

FROM RESEARCH TO INDUSTRY



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FUEL MELTING MARGIN ASSESSMENT OF FAST REACTOR OXIDE FUEL PINS USING A STATISTICAL APPROACH

Paper IAEA-CN-245-333

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■ Oxide fuel :

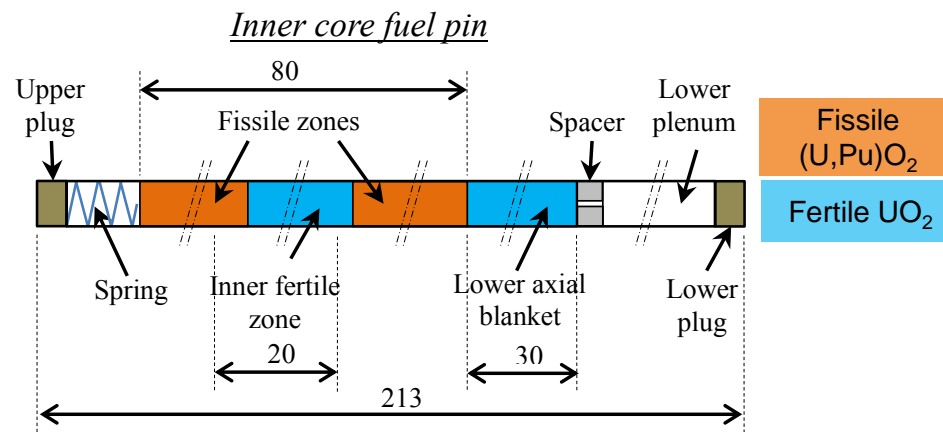
Cylindrical annular pellets obtained by sintering of a mixture of UO_2 and PuO_2 powders

■ Cladding tube and spacer wire :

special austenitic steel cold-worked 15%Cr-15%Ni with Titanium (AIM1)

■ Axially and radially heterogeneous core (CFV design)

- Inner core : 20-cm fertile plate inside the fissile area



■ Design criterion 1: **No melt of the fuel**

→fuel melting probability $P_{melt} < 1/10.000$ in the ASTRID core

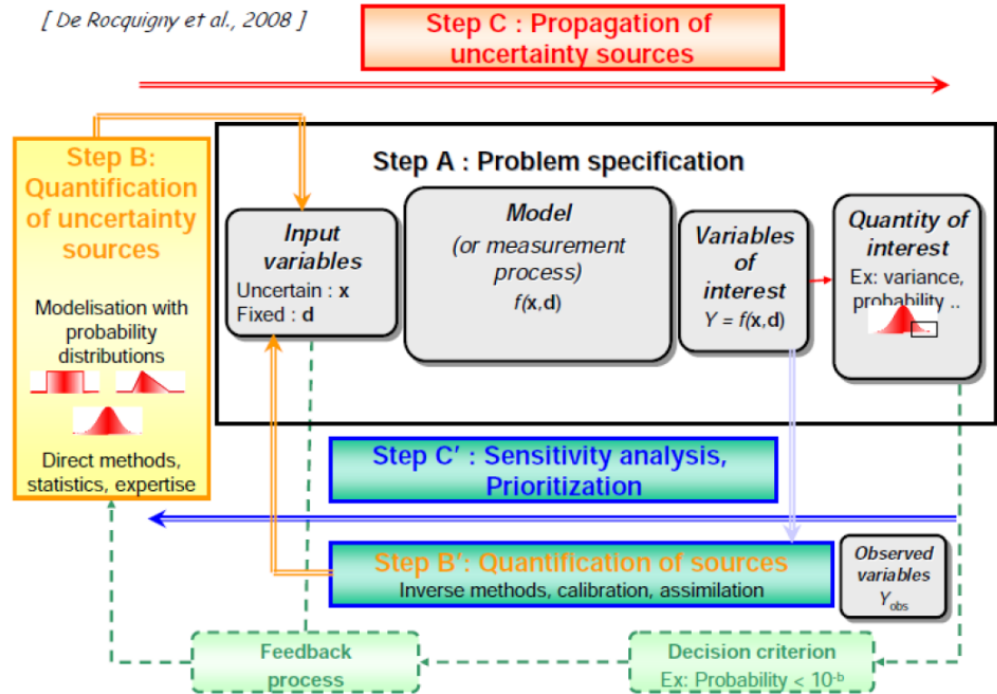
→Loadings, dimensions and properties have to be defined with their uncertainty

→**uncertainty propagation method ?**

- Old french SFR's : Gaussian hypothesis, variance sommation →conservative?

- **ASTRID: new approach with Monte-Carlo method**

- Introduction
 - ASTRID fuel pin design
- Problem specification
 - Uncertain input data
 - Design computation tools
 - No-melt design criterion
- Probability distributions
- Uncertainty propagation
 - Metamodel calibration
 - Global sensitivity analysis
- Fuel Melting probability assessment
 - Monte-Carlo direct computation
 - FORM/SORM approximations
 - Local sensitivity analysis
- Conclusion



A : PROBLEM SPECIFICATION

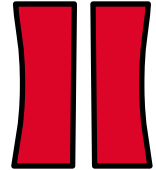
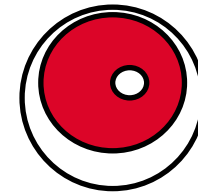
INPUTS/OUTPUTS ?

MODEL ?

UNCERTAIN / FIXED INPUTS

■ Uncertainty depending on manufacturing processes:

- Fuel pellet inner and outer diameters
- Cladding tube inner diameter
- Fuel pellet central hole off-centering
- Hour-glass shape of the pellet
- Fuel pellet off-centering within the cladding tube
- Porosity
- Stoichiometry O/M
- Plutonium content in the fuel
- Pellet surface roughness
- Initial helium fraction in the plenum



→ 3D defects

■ Uncertainty in irradiation condition:

- Linear Heat Rate (Neutron flux)
- Duration of first power rise
- Maximal clad temperature

■ Uncertainty in material law:

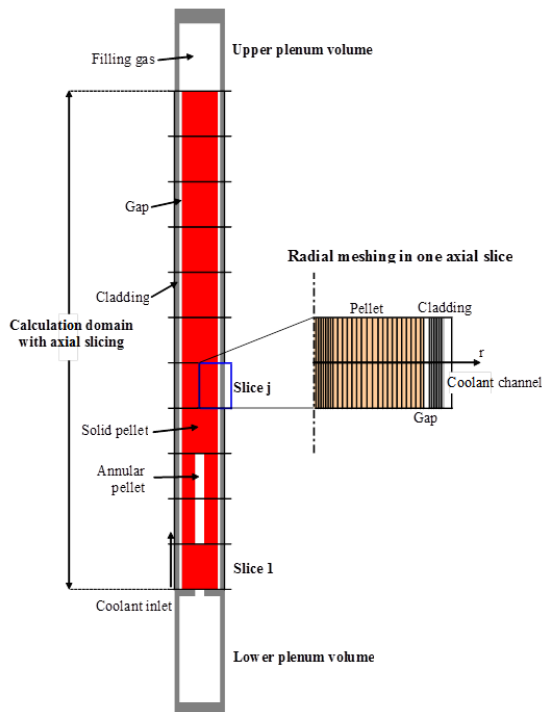
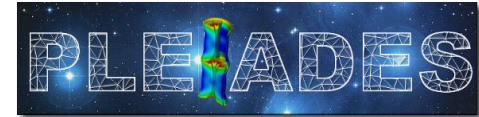
- Melting temperature → T solidus (U,Pu)O₂

■ Behaviour laws fixed :

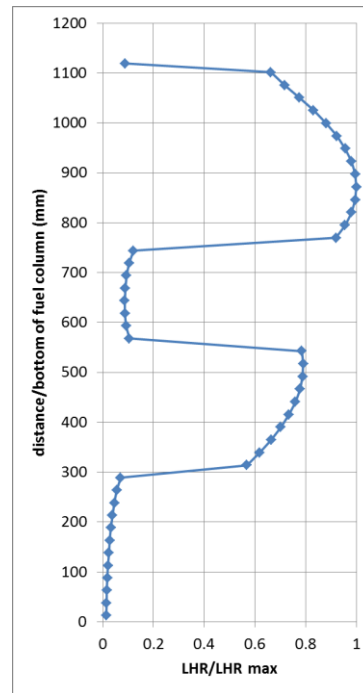
- Thermal conductivity fixed
- Gap closure model fixed (cf. papers M. Lainet and B. Michel)
- Etc.

SFR FUEL PINS MODEL

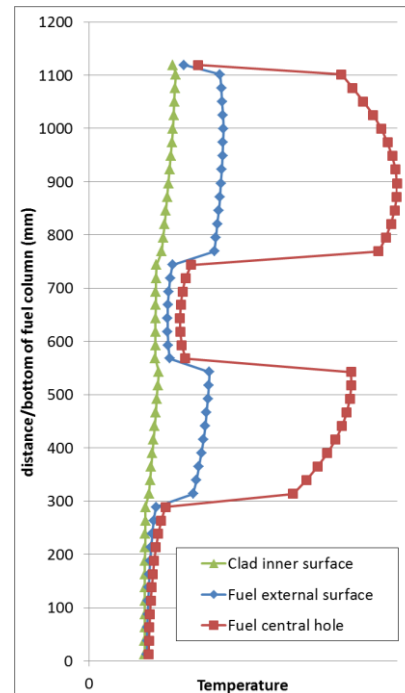
- Simulation with GERMINAL V2 code (CEA SFR fuel code in PLEIADES)
- 1,5 D model : radial FE computation in N slices
+ axial gas balance + coolant channel temperature calculation



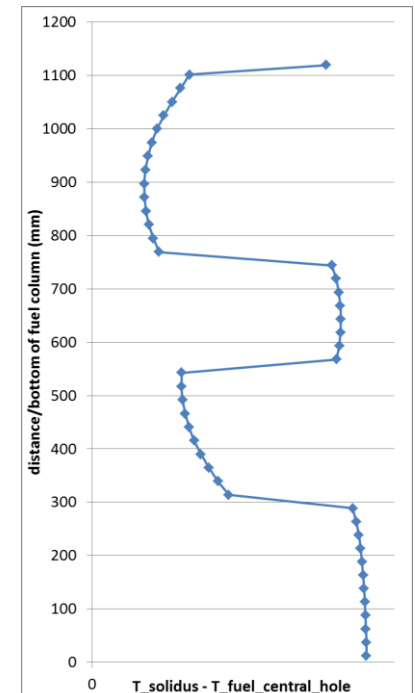
Linear Heat Rate



Temperatures

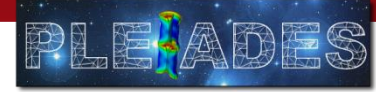


$T_{solidus} - T_{fuel\ central\ hole}$

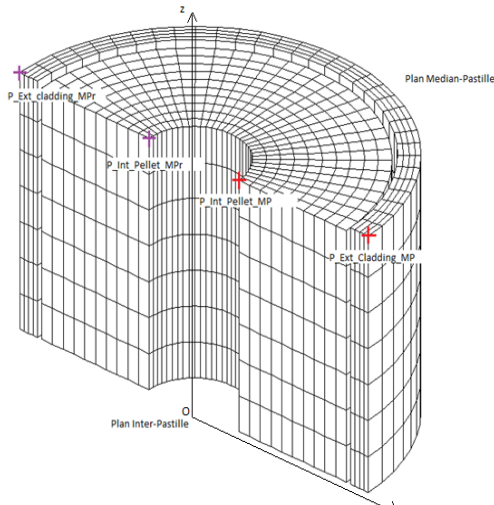


- Melting margin: $DT_{melting} = \min_X (T_{solidus}(\bar{X}) - T(\bar{X}))$
- $\rightarrow P_{melt} < 1/10000 \Leftrightarrow DT_{melting\ min} = ?$
- \rightarrow Impact of pellet 3D defects ?

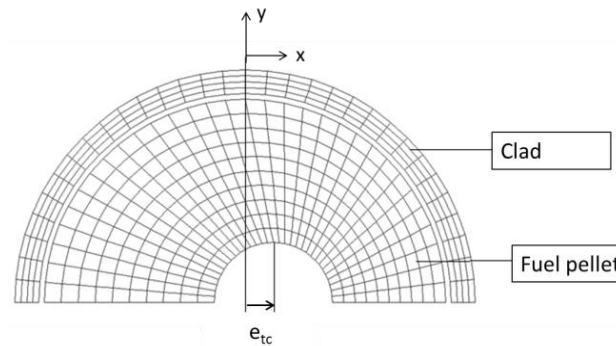
SFR FUEL PELLET DEFECTS MODEL



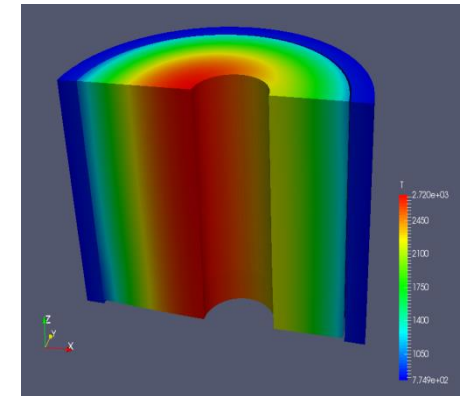
- LICOS code : specific design tool code of CEA PLEIADES platform
- Inputs = GERMINAL data on the slice where the melting margin is minimal
- Each defect is modeled separately :
 - central hole off-centering (*cho*)/ fuel pellet off-centering (*pco*)/ pellet hourglass shape (*hgs*)



3D mesh of 1/4 pellet w/ clad



Fuel central hole off-centering mesh



Fuel temperature field

- Computation of temperature elevation in the 3D pellet vs GERMINAL

$$\Delta T_{defect}(x) = T_{3D}(x) - T_{1D}(\bar{X})$$

- Addition of 3 defects temperature elevation effects

$$\Delta T_{defects}(\bar{x}) = \Delta T_{pco}(\bar{x}) + \Delta T_{cho}(\bar{x}) + \Delta T_{hgs}(\bar{x})$$

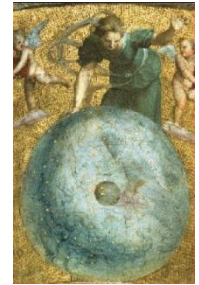
- Melting margin becomes

$$DT_{melting} = \min_{\bar{X}} [T_{solidus}(\bar{X}) - T_{1D}(\bar{X})] - \max_x (\Delta T_{defects}(x))$$

**B: QUANTIFICATION OF UNCERTAINTY
SOURCES
UNIFORM? GAUSSIAN? ...?**

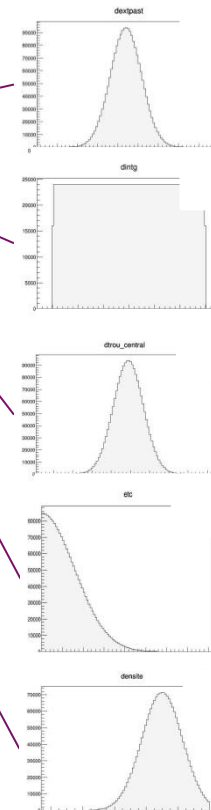
UNCERTAIN INPUT DATA MODEL

- URANIE CEA Simulation Platform is used to generate samples
- Choice of a distribution law for each input data
- Take into account manufacturing data, operating data from previous FBR...



Parameter	Type of distribution
Fuel pellet outer diameter	Gaussian
Cladding tube inner diameter	Uniform
Fuel pellet inner diameter	Gaussian
Fuel pellet off-centering within the cladding tube	Uniform
Fuel pellet central hole off-centering	Truncated Gaussian
Hour-glass shape of the fuel pellet	Truncated Gaussian
Plutonium content in fuel	Gaussian
Stoichiometry	Truncated Gaussian
Fuel pellet porosity	Truncated Gaussian
Fuel pellet surface roughness	Uniform
Initial Helium fraction in the free volume of the pin	Uniform

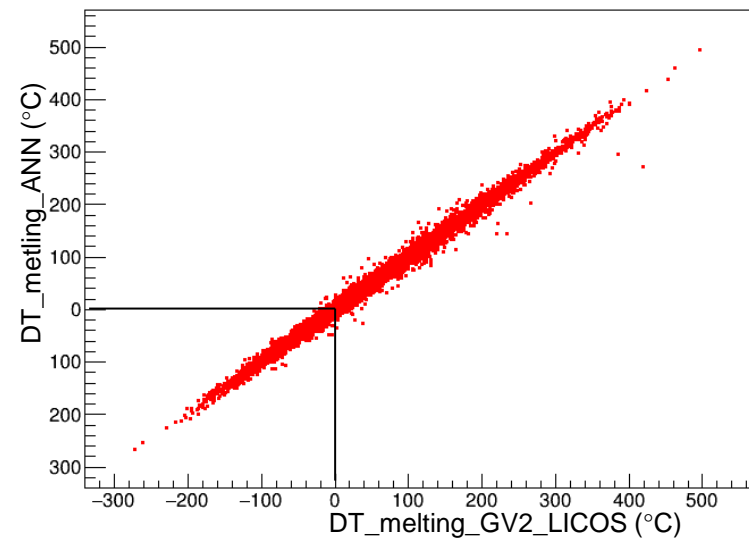
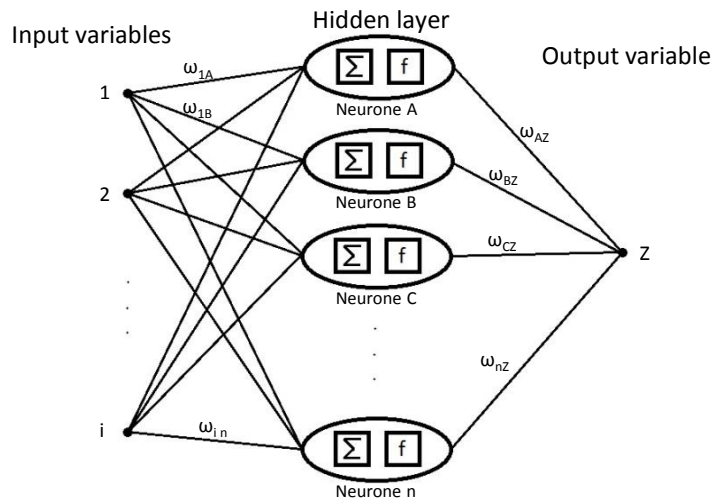
Parameter	Type of distribution
Linear heat rate :	
- Neutronic uncertainty	Uniform
- Equivalent Plutonium linear mass	Gaussian
Duration of the first power rise	Uniform
Maximal clad temperature	Uniform



- C: UNCERTAINTY PROPAGATION**
- META-MODEL**
- PROPAGATION**
- GLOBAL SENSITIVITY ANALYSIS**

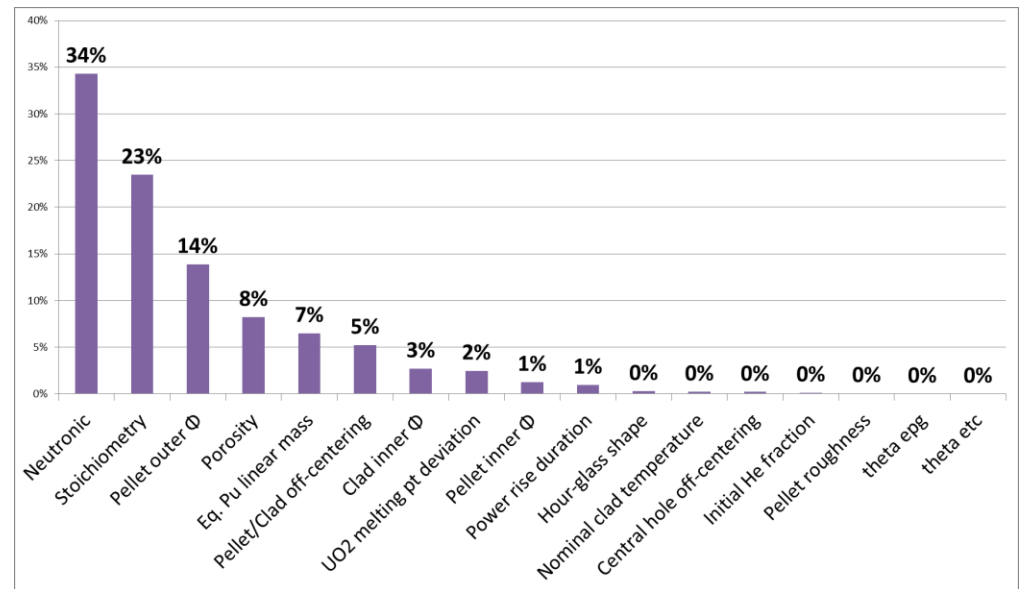
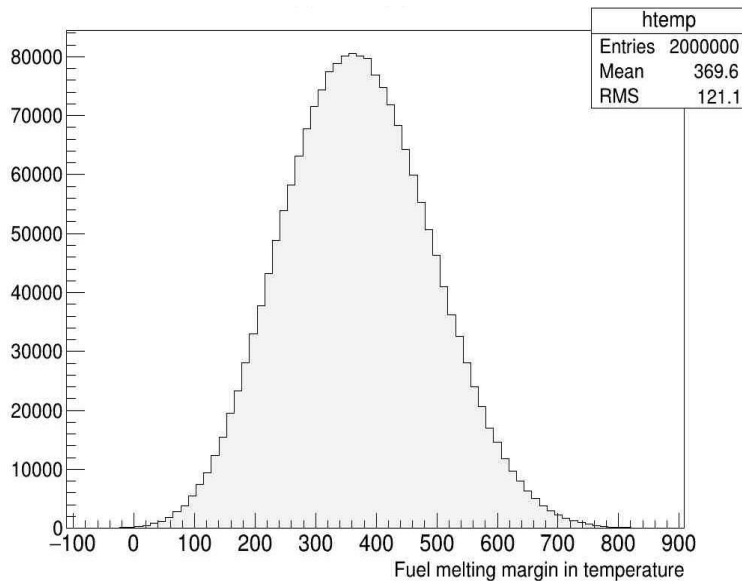
META-MODEL OF MELTING MARGIN

- Melting probability $\sim 10^{-4} \Rightarrow$ a sampling of at least 10^6 random points is necessary
- A meta-model will reduce computation time: $DT_{melting} = \hat{f}(u_i)$
- Non-linear evolution of $DT_{melting} \Rightarrow$ Artificial Neural Network (ANN)
- Specific database of 10 000 random points **chosen by importance sampling**



- Importance sampling \Rightarrow 2375 points lead to melting with ANN, 2359 points with the code
- Dispersion ~ 60 °C on $DT_{melting}$

- Latin Hypercube Sampling of 2.000.000 samples,
- Real probability distributions (\neq importance sampling)
- Gaussian shape of distribution of fuel melting margin in temperature
- URANIE computes first order Sobol sensitivity indices $S_i = \frac{Var(E(DT_{melt}|u_i))}{Var(DT_{melt})}$



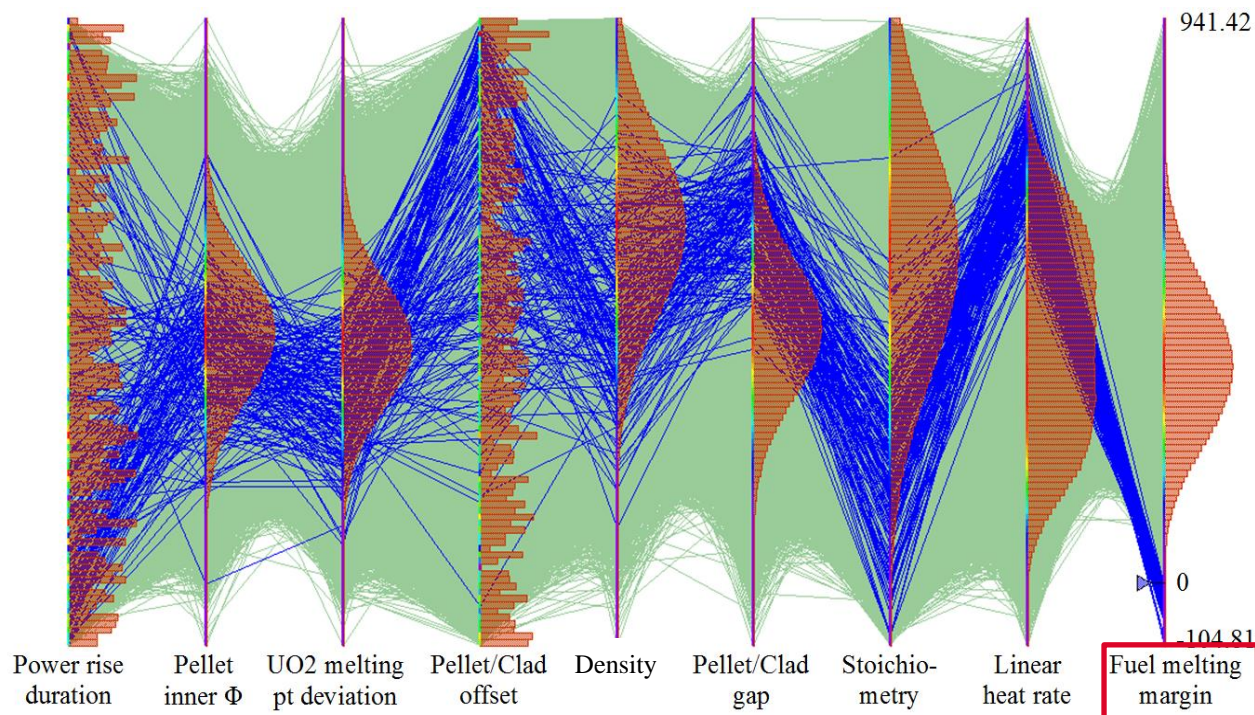
- $\sum_{i=1}^d S_i = 0.986 \Rightarrow$ observation of higher-order indices S_{ij} is not necessary

With the probability distributions considered :

- linear heat rate and stoichiometry have the biggest impact on the melting margin
- Initial gap, porosity and pellet/clad off-centering come after

Cobweb plot :

- each broken line represents variables values associated to a sample point
- 8 most impactfull uncertainty variables are presented
- Blue broken lines represent fuel melting samples (DT <0)



Melting occurs if:

- (LHR, gap, Pellet/Clad off-centering) are high
- (O/M, Density, melting point deviation, Pellet inner diam.) are low

MELTING PROBABILITY ASSESSMENT

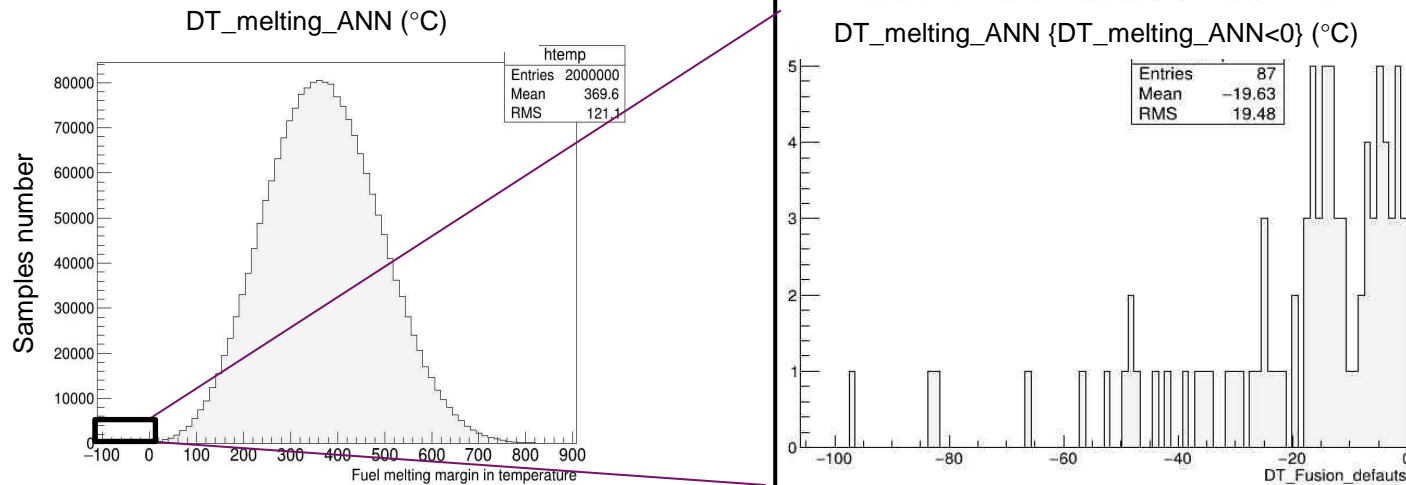
- MONTE-CARLO

- FORM/SORM

- LOCAL SENSITIVITY ANALYSIS

MELTING PROBABILITY ASSESSMENT

- Latin Hypercube Sampling of 2.000.000 samples, unbiased probability distributions



- 87 melting cases / $2 \cdot 10^6$ cases : $P_f = \frac{N_f}{N} \Rightarrow P_f = 4.3 \cdot 10^{-5}$
- Confidence Interval $1 - 2\alpha$ is given by:

$$P_f \pm \sqrt{\text{Var}(P_f)} * \Phi^{-1}(\alpha)$$

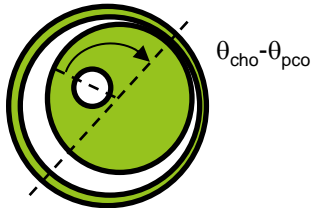
where $\text{Var}(P_f) = \frac{(1-P_f)*P_f}{N}$

and Φ is the Gaussian probability density distribution

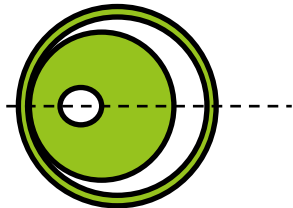
- For example : CI= 95 % $\Rightarrow P_f = 4.3 \cdot 10^{-5} \pm 21\%$
- $N \uparrow \Rightarrow \text{Var}(P_f) \downarrow \dots$

MELTING PROBABILITY METHODS COMPARISON

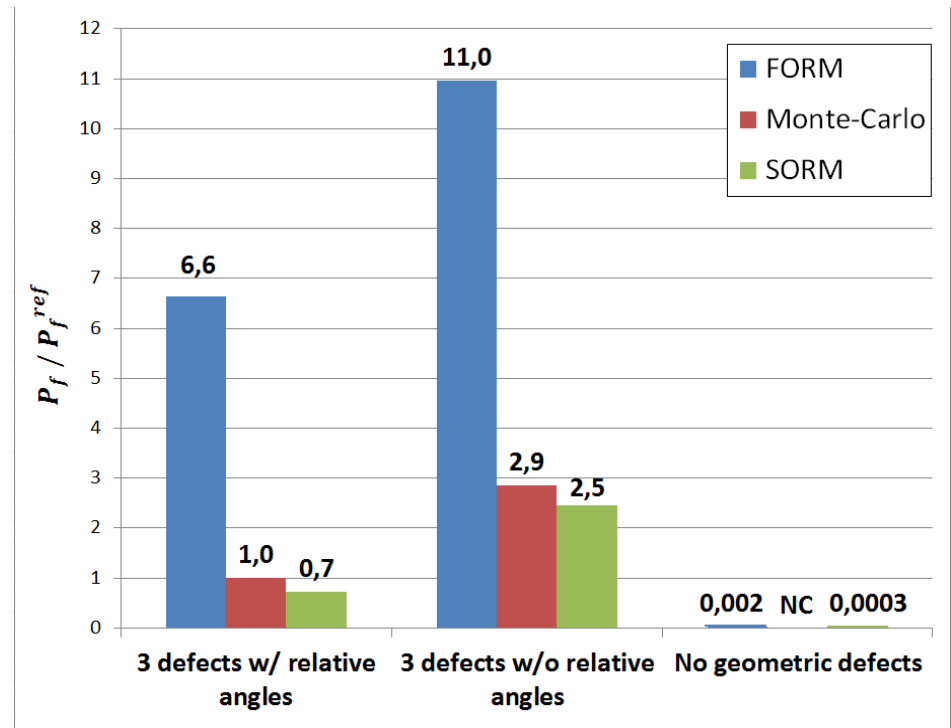
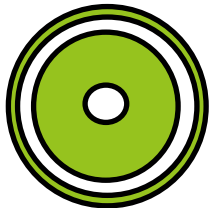
- Quasi-Monte-Carlo (LHS) result with 3D defects is considered as the reference
 - Comparison with First and Second order approximation methods FORM/SORM
- 1- Off-centering defects with relative angles (ref)



2- Off-centering defects aligned



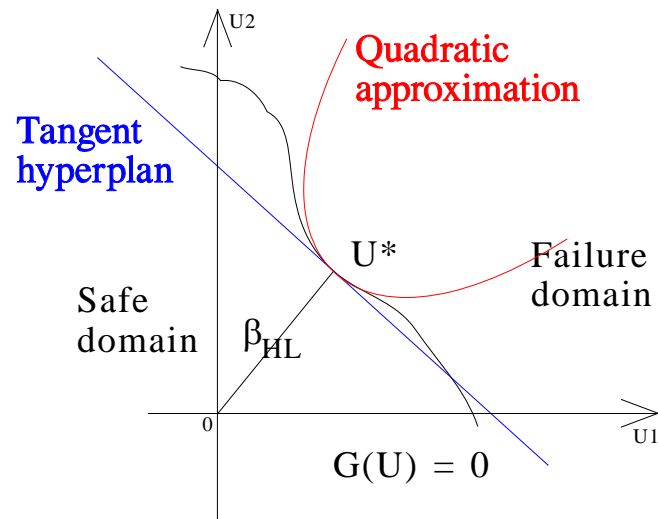
3- No off-centering, no hour-glass shape



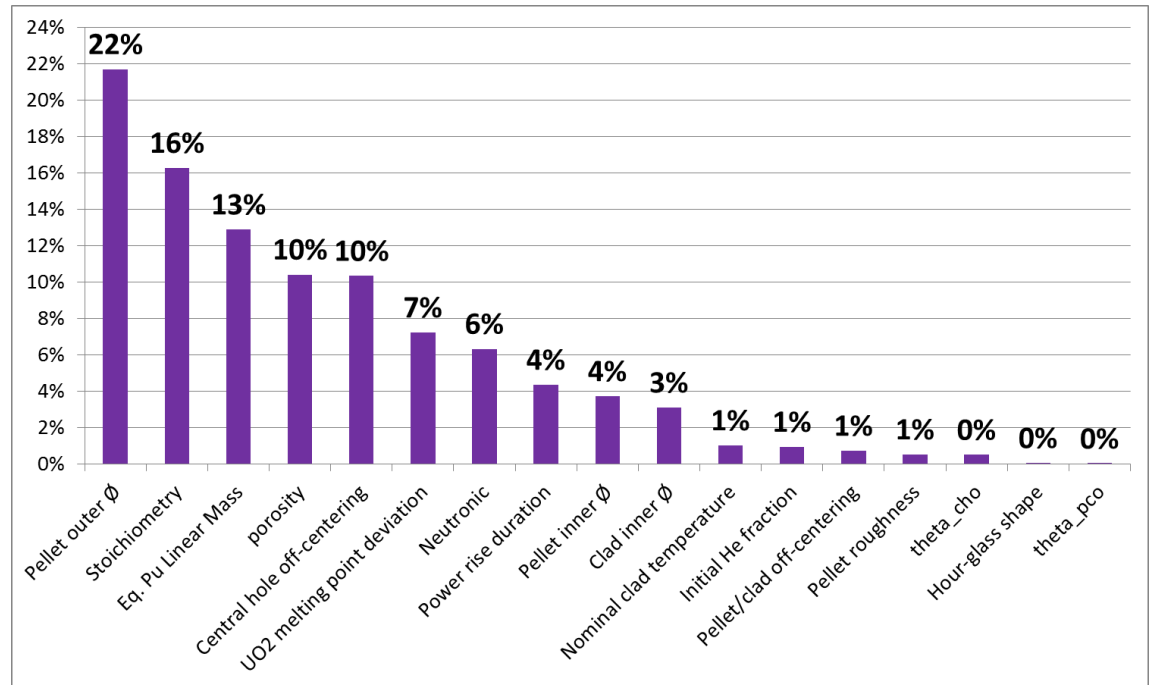
- Defects impact is significant ($P_f * 3000$)
- Angle between offsets reduces P_f by a factor 3
- FORM systematically overestimates P_f
- SORM is close to the reference case, with a small number of computations (~500)

LOCAL SENSITIVITY ANALYSIS

- Sensitivity around design point: $F_i = \alpha_i^2$ importance factor associated with variable u_i
- $\alpha_i = u_i / \beta_{HL} \sim$ coordinates in a standard normal space



Reliability assessment with FORM/SORM methods [Devictor 04]



- Hierarchy of variables is changed / global sensitivity analysis :
 - Pellet outer diameter is now first (3rd)
 - Neutronic uncertainty is at 7th place (1st before)
 - Central hole off-centering becomes significant
 - Pellet/clad off-centering becomes not significant (opposite / global)

CONCLUSIONS

- On the sensitivity of the melting margins to loadings and manufacturing uncertainties:
 - LHR, O/M ratio and pellet/clad gap size are first order parameters
 - Porosity, pellet-clad offset, central hole offset and melting point deviation have a significant influence on melting probability

- On the effect of pellet 3D defects:
 - Influence of off-centering must be taken into account
 - Initial hour-glass shape effect is not significant

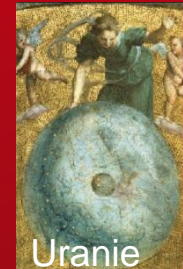
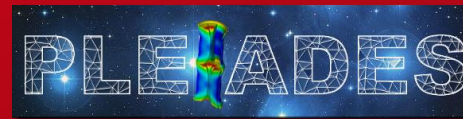
- The assessed melting probability respects ASTRID requirement

- On the melting probability assessment method:
 - FORM approximation overestimates the probability by a factor of 6
 - SORM gives a good approximation of melting probability
 - =>Non-linearity of failure surface is strong
 - Computation costs of approximations are ridiculous / Monte-Carlo direct

- Outlooks
 - Need to improve distribution of first order variables (O/M ratio, gap, Neutronic)
 - Taking into account correlations: porosity->LHR, shape→Eq MassLinear Pu, etc.
 - Same approach to be done on transients tests of control rod withdrawal

Thank you for your attention

And ASTRID, PLEIADES and URANIE colleagues for contributions



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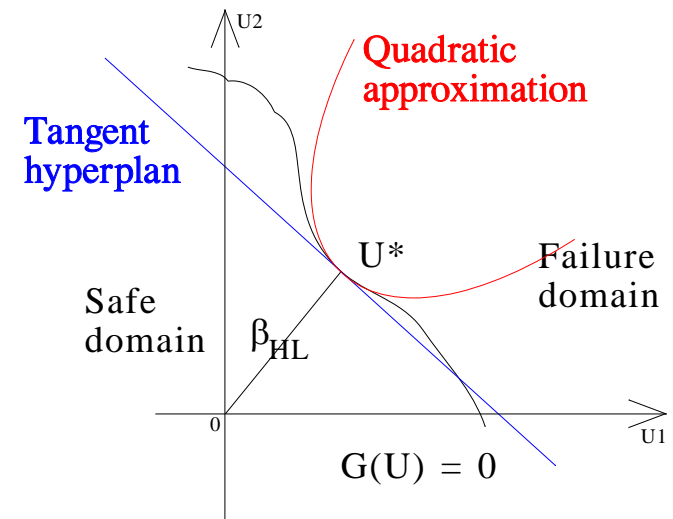
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APPENDIX A : FORM/SORM APPROXIMATION

- First and Second Order Reliability method :
 - Transformation of the random variables space in an standard normal space
 - Research of the design point U^* by calling the code
 - Build a linear (FORM) or quadratic (SORM) approximation of the failure surface near the design point
 - Computation of failure probability using failure surface approx.

- Assumptions:
 - Failure surface present one global minimum
 - Failure surface is continuous
 - Variables sets are continuous

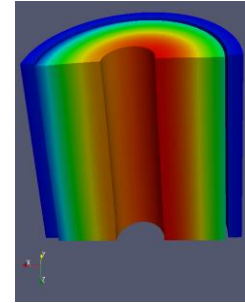
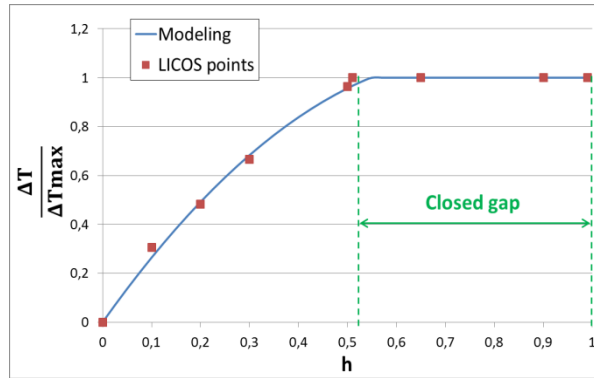
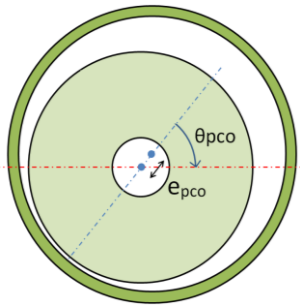
- Number of code computation \ll MC method
- Precision in the approximation depends on the non-linearity of the failure surface



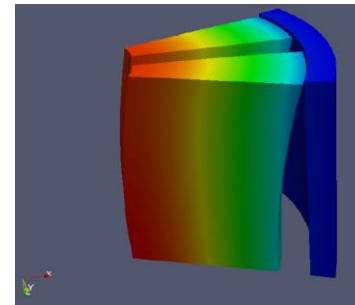
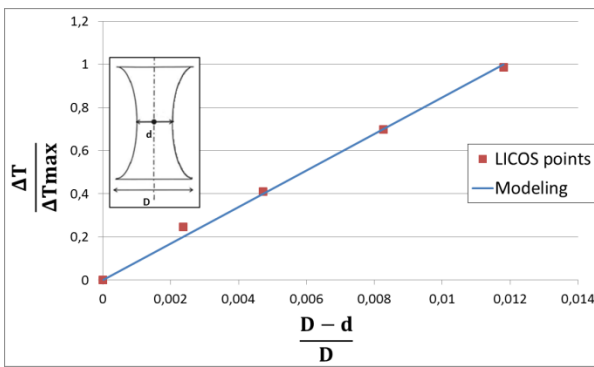
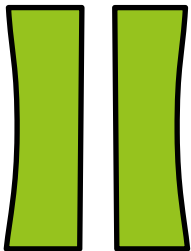
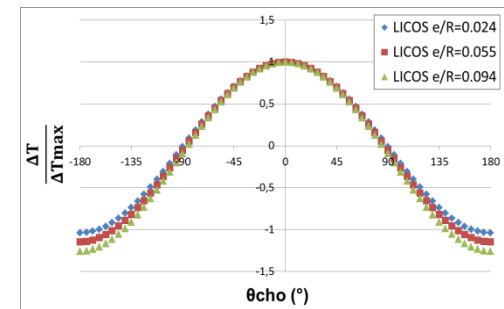
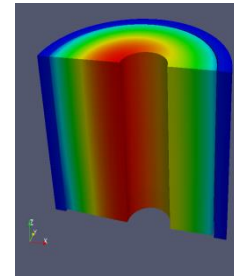
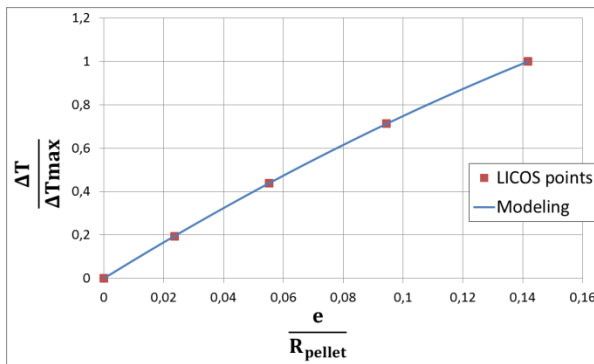
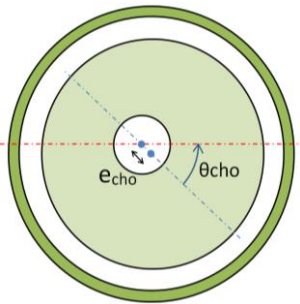
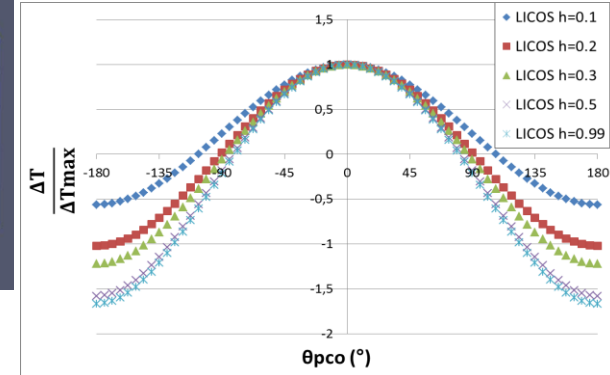
Reliability assessment with FORM/SORM methods [Devictor 04]

APPENDIX B: 3D DEFECTS META-MODEL

One meta-model is dedicated to each defect



$$h = \frac{e_{pco}}{gap}$$



APPENDIX C : THERMAL CONDUCTIVITY ANALYSIS

- Conductivity law is fixed BUT a large dispersion is due to uncertainty on stoichiometry and porosity:

