calculated data, except for the increased hydrogen production after cooldown initiation:
  - Potential need for further modelling improvement

Summary and Conclusions (II)

- Main contributors to the uncertainty of code results:
  - heat transfer coefficient due to forced convection to steam/argon
  - thermal conductivity of shroud insulation
  - input value for the external heater rod resistance

- Uncertainties on modelling of B_4C oxidation do not affect significantly the total calculated H_2 release rates

- This study was a first step towards a more general application of the GRS uncertainty methodology for the simulation of severe accidents

- Further steps shall include similar analyses for in-pile experiments (e.g. PHÉBUS) and for the TMI-2 accident, in order to extend:
  - the range of phenomena covered by the simulation
  - the database needed for the determination of uncertainty parameters