GEN IV International Forum℠

THERMAL-HYDRAULICS IN LIQUID METAL FAST REACTORS

Dr. Antoine Gerschenfeld

CEA, France

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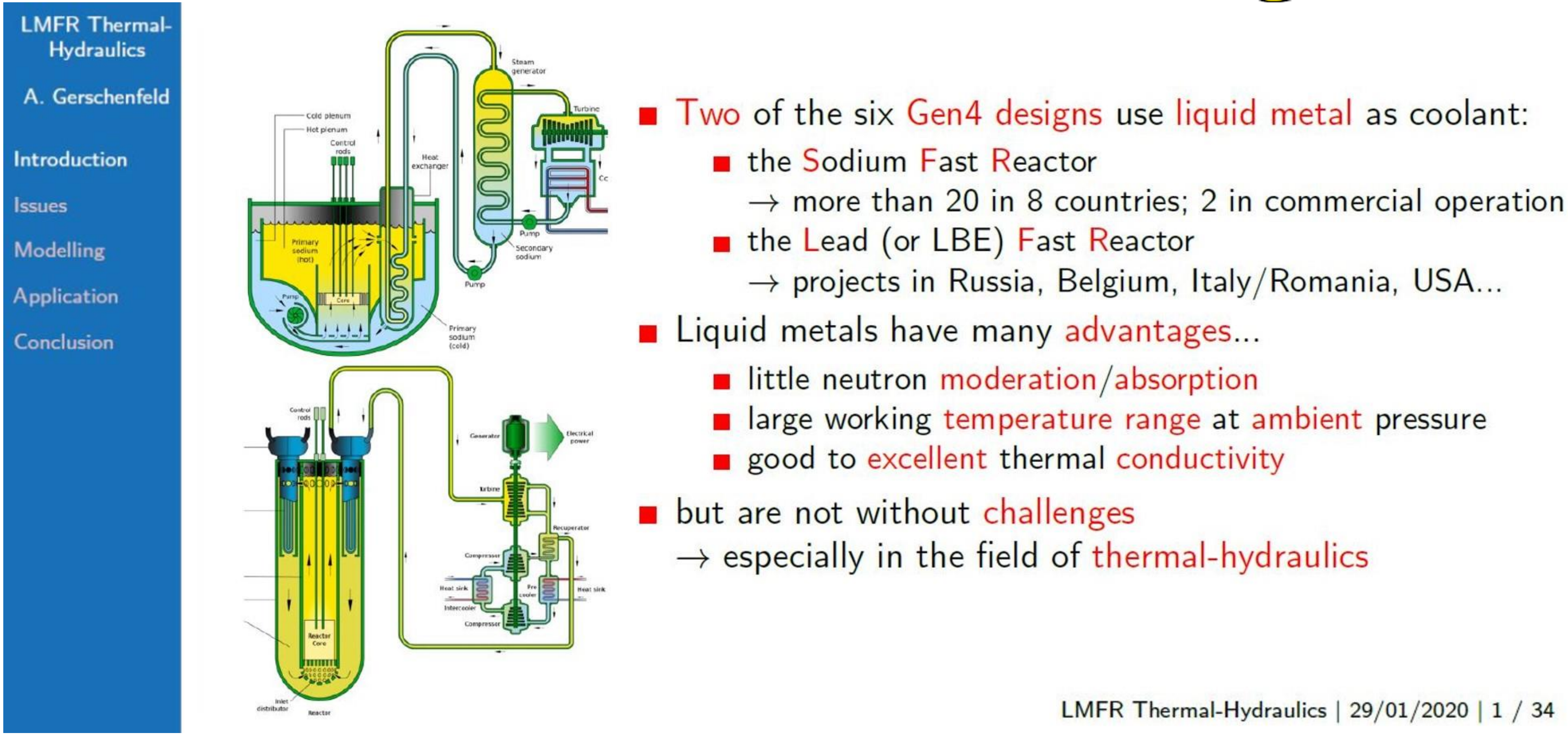
Meet the Presenter

Dr. Antoine Gerschenfeld earned his PhD from Ecole Normale Supérieure, France, in 2012, and has been coordinating R&D on the thermal-hydraulics of Sodium Fast Reactors at the Commissariat a l Energie Atomique et aus Energies Alternatives (CEA)'s Thermal-Hydraulics and Fluid Mechanics Section (STMF) since 2013. In that capacity, he has led the development of a subchannel thermal-hydraulics code (TrioMC) as well as the development of a tool for coupling coarse and fine models in a single reactor-scale simulation (MATHYS). He has also been involved in a number of collaborations: bilateral exchanges with DOE, JAEA and IPPE; EURATOM projects on liquid-metal reactors; and in international GIF, NEA and IAEA working groups.

Email: antoine.gerschenfeld@cea.fr

Introduction



- Two of the six Gen4 designs use liquid metal as coolant:
  - the Sodium Fast Reactor
    → more than 20 in 8 countries; 2 in commercial operation
  - the Lead (or LBE) Fast Reactor
    → projects in Russia, Belgium, Italy/Romania, USA...
- Liquid metals have many advantages...
  - little neutron moderation/absorption
  - large working temperature range at ambient pressure
  - good to excellent thermal conductivity
- but are not without challenges
  → especially in the field of thermal-hydraulics

Introduction

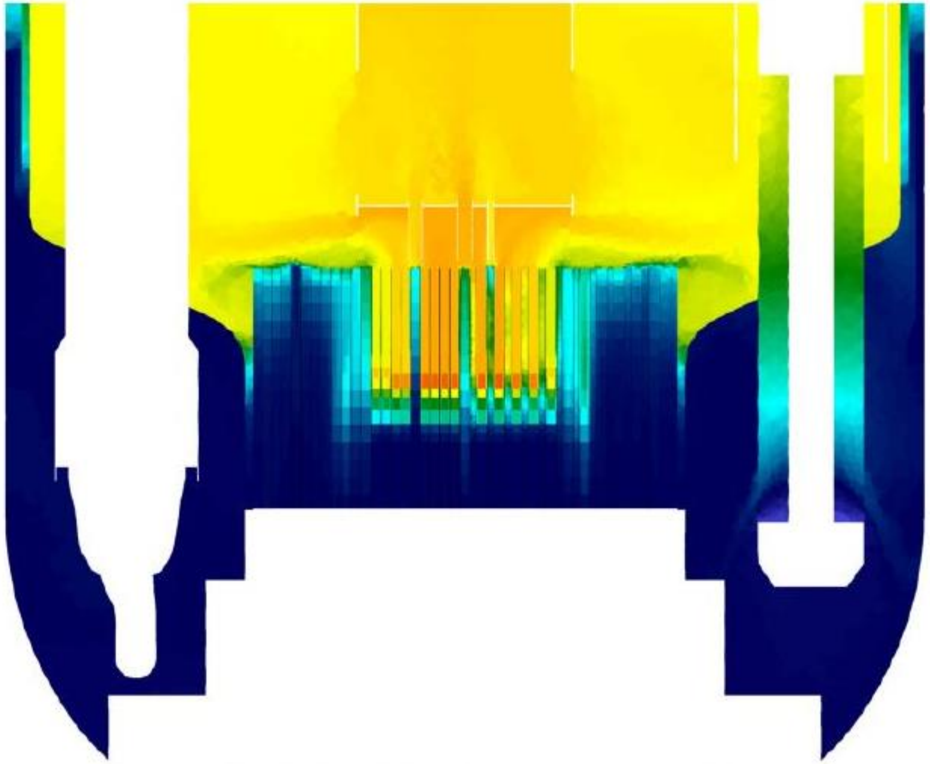
Thermal-hydraulics?

- the behavior (velocity, temperature, pressure) of all fluids in the reactor:
  - here → the liquid metal (Na, Pb, LBE)
  - but also : cover gas, power conversion cycle,...
- must be evaluated both:
  - in nominal operation → to assess the loads on structural materials → and justify their expected lifetime : 60 years!
  - in accidental scenarios → to assess the reactor's safety → and, if necesary, adapt its design

In this presentation

- main thermal-hydraulics issues in LMFRs
- the tools at our disposal to analyze them
- an example application of these tools → to the study of natural convection

Introduction



ASTRID primary pool

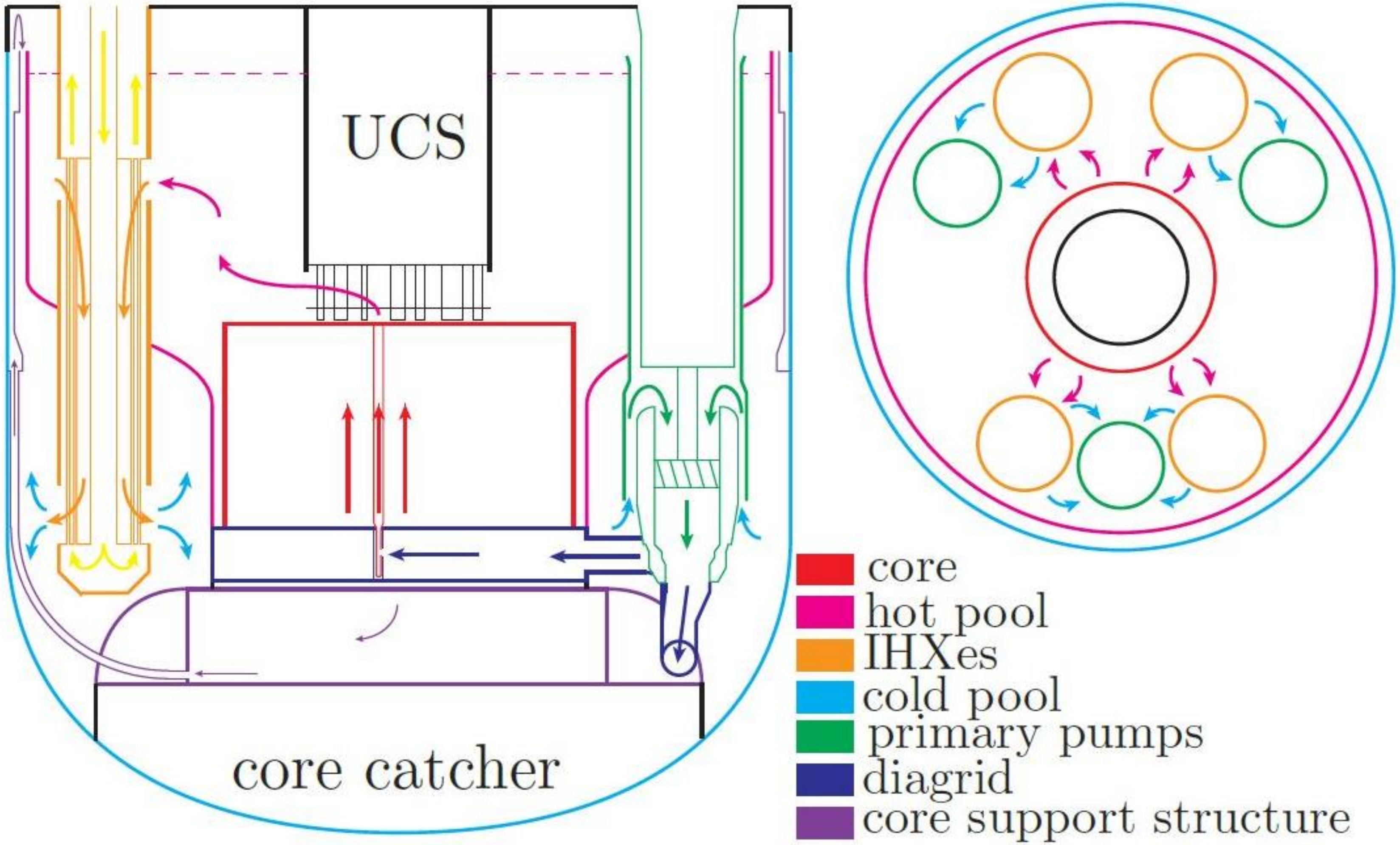
Common features of LMRs

- quite high working temperatures:
  - SFRs: 400° → 550°/650° (average/local)
  - LFRs: around the same

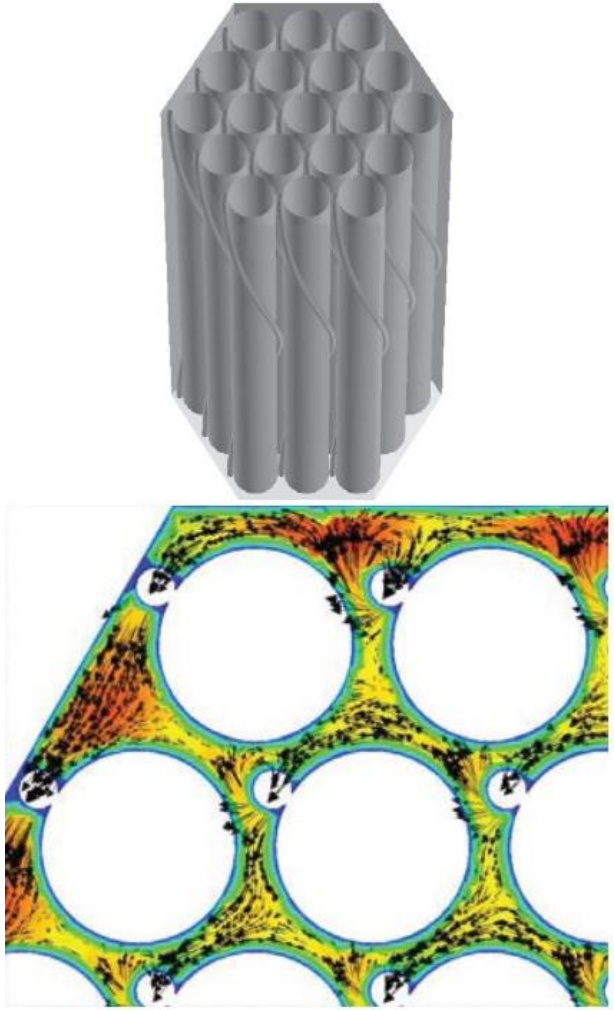
→ determined by material limits (steel ∼ 700°)

- no pressurization → pool-type designs:
  - minimize pipe break scenarios (like SMRs!)
  - large thermal buffer in accident scenarios
  - at top: cover gas
- in SFRs → intermediate loops:
  - protect primary from Na/H_2O reactions

Issues: overall view



Core / per-subassembly



quite complex structures: pins, wires/grids

Issues of interest

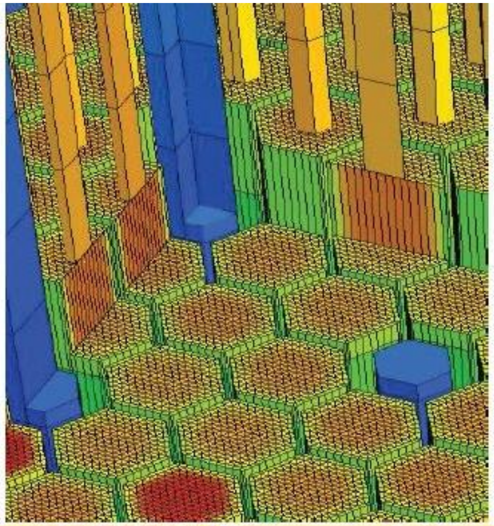
- Cladding temperatures:
  - nominal state : $T \leq 620^\circ$C
    ⇒ avoid rupture
  - accidents : $T \leq \sim 1200^\circ$C
    ⇒ avoid melting

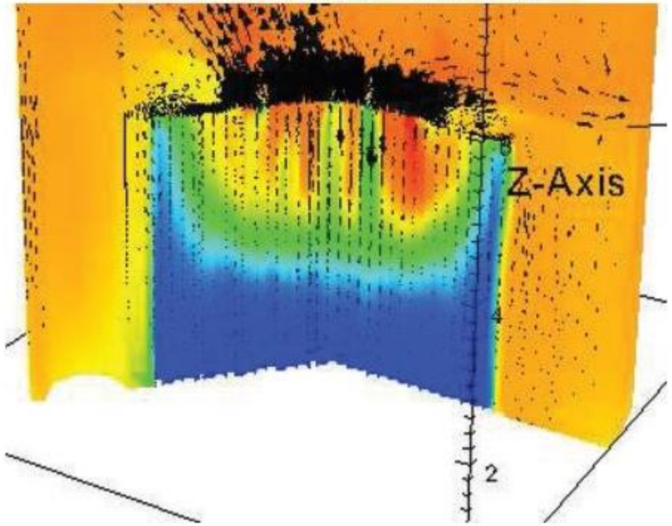
→ if possible locally: at least pin-by-pin!

TH phenomena to model

- nominal state: mixing by wires or grids
- accidental states:
  - coolant boiling → for SFRs
  - cladding rupture ⇒ gas release
  - partial or total blockage

Core / overall behavior





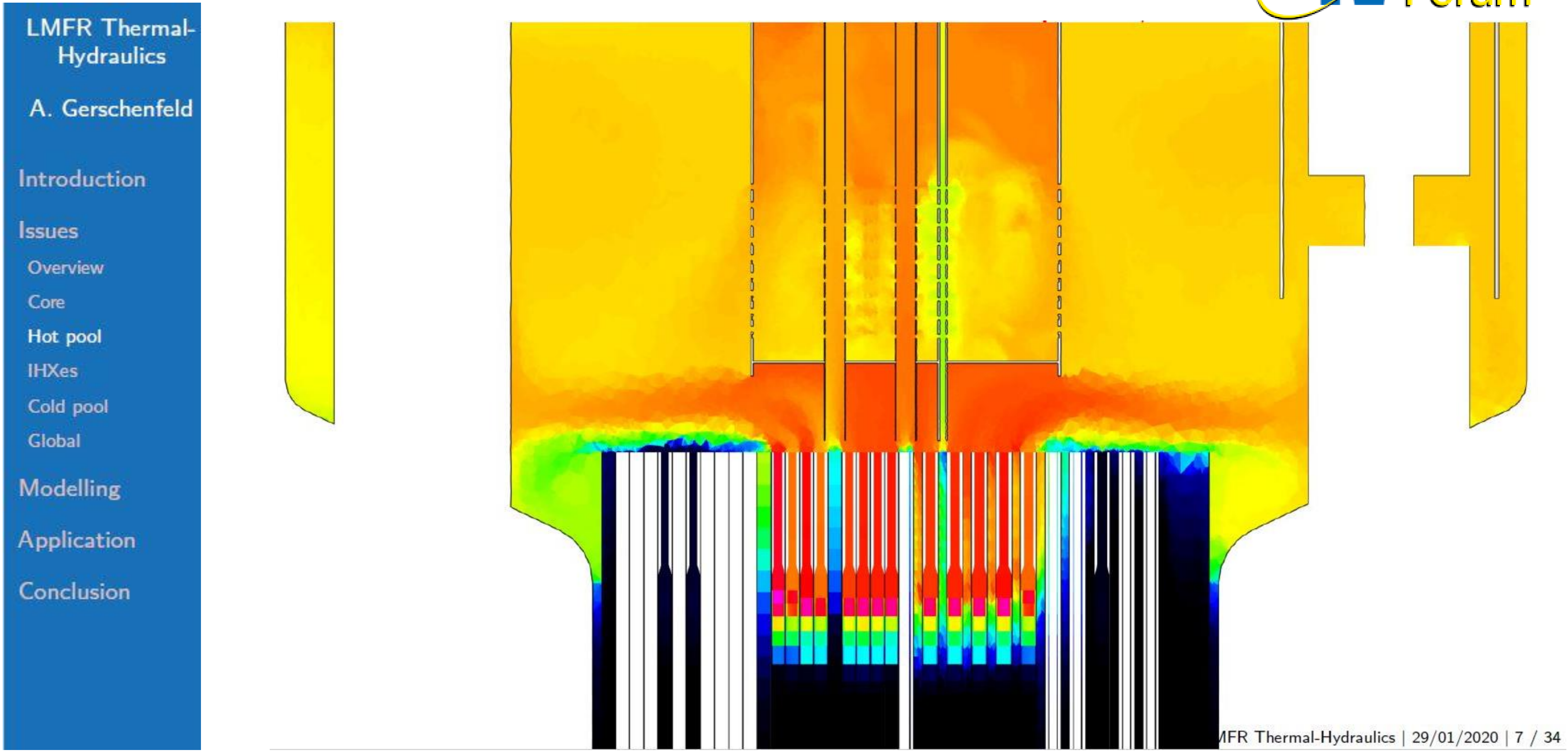
Normal operation

- flowrate repartition between S/As
  ⇒ optimisation
- core mechanical behavior
  ← hex can temperatures

Accidental scenarios

- core cooling by inter-wrapper flow
  in particular : internal storage
- coupled effects with:
  - core neutronics
    ⇒ point kinetics or more complex
  - fuel thermal mechanics

Hot pool / Core outlet

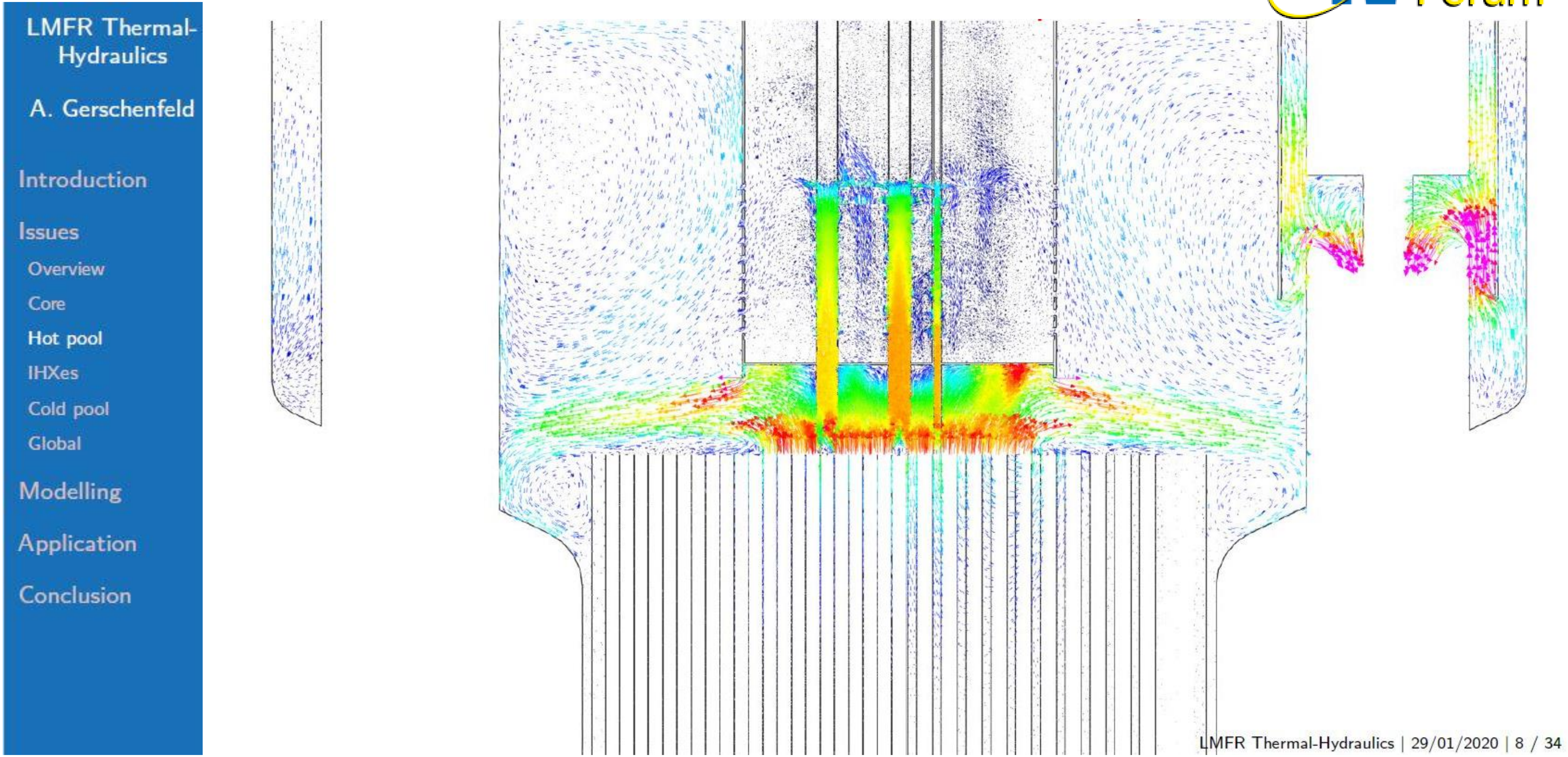


LMFR Thermal-Hydraulics

A. Gerschenfeld

- Introduction
- Issues
  - Overview
  - Core
  - **Hot pool**
  - IHXes
  - Cold pool
  - Global
- Modelling
- Application
- Conclusion

Hot pool / Core outlet



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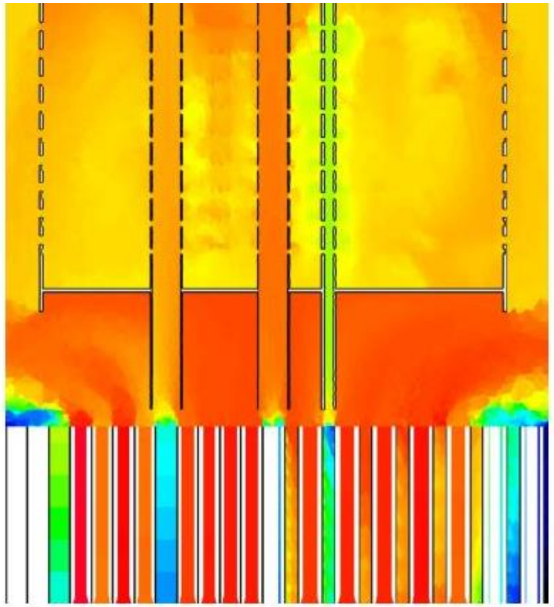
Hot pool / Core outlet



Upper Core Structure

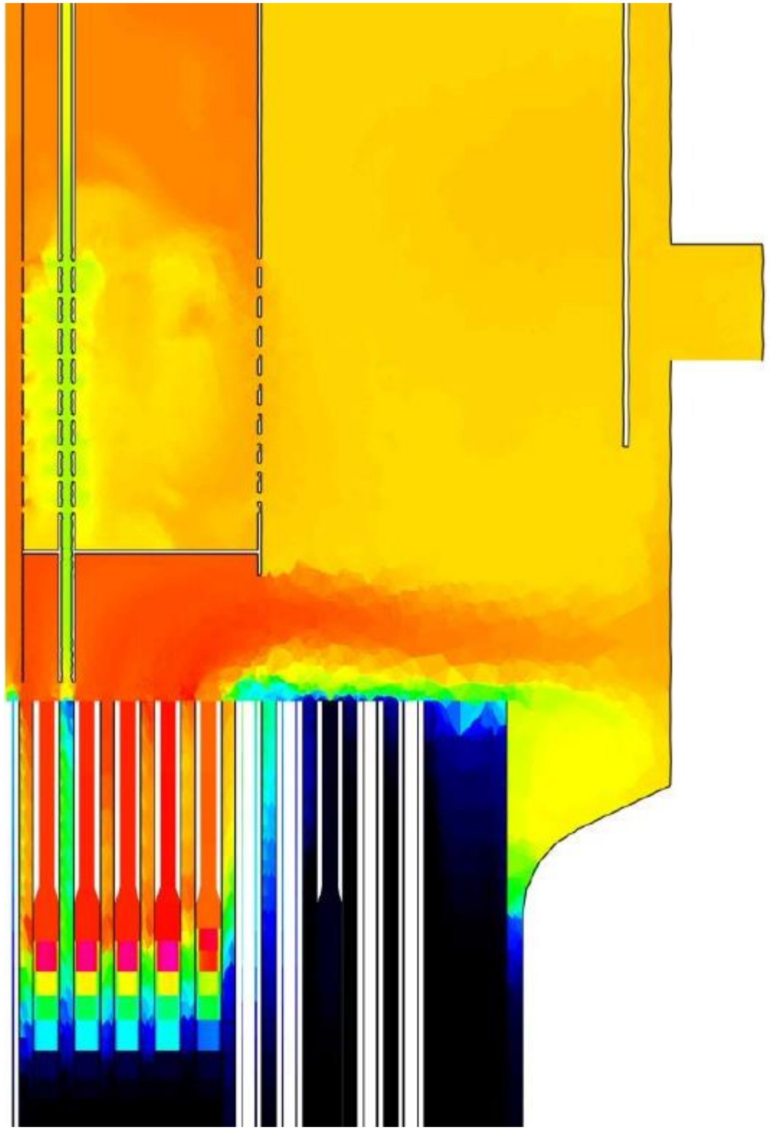
very complex:

- S/A outlet thermocouples
- control rod guidelines
- core outlet temperature differences:
  - fuel → 550°
  - CR tubes → 430°

Issues

- nominal state:
  thermal fluctuations due to jet mixing
- incidents / accidents :
  - hot/cold shocks
    → thermal loads
  - reliability of core outlet temperature measurements

Hot pool



very large liquid volume!

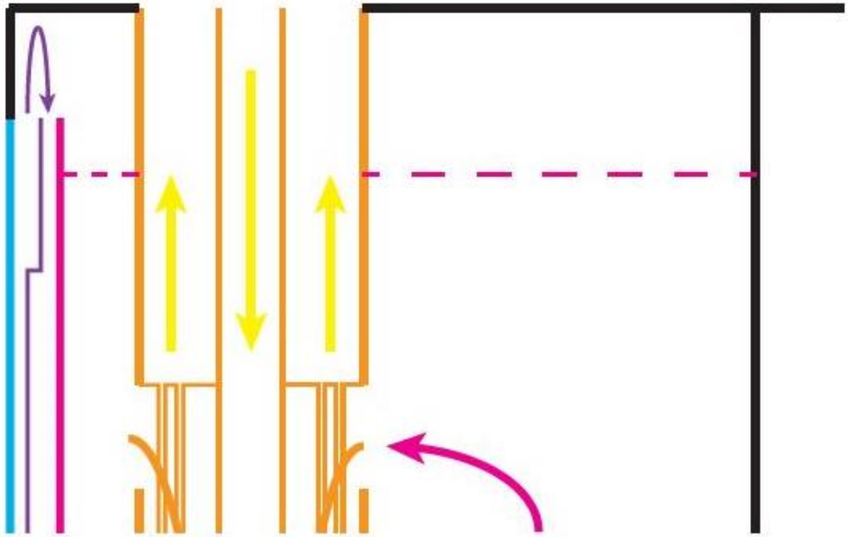
Steady-state issues

- core outlet jet shape
  → in full and partial regimes
- thermal interface position
  → inner vessel thermals:
  loads, fluctuations

Accidental issues

- hot / cold shocks on vessel, components
- flow changes at low flowrate:
  jet shape change, stratification

Free surface



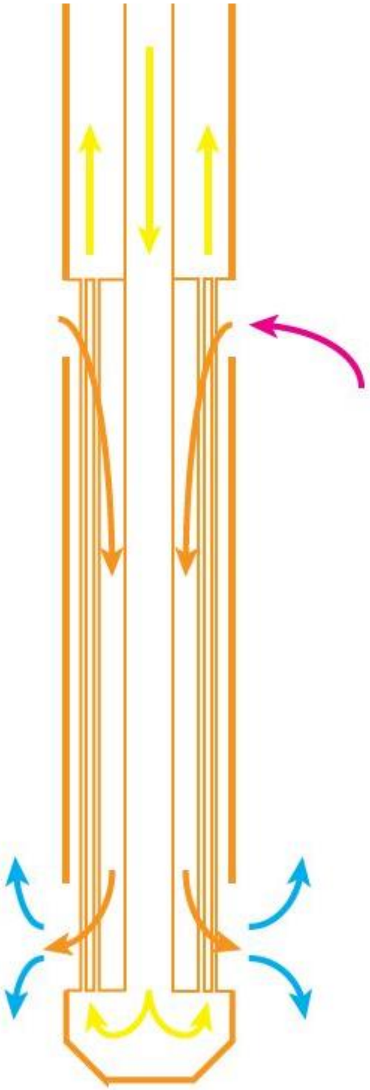
Issues in normal operation

- in steady-state:
  - wave formation → thermal loads
  - cover gas: reactor slab heating
  - in SFRs: vortex formation → possible gas entrainment!
- during load-following:
  - flowrate variation → level changes!

Issues in accidental scenarios

- in LFRs : seismic sloshing → mechanical loads!

Intermediate heat exchangers (SFRs)



complex components : thousands of tubes!

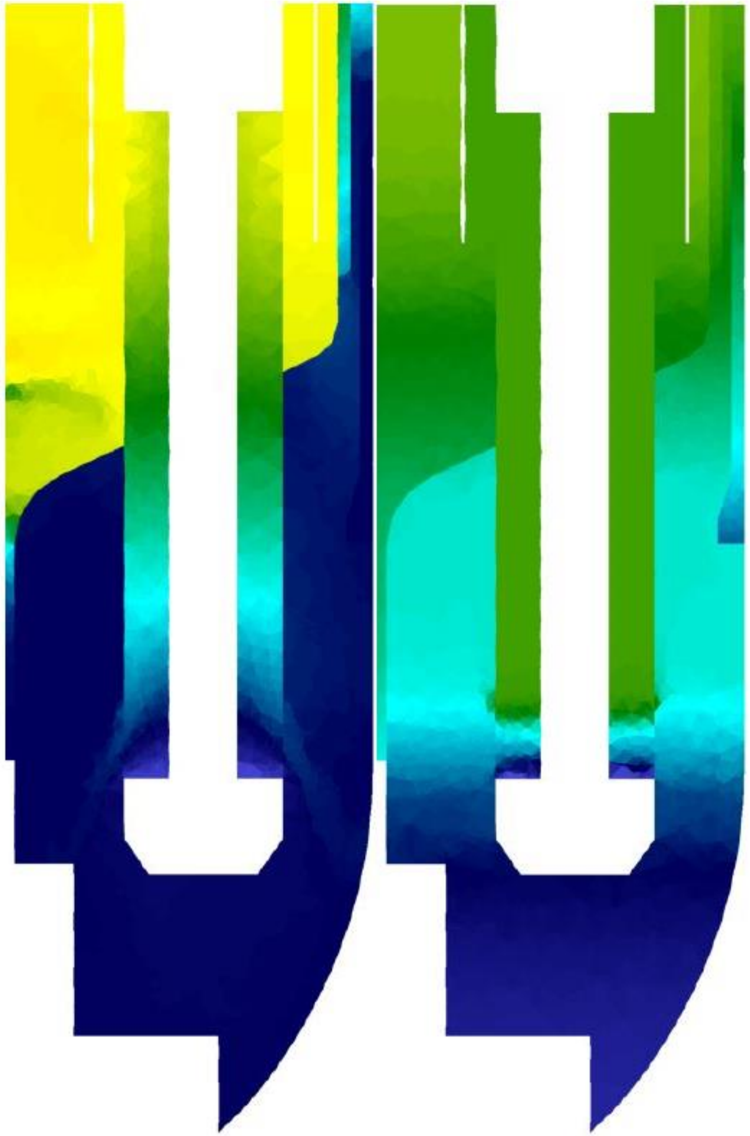
Issues in normal operation

- performance : pressure drop, heat transfers
- thermal loads during startup/shutdown

Issues in accidental scenarios

- possible 3D effects : in particular, recirculations at low flowrate
- outlet jet behavior in cold pool
  (⇒ stratification)
- hot / cold shocks : risk of tube rupture

Cold pool



even larger than the hot pool!

Nominal state issues

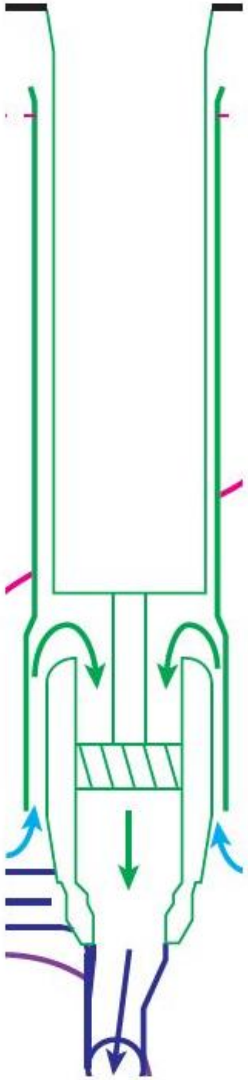
- stratification above IHXes
- IHX outlet jet : shape, stability...

⇒ thermal loads on inner and main vessel

Accidental issues

- jet / stratification changes during:
  - loss-of-flow transients → thermal buffer
  - dissymetric events (one intermediate loop) → hot shock propagation

Pumps



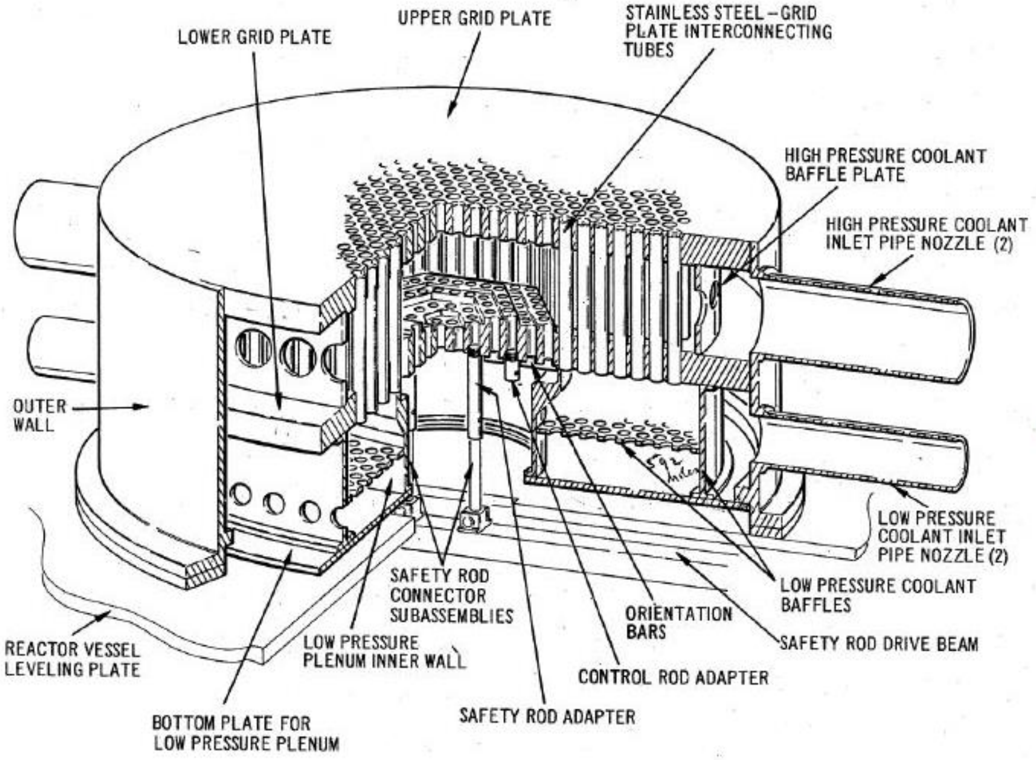
Issues

- nominal state: performance

$$\Delta P_{pump} = f(\omega_{pump}, Q_{pump})$$

- accidental states :
  - pressure drop at stop
  - overspeed, reverse flow (pump-diagrid break) $\Rightarrow$ cavitation!
  - seizure at high temperatures

Diagrid



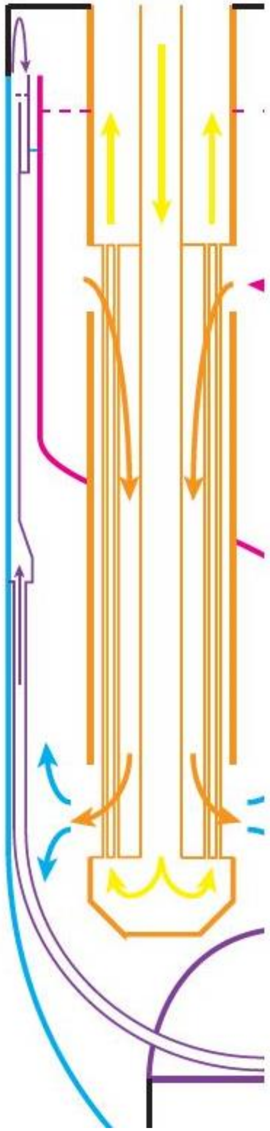
Steady-state issues

- hydraulics:
  - pressure drop
  - local flow effects close to inlet pipes
- in SFRs: possible gas accumulation

Accidental issues

- thermal dilation (strong neutronic effects!)
- dissymetric behavior:
  - single-pump trip, pump-diagrid pipe break → uneven flow at core inlet
  - intermediate loop pump trip → uneven temperature

Vessel cooling system



Keep main vessel at cold temperature → very important!
usually uses 10-20% of pump flowrate

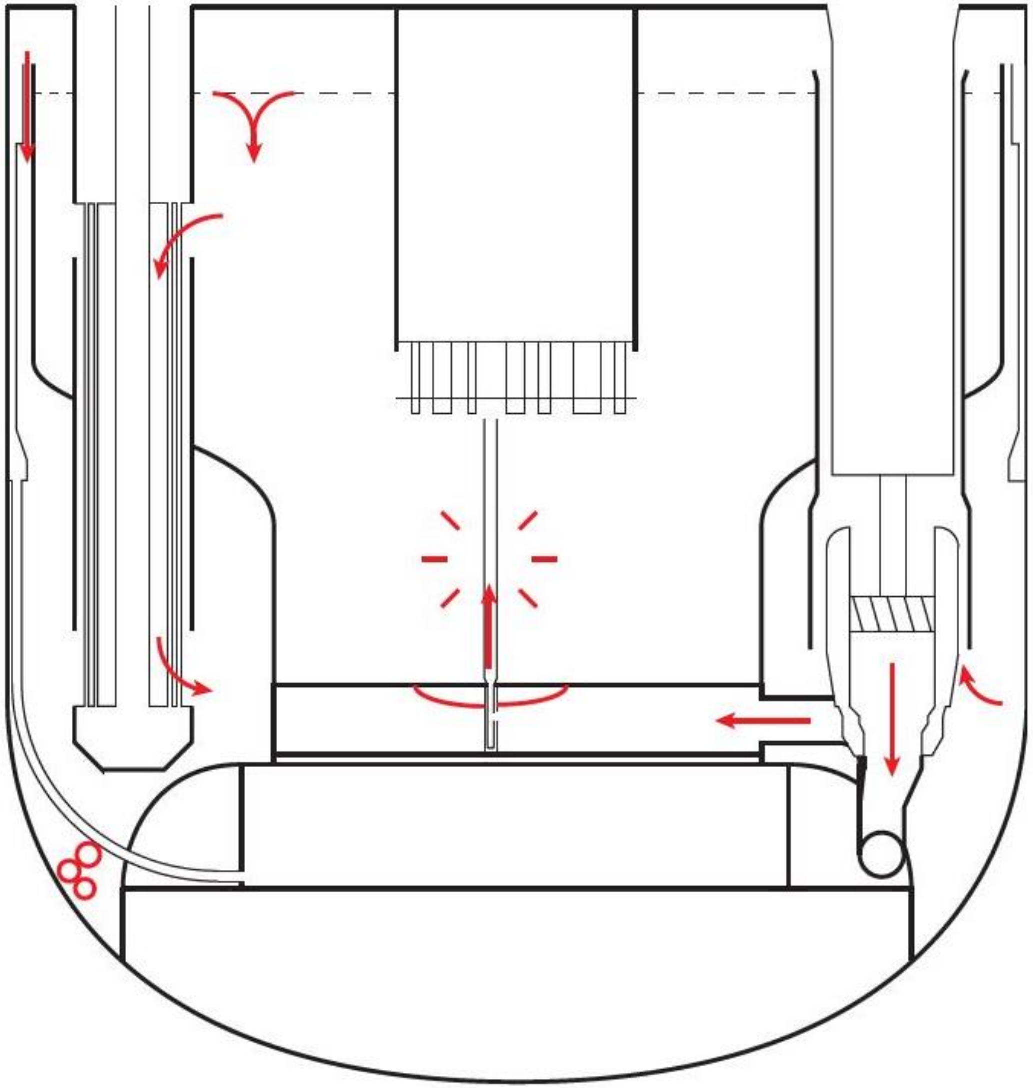
Steady-state issues

- complex thermal transfers:
  hot pool → cold pool → vessel cooling system
- potential for gas accumulation
  → especially in weir-type designs

Accidental scenarios

- possible flow reversal in VCS
  → can contribute to thermal buffer

Issues / Global

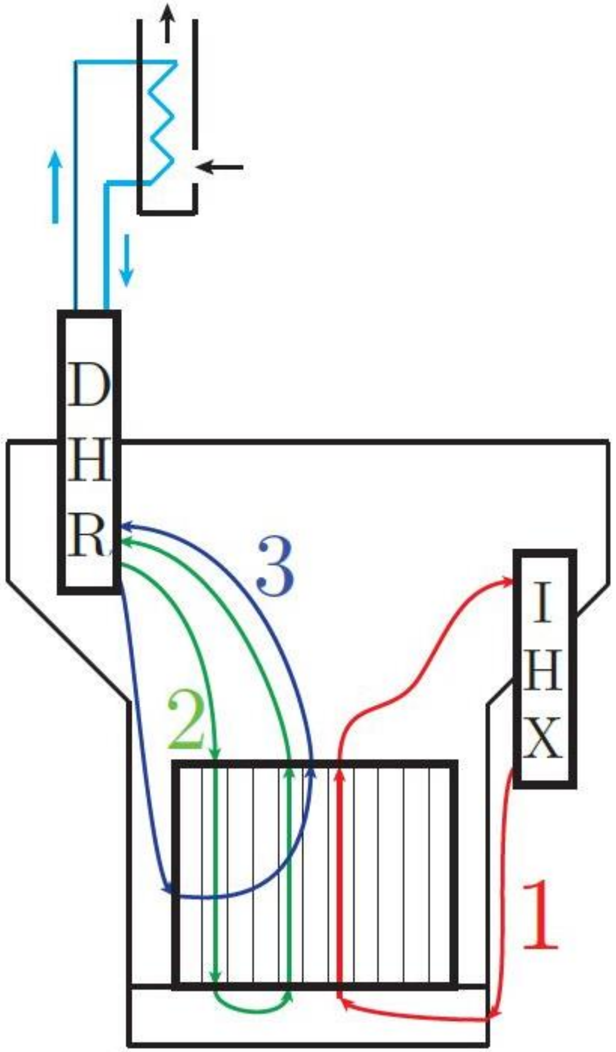


Some phenomena involve the complete reactor!

Gas in the primary circuit

- sources:
  - free-surface vortices
  - entrainment at the weir
  - nucleation of dissolved gas in cold regions
  - cladding rupture
- transport: with the flow
  bubble coalescence / dissociation!
- accumulation: at top of diagrid
- possible consequences:
  gas pocket in core → power transient!

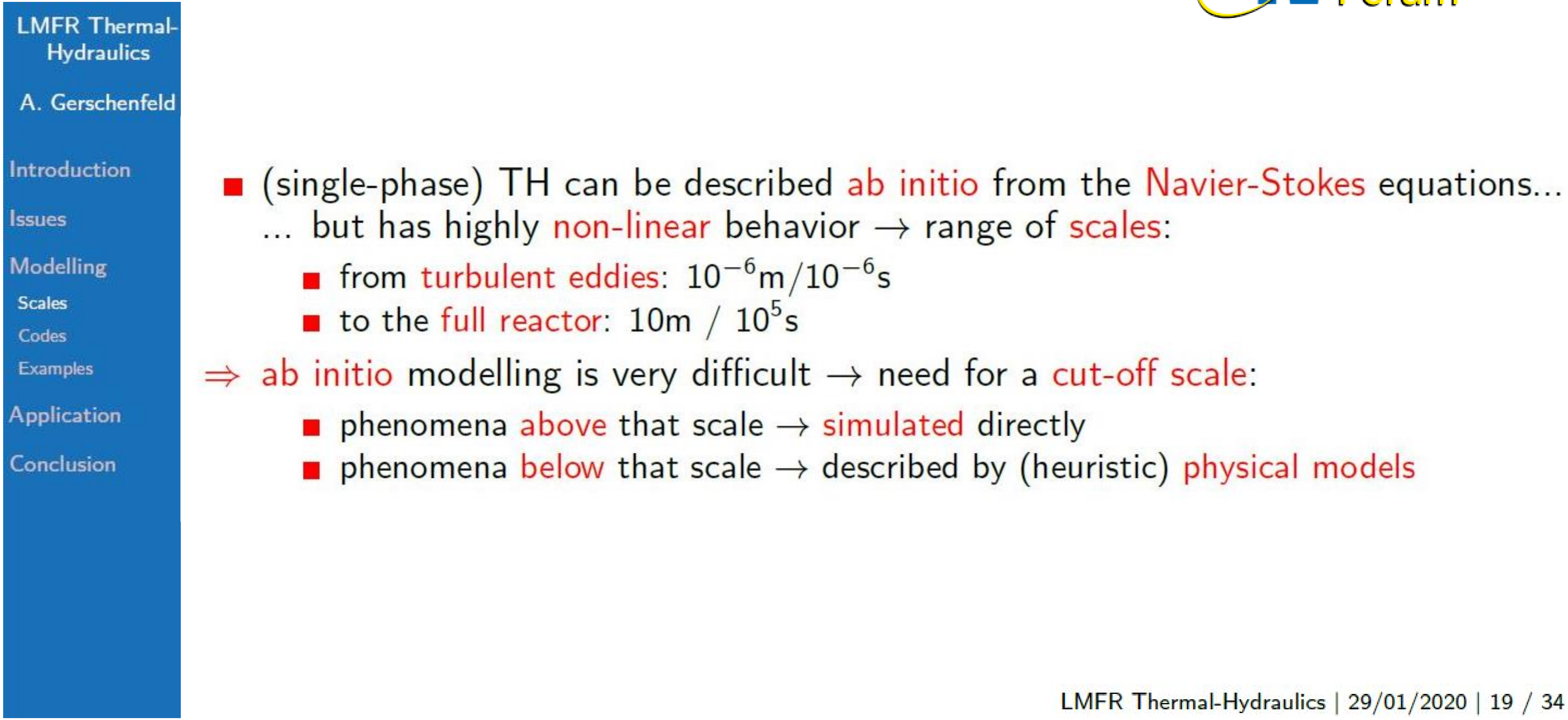
Issues / Global



Decay Heat Removal

- can be done passively in LMRs:
  - LM/LM exchangers in hot pool
  - passive decay heat removal loop
  - LM/air exchanger in chimney
- primary natural convection → many paths:
  1. "normal" path
  2. recirculations between S/As
  3. and in interwrapper region
- in passive circuits:
  - avoid freezing!
  - natural convection startup
- intermediate loops may also contribute

Modelling thermal-hydraulics



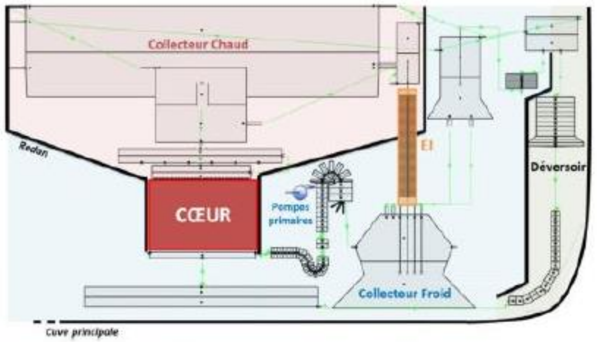
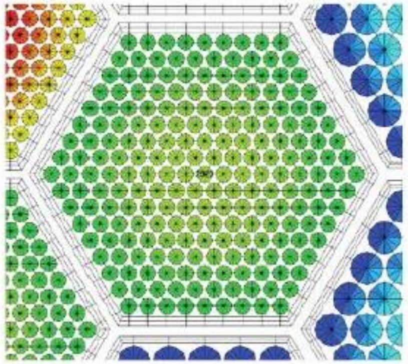
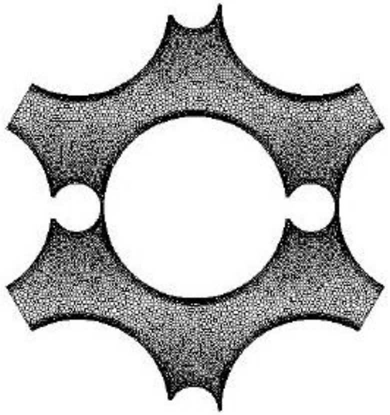
- (single-phase) TH can be described ab initio from the Navier-Stokes equations... ... but has highly non-linear behavior → range of scales:
  - from turbulent eddies: 10^{-6}m/10^{-6}s
  - to the full reactor: 10m / 10^{5}s

⇒ ab initio modelling is very difficult → need for a cut-off scale:

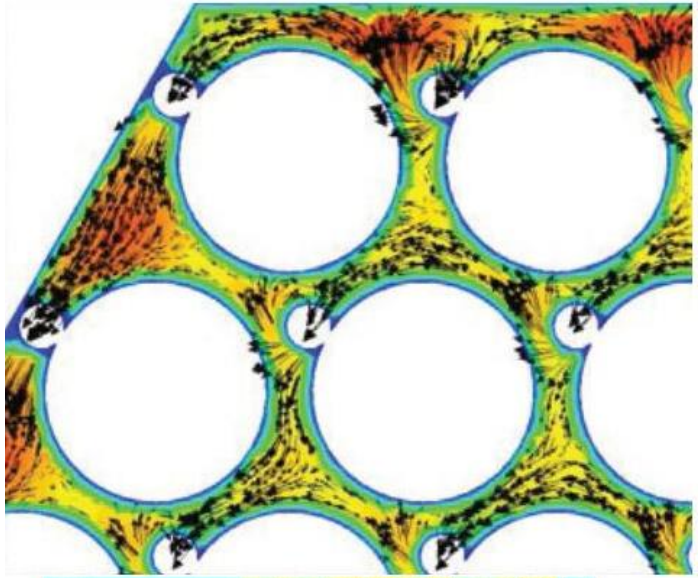
  - phenomena above that scale → simulated directly
  - phenomena below that scale → described by (heuristic) physical models

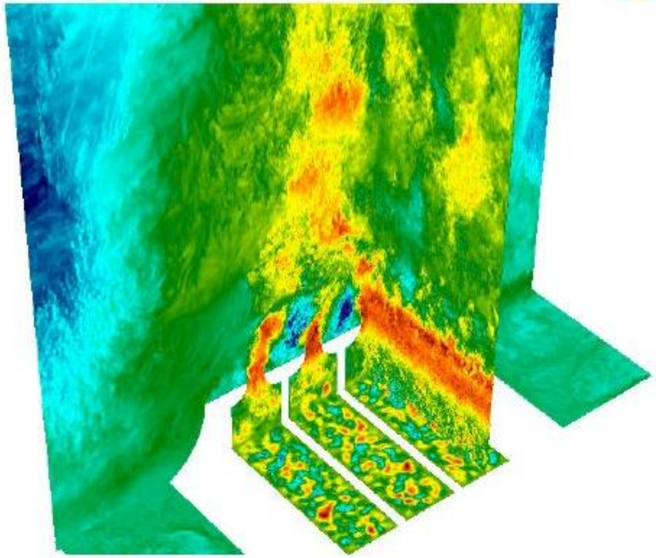
Modelling / Codes

⇒ various thermal-hydraulics codes, according to the choice of cut-off :

Scale	System (STH)	Subchannel (SC)	CFD
			
Simulation scale	channel (1D) volume (0D, 3D)	subchannel (between pins)	microscopic (DNS) fine (LES, RANS)
Physical models	every phenomenon (heat transfer, pressure drop)	fine geometry (wires, grids...)	nothing (DNS) turbulence (LES/RANS)
Code used at CEA	CATHARE	TrioMC	TrioCFD

Modelling / Codes

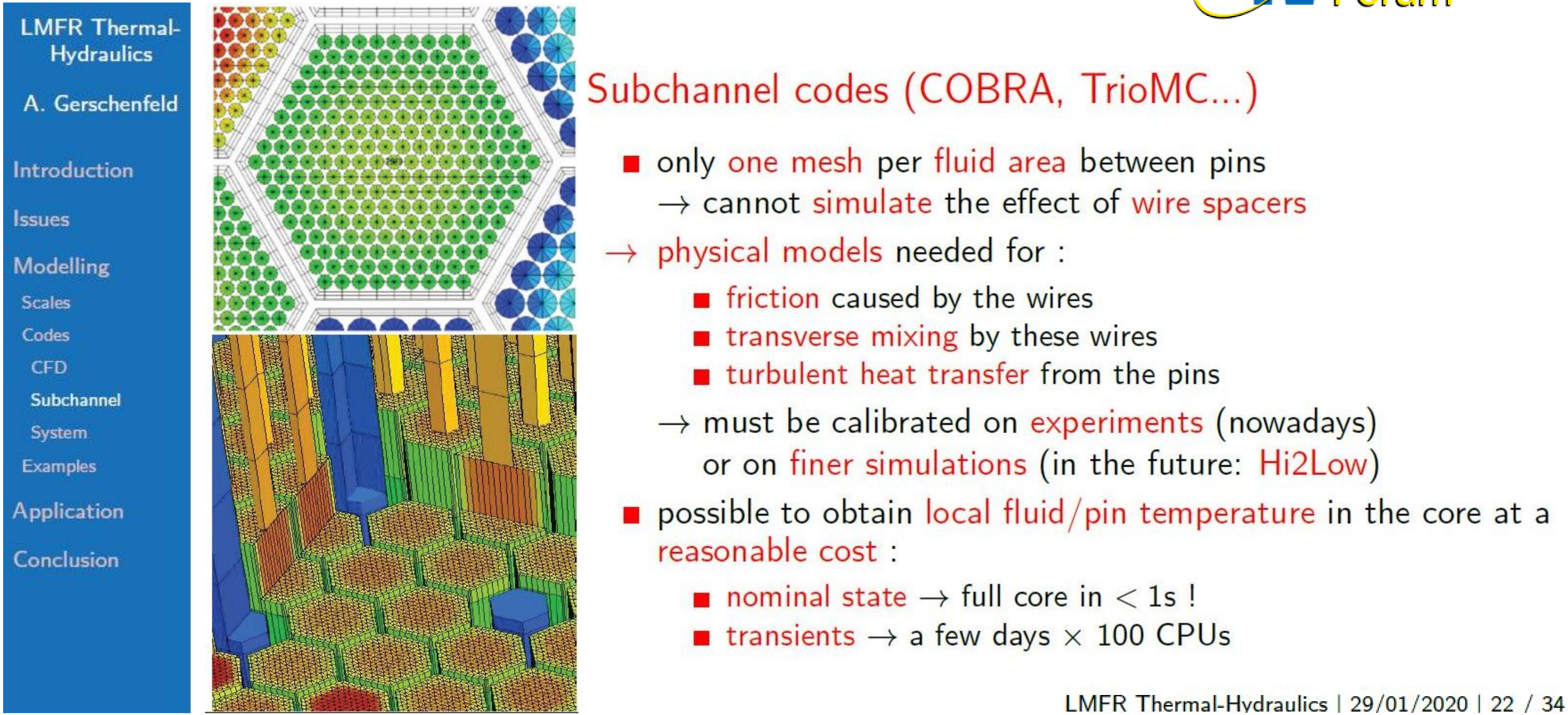




CFD codes (OpenFOAM, Fluent, TrioCFD...)

- directly model the geometry of a fluid region
- predict turbulence by either :
  - simulating it directly (DNS)
    → very small meshes (10^{-6}m)
  - modelling the smallest fluctuations (LES)
    → somewhat larger meshes (10^{-5}m)
  - modelling all fluctuations by an average dissipation (Reynolds-Averaged Navier-Stokes)
    → large meshes (10^{-4}-10^{-3}m)
- RANS lowers numerical costs, but :
  - the turbulence models must be validated (numerically or experimentally)
  - information on turbulent fluctuations is lost!
- typical computation (10-100 CPUs, 10s of days):
  - DNS → 10cm of a single subchannel
  - RANS → a few subassemblies

Modelling / Codes



LMFR Thermal-Hydraulics

A. Gerschenfeld

Introduction

Issues

Modelling

Scales

Codes

CFD

Subchannel

System

Examples

Application

Conclusion

Subchannel codes (COBRA, TrioMC...)

- only one mesh per fluid area between pins
  → cannot simulate the effect of wire spacers

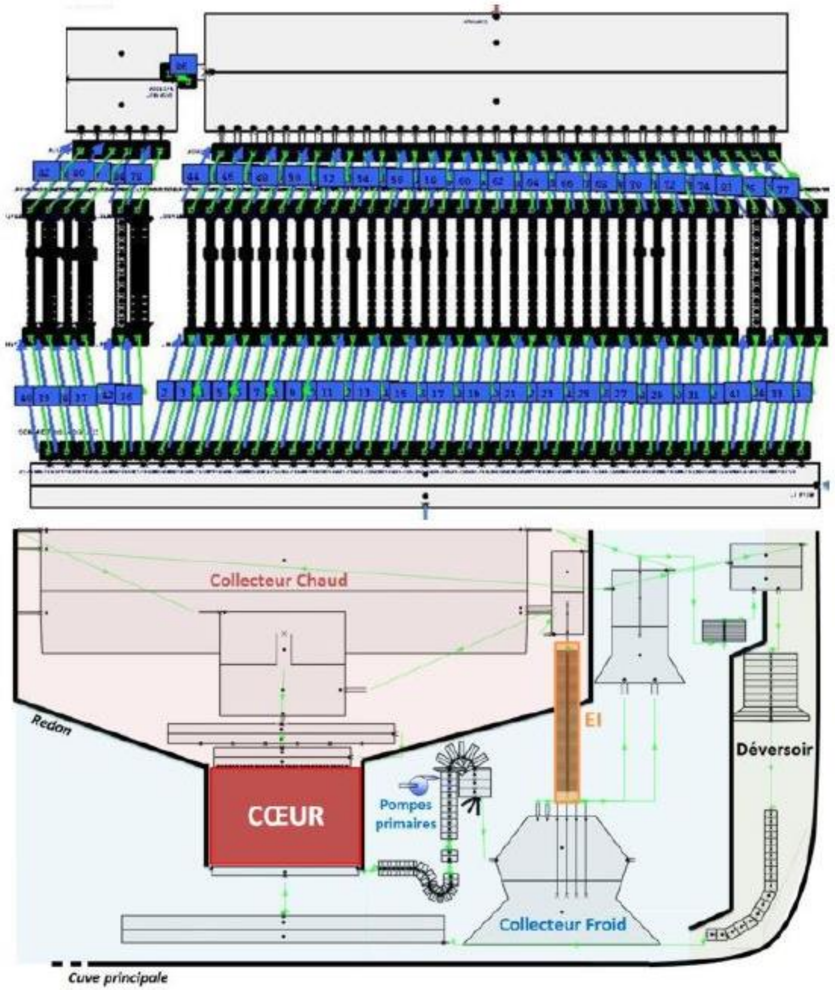
→ physical models needed for :

  - friction caused by the wires
  - transverse mixing by these wires
  - turbulent heat transfer from the pins

  → must be calibrated on experiments (nowadays) or on finer simulations (in the future: Hi2Low)

- possible to obtain local fluid/pin temperature in the core at a reasonable cost :
  - nominal state → full core in < 1s !
  - transients → a few days × 100 CPUs

Modelling / Codes



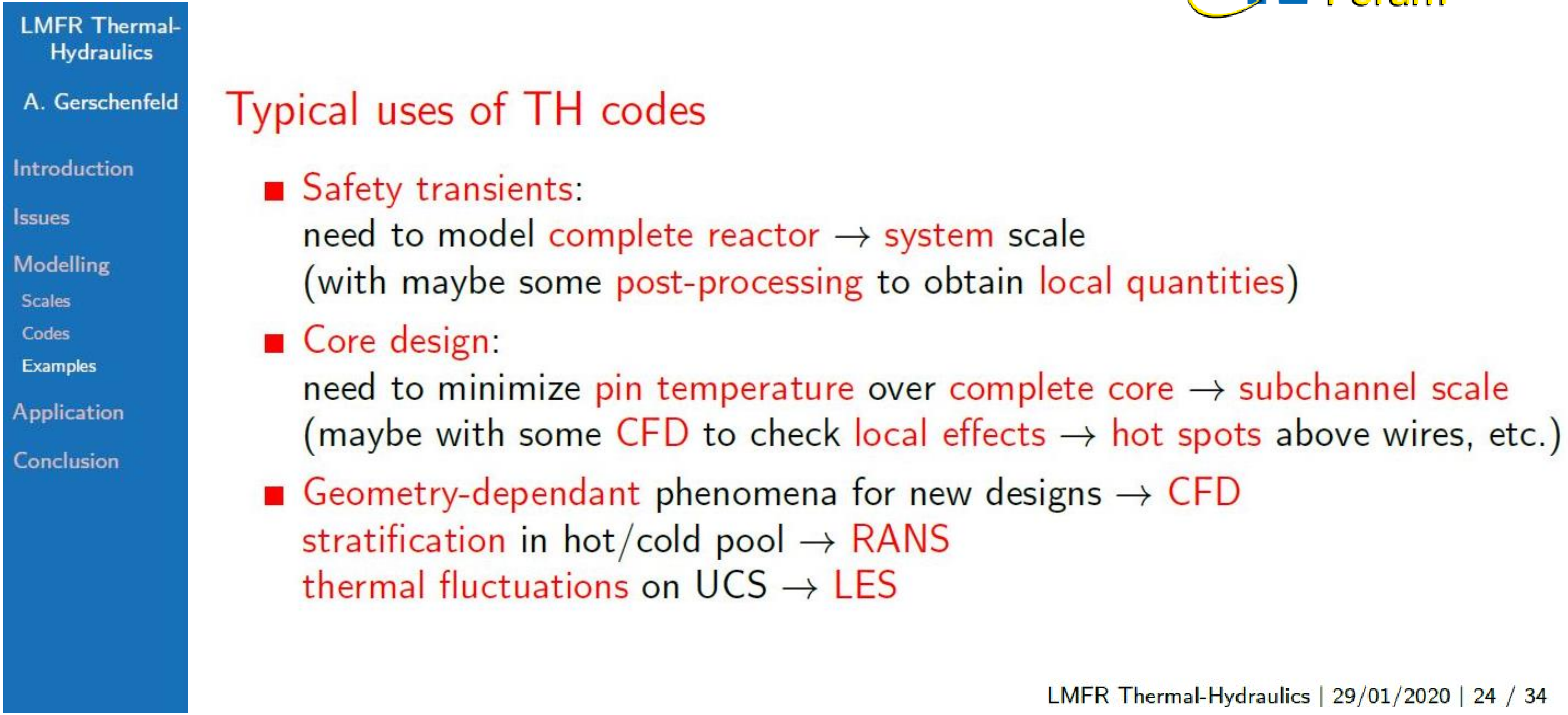
System codes (RELAP, TRACE, CATHARE...)

- the original TH codes (RELAP-1 : 1966!)
- the coarsest mesh possibles :
  - pipes in 1D (multi-channel core)
  - volumes in 0D, sometimes in coarse 3D
- physical models for all phenomena: friction, heat transfer...
- but also additional models for full reactor simulation:
  - core: neutronics (usually point kinetics)
  - pumps, heat exchangers
  - all circuits : primary, intermediate...

⇒ can compute a complete reactor transient...

- ... with low numerical cost! 15 min × 1 core

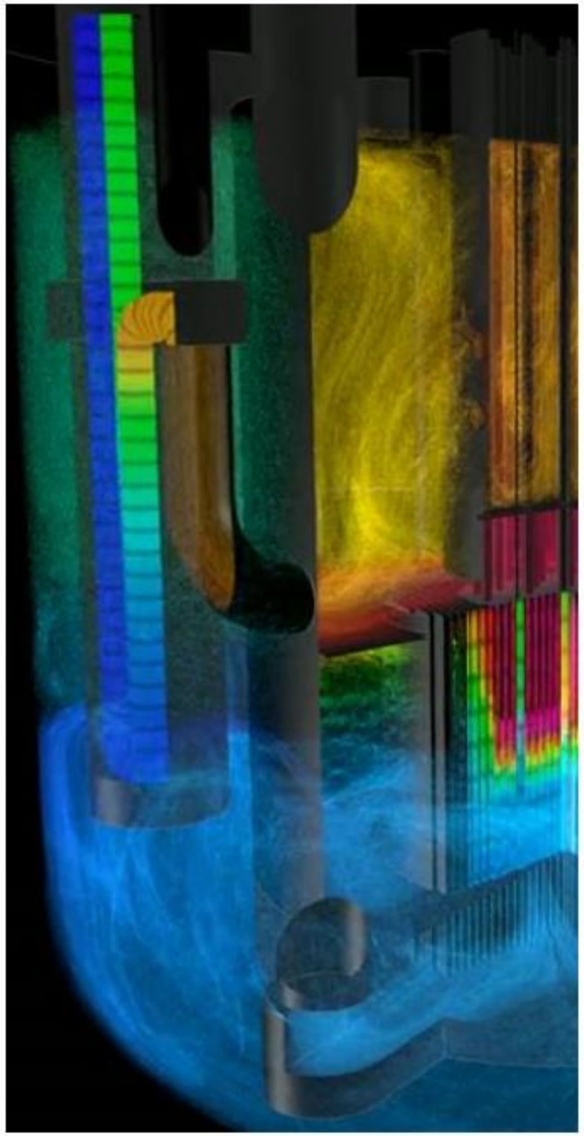
Modelling / Codes



Typical uses of TH codes

- Safety transients:
  need to model complete reactor → system scale
  (with maybe some post-processing to obtain local quantities)
- Core design:
  need to minimize pin temperature over complete core → subchannel scale
  (maybe with some CFD to check local effects → hot spots above wires, etc.)
- Geometry-dependant phenomena for new designs → CFD
  stratification in hot/cold pool → RANS
  thermal fluctuations on UCS → LES

Application



Modelling natural convection in LMRs

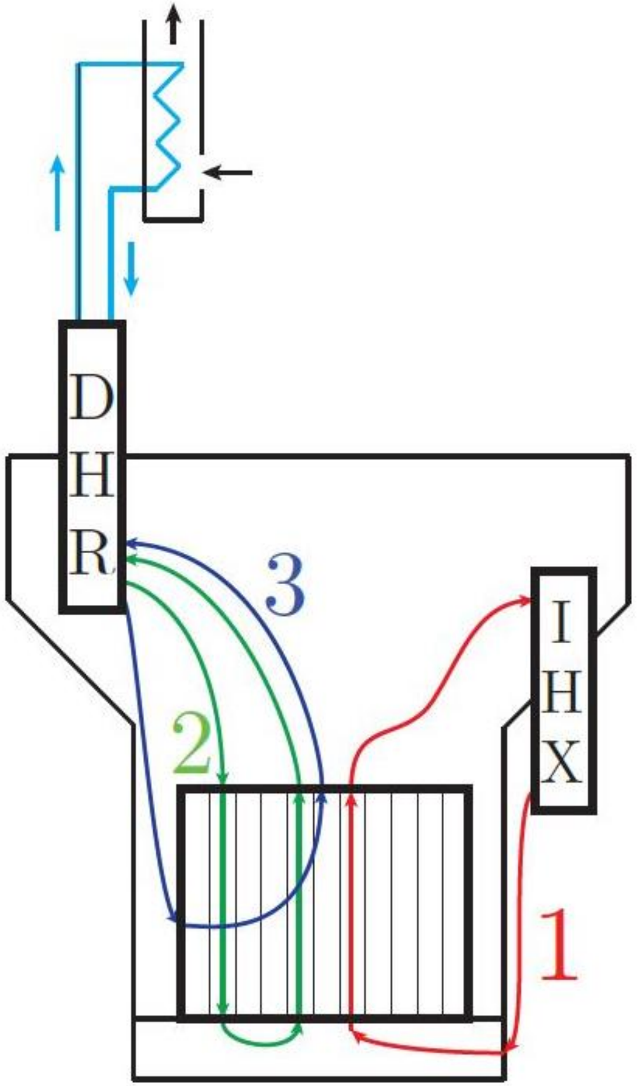
- natural convection is a global phenomenon
  → natural choice system scale / STH (0D/1D/coarse 3D)
- but pool-type designs are favor complex 3D effects:
  - in large pools: jet behavior, stratification
  - in the core: radial heterogeneity in S/As,
    cooling by inter-wrapper flow

⇒ these are hard to predict at the system scale!
either by physical models or explicit simulation

Simple approaches

- if there is no local → global feedback:
  STH result → local post-processing
- conservative hypotheses, if possible

Natural convection



Effect on decay heat removal

Competition between three paths :

1. normal primary circuit flow
2. convection loops between S/As
3. flow in the inter-wrapper gaps

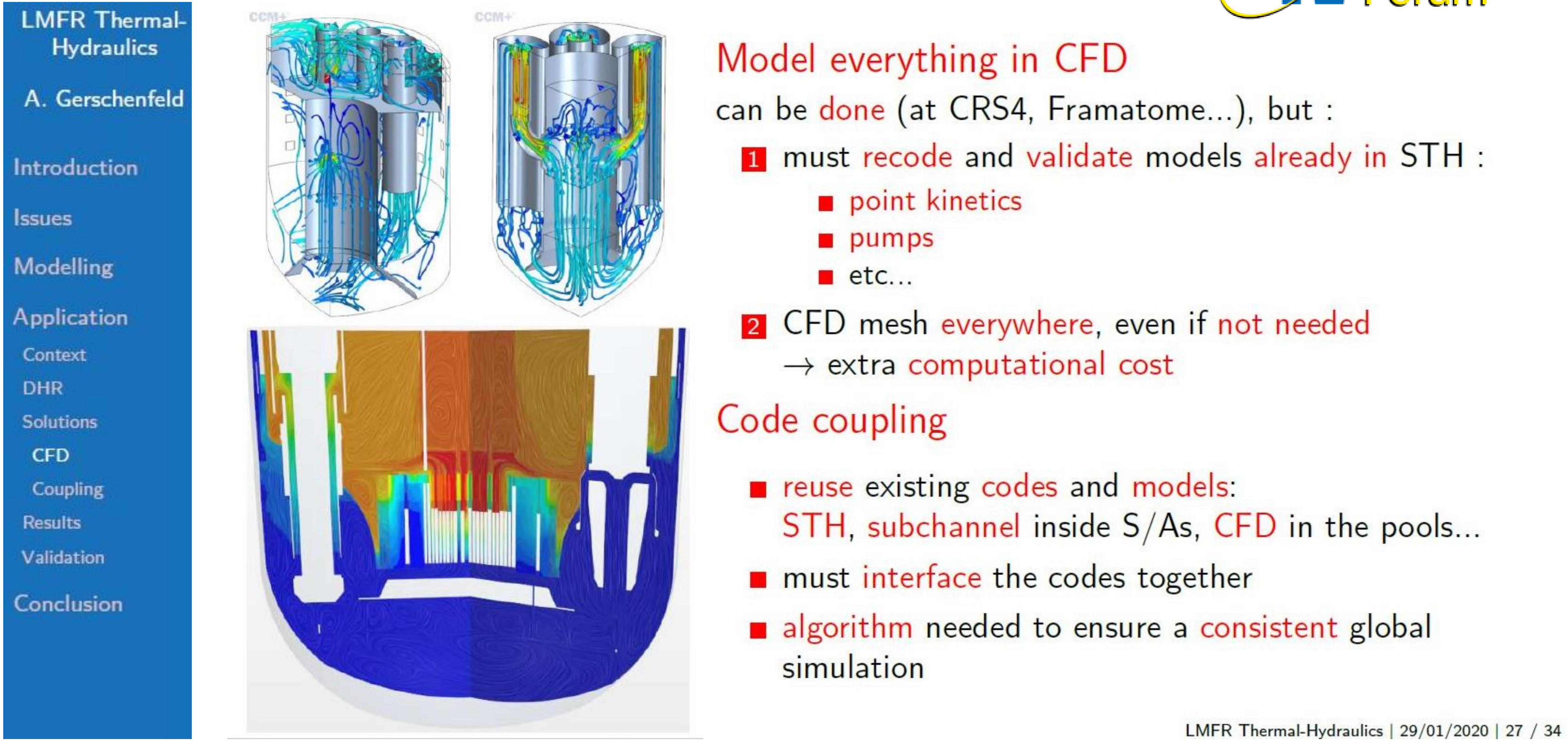
⇒ only (1) can be modeled in STH!

How to model?

- STH approach :
  (2) miscalculated, (3) neglected
  ⇒ T_{core} overestimated (conservative)
  Q_{prim} overestimated (bad)

⇒ an approach including local feedbacks is needed

Natural convection



LMFR Thermal-Hydraulics

A. Gerschenfeld

- Introduction
- Issues
- Modelling
- Application
  - Context
  - DHR
  - Solutions
    - CFD
    - Coupling
  - Results
  - Validation
- Conclusion

Model everything in CFD

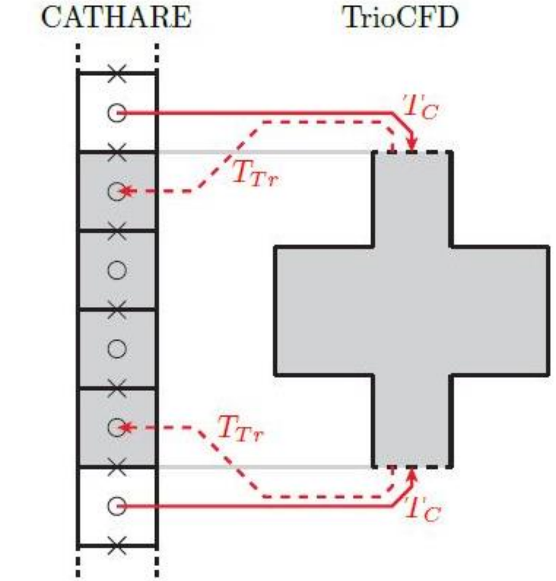
can be done (at CRS4, Framatome...), but :

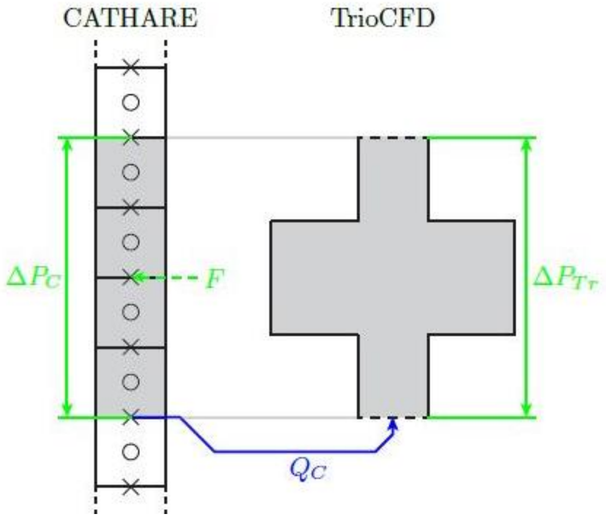
1. must recode and validate models already in STH :
   - point kinetics
   - pumps
   - etc...
2. CFD mesh everywhere, even if not needed
   → extra computational cost

Code coupling

- reuse existing codes and models:
  STH, subchannel inside S/As, CFD in the pools...
- must interface the codes together
- algorithm needed to ensure a consistent global simulation

Natural convection / Code coupling





Thermal coupling

- in CFD : boundary conditions
  - hydraulic : uniform velocity
  - thermal : external temperature taken from STH
- in STH : imposed temperatures at the meshes inside the domain

Hydraulic coupling

- in CFD : imposed flow

⇒ STH computes the flowrate $Q \rightarrow$ what feedback?

- to obtain the right Q, the STH outside the domain must “see” the ΔP from the CFD

⇒ momentum source term F inside the overlapped domain so that $\Delta P_{STH} \simeq \Delta P_{CFD}$

Natural convection / Results

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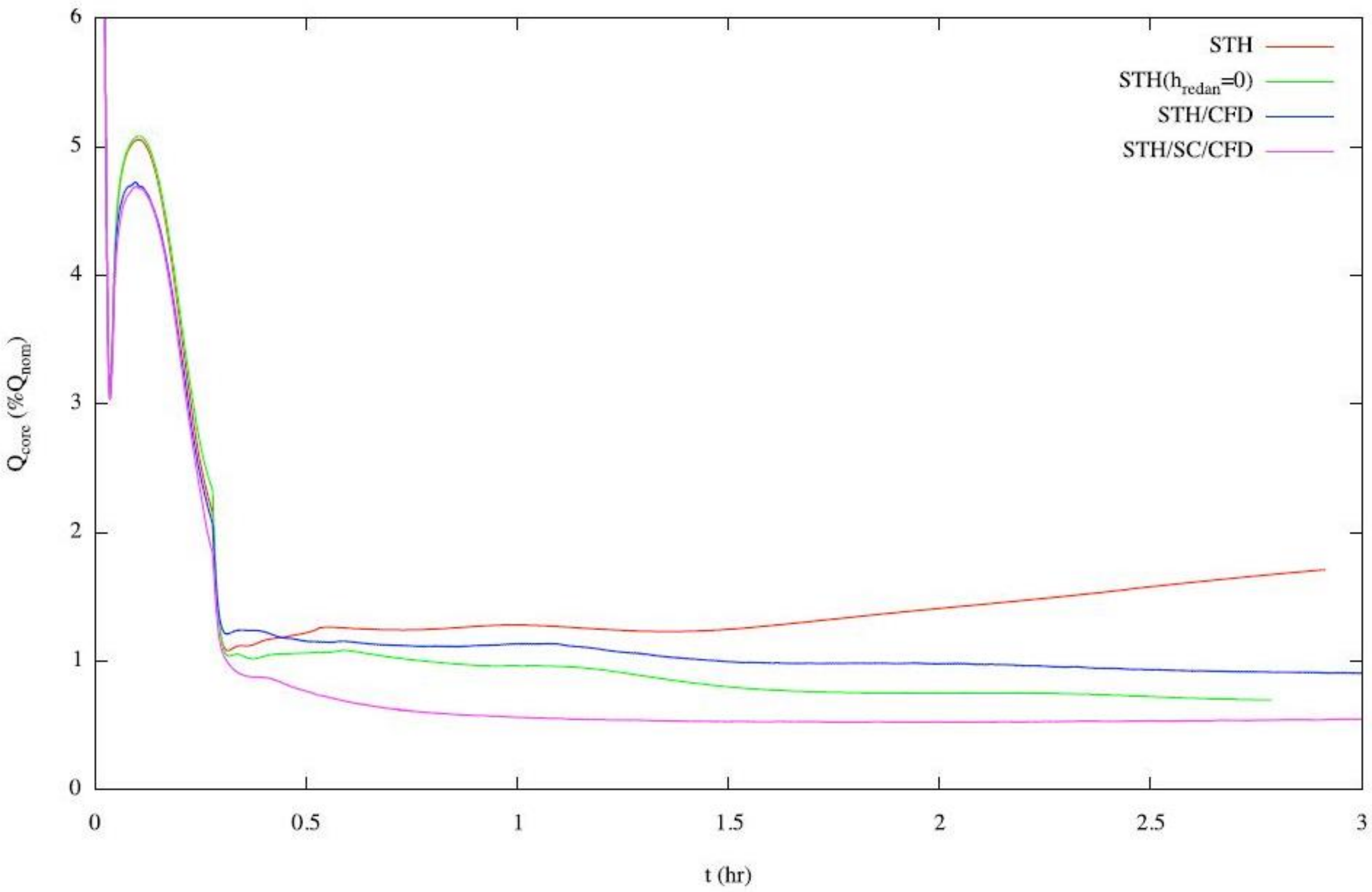
Overview

Nominal state

Long-term natural convection

Natural convection / Results

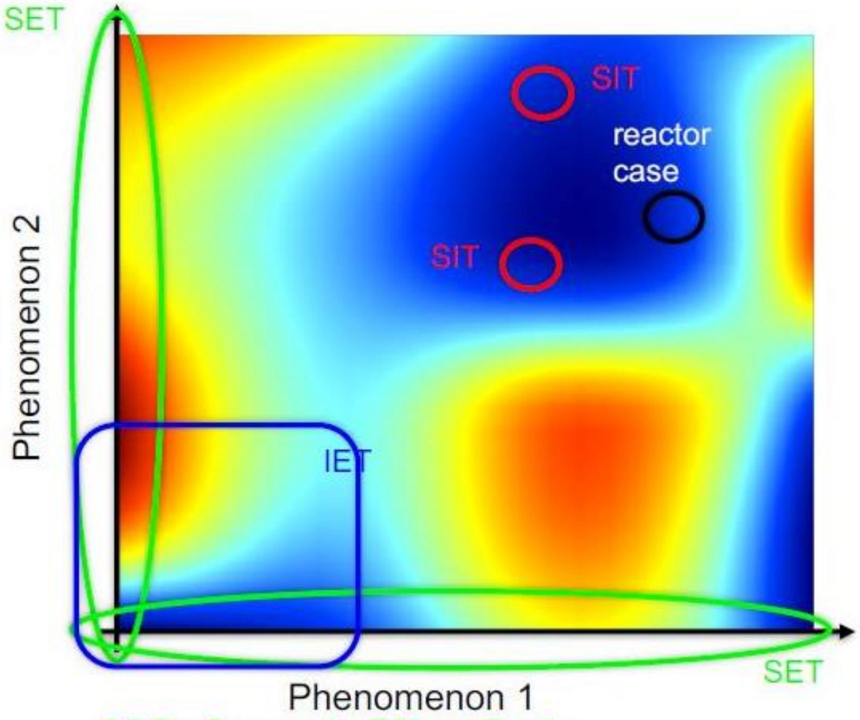


Flow rate prediction

- red: pure STH
  → homogeneous pools
- blue: STH + pool CFD
  → stratified pools
- green: corrected STH
  ($h = 0$ between pools)
- purple: STH + CFD
  + subchannel core for IWF

⇒ Q_{core} overestimated by up to 100% !

Natural convection / Validation



SET : Separate Effect Tests

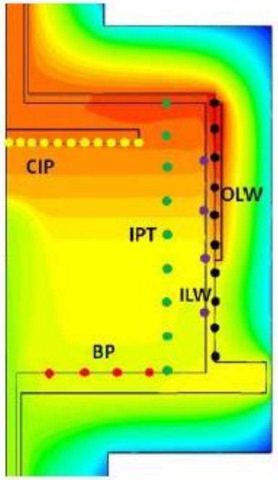
IET : Integral Effect Tests

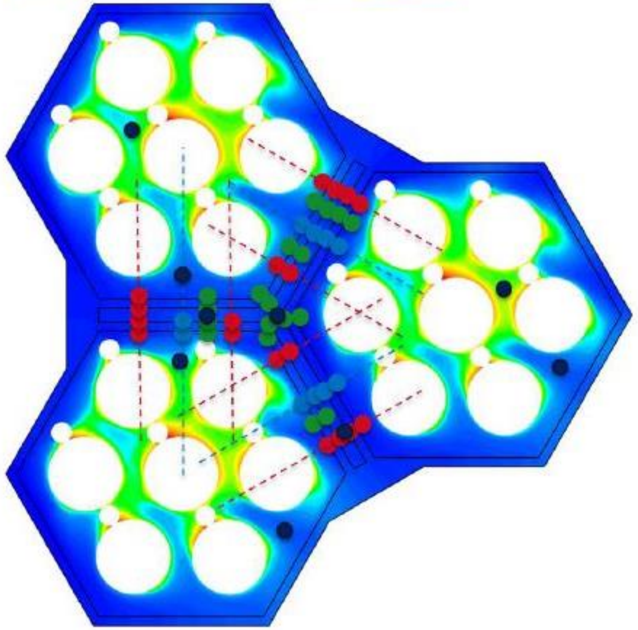
SIT : System and Industrial Tests

- all physical models introduced must be established experimentally:
  - from nothing for DNS CFD...
  - to everything for the system scale!

  → validation of the physical models
- because of the non-linearities of thermal-hydraulics, interactions between phenomena may produce new effects
  → which must also be validated!
- leads to a hierarchy of experiments :
  - separate effect tests (skipped here): study one phenomenon in detail
  - combined effect tests: study interactions (requires large experiments)
  - system/industrial tests (integral validation): everything in a reactor case

Natural convection / Validation

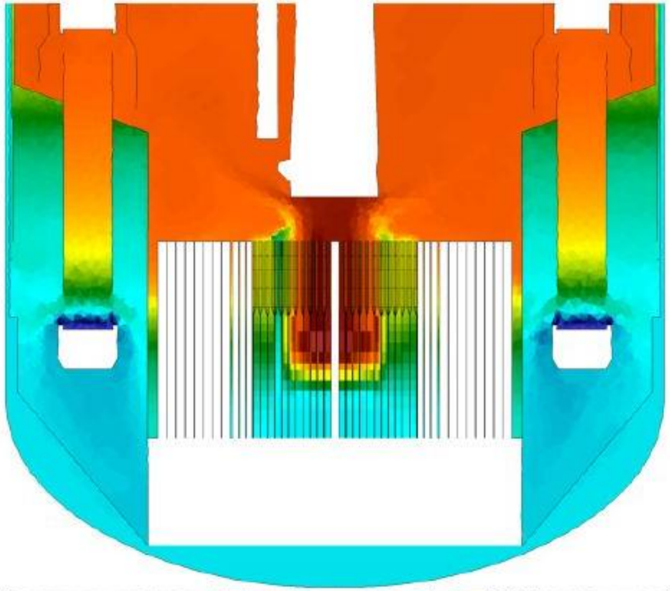




Combined effects

1. impact of 3D effects on natural convection:
   - analytical: TALL-3D (KTH)
   - more integral: CIRCE (ENEA ← ALFRED)
   - reactor similarity: E-SCAPE (SCK/CEN ← MYRRHA)
2. coupling between S/As and inter-wrapper flow:
   - analytical: THEADES (KIT)
   - coupled to hot pool DHR: PLANDTL-1/2 (JAEA)
3. both together: possible in large LM experiments
   → requires simulated S/As in pool
   - CLEAR-S (China)

Natural convection / Validation



Integral scale (public availability)

1. PHENIX end-of-life tests:
    - natural convection → NC test (IAEA/EU)
    - cold pool 3D effects → dissymetric test (EU/GIF)
2. EBR-II tests:
    - (U)LOF → SHRT-17/45R (IAEA)
    - ULOHS → BOP-301/302R (GIF)
3. FFTF tests:
    - ULOF → LOFWOS#13 (IAEA)

      → benchmark in progress

IAEA and GIF play a key role!

Conclusion

- LMRs give rise to many interesting thermal-hyhdraulics phenomena
  → we need to describe them:
  - in normal operation
  - and in accidental scenarios
- range of codes, according to modelling scale:
  - 100% simulation → DNS CFD (in single-phase)
  - then LES (preserves fluctuations) and RANS CFD (destroys fluctuations)
  - then subchannel
  - system scale (100% modelling)
- in many cases, a single code will be suitable for a given study
  - local 3D phenomena: with fluctuations → LES CFD, without → RANS CFD
  - assembly TH : single S/A → CFD, whole core → subchannel
  - reactor transients → STH
- however, some cases may be unsuitable for a single scale
  → in that case, code coupling is a possibility!
- most of the work lies in validating the physical models

Upcoming Webinars

25 February 2020 (8 pm US EST)	SFR Safety Design Criteria (SDC) and Safety Design Guidelines(SDGs)	Mr. Shigenobu Kubo, JAEA, Japan
26 March 2020	MicroReactors: A Technology Option for Accelerated Innovation	Dr. DV Rao, LANL, USA and Dr. Jess Gehin, INL, USA
29 April 2020	GIF VHTR Hydrogen Production Project Management Board	Dr. Sam Suppiah, CNL, Canada