The SAMOSAFER project

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Task 6.1 Objectives

♦ Sub-task 2: plant operational states

“ CNRS and the other partners of this task will **refine the definition of the reactor operational states** (normal operation conditions), **the operating procedures**, and **the emergency operating procedures** to **identify any deviation from normal operation** and to allow a quantitative risk estimate

Framatome and EDF will provide guidance and review for the definition of the plant operational states and the safety margins. ”

Usual operating management approach

- Normal operation is the domain where:
  - The plant is producing energy or maintenance is being performed
  - The plant safety is fully demonstrated
  - The plant lifetime is guaranteed
- Normal operation range is limited by physical constraints (high/low temperature, pressure, solubility…)
- During normal operation transients
  - All plant parameters have to remain within their limits assigned for the normal operation
  - **Control functions** are meant to maintain the plant parameters within those limits while boundary conditions are evolving
- If limits of the normal operation are exceeded, it is an abnormal event (AOO or DBA)
  - **Limitation functions** can bring back smoothly the plant in normal operating range (AOO)
  - **Protection functions** can bring back the plant to a safe state (AOO and DBA)
- Safe fallback mode has to be defined: safe state(s), controlled state(s)
- Strategies to reach the controlled and safe state(s) have to be defined for any kind of initiating events
  - Appropriate automatic protection functions
  - Possible manual actions

Operation management and economy issues

♦ Beyond safety preoccupations, the MSR design must satisfy operational constraints and optimize economical issues :

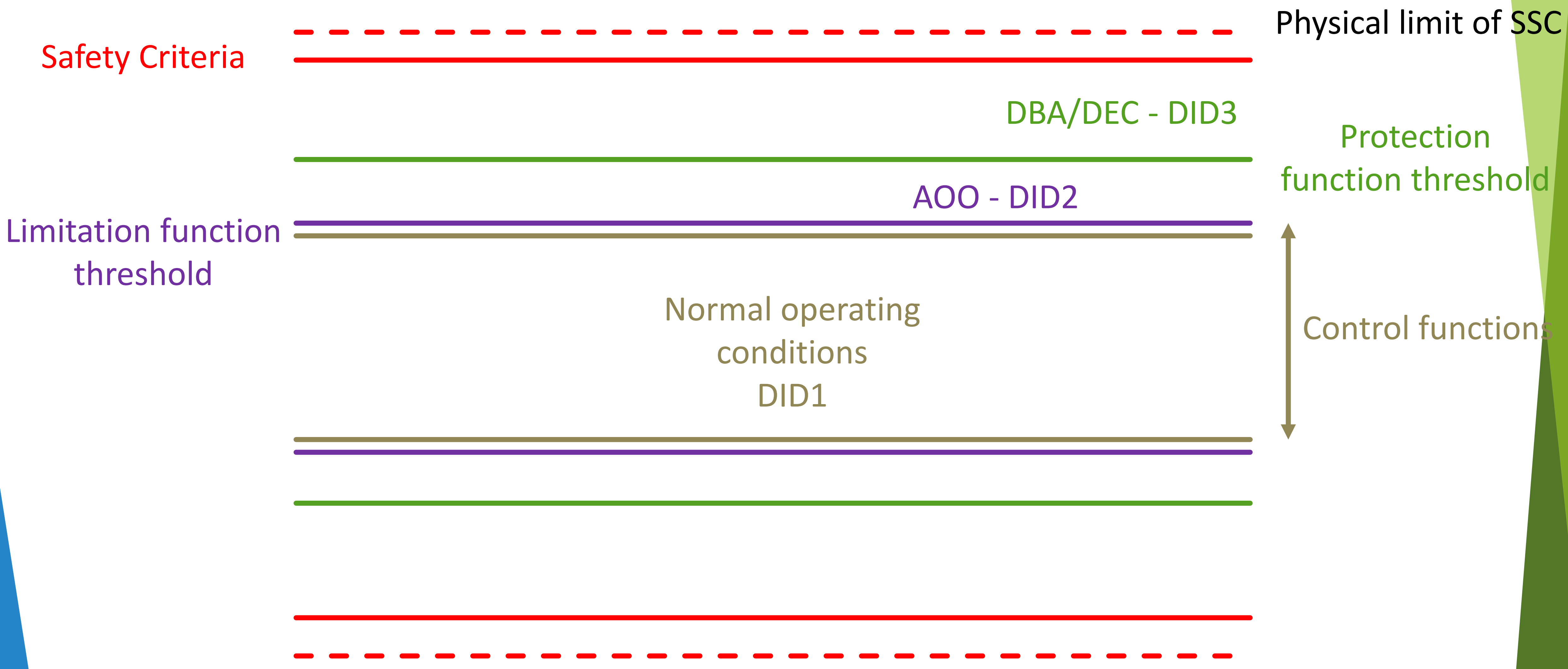
- **Maximize reactor availability**
- **Preserve the investment**

♦ Definition of the normal operation domain is a compromise between several factors

- Large operating domain allows accommodating small disturbances
  => improved availability
- Large operating domain may cause harsh mechanical loading
  => potential ageing issue
- Efficient control & limitation systems, if achievable, enable to accommodate disturbances within a reasonable operating range

♦ In any case appropriate safety margins have to be ensured between normal operation and the risk of barriers degradation

Usual operating management approach



Methodology and results

Methodology & progress for this subtask

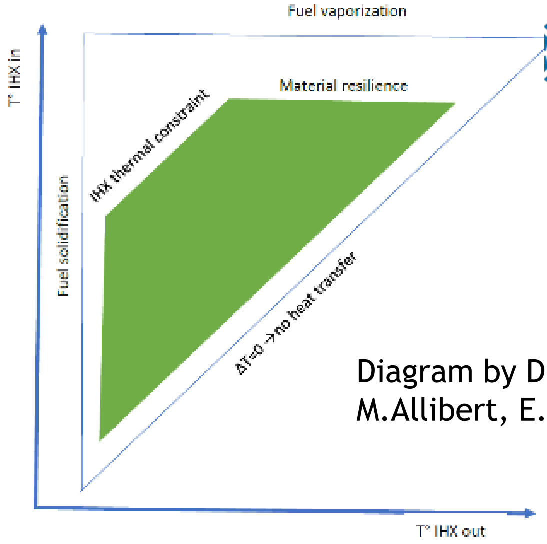


Diagram by D.Heuer, M.Allibert, E.Merle (CNRS)

Methodology definition

Step 2&3
Identification of main plant parameters and their range

Deliverable D6.2

10/2020

06/2021

11/2021

03/2022

09/2022

Step 1
Definition of the normal operating states

Milestone S15

Step 4
Definition of the limitation and the protection strategy

1st step : Define the normal operating states

- Progress : a preliminary list of normal operating states has been proposed:
  - Start-up of the reactor / Criticality reaching
  - Power production
  - Shutdown without fuel salt draining
  - Shutdown with fuel salt draining (for component handling)

- As first proposition, for the next steps of the method, it is focused first on the **power production mode**, notably since it is the better-known state

Steps 2 – 3 : For each state – Identification of main plant parameters

- Direct identification of Main Plant Parameters (MPP) appears to be controversial
  - Identify first all the relevant parameters
  - Understand the dependencies between the parameters

Nota : Both the parameters themselves and their range can be different for the different normal operating states

	A	B	C	D	E	F	G	H
1	Physical parameter		Minimal boundary	Maximal boundary	Other boundaries	:rol faisability (measurem	Control	Controlling parameter
3	**Fuel circuit**							
4	Fuel salt temperature		**Tmin** - Start of solidification temperature (Liquidus temperature)	**Tmax** - Maximum acceptable temperature for structures and equipment at hottest areas	**Maximum cooling (ΔTfuel)**, due to IHX thermal constraint	YES	YES	Fuel salt flowrate
5	Fuel salt flowrate		**Qmin** : Minimal flowrate to remove the residual power	**Qmax** - corresponding to erosion apparition OR mechanical loads on heat internal structures, namely HX	**Qmax, HX outlet** (exceeding speed that may create en temperature gradient) --> To be confirmed, according to MSR design **Qmax, core expansion tank** (perturbation on free level) **Qmax - No cavitation in pumps**	YES	YES	

Steps 2 – 3 : For each state – Identification of parameters

Example : for the temperatures, the following operating diagram represents the limits identified :

- Max temperature (material resistance)
- Min temperature (salt freezing or Pu precipitation)
- ΔT (Heat exchanger thermomechanical constraint)

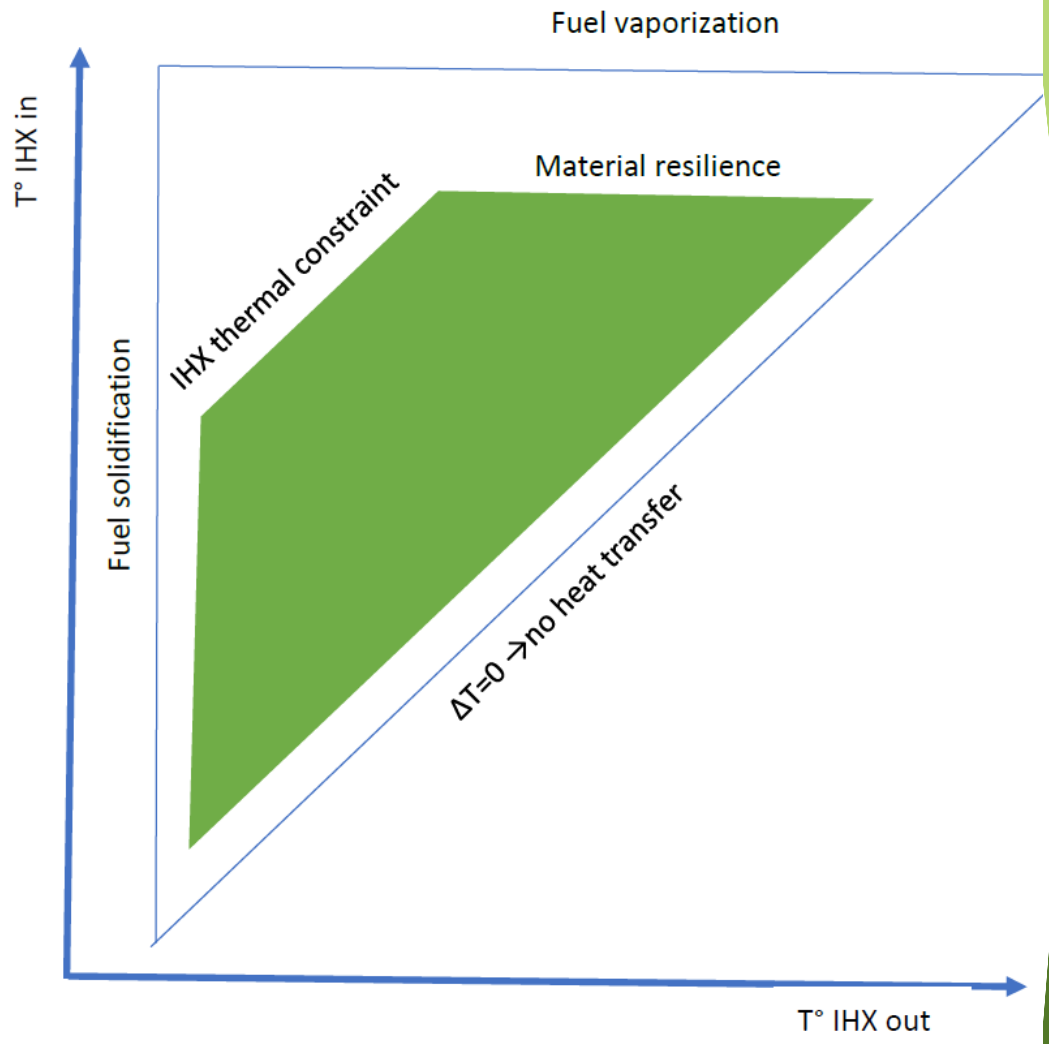


Diagram by D.Heuer, M.Allibert, E.Merle (CNRS)

Steps 2 – 3 : For each state – Identification of parameters

In order to **define the early stages of monitoring and control functions**, the **dependencies between parameters** are identified

What happens to parameter in column A when the parameter in the other column increases? (considering other parameters constant)	Fuel salt temperature	Fuel salt flowrate	Reactor thermal power	Reactivity	Fuel salt level
Fuel salt temperature		Average T is stable (critical T) DT decreases as long as IHX is able to remove heat. Does fuel flow has an impact on heat production?	Average T is stable (critical T) DT increases	Average T increases and comes back to critical T DT increases	No impact (but reversely, if T increases, lvl increases)
Fuel salt flowrate (forced flow)			No impact	No impact	No impact
Reactor thermal power				Increases	No impact
Reactivity					Depends on reactor status: - during reactor filling: increase of reactivity - while reactor is full: no impact
Fuel salt level					

Step 4 : Definition of the limitation and the protection strategy to set up

- The definition of the limitation and the protection strategy implies :
  - Definition of possible « **safe state(s) »** for MSR
  - Definition of **strategy** to reach « safe state(s) » identified

- Different kinds of safe states for MSR may be defined

Reminder that in France, in ASN Guide n°22 (addressed to PWR conception) :

- A "**safe state**" corresponds to a stabilized state of a nuclear powerplant, where the sub-criticality, the decay heat removal and the containment of radiological material are **sustainingly** ensured.
- A "**controlled state**" corresponds to a state of a nuclear powerplant, where the sub-criticality, the decay heat removal and the containment of radiological material are ensured at **short term** and where main parameters characterizing the safety functions previously-mentioned **do not evolve rapidly and negatively**.

*Nota : there is **not** a **single** safe state **nor** a **single** controlled state.*

Step 4 : Definition of the limitation and the protection strategy to set up

♦ On a MSR, the only states where all these criteria are met correspond to the states where the fuel salt is **transferred/drained** (in normal storage tanks, or in emergency draining tanks), in order to **reach sub-criticality**.

Nevertheless, **given the MSR specificities**, proposition for MSR of **at least 3 safe states** (in order of desirability)…

- Fuel salt transferred in normal storage tanks, DHR ensured sustainingly
- Fuel salt drained in emergency draining tank, DHR ensured sustainingly
- Fuel salt drained in core catcher, DHR ensured sustainingly

… and at least **a controlled state** :

- Fuel salt in the fuel circuit, **critical at low power**, heat removal ensured by natural convection*

** to be confirmed : the natural convection could not be necessary*

♦ The acceptability of these potential safe and controlled states has **consequences on the design (performances) and safety classification**, notably on the heat removal system associated to the fuel circuit.

In the safety demonstration, the systems necessary to reach controlled and safe state must have high safety classification. From an economic point of vue, there is an **interest to limit the number of equipment with high safety classification**.

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Thank you for your attention

Appendix : Methodology for this subtask

♦ Proposition to adopt the following approach :

1. Define the **normal operating modes for the reactor**

2. For each normal operating mode, draw up a list of relevant **Plant Parameters**

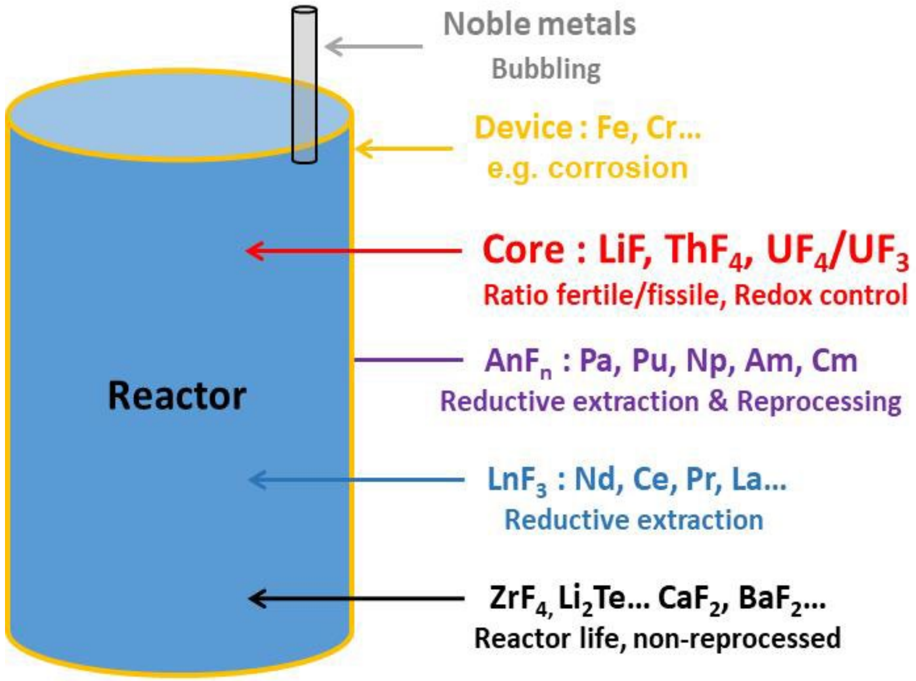
3. For each Main Plant Parameter, define the limits of the acceptable **range** for the parameter

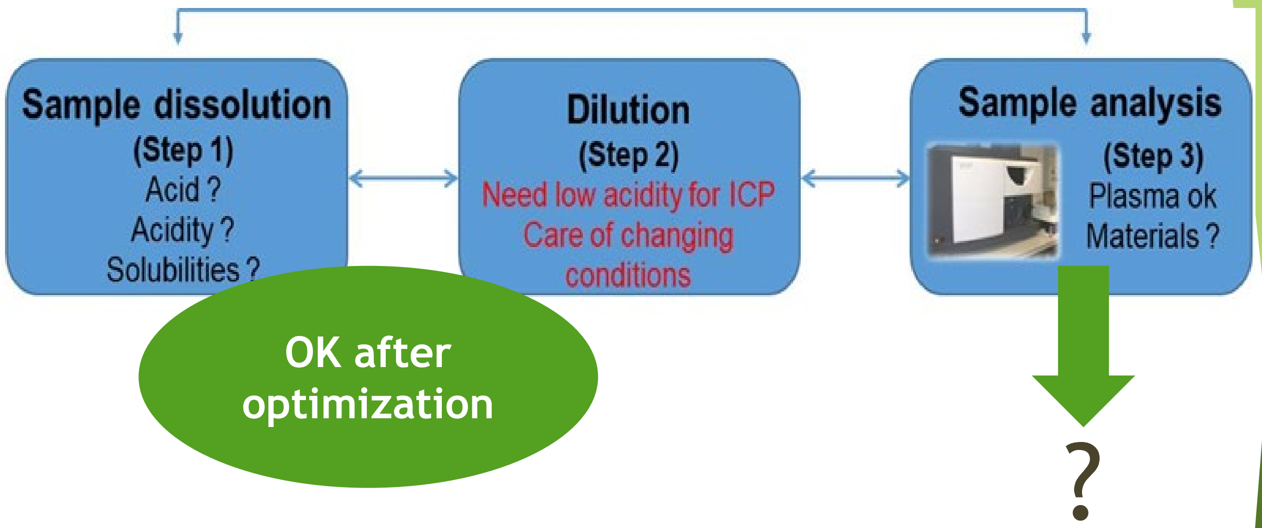
4. For each Main Plant Parameter, define the **limitation and the protection strategy** to set up

Task. n°	Task title	Lead beneficiary	Dates
6.1	Safety margins and plant operational states (CNRS, CEA, Framatome, EDF, POLITO)	CNRS	M01 – M30
6.2	Monitoring systems, inspection and maintenance procedures (POLITO, CNRS, Framatome, POLIMI)	POLITO	M06 – M36
6.3	Redox and salt composition control (CNRS, JRC)	CNRS	M01 – M48
6.4	Safety demonstration of the decay heat removal function (PoliMi, CNRS, EDF, PSI, Framatome)	KIT	M24 – M48
6.5	Uncertainty quantification of safety demonstration calculations (TU Delft, CNRS)	TU Delft	M24 – M54
6.6	Scaling in reactor design and effects on safety level (CNRS, Framatome, CEA, IRSN, EDF)	CNRS	M12 – M54

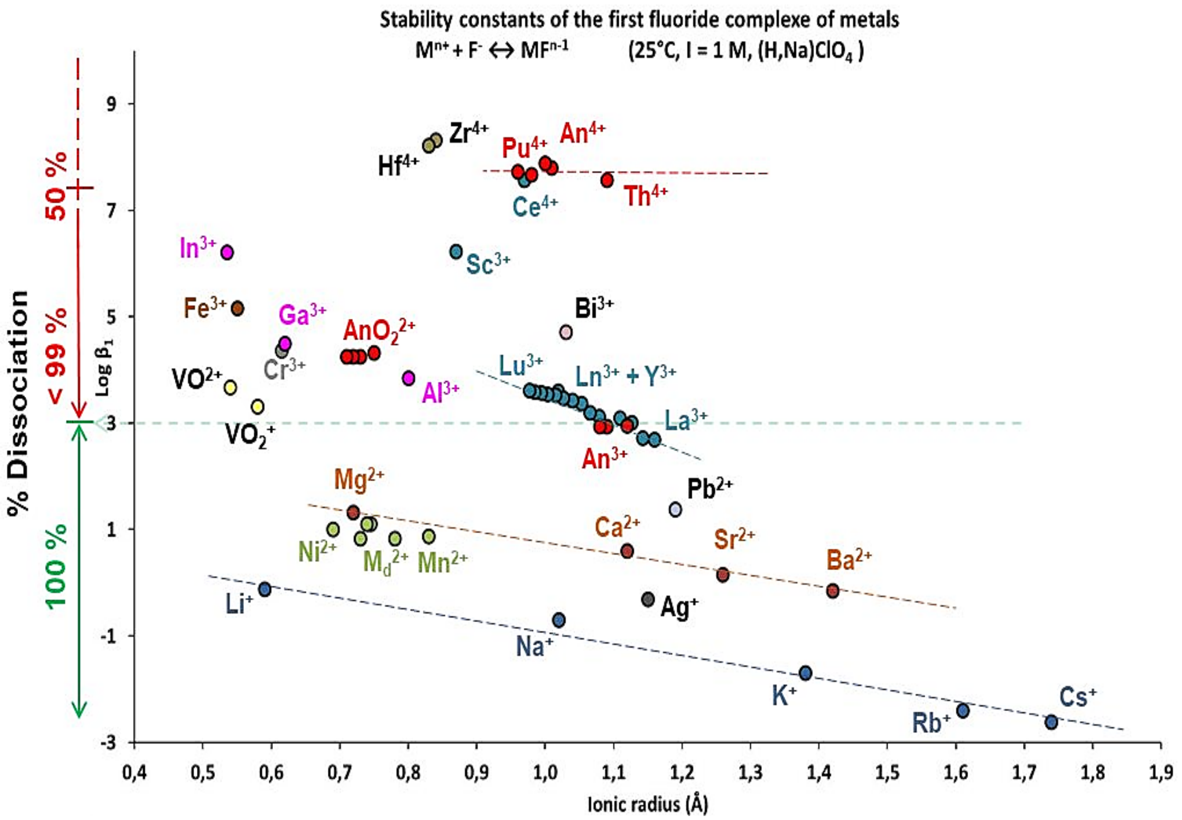
Task 6.3: Redox and fuel composition control

Use of ICP-OES to analyse the core fuel composition





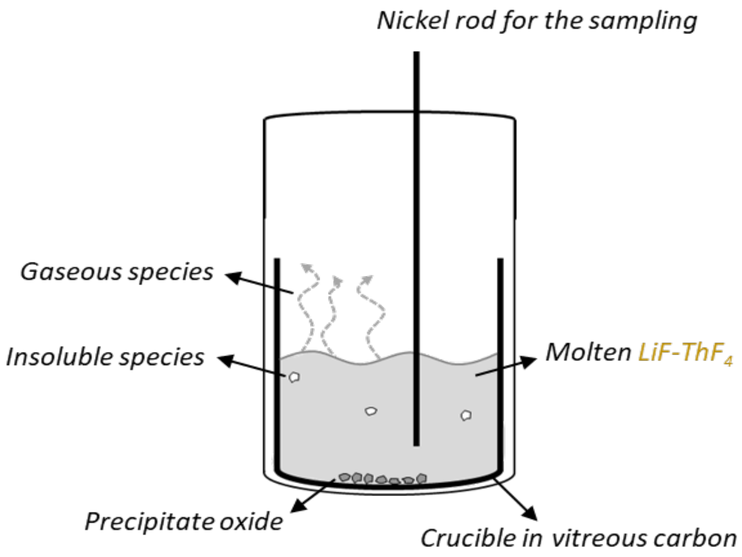
Dissociation of fluoride in plasma



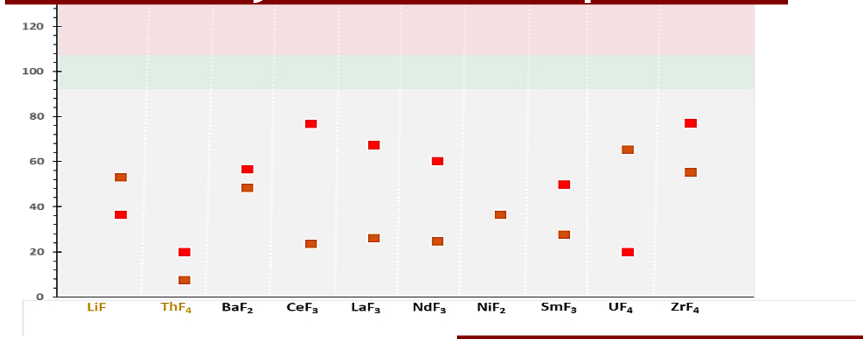
- *Difficulty to reach 100% of dissociation of fluorides in plasma leads to errors in the analysis*
- *Some pure fluoride powders of Ni, Fe, Zr,… are not analyzed with high accuracy*
- ***But, when the pure powders are dissolved in FLiNaK salt we reach a high accuracy of analysis***

Analysis of LiF-ThF_4 salt

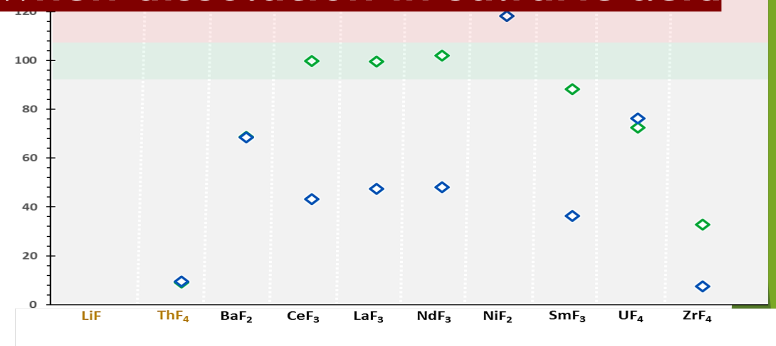
Tests in LiF-ThF_4 containing U, Ba, Ce, La, Nd, Ni, Sm, Zr



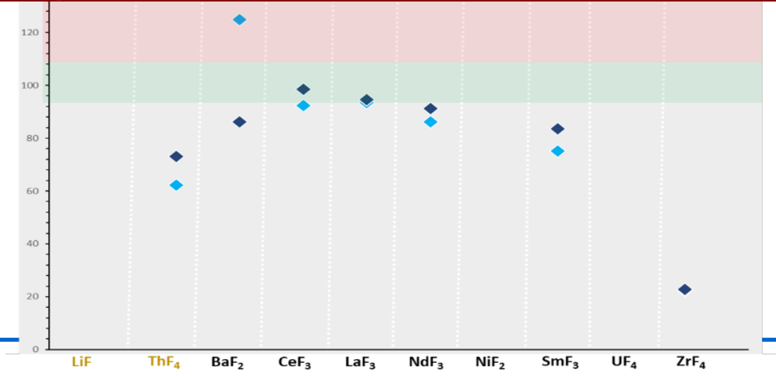
Direct analysis of the sample : BAD



Sample dissolved in FLiNaK and analyzed : Good when dissolution in sulfuric acid

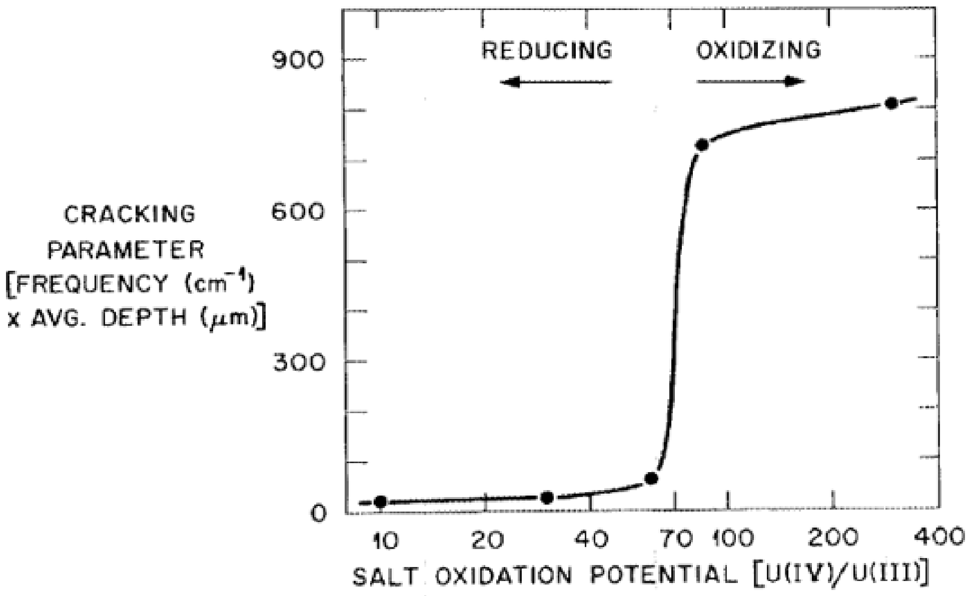


Sample dissolved in LiCl-KCl and analyzed :Best result



Task 6.3: Redox and fuel composition control

Control of the redox potential of the salt to prevent the corrosion

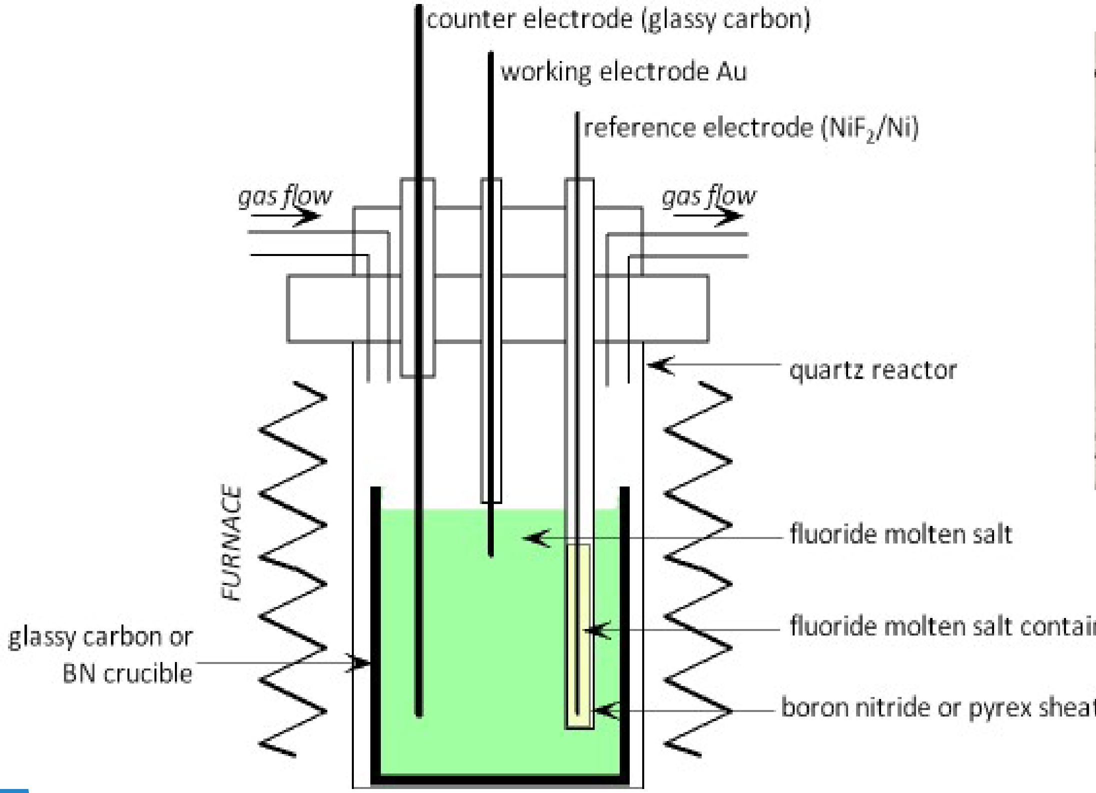


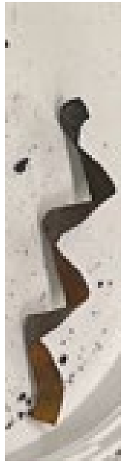
From ORNL: the ratio UF_4/UF_3 directly related to the corrosion

Addition of Be metal to reduce the ratio

For MSFR, addition of U metal is proposed to control the ratio

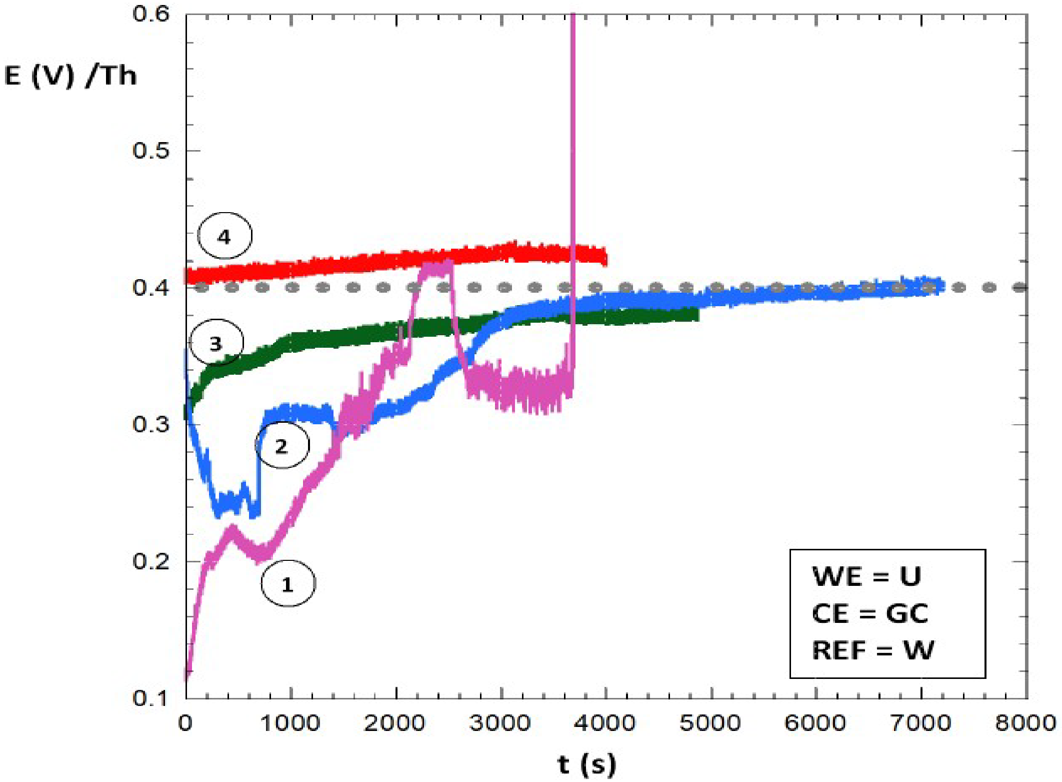
Control of the redox potential of the salt by producing UF_3



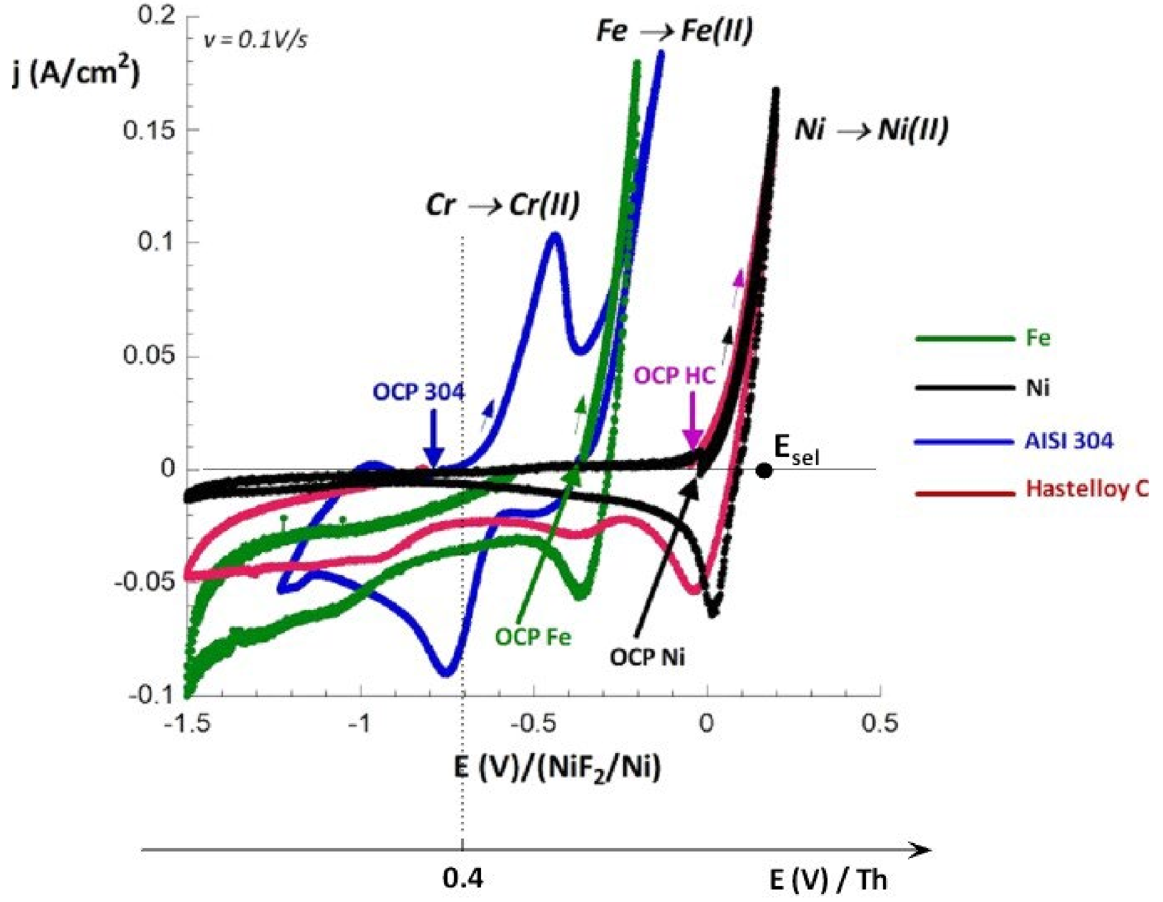


Measurement of OCP on U electrode in LiF-ThF_4-UF_4. Observation of the reaction between U metal and UF_4 to produce UF_3

$$3UF_4 + U \rightarrow 4UF_3$$



Comparison of the redox potential of the salt with the potentials of the redox systems of the structural materials



The potential applied by the reaction between UF_4 and U metal can prevent the corrosion.

Thank you for your attention

CORE DESIGN AND POWER STABILITY OPTIMISATION

A. Laureau CNRS / IN2P3 / LPSC

Avignon
Palais des Papes
November 28, 2023

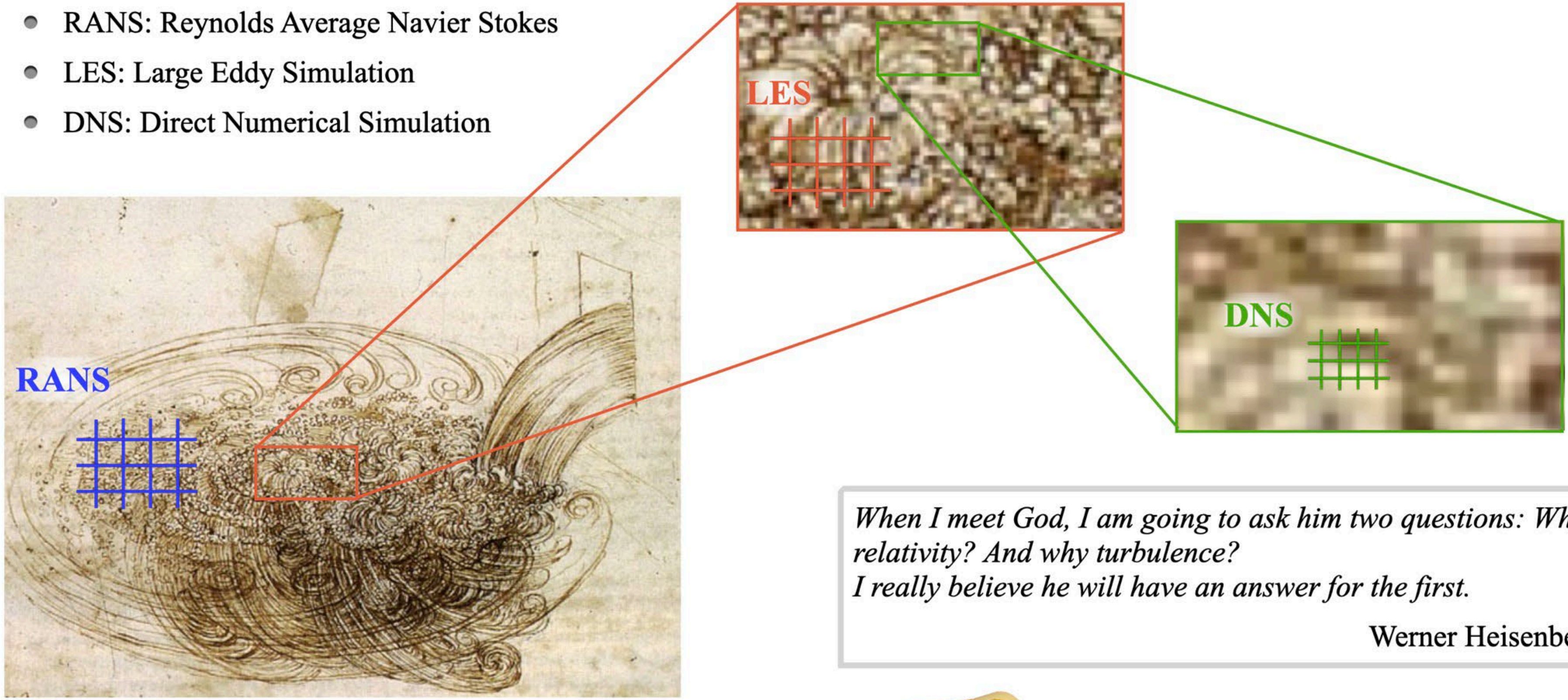
Outline

I - Introduction	• What are we talking about?
III - (advanced) Thermalhydraulics	• Turbulence modeling • Numerical constraints • Detached Eddy Simulation - DES
III - (simplified) Neutronics	• Requirements and simplifications
IV - Results	• Application to the MSFR "EVOL shape" • Bonus
V - Conclusions	• What's next?

WHAT ARE WE TALKING ABOUT?

Family code: CFD - Computational Fluid Dynamics

- RANS: Reynolds Average Navier Stokes
- LES: Large Eddy Simulation
- DNS: Direct Numerical Simulation

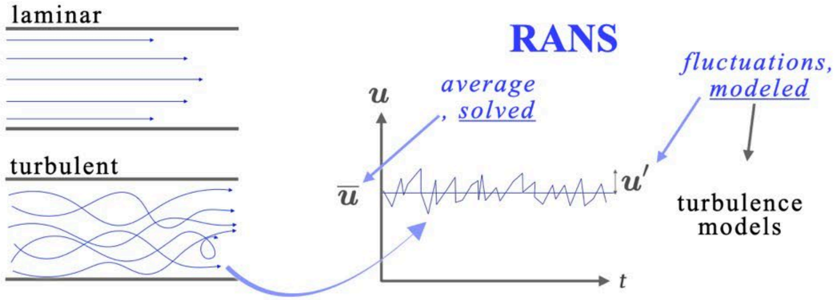


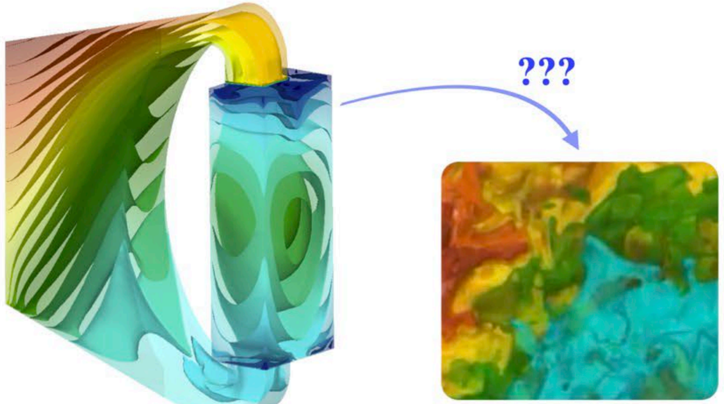
[Léonard de Vinci]

RANS - ideal case

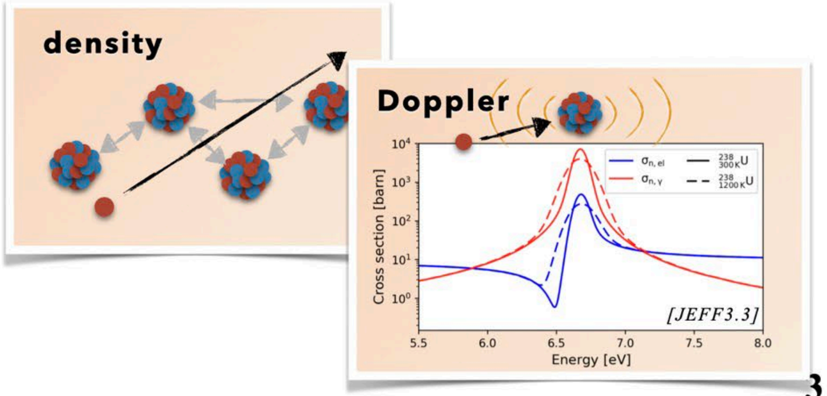
LES - real life

> *When I meet God, I am going to ask him two questions: Why relativity? And why turbulence?*
> *I really believe he will have an answer for the first.*
>
> Werner Heisenberg





Classic RANS approach



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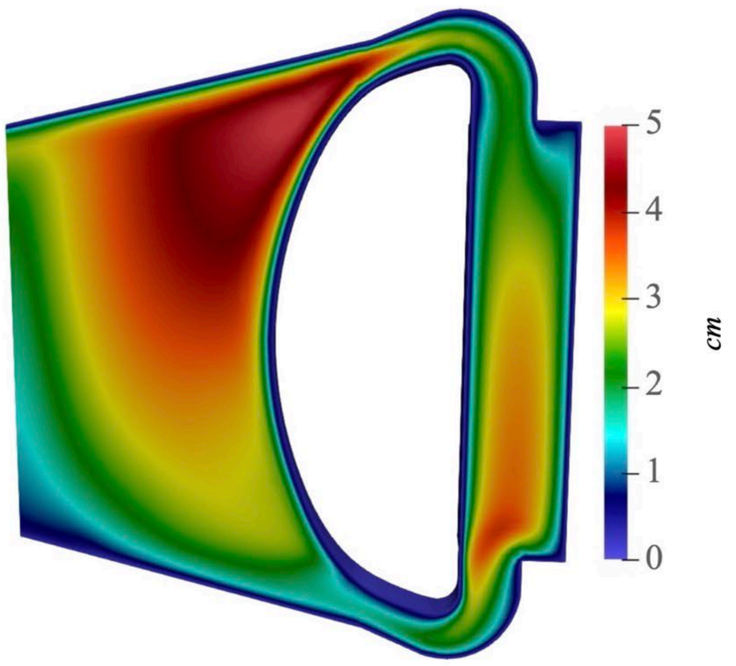
NUMERICAL CONSTRAINTS

Need to solve the (large) eddies

- Strong constraint on the mesh size according to the eddies size

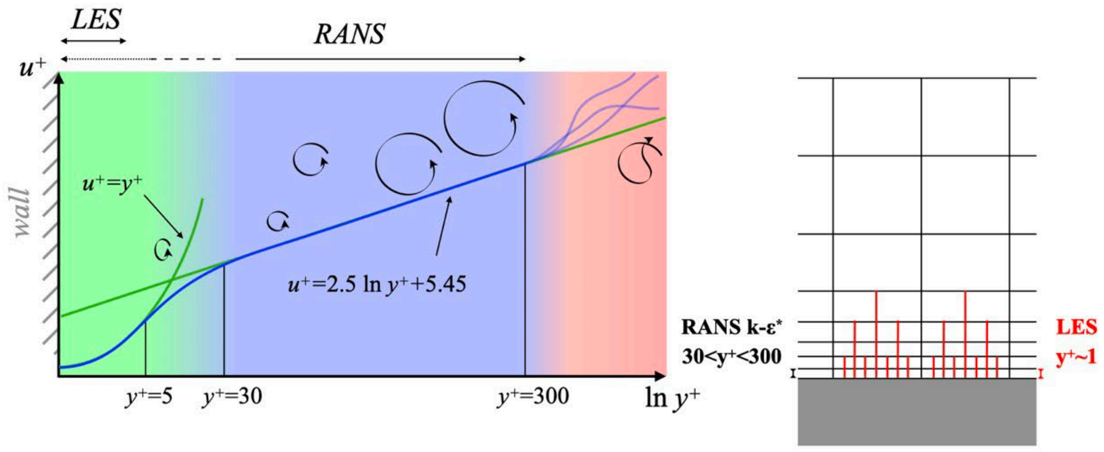
$$\lim_{m\to\infty} \text{RANS} \neq \lim_{m\to\infty} \text{LES} = \text{DNS}$$



"theoretical" maximal meshes size estimated with a k-ε calculation assuming for 90 % Kolmogorov's energy spectrum

Contraint on the first mesh

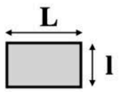
- "Dimensionless distance" y^+ close to 1 in the viscous sublayer



U [m/s]	L [m]	y [mm] for $y^+ = 1$
2	2	$3.0\ 10^{-2}$
3	2	$2.0\ 10^{-2}$
2	0.3	$2.4\ 10^{-2}$
2	0.03	$1.9\ 10^{-2}$

"theoretical" meshes size for a given y^+ with analytical analysis

- Limit the aspect ratios (1)
  ➙ $L/l \leq 2$ is ok
  ➙ $L/l \leq 20$ is ok "for simple shear flows"



- Different rules depending on sources...
  ... sensitivity on the mesh size is important!!

1: [@ANSYS - Quick Guide to Setting Up LES-type Simulations]

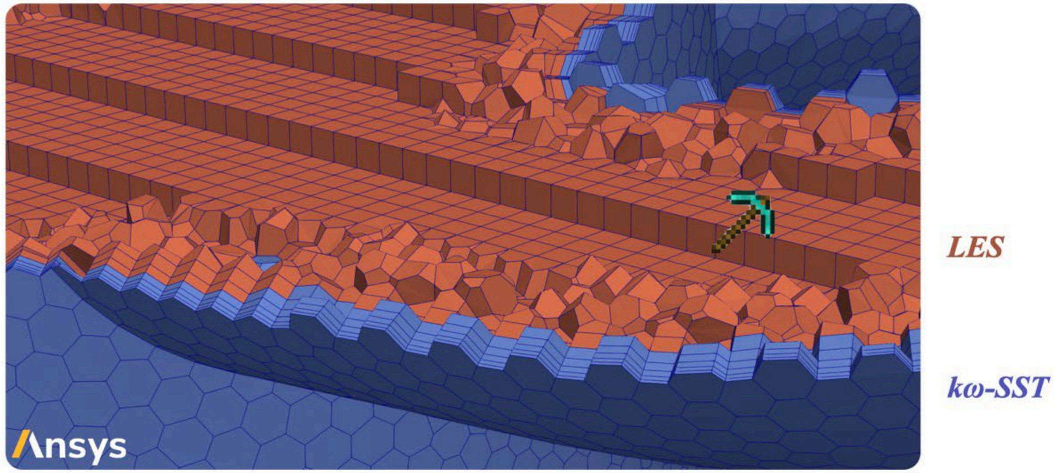
NUMERICAL CONSTRAINTS

Summary

- ~1×1×1cm^3 far from the wall
- L/l ≤ 2 and y+ means 0.02×0.04×0.04 mm close to the wall...
  This is a huge constraint on:
  - the number of meshes
  - the time step

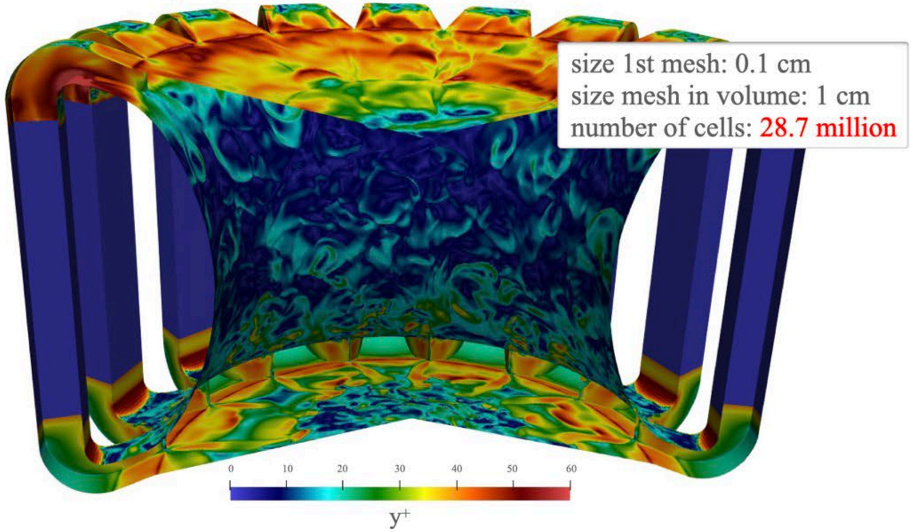
Hybrid approach

- LES far from the wall and RANS close to wall:
  IDDES - k-ω-SST-DES model [1] with OpenFOAM
- k-ω-SST wall function allows local value in the transition range

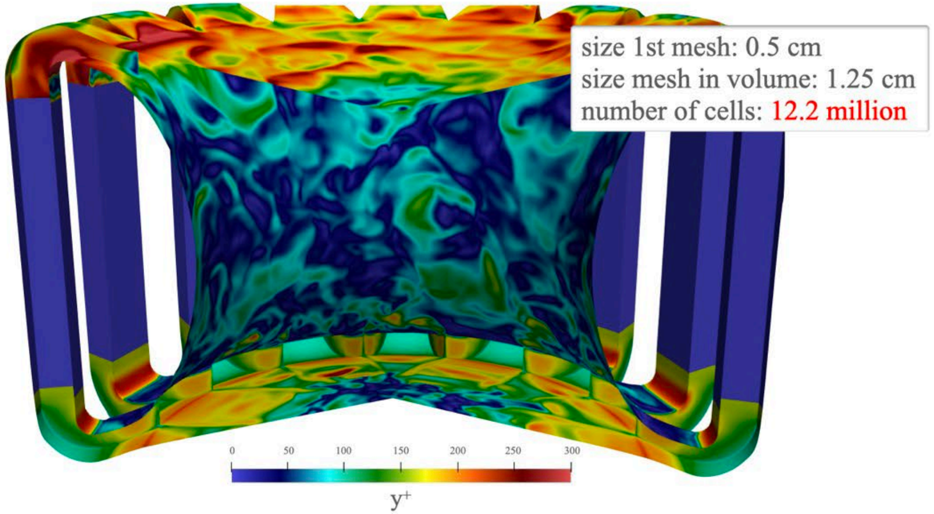


DES approach (detached eddy simulation)

Mesh A - fine (used for the next illustrations)



Mesh B - "coarse"



1: [*M. S. Gritskevich, A. V. Garbaruk, J. Schu¨tze, F. R. Menter, Development of DDES and IDDES formulations for the k-ω shear stress transport model, Flow, turbulence and combustion 88 (3) (2012) 431–449*]

OUTLINE

REQUIREMENTS AND SIMPLIFICATIONS

Why a simplified neutronics approach?

- Due to the large power fluctuations:
  - How can we get a "steady state" to start the calculation?
  - More difficult to compare configurations
- Faster process for geometry optimisation (next step/objective)

Simplified approach

- Power shape from the neutron transport Serpent2 code
- Reactivity calculation based on local temperature distribution
- No update of the total power

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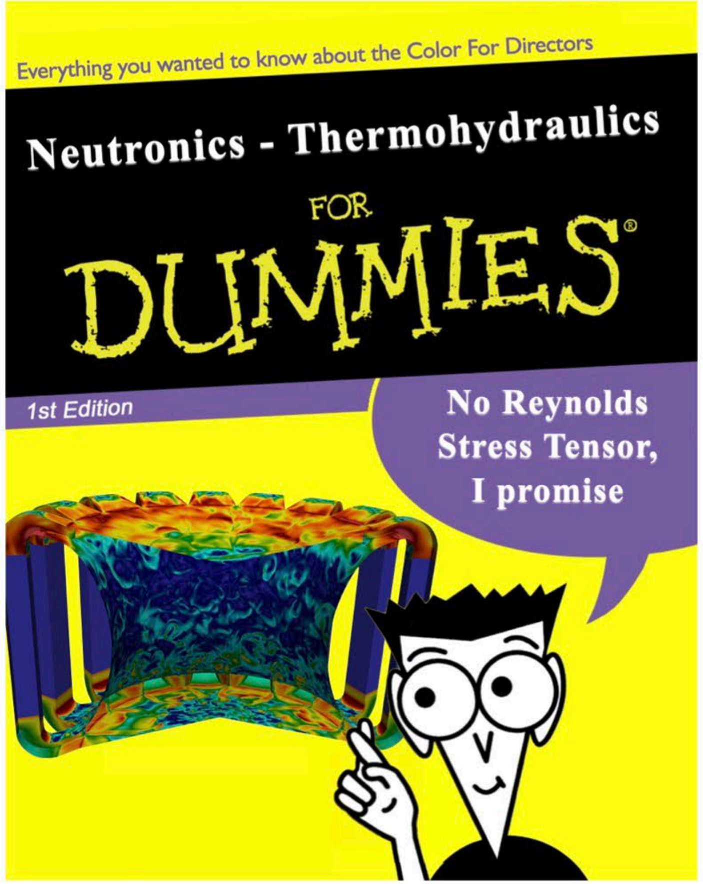
WHAT'S NEXT?

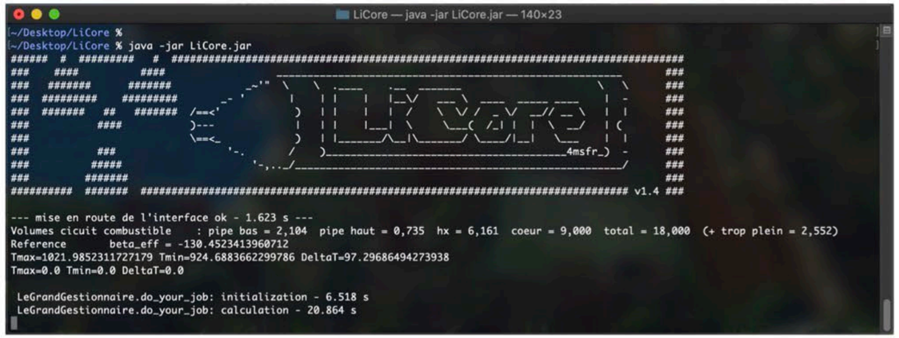
Conclusions

- Power stability modeling capability is fine
- The core design (shape) has to take into account power fluctuations
- EVOL-Shape has been optimized according to RANS...
  ... A new optimization is proposed with higher fidelity model



Perspectives

- Core shape optimization
- A law can be extracted from the temperature fluctuation characterization...
- Usable by system codes (LiCore, Mosaics, Modelica...)
  And see how it impacts the system behavior



THANK YOU FOR YOUR ATTENTION!

Do you have some questions?