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C. Cozzo, G. Khvostov, R. Ngayam-Happy :: Paul Scherrer Institut

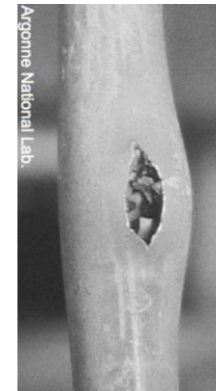
Fuel Thermomechanical modelling with Falcon at PSI

NuFuel-MMSNF 2019 Workshop, PSI, Villigen, Switzerland, 4-7 Nov. 2019

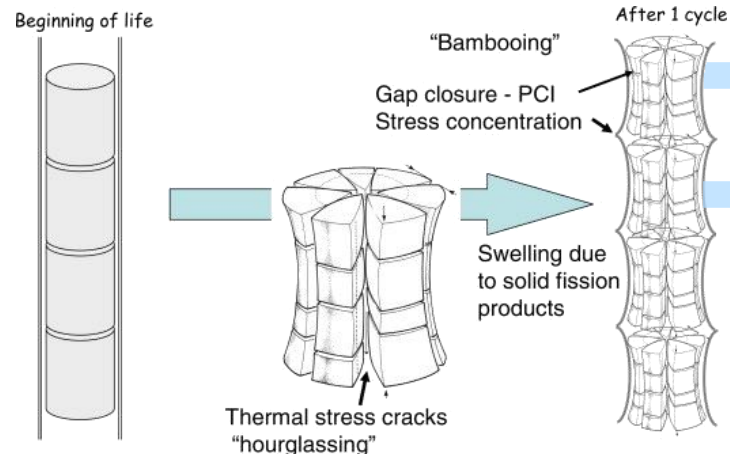


The Fuel in Reactor

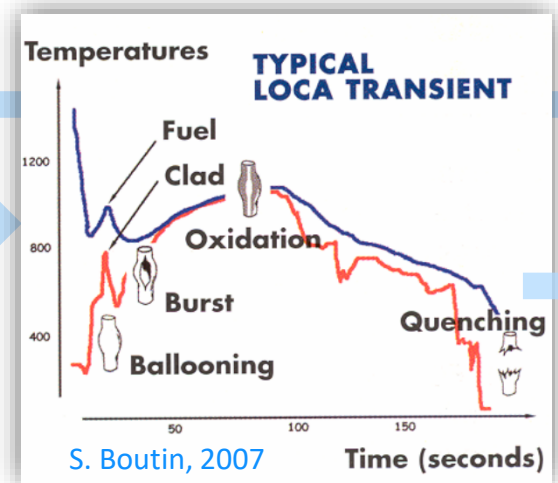
- Operation conditions
 - ~200 K/mm thermal gradient
 - Gap closure, Hourglassing
- Accident: Example of a Loss of Coolant Accident (LOCA)
 - Breach: dispersal of radioactive particles
 - Ballooning: compromises the cladding geometry



M. Veshchunov, 2007



S. D. Olander, 2009

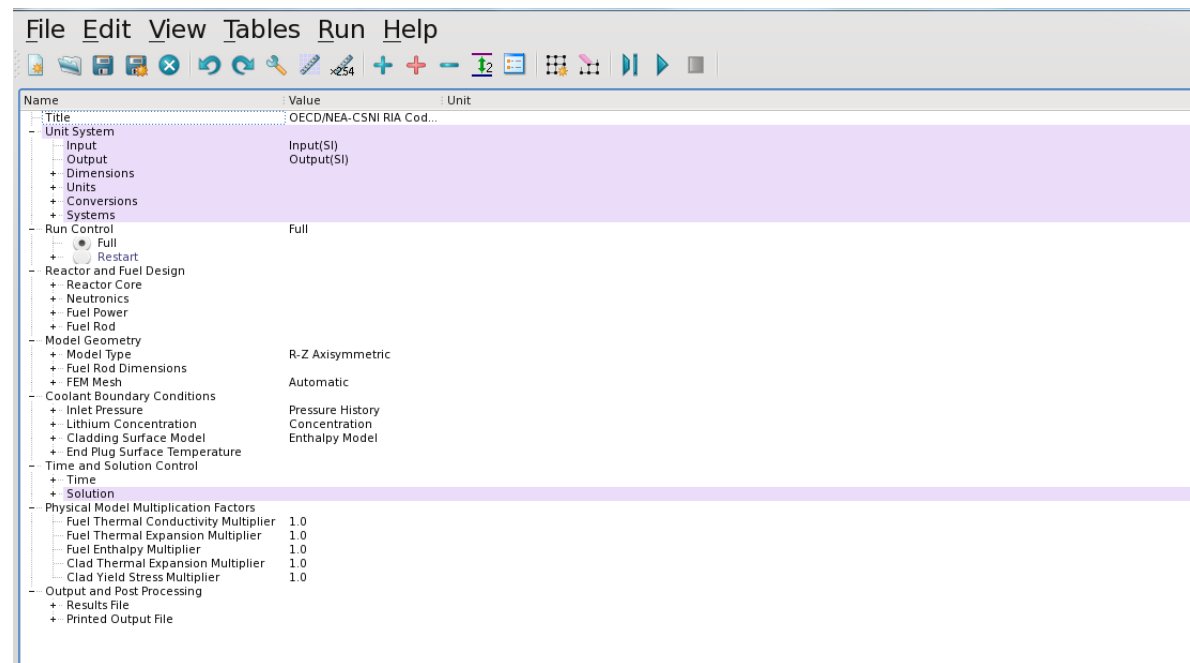
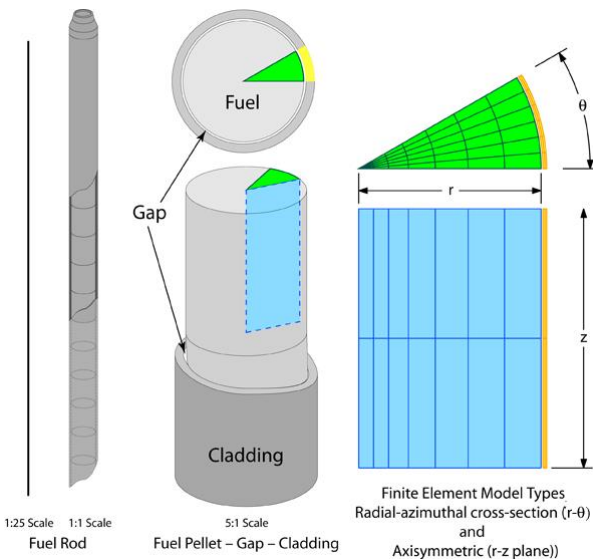


Dry Storage

Safety first!

- Introduction
- Presentation of the code
- Formation of fuel central void
- Core-wide LOCA analysis
- OECD/NEA RIA fuel code benchmark
- ATF developments
- Conclusions and outlook

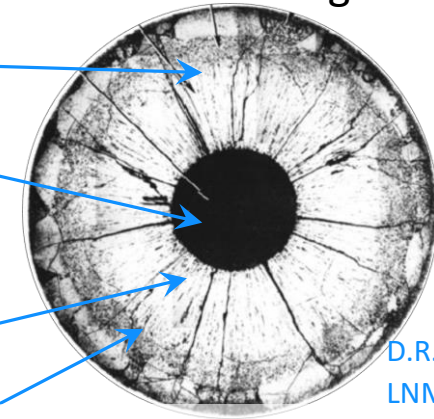
- FALCON: **F**uel **A**nalysis and **L**icensing **C**ode—**N**ew
 - Developed by EPRI (U.S.)
 - LWR fuel performance analysis and modeling code validated to high burnup
 - Based on a robust finite-element thermal/mechanical 2D numerical structure
 - Combination of both steady-state and transient capabilities
 - Material data from MATPRO package or NFIR program
 - PSI is part of the development team: FGR and gaseous swelling (GRSW-A Model), SiC, U_3Si_2



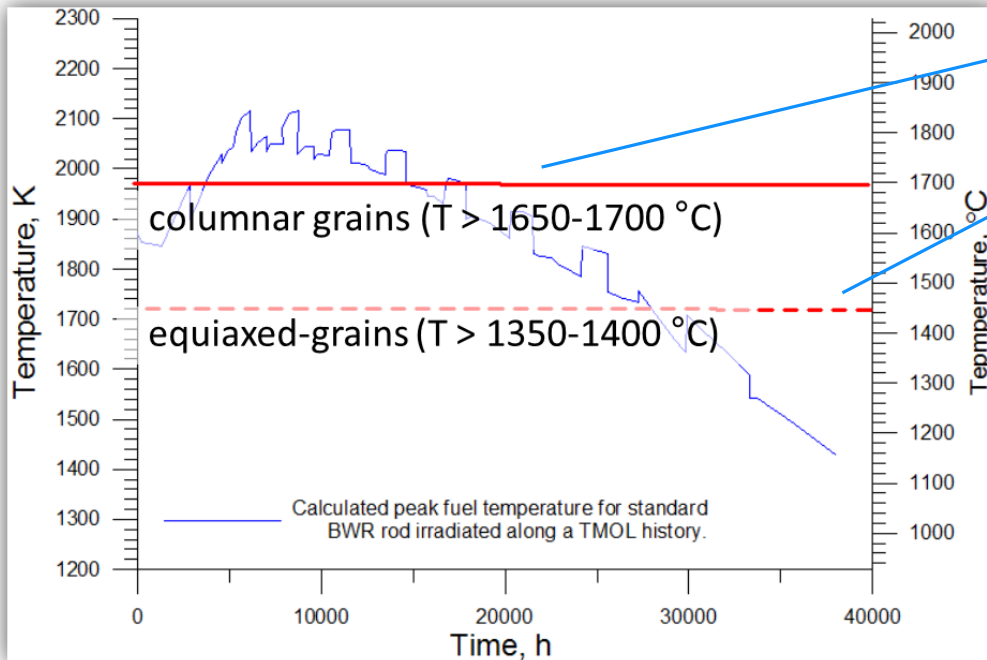
Central void: High-T. Fuel Restructuring

TMOL (maximum operating LHGR) allows high temperature restructuring

- increase in local density
- eventually, formation of central void
- Thermo-mechanical behaviour ?



D.R. O'Boyle et al, LNM (1969) 27-41



Model:

Falcon coupled with the GRSW-A module*

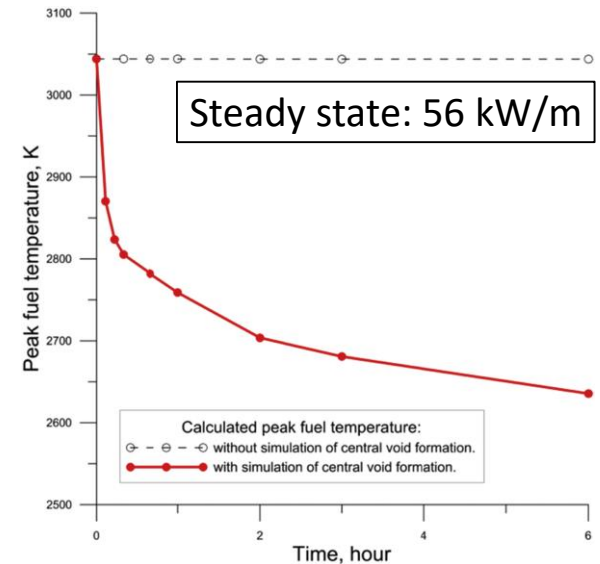
- Recursive start
- Update of the FEM mesh
- Formation of the central void caused by the migration of as-fabricated pores
- Assumptions:
 - Sweeping out of initial pores
 - $V_{\text{pores}} \rightarrow V_{\text{ol central void}}$
 - Volume change is anisotropic

Steady state

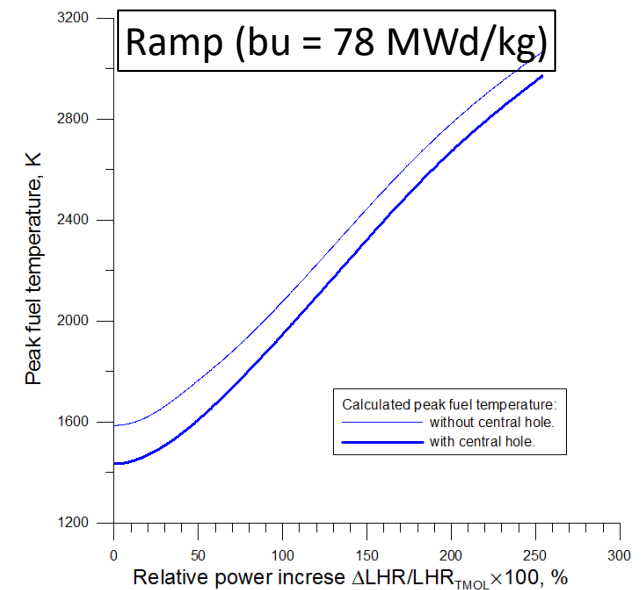
- When Central void is modelled:
 - Fuel T_{MAX} is rapidly decreasing
 - Lower FGR and RIP

Power ramp

- Lower fuel temperature
- Lower cladding stress and strain
- due to fuel creep into central void



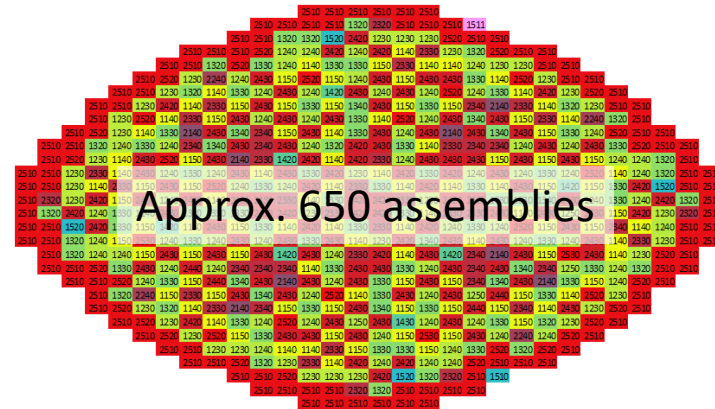
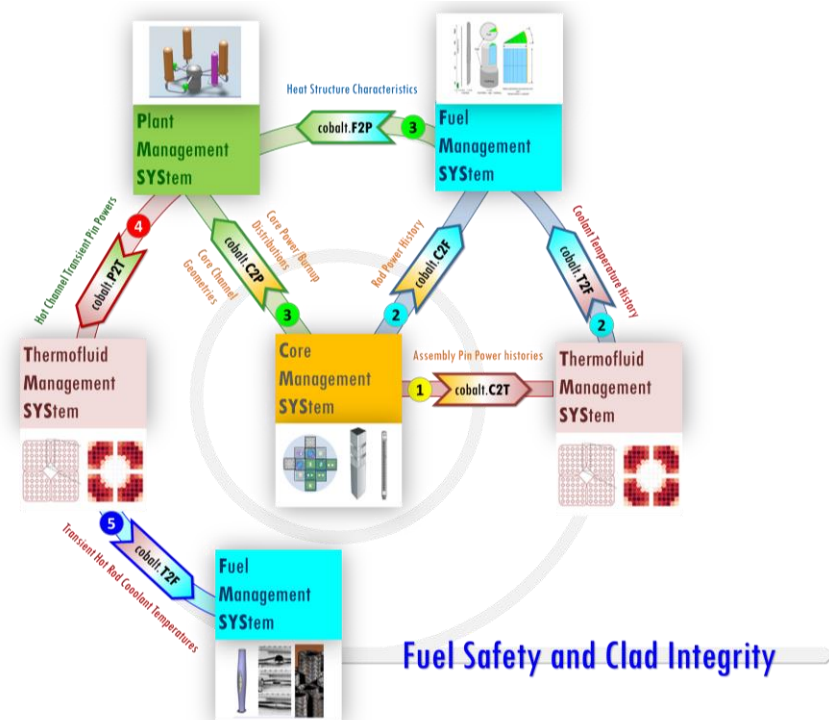
G. Khvostov, 2018



G. Khvostov, 2018

LOCA Core-wide Estimate on Fuel Failures

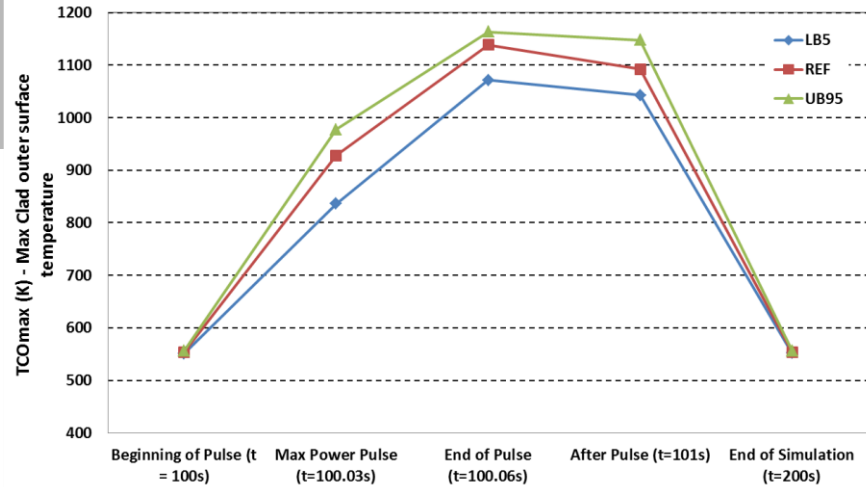
- Postulated LOCA scenario for a BWR/6
- Which rods in the whole core are most susceptible to fail?
 - Data flow
 - Safety analysis for the fuel
 - Steady state and transient



- Outcomes:
 - Multi-physics coupling of STARS codes
 - No predicted fuel failure
 - Used for other safety analyses
 - KKB, EPR (STUK), ATF (swissnuclear)

- 3-phase benchmark
 - Phase 1 (2010-2013): comparison of fuel performance codes RIA simulations of real experiments: NSRR VA-1 and VA-3 (conducted at JAEA test reactor), CABRI CIP0-1 and CIP3-1 (conducted at CEA test reactor)
 - ✓ Difficulty to compare the participating codes on the same bases
 - ✓ Large scatter between simulation results
 - Phase 2 (2014-2016): benchmarking code results on uncertainty quantification (UQ) and sensitivity analysis (SA) with focus on very simplified theoretical cases for fresh fuel
 - Phase 3 (2018-2020): extension of phase 2 UQ/SA methods to real cases of irradiated fuel, mainly CIP0-1
- PSI objective: Development of FALCON UQ/SA framework for transient simulations (LOCA, RIA)
- Development of in-house tools (in Python mostly) coupled to Falcon for UQ/SA

Phase 2: Uncertainty band & Influential parameters on TCO (+ comparison to other participants)



TCOmax	Beginning of Pulse (t = 100s)		Max Power Pulse (t=100.03s)		End of Pulse (t=100.06s)		After Pulse (t=101s)		End of Simulation (t=200s)	
	FALCON	OTHERS	FALCON	OTHERS	FALCON	OTHERS	FALCON	OTHERS	FALCON	OTHERS
Injected Energy	-0.07380674		0.338863189	73%	0.912842254	93%	0.944984462	100%	0.002910875	7%
Full Mid Height Width	-0.1152902		-0.87897387	93%	-0.00184671	100%	-0.03753298	20%	-0.0626266	7%
Coolant Flow	-0.07682599		-0.11933455		0.039924133		-0.11617675	29%	0.050191752	7%
Coolant Temperature	0.999973163	100%	0.104421398	67%	0.072433294	27%	0.178405706	33%	0.999975762	100%
Coolant Pressure	0.030683622	13%	-0.02060936	7%	-0.06417047	13%	-0.04325229	40%	-0.0313473	27%
Filling Gas Pressure	-0.0820687		0.013068547		-0.03912861		0.032920985		-0.02859456	7%
Fuel Roughness	0.065881427		-0.15285226	71%	-0.41544994	71%	-0.19183739	21%	0.015270213	7%
Cladding Roughness	0.144097441		-0.09665245	67%	-0.16483345	60%	0.020200072	27%	-0.14763069	7%
Fuel Porosity	0.025376848		-0.07318402		-0.04086119		0.03132773	13%	-0.02930432	7%
Fuel Theoretical Density	0.092800387		-0.01668961		0.052662625		0.031655745	7%	0.081379082	7%
Cladding Inside Diameter	-0.0699516		0.021420946	40%	0.011535384	33%	-0.09278486	7%	-0.0874313	7%
Cladding Outside Diameter	-0.03955653		0.076239107	67%	0.084426168	73%	0.009547664	7%	0.048642738	7%

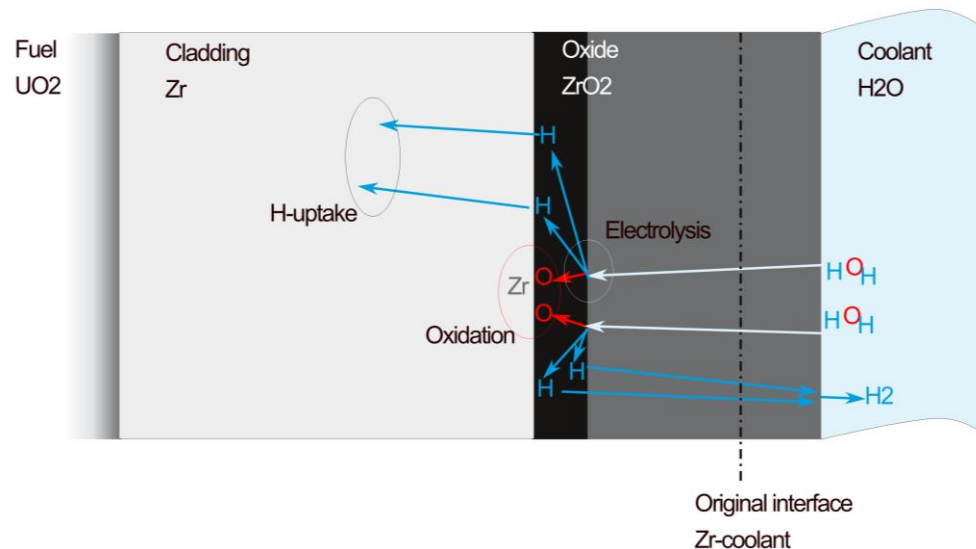
Phase 3: Influential parameters on several properties

INPUT parameter	EINJ	DHR	TFC	TFM	TFO	TCI	TCO	TNa1	TNa2	ECTH	ECT	EFT	SCH	RFO	GAP	HFC	FGR	CFP
Fuel clad radial gap	n.c.	-0.11833796	-0.06427361	0.00487512	0.25646591	0.01139578	-0.12262807	-0.09653941	-0.12288457	-0.72431111	-0.83872797	-0.05501688	-0.57622141	-0.68040051	0.03148729	-0.13901748	-0.00355809	n.c.
Cladding roughness	n.c.	0.18899272	0.05737043	0.16268057	0.73546689	-0.42119703	-0.40931073	-0.47825996	-0.44984775	-0.03566639	-0.05351984	0.06481212	0.1360339	-0.03176479	0.15397735	-0.80748969	0.17800645	n.c.
Fuel roughness	n.c.	0.00850671	-0.01863497	0.08265357	0.54261007	-0.33912698	-0.31065627	-0.32481962	-0.30971874	0.09049876	0.06606465	0.10755869	0.22549464	0.06658666	0.12895972	-0.60638416	0.08288457	n.c.
Zirconia thickness	n.c.	-0.05226581	-0.07740194	-0.08233556	0.01684842	-0.12064802	-0.07177229	-0.04112053	-0.04769219	0.00066752	0.12633466	0.20374259	0.02431411	-0.04210305	-0.01137928	-0.07243081	-0.04672167	n.c.
Injected energy in the rod	n.c.	0.7599325	0.80089102	0.47401335	0.13038326	0.74678467	0.56652516	0.00574214	0.20531163	0.25307583	0.04127653	-0.04028651	0.11832446	0.48370359	0.46180455	0.12129303	0.13225231	n.c.
Radial power profile																		
Power pulse width	n.c.	-0.46839121	-0.18443711	-0.26603615	-0.25896347	-0.34904223	-0.40933473	-0.46828171	-0.45272182	-0.13890497	-0.16284707	-0.19105228	0.01710943	-0.15806045	-0.18915773	0.04259506	-0.35522688	n.c.
Fuel thermal conductivity model	n.c.	-0.10463362	0.11910148	0.09665042	0.15160129	0.24289207	0.48666167	0.45450386	0.54109353	0.00578114	0.04253956	0.03341934	-0.0681287	0.07108528	0.14235056	-0.0440111	-0.16330908	n.c.
Fuel thermal expansion model	n.c.	-0.04567014	-0.0078677	0.01271432	-0.03469137	-0.09679742	-0.00108903	0.01761644	0.02651316	0.51499887	0.51327833	0.87092027	0.34259056	0.44872422	0.58873022	-0.02512863	0.03171379	n.c.
Fuel enthalpy	n.c.	0.08949074	-0.38923873	-0.55713943	-0.12582915	-0.020009	-0.13661142	-0.25955749	-0.23453386	-0.31344784	-0.13725643	-0.27826446	-0.01922748	-0.23671042	-0.36872722	0.10443111	-0.75322733	n.c.
Clad thermal expansion	n.c.	-0.04671417	-0.06761569	-0.01314333	0.10163504	-0.04491562	-0.00996325	0.02729918	0.01766444	-0.08495912	0.01226281	-0.00174754	-0.0759949	-0.03254631	-0.08336008	-0.09683492	0.00732018	n.c.
Clad Yield stress	n.c.	-0.00234756	0.04710268	-0.01662042	-0.07623491	0.12264607	0.13035926	0.11663842	0.1240636	-0.0438266	-0.07898897	0.01947799	0.18257106	-0.02949224	0.00672917	0.13385585	-0.01624391	n.c.

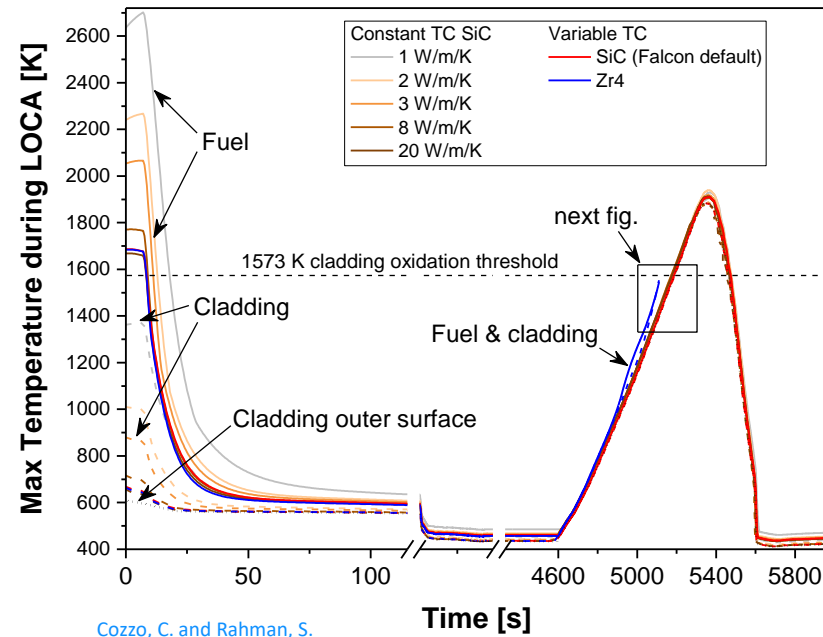
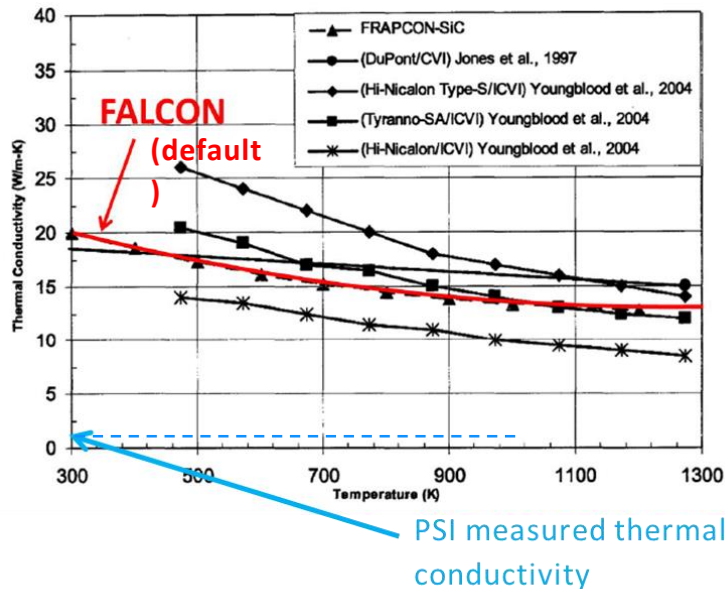
- Falcon results agree with other participants
- Methodology applicable to other UQ/SA activities

Hydrogen uptake

- During normal operation
 - The cladding oxidizes
 - Hydrogen is produced
 - H in the cladding can precipitate in hydride
 - The cladding become brittle
- In-house PIE data on cladding from Swiss NPP
 - Model development on hydrogen pickup for Falcon

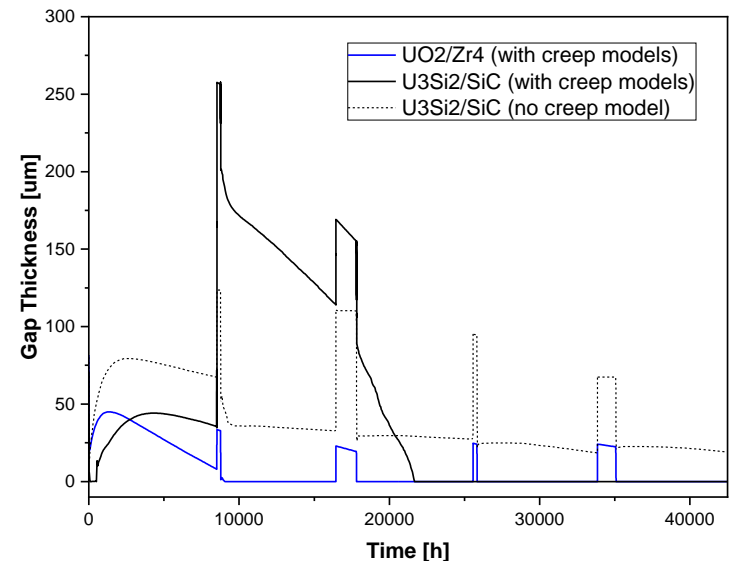
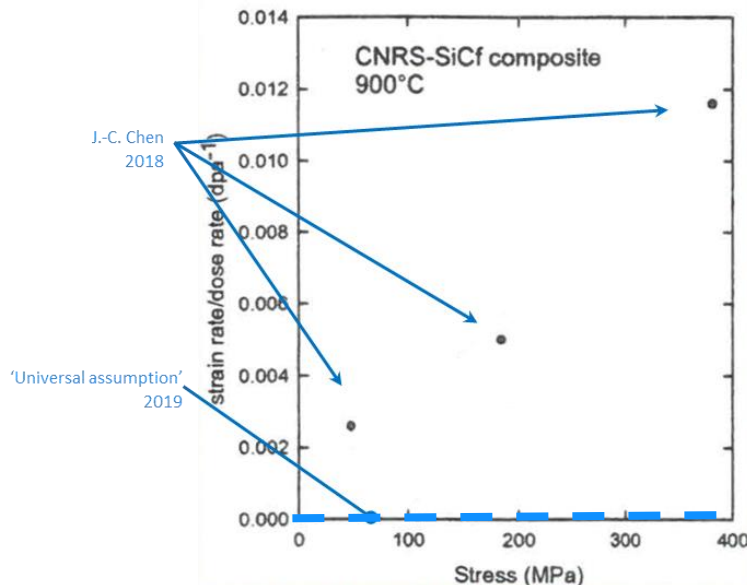


- Screening SiC/UO2 performance with Falcon
 - Duplex SiC/SiC composite cladding: Specific heat, thermal expansion, irradiation swelling, Young’s modulus, Yield stress, Ultimate tensile stress, shear modulus, density and maximum temperature (1573 K)
- Low conductivity + gap remains open = high fuel temperature



Cozzo, C. and Rahman, S.
<https://doi.org/10.1016/j.pnucene.2018.03.016>

- Screening U_3Si_2/SiC performance with Falcon
 - U_3Si_2 fuel: Thermal expansion, conductivity, heat capacity, melting point, density, Young's modulus, Poisson ratio and irradiation swelling, creep
 - Duplex SiC/SiC composite cladding: Max temperature, creep (preliminary)
- With U_3Si_2 fuel the gap closes late but the fuel temperature is not high



Cozzo, C. et al., Top Fuel 2019

- Falcon developments allow assessing fuel safety
 - In operation and accident conditions
 - For complex phenomena
 - With conventional and advanced materials

- Methodologies using Falcon are developed to solve complex multi-physics problems

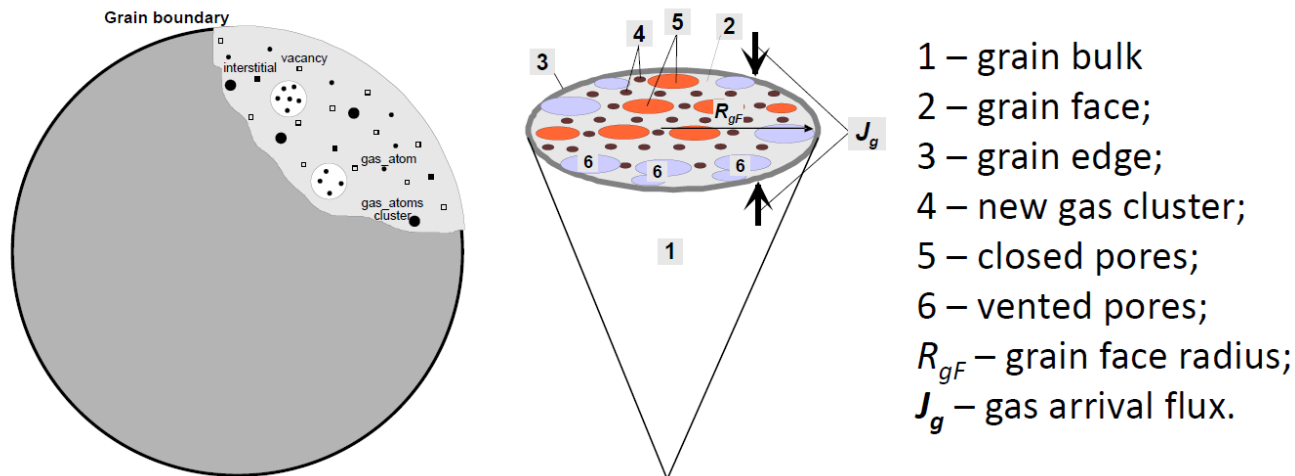
- Future developments include:
 - Refinement of the ATF models
 - Uncertainty quantification (UAM-III BWR analyses)
 - Dry storage

My thanks go to

- H. Ferroukhi
- M. Krack
- Falcon dev. team
- STARS team members



- Analysis of meso- and microscopic local phenomena occurring in the fuel and affecting the microstructure and gas kinetics under steady-state and transient conditions
- Fuel grain is represented by a sphere and its surface by 14 round faces
- Modeled phenomena:
 - Aggregation (at high T) and subdivision (low T) of grains
 - Intra-granular processes: Kinetics of point defects in the lattice – Generation and dissolution of FG mono-atoms – Nucleation, Diffusion, Coalescence, Trapping of gaseous bubbles – Bubble growth and arrival at the grain boundaries
 - Inter-granular processes: Formation and growth of closed gas-pores and their evolution to vented pores (FG released)
- GRSW-A is much more (CPU) time consuming than the other FGR models (10-100 times)

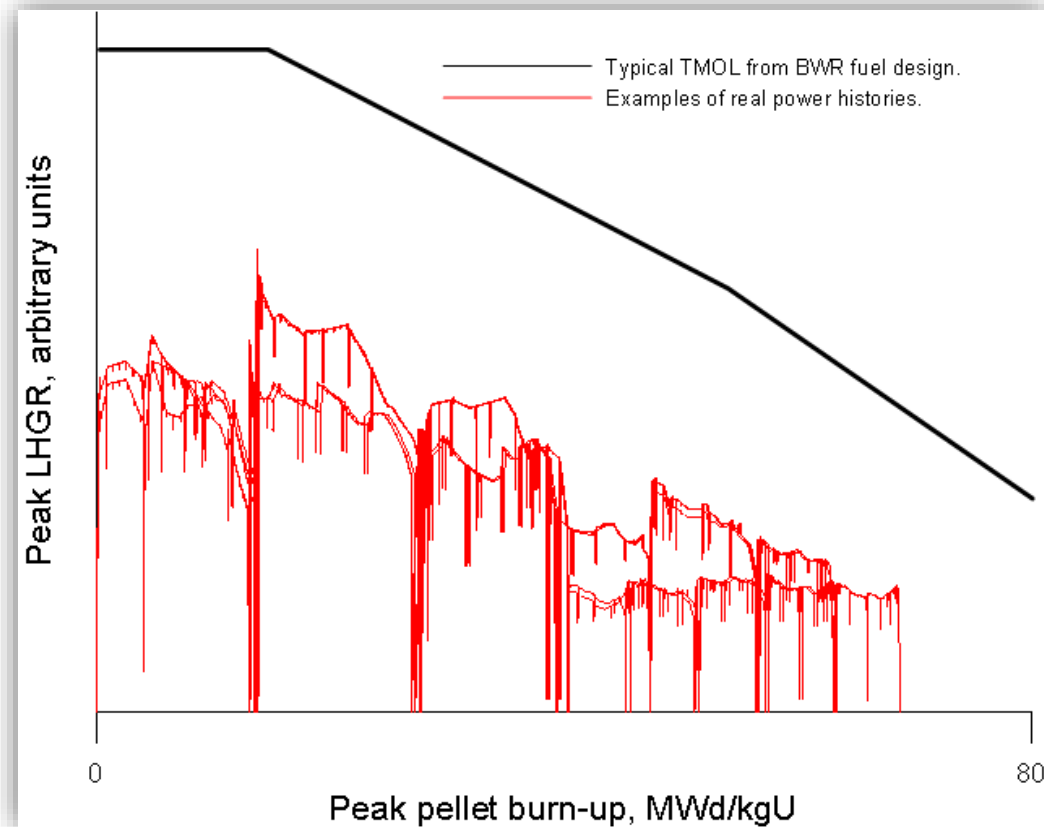


G. Khvostov, K. Mikityuk, M. A. Zimmermann, Nuclear Engineering and Design 241, 2983 (2011)

- Thermo-Mechanical Operational Limit (TMOL):
the maximum allowed local LHGR during SST irradiation.
- Decreases with BU

- Steady state: $\text{LHGR}_{\text{TMOL}}$
→ no fuel melt
→ no lift-off

- Ramp: $\text{LHGR}_{\text{TMOL}}$
→ no fuel melt
→ Cladding hoop stress < PCI/PCMI threshold



G. Khvostov, 2017