REDUCTION OF RADIOLOGICAL ACCIDENT CONSEQUENCES

WP:	**WP5.3 «INNOV - Innovation»**
Speaker:	Edouard Pouillier
Affiliation:	EDF – Electricité de France
Event:	R2CA
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Where:	Paris

Commission européenne

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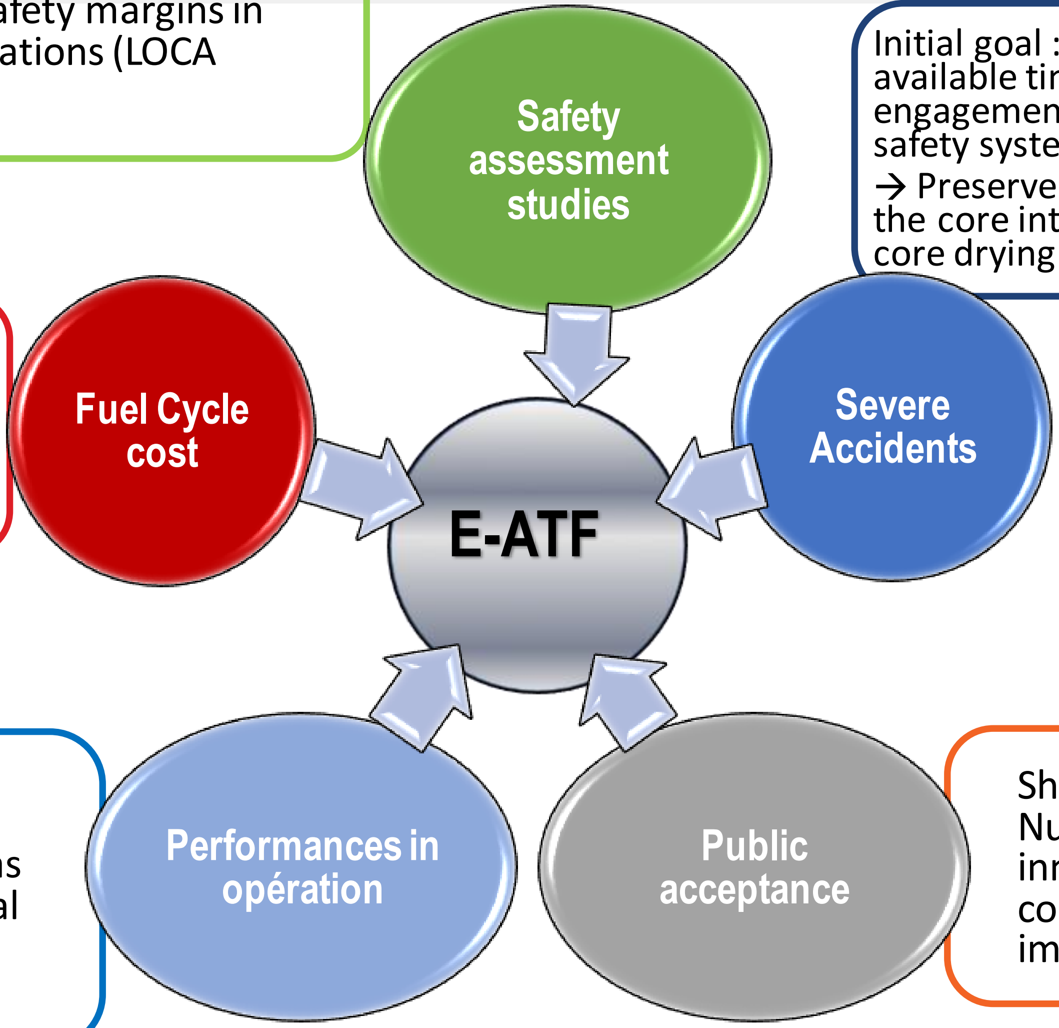
E-ATF Fuels : Multiple Issues

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

Increase the safety margins in accidental situations (LOCA essentially)

Initial goal : increase the available time before the engagement of the ultimate safety systems
→ Preserve as long as possible the core integrity in case of core drying up

Potential opportunity of cost savings with more robust fuels



Fuel performance and reliability at least equivalent as those or the actual products

Show that the Nuclear Industry innovates to continuously improve the safety

E-ATF International competition is launched

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

USA-Westinghouse
U_3Si_2 + **SiC/SiCf** cladding
U_3Si_2 + **Cr coated Zr** cladding

USA-EPRI
Lined Mo cladding

USA -ORNL
FeCrAL cladding
SiC/SiCf cladding

USA-GNF
FeCrAl cladding

GB- NNL (with W)
U_3Si_2 fuel

RUSSIA
Cr coated Zr
SiC/SiCf

CHINA
FeCrAl cladding
SiC/SiCf cladding
Coated Zr cladding
$UNSi_y$ fuel
FCM fuel

JAPAN
FeCrAl cladding
SiC/SiCf cladding

FRANCE-FRAMATOME CEA
Cr doped + Cr coated Zr
SiC/SiC cladding
France – FRAMATOME (Cr coated Zr)
Belgium – Westinghouse (Cr coated Zr)

KOREA-KAERI
Cr doped + **FeCrAl** cladding
SiC/SiC cladding
Microcell fuel

- **All the countries are engaged in the e-ATF development :**
  Cladding material : Cr coated Zr Alloys, FeCrAl
  Fuel pellet material : Cr doped fuel and U_3Si_2

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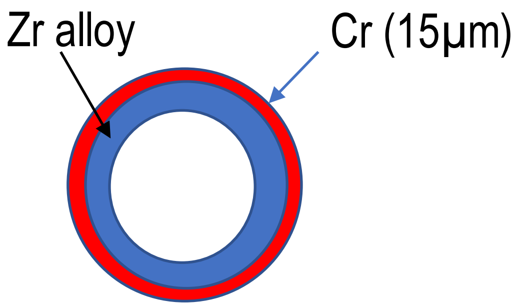
Content



- Overview of the bibliographic survey on e-ATF
  - Chromium coated Zr alloys
  - Outcome from Il TROVATORE

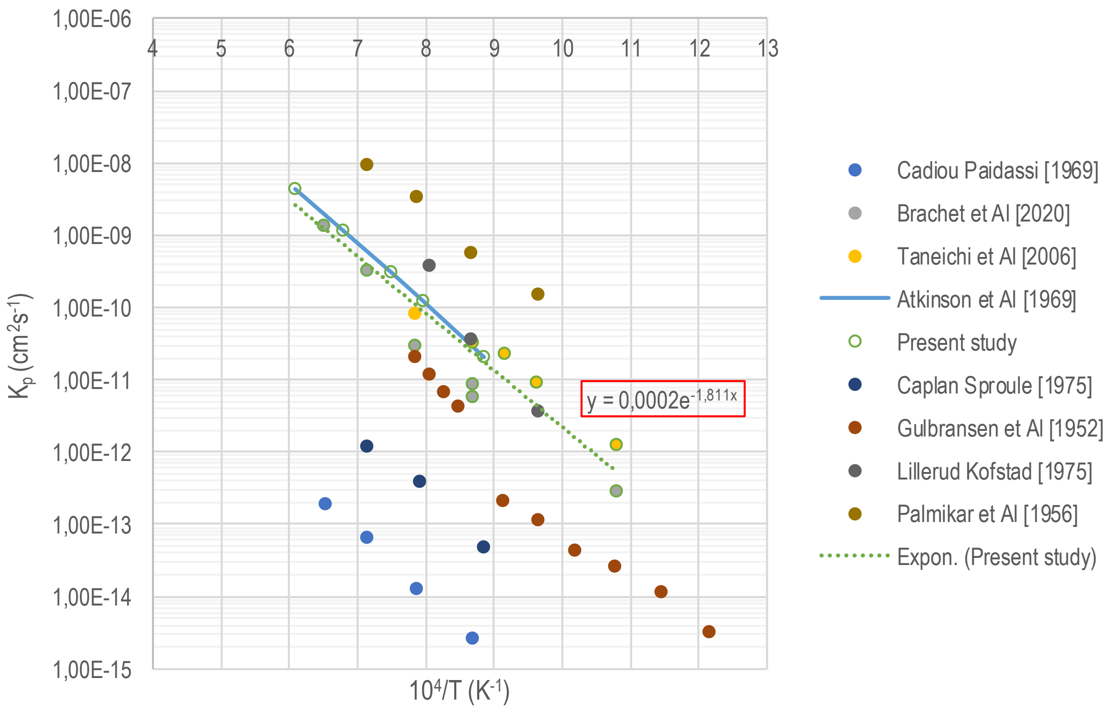
- *Fuel codes sensibility analysis on LOCA performance and comparaison e-ATF / standard fuel*
  - TRANSURANUS comparaison ATF / standard fuel and sensibility analysis (JRC)
  - FRAPTRAN sensibility analysis on LOCA performance (Zr alloy /Cr coated Zr alloy) (Tractebel)
  - DRACCAR comparaison eATF / standard fuel (Zr alloy /Cr coated Zr alloy) (IRSN)
  - DRACCAR comparaison eATF / standard fuel (Zr alloy /Cr coated Zr alloy) (EDF)

Bibliographic survey on ATF concept

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

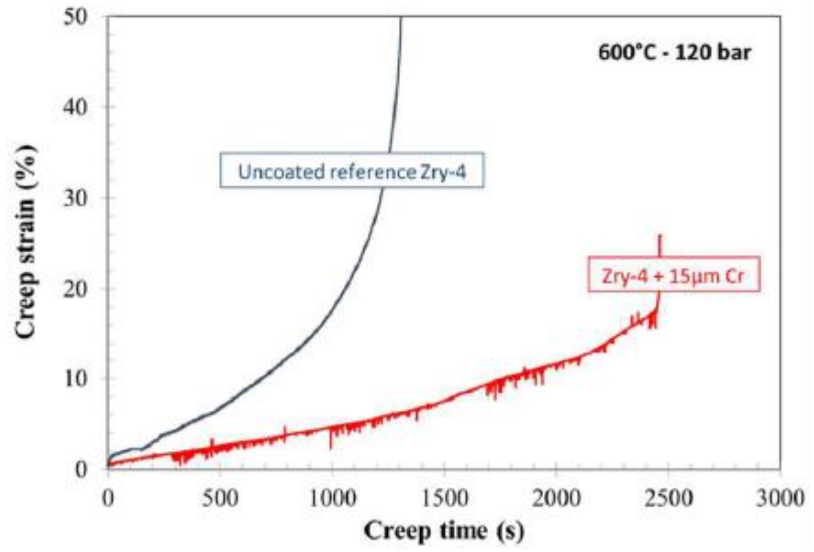
- *Oxidation kinetics of pure chromium*

Arrhenius plot of the rate constant of the parabolic law describing the growth of Cr2O3



An oxidation model for pure Chromium have been proposed into the R2CA Project

- *Creep law for the entire Chromium coated cladding concept*



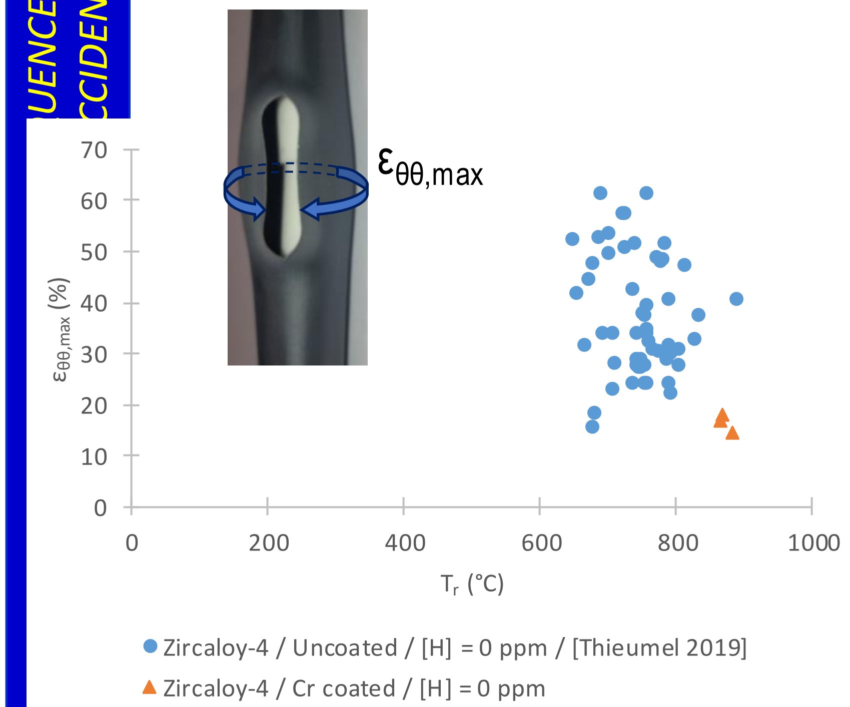
Typical creep curves obtained on uncoated & 15µm thick Cr-coated Zry-4 clad segments at 600°C, for an applied internal pressure of 120 bar

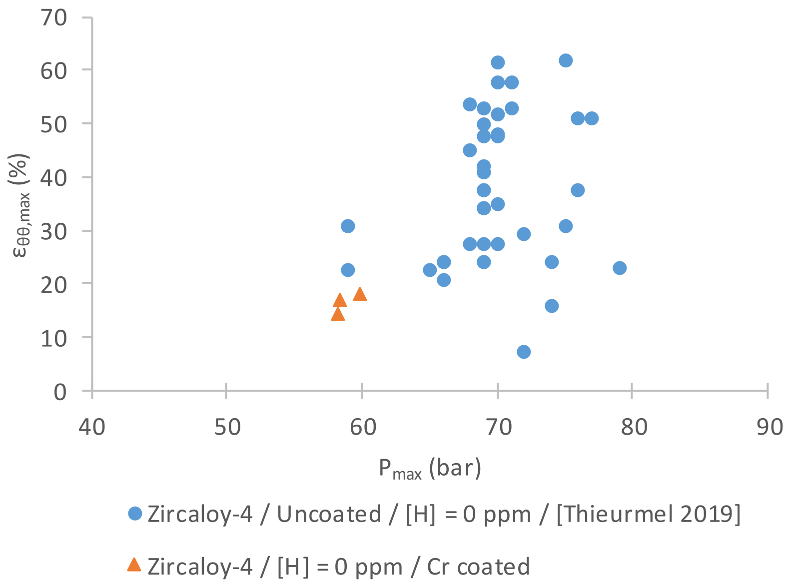
+ The phase kinetics model does not to be custom
+ Creep rate is reduced to a factor of 2 to 3

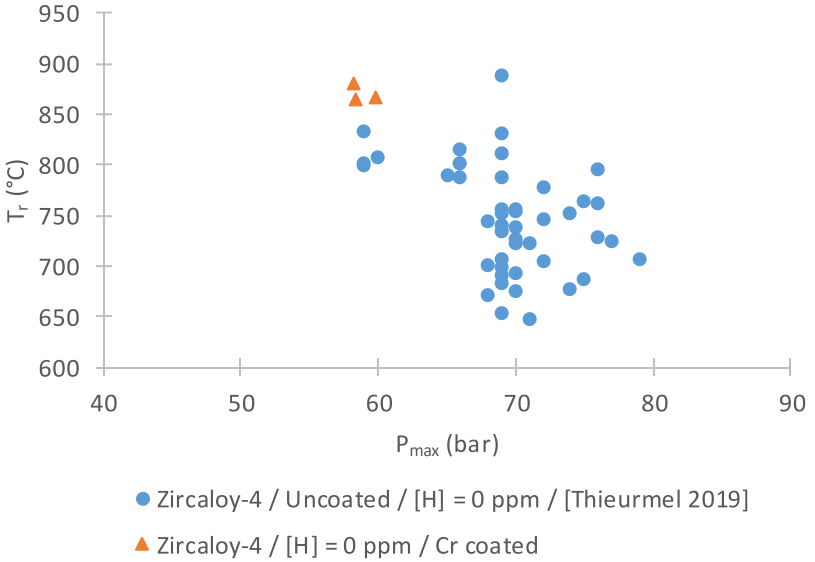
Ref : Proceedings Topfuel 2016-2018 + M. Dumerval et al., Numat 2020

Bibliographic survey on ATF concept

- *Fracture thresholds*







Hazan [2020]

<u>Effect of chromium coating:</u>

- lower balloon diameter
- higher burst temperature

→ <u>Mechanical strengthening induced by chromium coating</u>

+ Fracture thresholds expressed in deformation can be reduce to a factor at least of 2

Bibliographic survey on ATF concept

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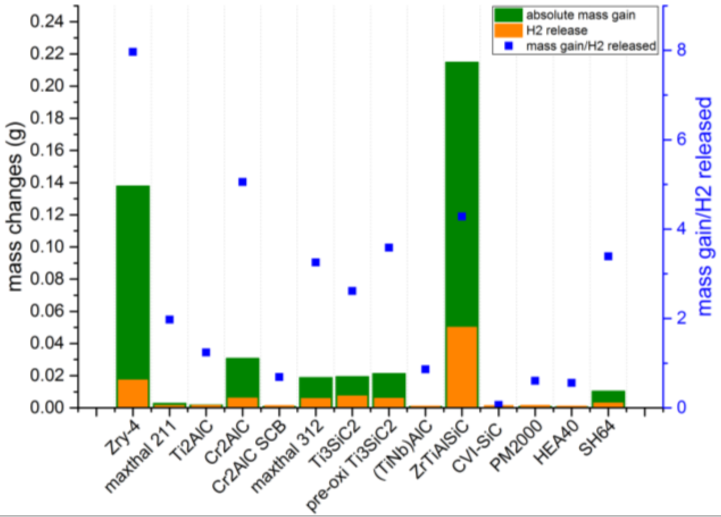
REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

Outcome from Il TROVATORE (Published results)

- Static autoclave and loop tests under PWR conditions at IIT & SCK showed
  - Excellent performance of currently used zirconium alloys (passivation by formation of zirconia layer)
  - Chromia showed lowest corrosion rate after zirconia
  - Alumina and alumina forming coatings showed poor performance (alumina dissolves under PWR conditions)
- Steam oxidation tests at KIT at 1200°C showed
  - Low reaction rates of alumina
  - Low reaction rates of SiC (lowest mass gain and hydrogen release)
  - FeCrAl show high resistance against steam corrosion



Grosse, Mirco M., et al. "Investigation of corrosion and high temperature oxidation of promising ATF cladding materials in the framework of the Il trovatore project." *Global/Top Fuel 2019: Light Water Reactor Fuel Performance Conference*. American Nuclear Society, 2019.

ATF properties included in TRANSURANUS

Cladding	Fuel
SS	UO_2 and Gd-doped UO_2 (reference)
FeCrAl	U_3Si_2
Hastelloy-N	Doped UO_2 (Cr_2O_3)

ATF properties considered

- Creep anisotropy coefficients (Anisotrp)
- Elasticity constant (ELOC)
- Poisson's ratio (NUELOC)
- Strain due to swelling (SWELOC)
- Thermal strain (THSTRN)
- Thermal conductivity (LAMBDA)
- Creep strain (ETACR)
- Yield stress (SIGSS)
- Rupture strain (ETAPRR)
- Burst stress (SigmaB, only for cladding)
- Fraction of heavy metals (ANSWME, only for fuels)
- Crystallographic Phase Transition (ZrBeta , only for cladding)
- Specific heat at constant pressure (CP)
- Density (RO)
- solidus–liquidus melt temperature (SOLIMT)
- Heat of melting (FH)
- Emissivity (EMISS)

TRANSURANUS comparison ATF / standard fuel and sensibility analysis (JRC)

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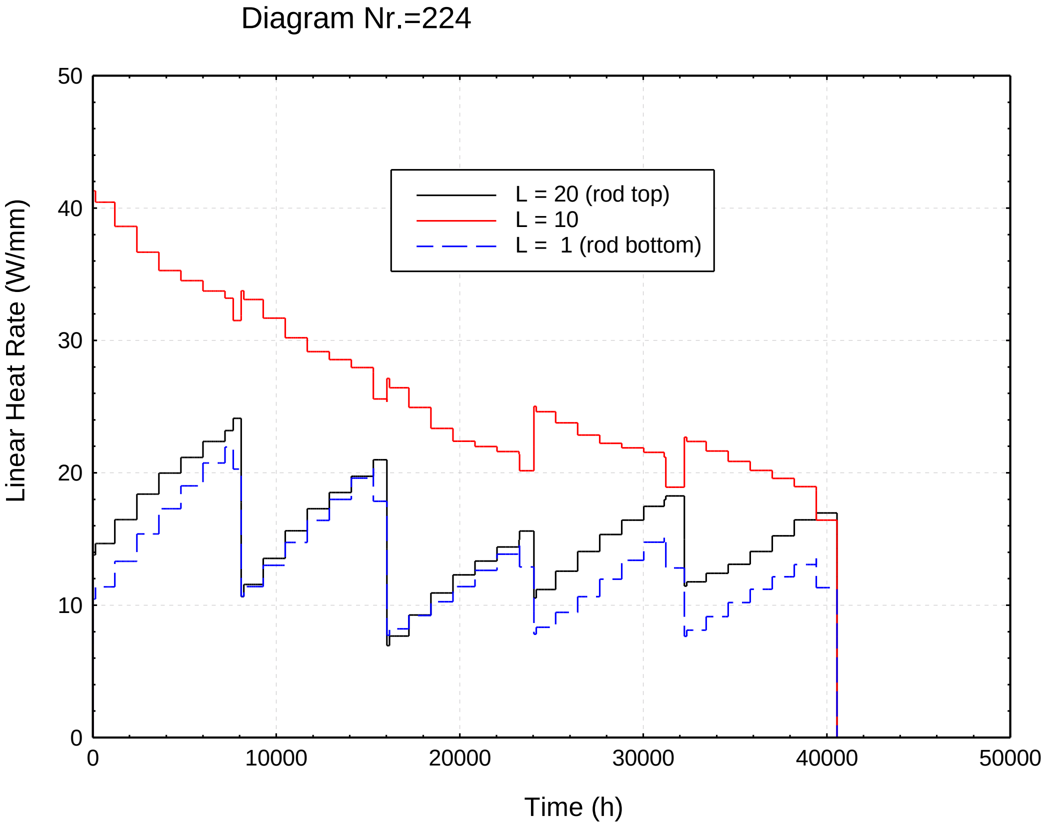
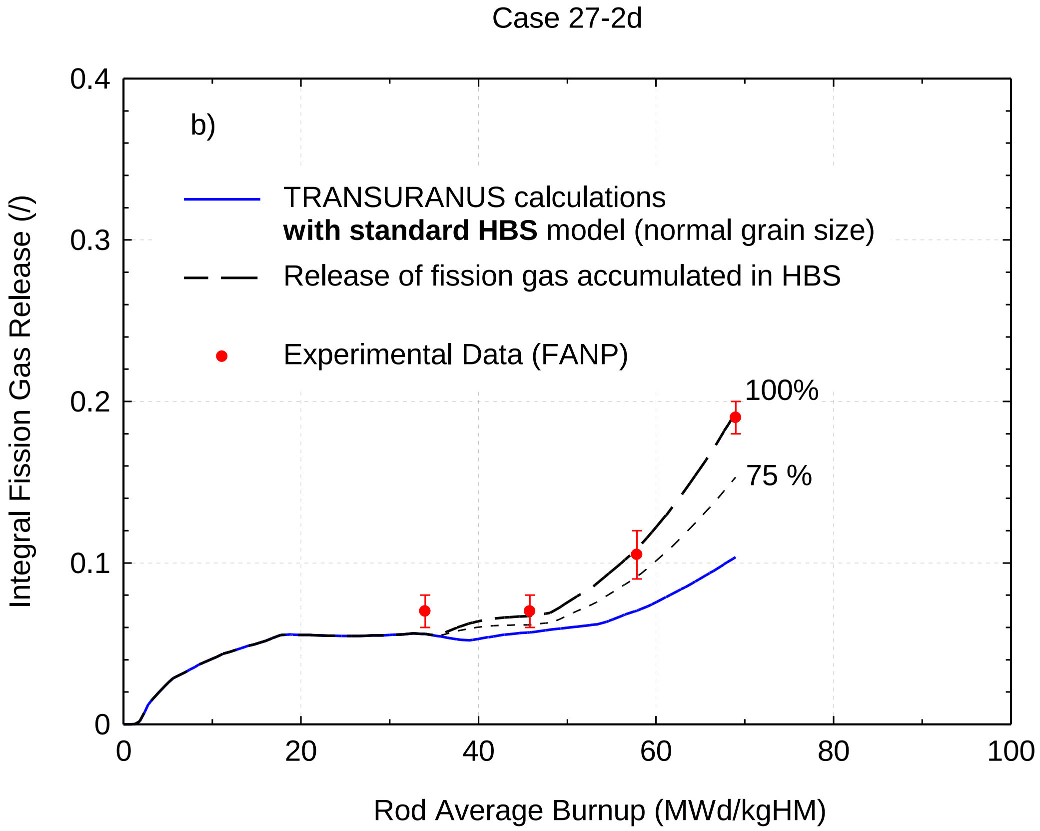
REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

TRANSURANUS comparison ATF / standard fuel : FUMEX-II case considered

- Case 27 provided by Framatome
- PWR rod with Zry4 cladding

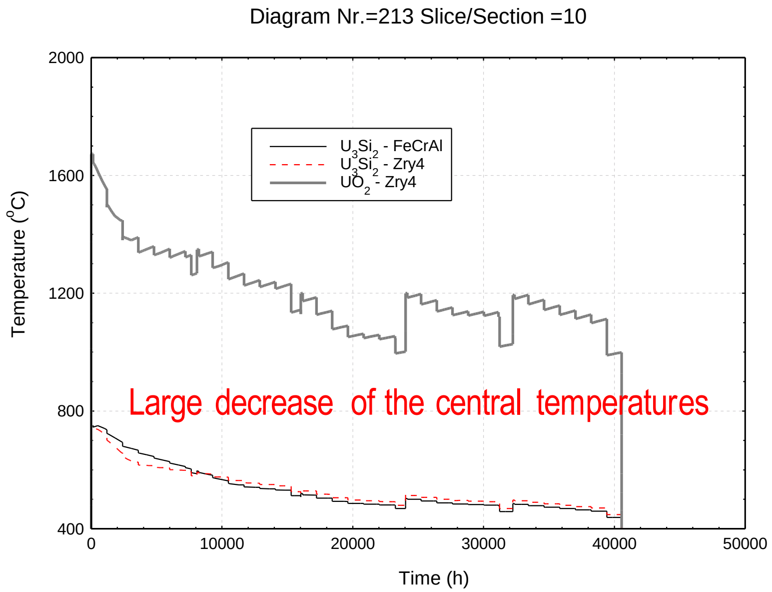


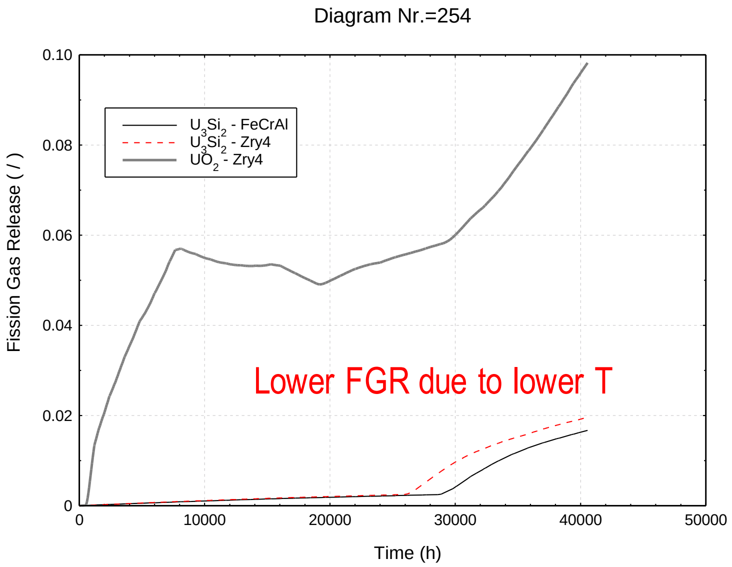


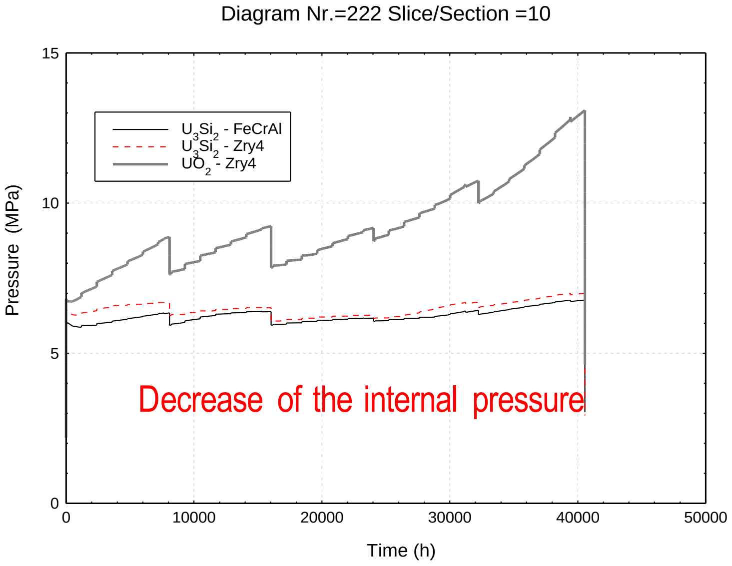
TRANSURANUS comparison ATF / standard fuel and sensibility analysis (JRC)

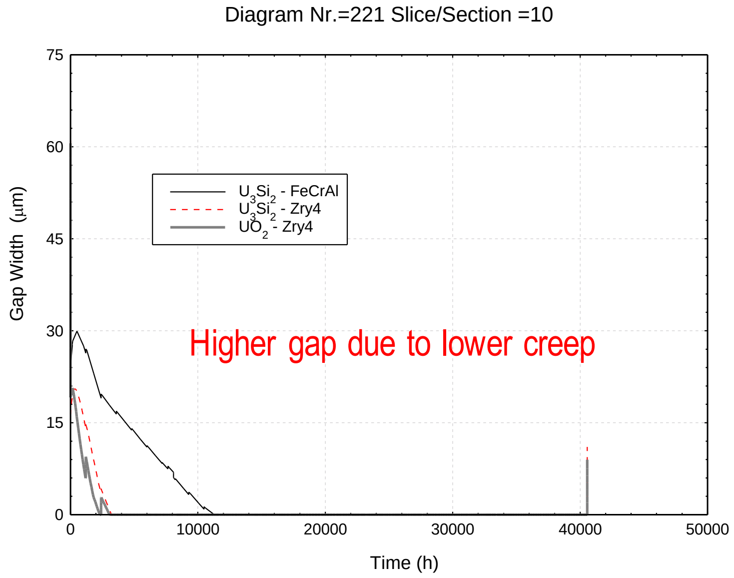
TRANSURANUS comparison ATF / standard fuel : Impact of ATF on central temperatures

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS



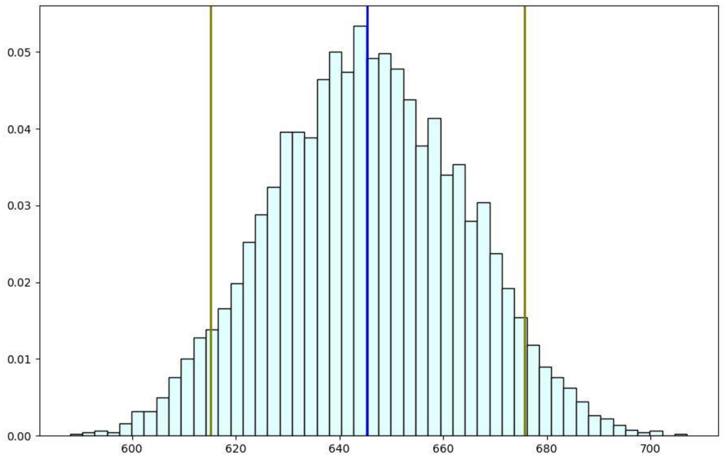






Sensibility analysis : Uncertainties considered in TUStat and in new TUPython

- In general three types (TUPython)
  - Material properties
  - Fabrication parameters
  - Irradiation parameters



- In this case

Fuel material property	Uncertainty range
Thermal conductivity	±5%
Thermal expansion coefficient	±5%
Creep rate	0.5-10 (multiplication factor)
Density	±2%
Elastic modulus	±30%
Swelling	±20%
Heat capacity at constant pressure	±5%

Clad material property	Uncertainty range
Thermal conductivity	±20%
Thermal expansion coefficient	±30%
Creep rate	±50%
Poisson ratio	±10%
Elastic modulus	±5%
Heat capacity at constant pressure	±5%
Yield stress	±30%

No significant effect of material property uncertainties (TUPython) on central fuel temperature

Stronger impact on clad hoop stress

Summary and conclusions

- Successful implementation of new ATF properties (U_3Si_2, FeCrAl, Hastelloy) reflect excellent structure of the TRANSURANUS platform
- Preliminary simulations confirm reduced ATF fuel temperatures and clad creep →improve the fuel rod behaviour under normal operation conditions
- Need to extend models/material properties (e.g. FG model and TUBRNP version for Cr-doped fuel, high temperature properties for Cr-coated cladding, etc.)
- New TUPython tool also extend the UA/SA analysis to include e.g. Pearson coefficients

FRAPTRAN sensibility analysis on LOCA performance (Zr alloys /Chromium coated Zr alloys) (Tractebel)

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REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

The considered scenario is a LBLOCA at one of the cold legs, which leads to a maximum reflood PCT of 1189 °C, and maximum ECR of 6.76%,

This sensitivity studies adress various modelling paramaters (oxyadation kinetics, deformation model, and rupture criteria)

<u>Test matrix :</u>

· P0: reference fuel + FRACAS-I deformation model (mechan = 1) + BALON2 burst model (noball = 0)
· P1: P0 + Zr corrosion model x 0.1 + C-P correlation x 0.5 – Impact of reduced corrosion and high temperature oxidation
· P2: P1 + BALON2 off (noball = 1) with default rupture strain (1.0) - Impact of ballooning model
· P3: P1 + FEA + irrupt=1 (NUREG-0630 fast ramp) - Impact of FEA + rupture model
· P4: P1 + FEA + irrupt=2 (NUREG-0630 slow ramp) - Impact of FEA + rupture model
· P5: P1 + FEA + irrupt=0 + ruptstrain = 1.0 - Impact of FEA + rupture model
· P6: P1 + FEA + irrupt=0 + ruptstrain = 0.8 - Impact of FEA + rupture strain
· P7: P1 + FEA + irrupt=0 + ruptstrain = 0.5 - Impact of FEA + rupture strain
· P8: P1 + FEA + irrupt=0 + ruptstrain = 0.25 - Impact of FEA + rupture strain
· P9: P1 + FEA + irrupt=0 + ruptstrain = 1.0 + sigcladanneal = 0.1 - Impact of FEA + annealing time

FRAPTRAN sensibility analysis on LOCA performance (Zr alloys /Chromium coated Zr alloys) (Tractebel)

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

Conclusions :

The existing FRAPTRAN model options allow to simulate the following behaviours of Cr-coated claddings with reduced corrosion and high temperature oxidation, BALOB2 off, FEA model with NUREG-0630 burst strain model or user-defined rupture strain, and reduced annealing rate:

· Delayed burst;
· Lower cladding temperatures;
· Decreased ECR.

However, some code modifications in FRAPTRAN are required in order to be able to simulate the reduced burst strain of Cr-coated cladding:

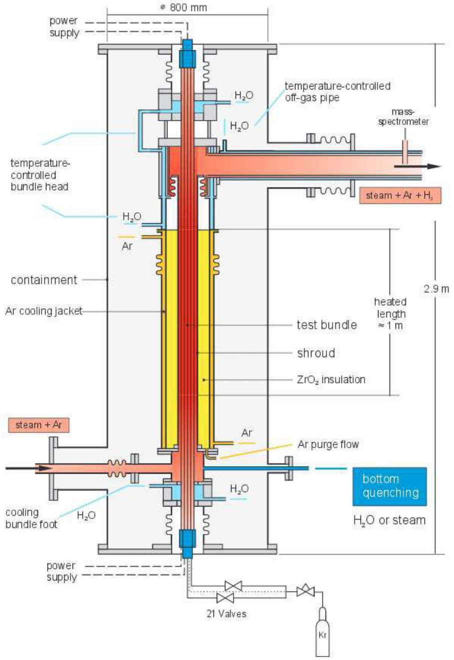
· Burst criteria: some multipliers on the burst stresses and strains and on the instability strain for BALON2 model are available in FRAPTRAN but doesn't allow to affect the burst time. Specific burst stress or strain models should be developed based on the separate effect tests and implemented in FRAPTRAN;
· The reduced annealing rate seems favourable for simulating slightly reduced strain at burst with delayed burst, but need to be validated against test data.
· The high temperature creep law of Cr-coated cladding should de developed and implemented.

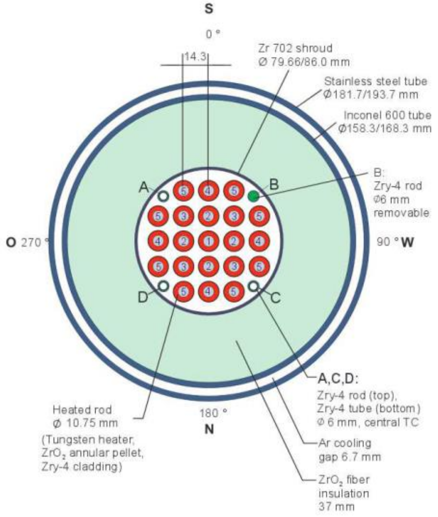
DRACCAR comparaison eATF / standard fuel (Zr alloy /Cr coated Zr alloy) (IRSN)

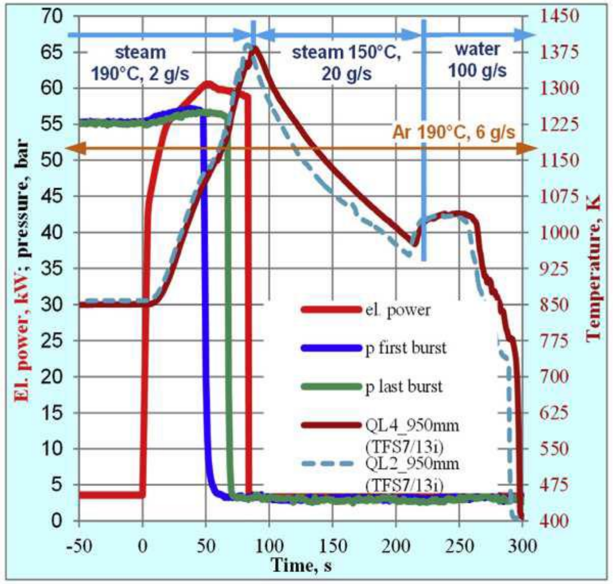
REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- Reassessment of QUENCH L1 from QUENCH LOCA program (KIT) simulation using ATF material properties

- Preliminary investigation on QUENCH-L1
  - Creep rate for Cr coated Zry-4 taken equal to standard Zry-4 creep rate divided by 2
  - Burst stress criterion kept identical to standard Zry-4
  - No modification of oxidation model



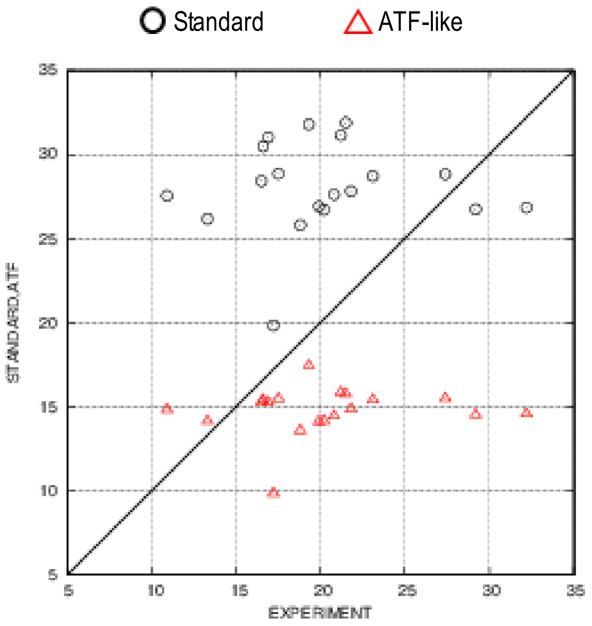




DRACCAR comparaison eATF / standard fuel (Zr alloy /Cr coated Zr alloy) (IRSN)

- Standard vs ATF QL-1 DRACCAR results

	Unit	EXPERIMENT	STANDARD	ATF
Number of burst rods	-	21	21	21
Maximum rod temperature measured in the bundle	˚C	792.8	877.5	885.0
Rod index of maximum temperature	-	19	19	19
Elevation of maximum temperature	mm	950.0	950.0	950.0
Maximum rod pressure measured in the bundle	bar	57.0	58.5	58.7
Rod index of maximum pressure	-	3	20	20
Maximum rod strain measured in the bundle	%	32.2	31.9	17.4
Rod index of maximum strain	-	20	4	16



Final circumferential strain (%)

<u>Conclusions :</u>

- maximum strain using "ATF-like" creep rate is half of the standard simulation case
- No specific modification of temperature simulation
- Burst for ATF-like is slightly delayed in comparison to Standard laws
  Using same stress criterion and lower creep rate is consistent with burst occurrence at higher burst pressure / temperature
- Location of burst prediction is not affected by material laws (same T predicted)
  Large discrepancies code/simulation (hot spot distribution effects)

DRACCAR comparaison eATF / standard fuel (Zr alloy /Cr coated Zr alloy) (EDF)

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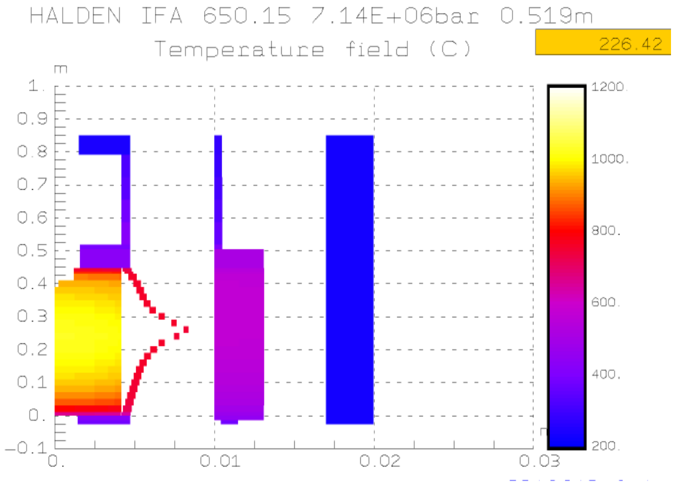
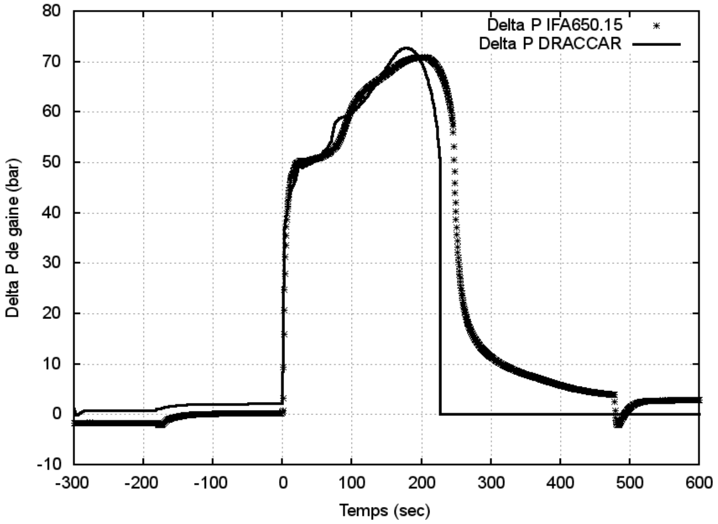
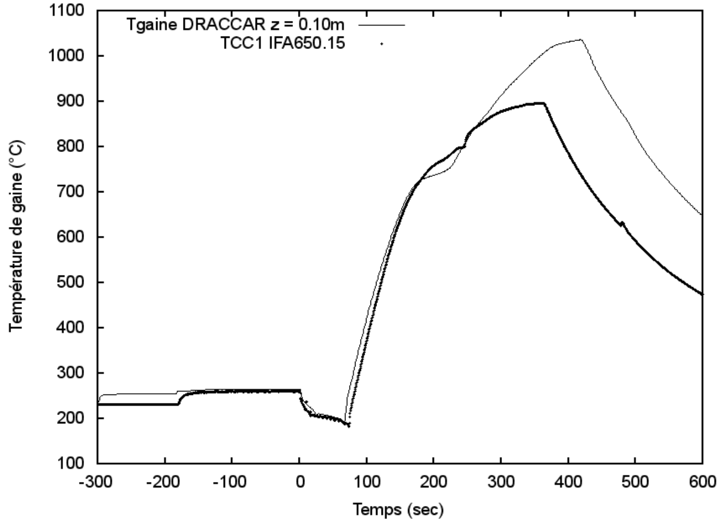
REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- Reassessment of IFA650.15 from HALDEN program (OCDE) simulation using ATF material properties

- Preliminary investigation on IFA650.15
  - Creep rate for Cr coated Zry-4 taken equal to standard Zry-4 creep rate divided by 2
  - Burst stress criterion kept identical to standard Zry-4
  - Switch off oxidation model







<u>Conclusions :</u>

- No specific modification of temperature simulation
- Burst for Cr coated Zr is slightly delayed in comparison to Standard cladding results higher ECR is expected
- Location of burst prediction is not affected by material laws (same T predicted)

General Conclusion and outlook

- Successful implementation of new e-ATF properties (Cr coated Zr Alloys, U_3Si_2, FeCrAl, Hastelloy) in TRANSURANUS platform and Cr coated Zr Alloys, for FRAPTRAN and DRACCAR
- Preliminary simulations for all e-ATF confirm a delay of burst event for e-ATF fuel lower central temperatures → higher ECR at burst are expected
- Need to extend models/material properties (e.g. FG model for Cr-doped fuel and high temperature creep law for Cr-coated cladding, etc.)