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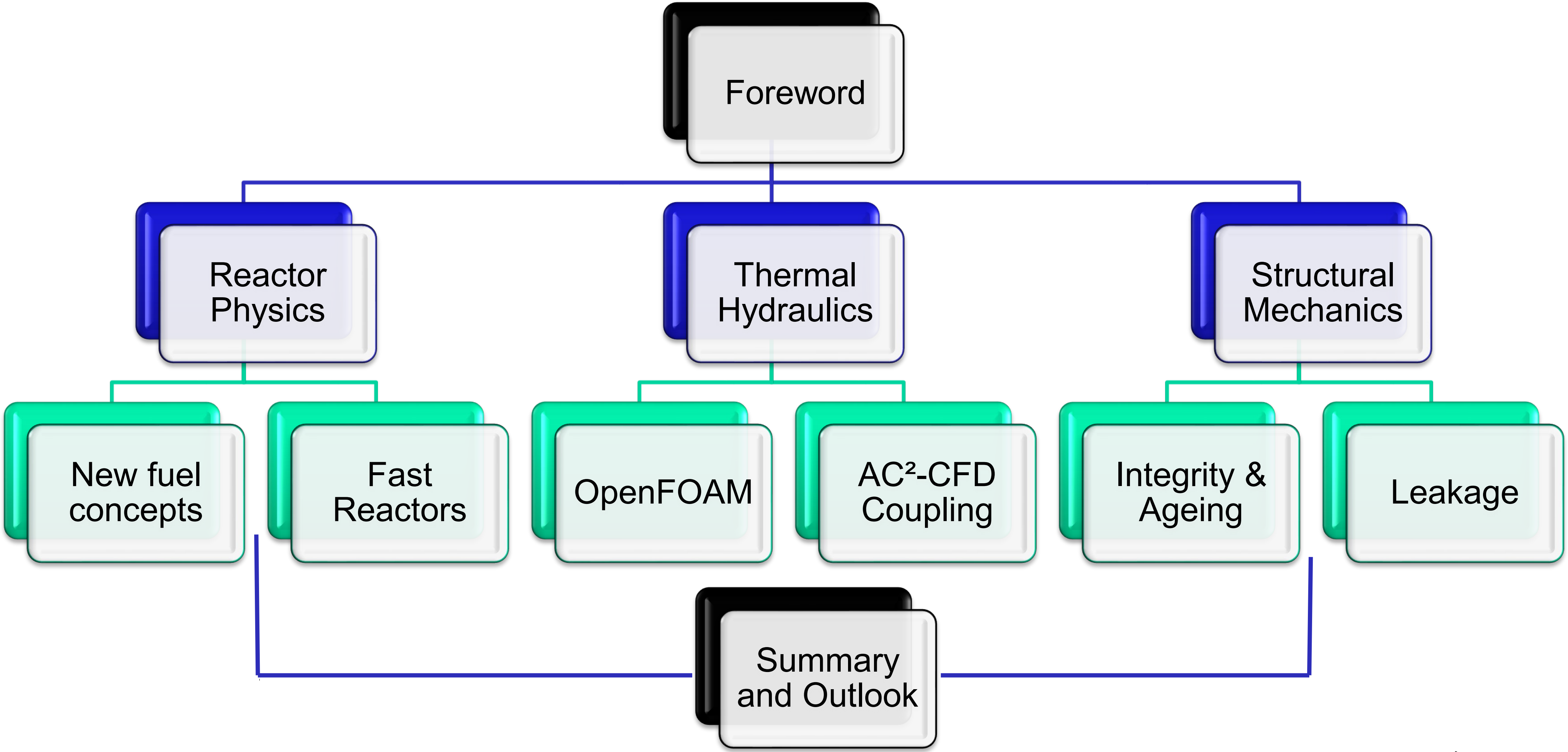
Safety Research at GRS to enhance Nuclear Safety in Europe

EUROSAFE 2019

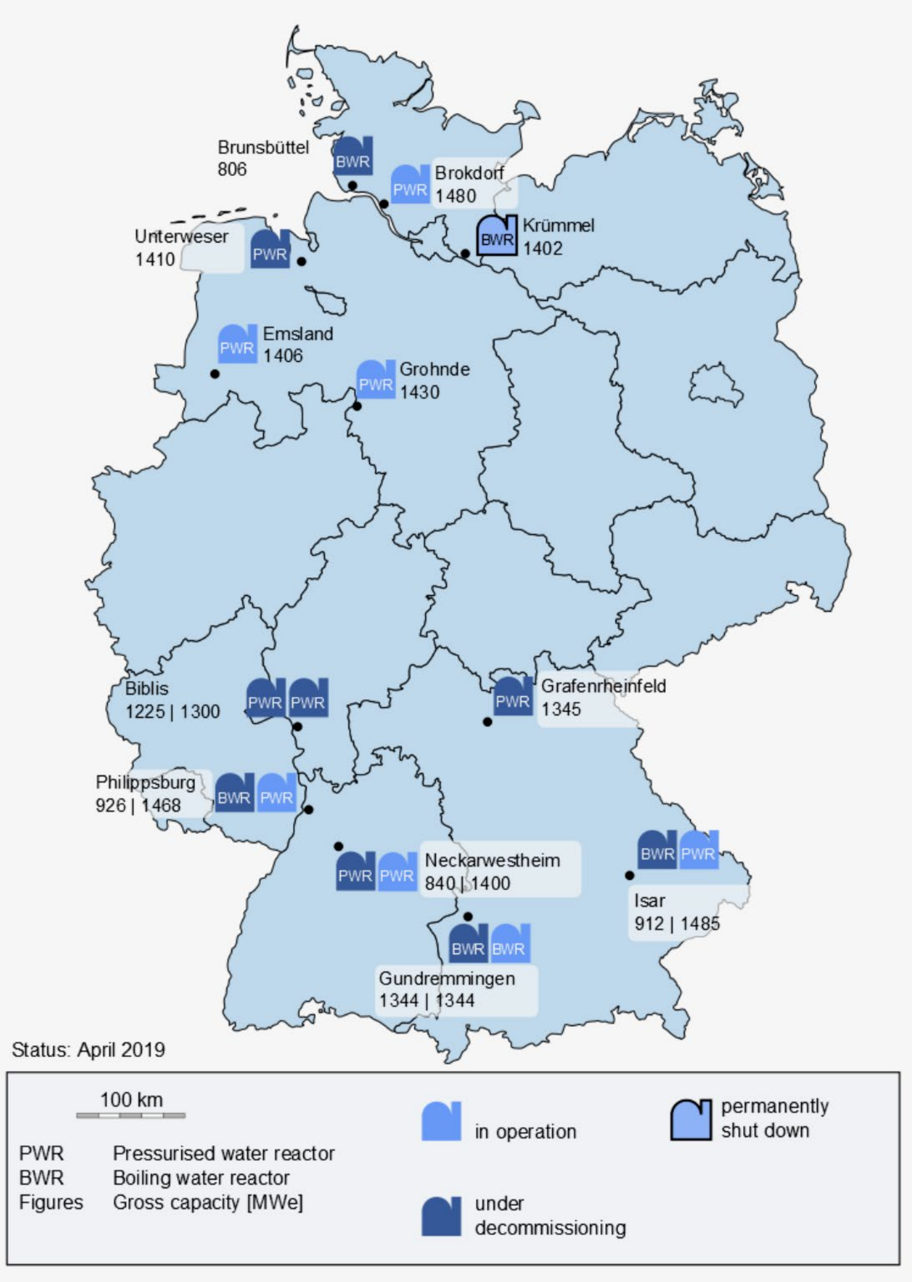
Outline



Foreword
Reactor Physics
Thermal Hydraulics
Structural Mechanics
New fuel concepts
Fast Reactors
OpenFOAM
AC²-CFD Coupling
Integrity & Ageing
Leakage
Summary and Outlook

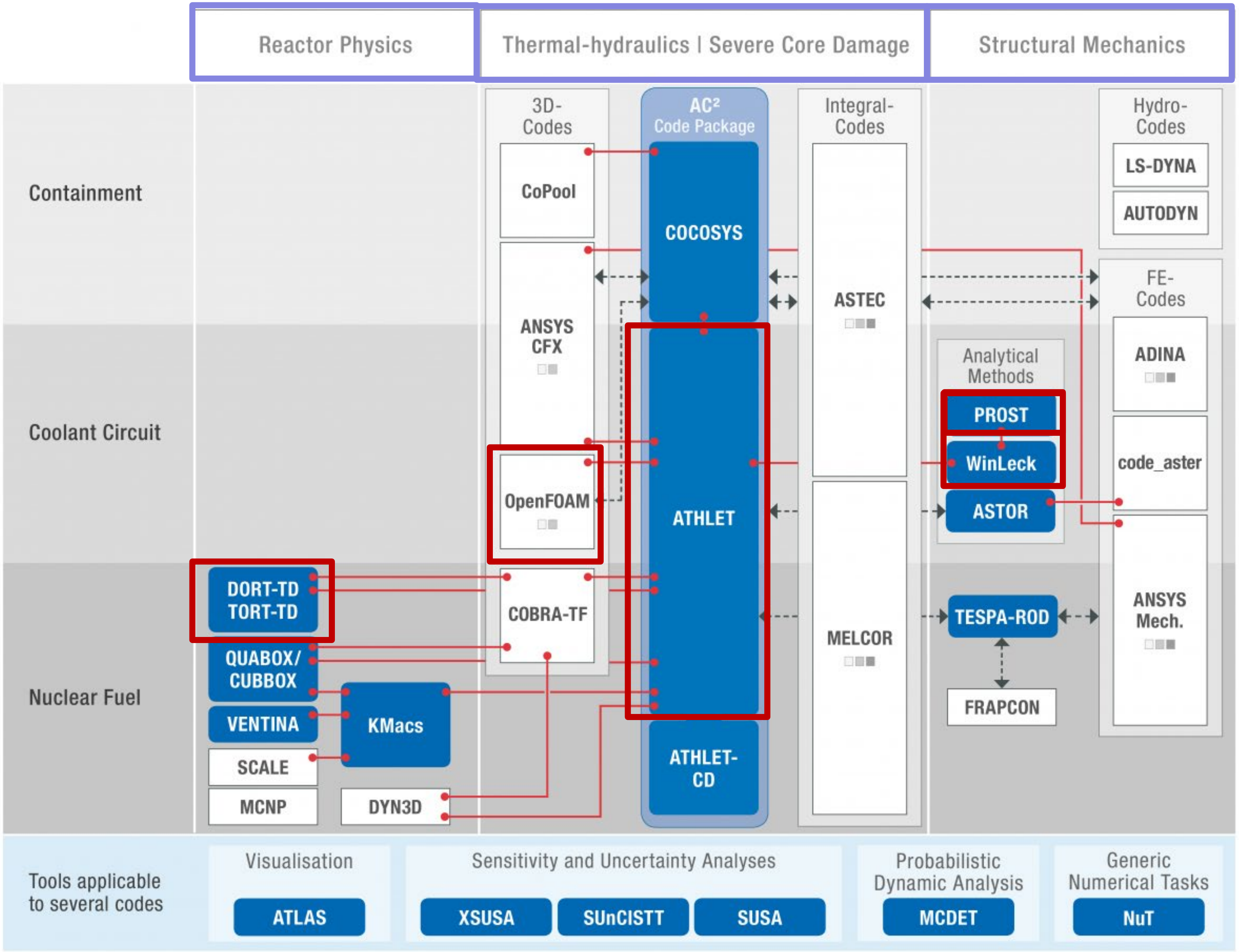
Changed Political Framework in Germany (1)

- After Fukushima the 13th Amendment of the Atomic Energy Act came into force on August 6th 2011 – 17 NPPs in operation:
  - Licences of the 7 oldest NPPs and of Krümmel NPP expired
  - Stepwise shutdown of the remaining 9 NPP until 2022 – today 7 NPPs in operation
- But no phase out of nuclear energy research in Germany, e.g. we maintain the ability for safety assessments
  - of foreign NPPs and New Builds
  - of new Safety Features (like the passive safety systems)



Changed Political Framework in Germany (2)

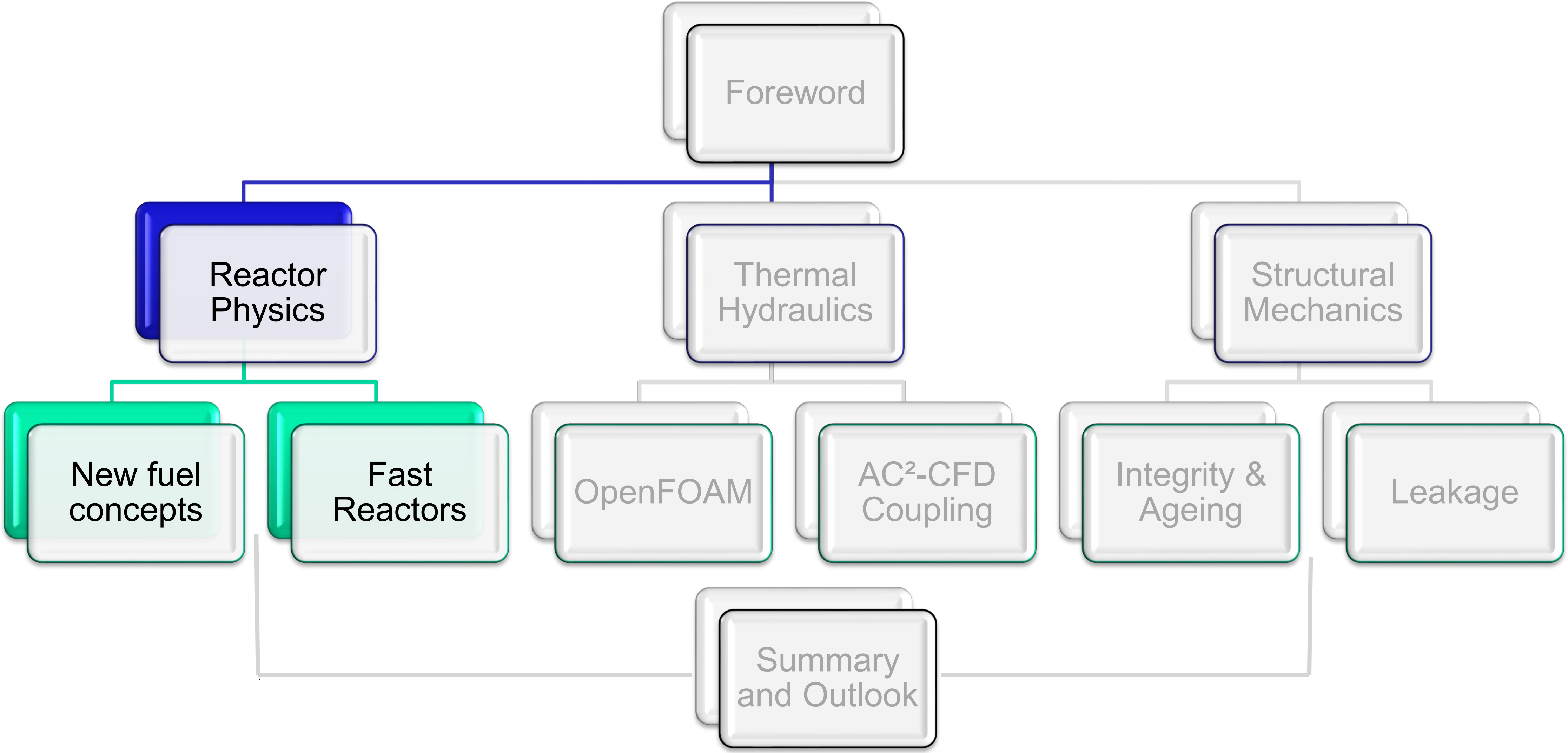
- Therefore, GRS e.g.
  - Continuously reviews possible candidates for new builds primarily in our neighbourhood
  - Promotes comprehensive safety research
  - Extends / validates its codes, which have been successfully applied in nuclear procedures in the past
  - Identifies modelling gaps and develops strategies for there closure



GRS code system

- Examples of various codes in all three areas are presented next

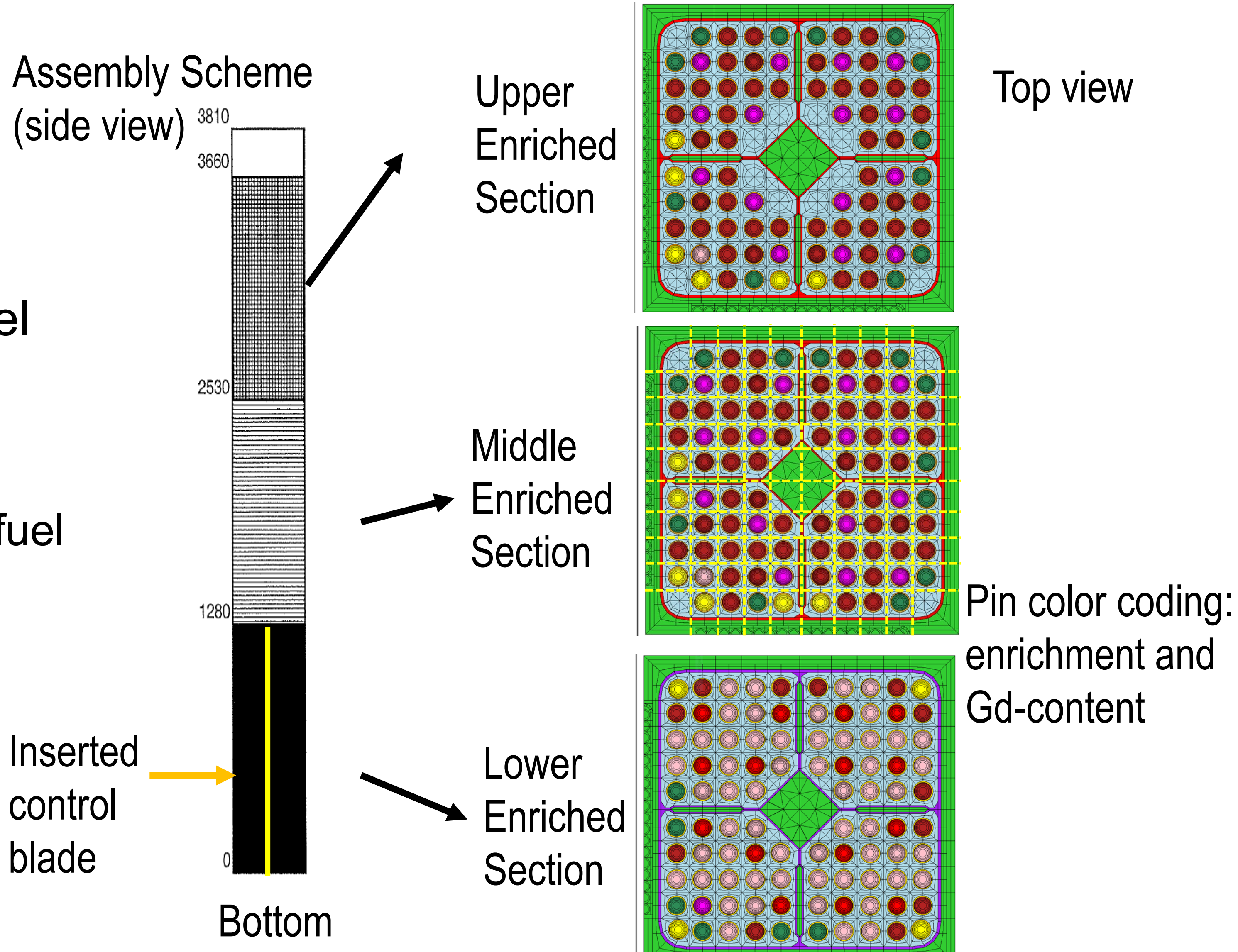
Reactor Physics



Neutron Kinetics: (A)LWR

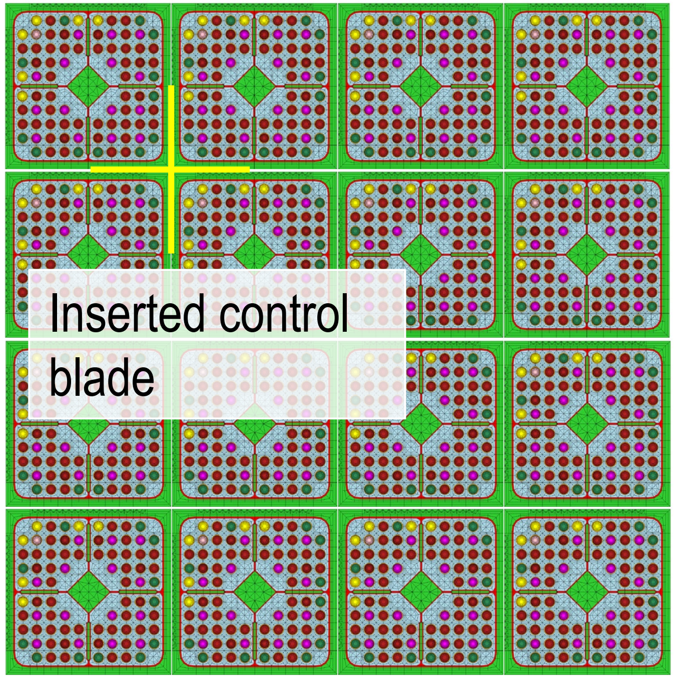
(Advanced) Light water reactors

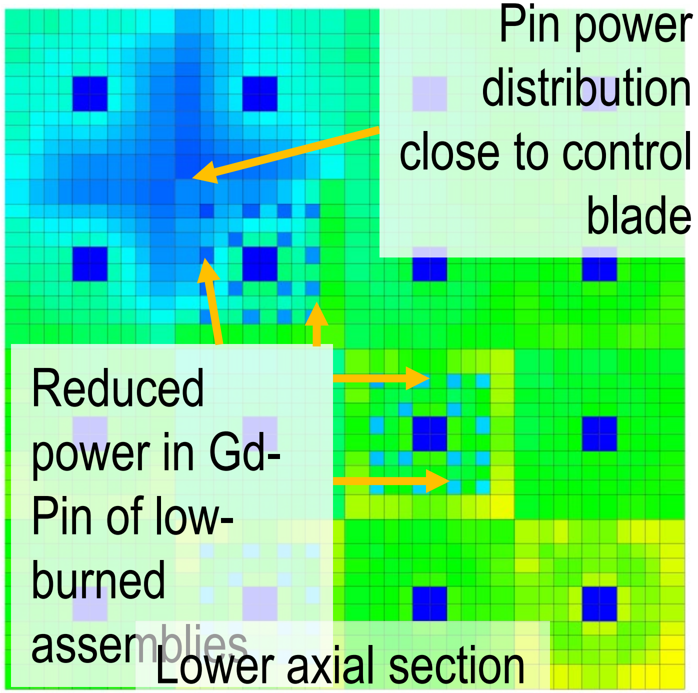
- Complex, highly optimized fuel assembly designs
  - Longer fuel cycle length,
  - Higher burn-up and/or higher fuel enrichment,
  - Advanced loading pattern,
  - Use of burnable absorbers
- Example:
  - SVEA96 Optima2 assemblies

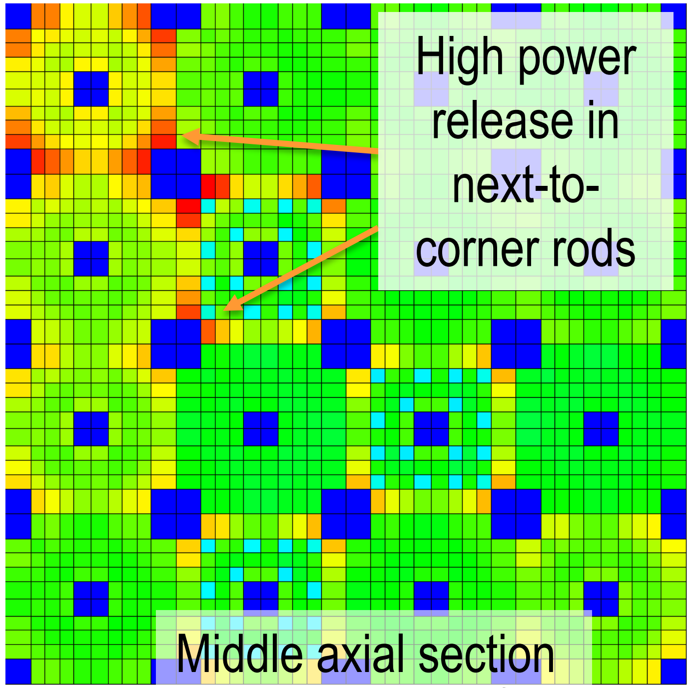


Multi-Physics Pin-by-pin Simulation of Local Phenomena in BWR

- TORT-TD/CTF: Coupled 3D time-dependent pin-by-pin neutron transport and subchannel thermal hydraulics code
- *Pin-by-pin* steady state power distribution in a 4-by-4 mini core







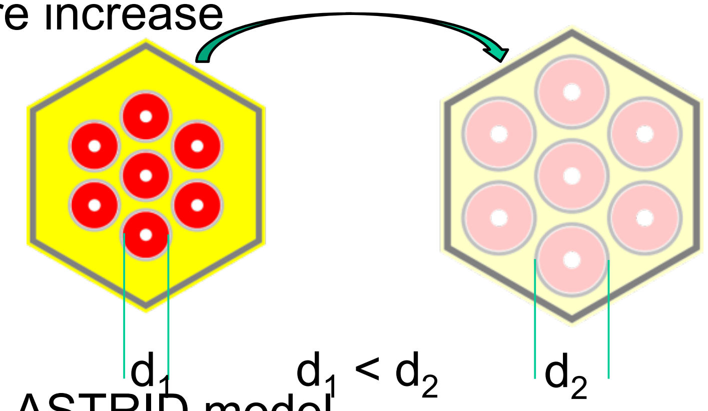
Fast Reactors

Fast reactors, in particular liquid metal-cooled – PARCS/ATHLET

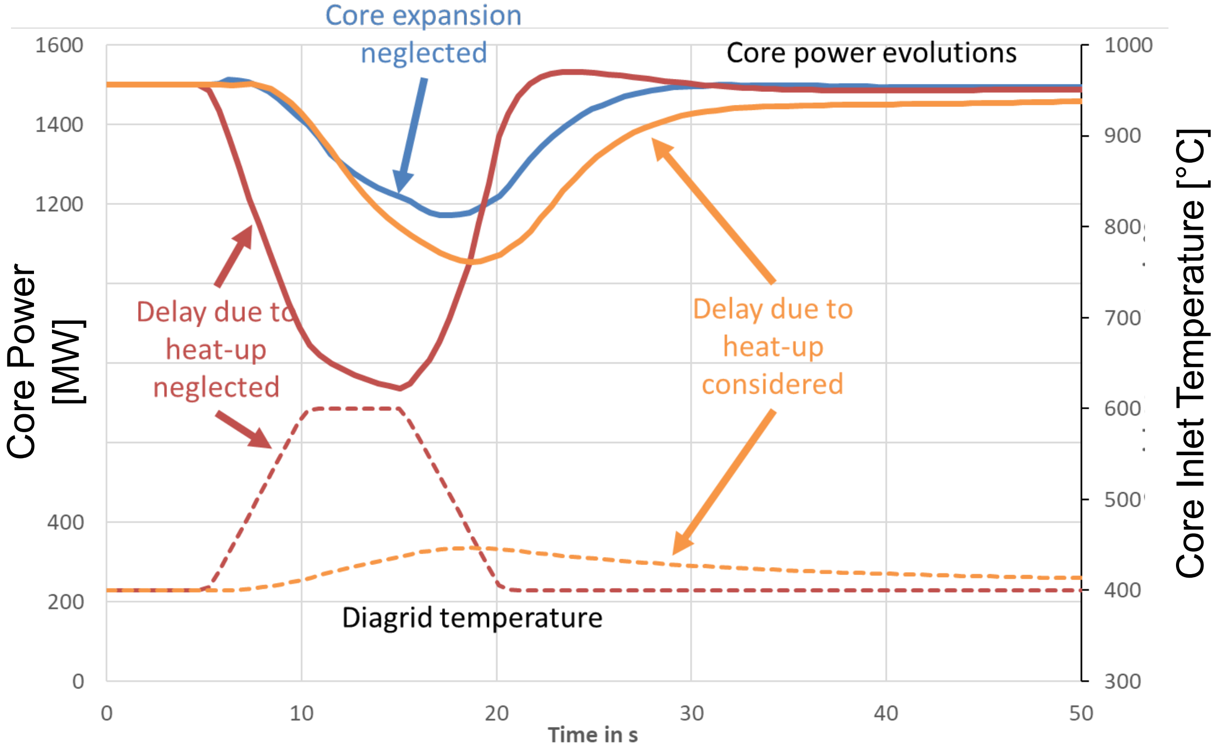
- Importance of neutronic feedback from thermal expansion of core structures
  - Radial core expansion (diagrid)
  - Axial core expansion (fuel, cladding)

Acc. Driven System simulation

- PARCS extension for simulation of time-dependent spallation neutron sources in sub-critical reactors (e.g. MYRRHA)



Na-cooled ASTRID model



Reactor Physics - Summary

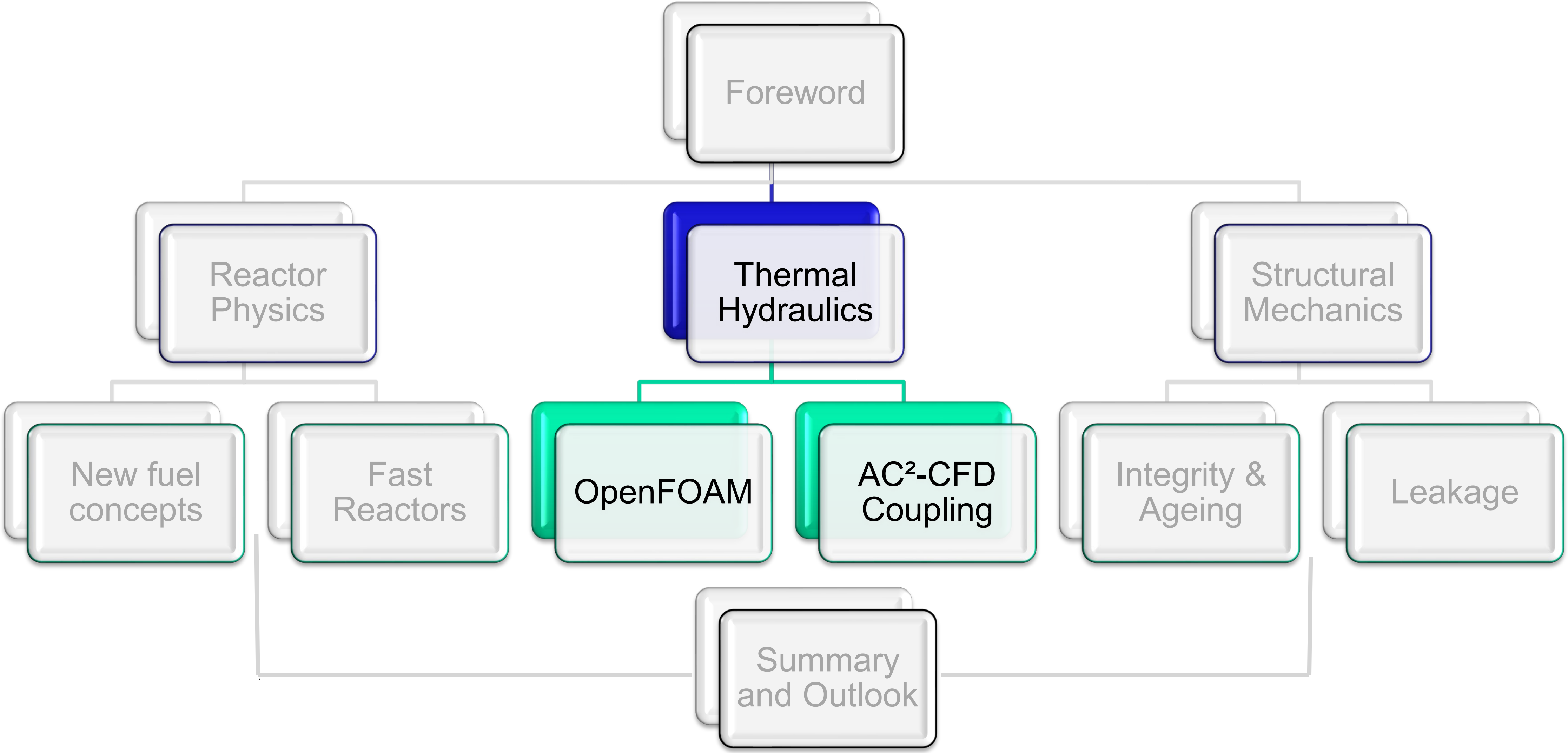
Presented research priorities:

- High-fidelity multi-physics pin-by-pin modelling of advanced fuel assemblies of (A)LWR
- Advanced tool for high-fidelity multi-physics simulation

Additionally research priorities:

- Cores with longer fuel cycle length, higher burn-up and/or higher fuel enrichment, advanced loading pattern, and the increasing use of burnable absorbers;
  transfer of knowledge to innovative designs including SMRs
- New fuels, claddings, and fuel assemblies are developed or already used, which requires further development and validation of the GRS evidence tools.
- This is not just a matter of providing new models and procedures that work on same scale previously considered in simulations.

Thermal Hydraulics



Containment simulation with OpenFOAM

- The German nuclear research community considers the increased use of the open-source CFD code OpenFOAM for research purposes
  - this decision was ultimately driven by freely accessible source code

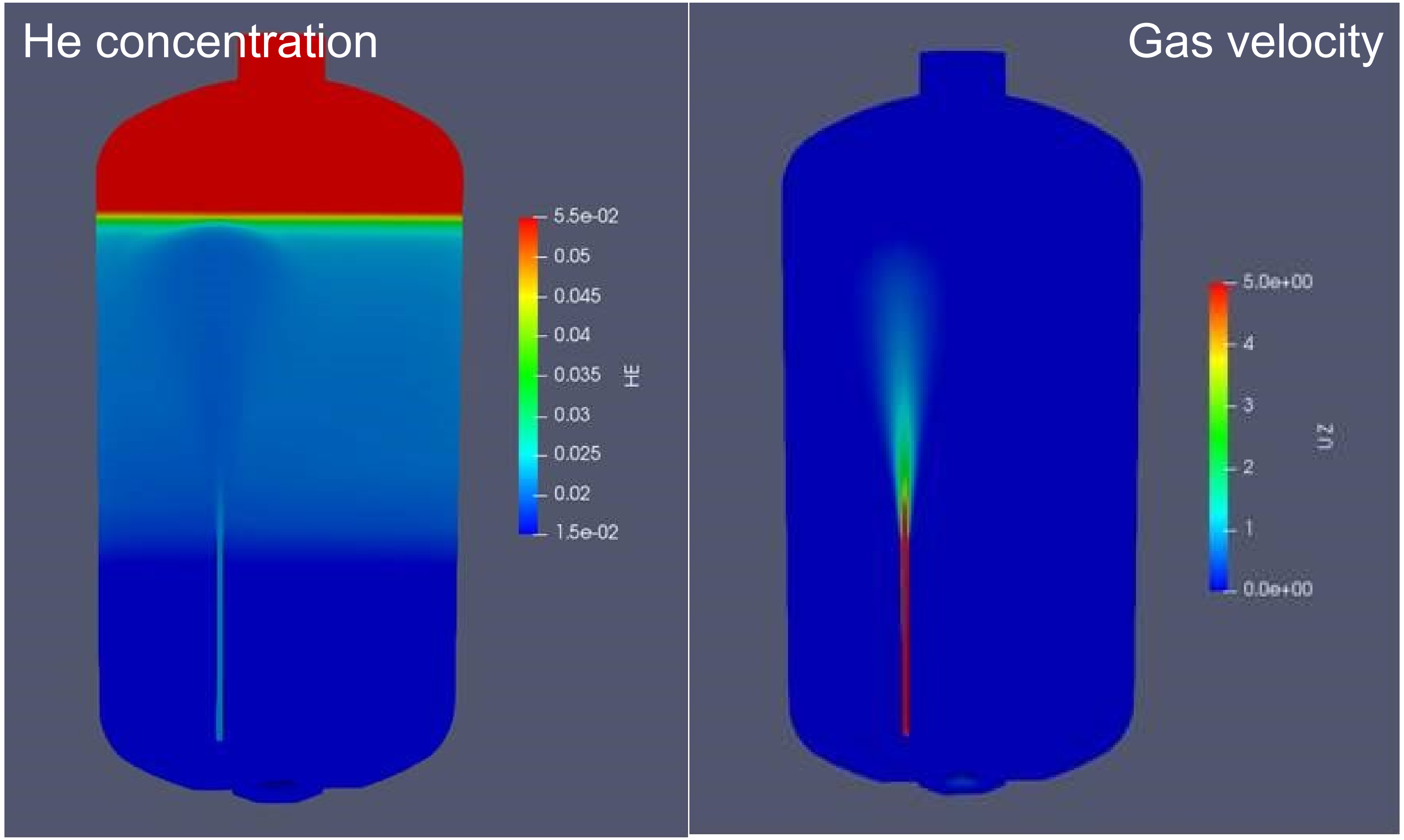
- GRS developments and validates models for:
  - simulation of the flow and the composition of gases (in particular H_2 concentration),
  - wall and volume condensation
  - thermal radiation
  - PARs (passive catalytic hydrogen recombiners)

Containment simulation with OpenFOAM

- Simulation of the flow and the composition of gases:
  - In severe accidents H_2 is released into the containment
  - It is important to predict, if gas mixture exceeds the flammability or detonation limits (global or locally).
- Accurate simulation of the gas flow with all relevant phenomena:
  - Turbulence modelling and gas mixing
  - Influence of walls and other structures
    (validation of wall functions and heat transfer wall / gas)
  - Diffusion modeling
    (extension and modification of transport equations for energy and species mass fractions)

Containment simulation with OpenFOAM

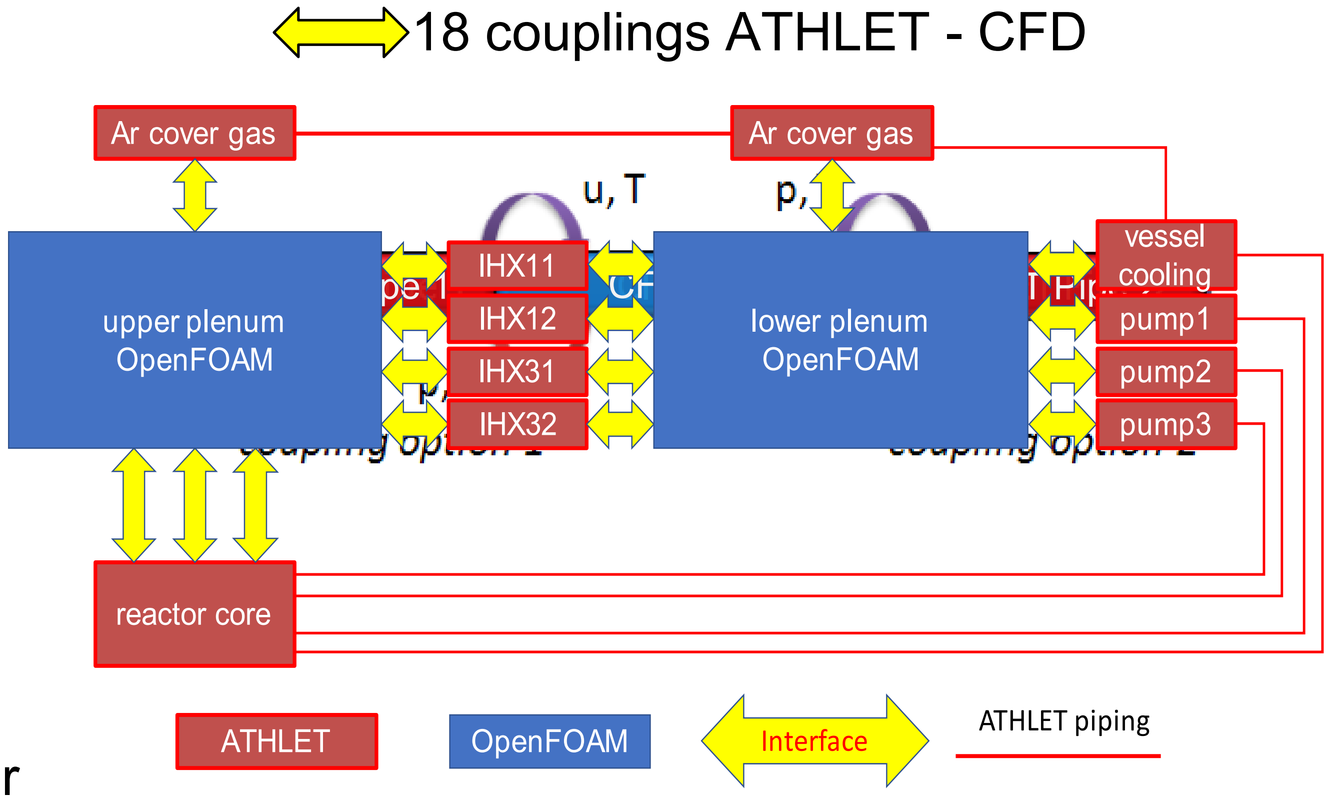
- Model validation by simple test cases and large-scale experi-ments (e.g. THAI, Panda, .. test series)
- OECD/NEA Panda benchmark
  - Dissolution of stable Helium layer by a vertical gas jet
  - He replaces H_2 in the Panda tests



Coupling: AC² - CFD

- 3D effects cannot be directly treated by 1D system TH codes
- 3D simulation only of selected areas with complex flow behavior using CFD(OpenFOAM)
- Rest of the system is modelled by ATHLET code
- 3D effects play important role in safety assessment
  - Pool-type sodium cooled fast reactor

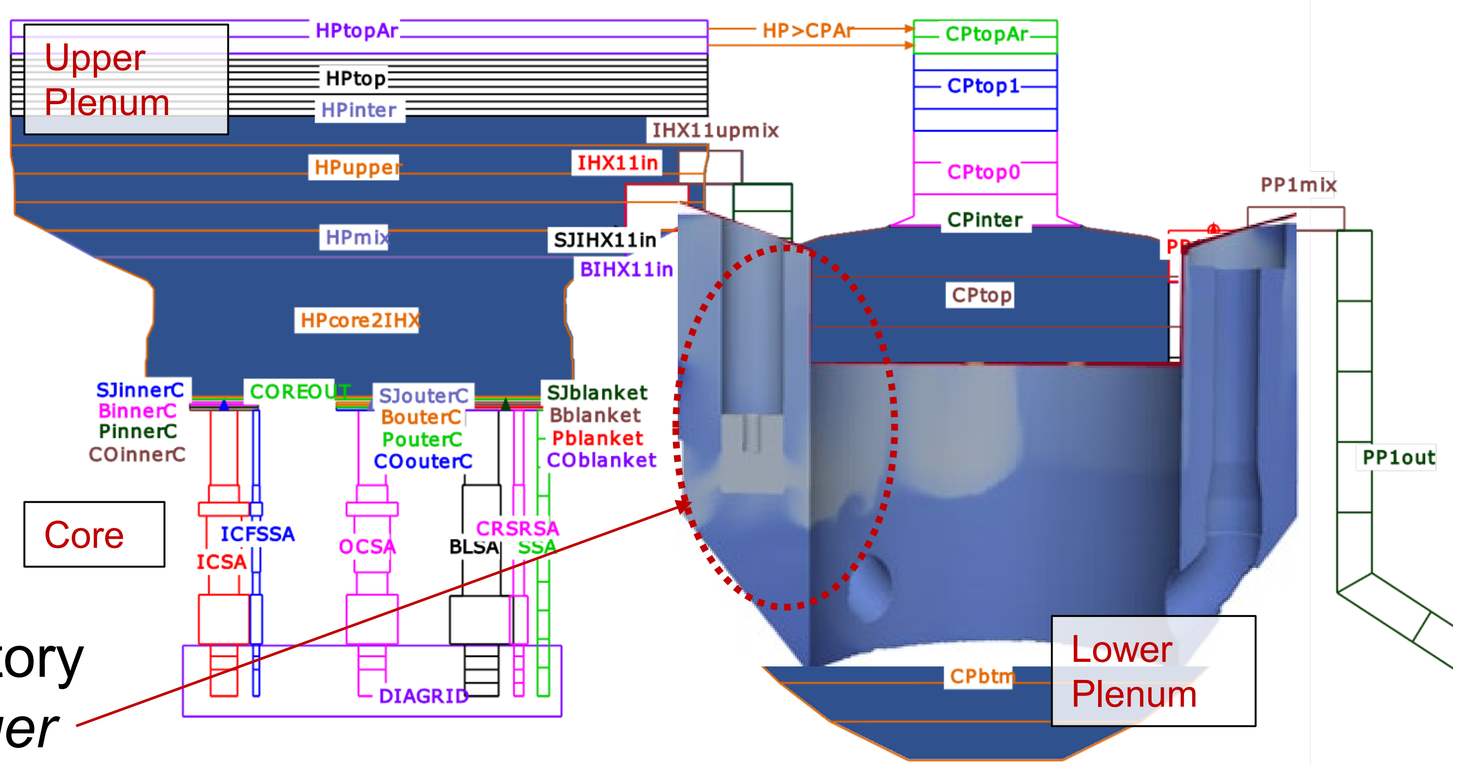
Example: Phénix reactor simulation



Coupling: AC² - CFD

Example: Phénix reactor simulation – ATHLET

- Different numerical methods implemented for stabili-zation of solution:
  - Under-relaxation:
    $$\boldsymbol{\alpha}^{n} = \boldsymbol{\alpha}^{n-1} + w(\boldsymbol{o}^{n} - \boldsymbol{\alpha}^{n-1})$$
  - Quasi-newton:
    $$\boldsymbol{\alpha}^{n} = \boldsymbol{\alpha}^{n-1} - w\mathbf{J}^{-1}\boldsymbol{R}^{n}$$
- First validation confirm influences of 3D effects like different temperature history at *intermediate heat exchanger outlet*



Thermal Hydraulics - Summary

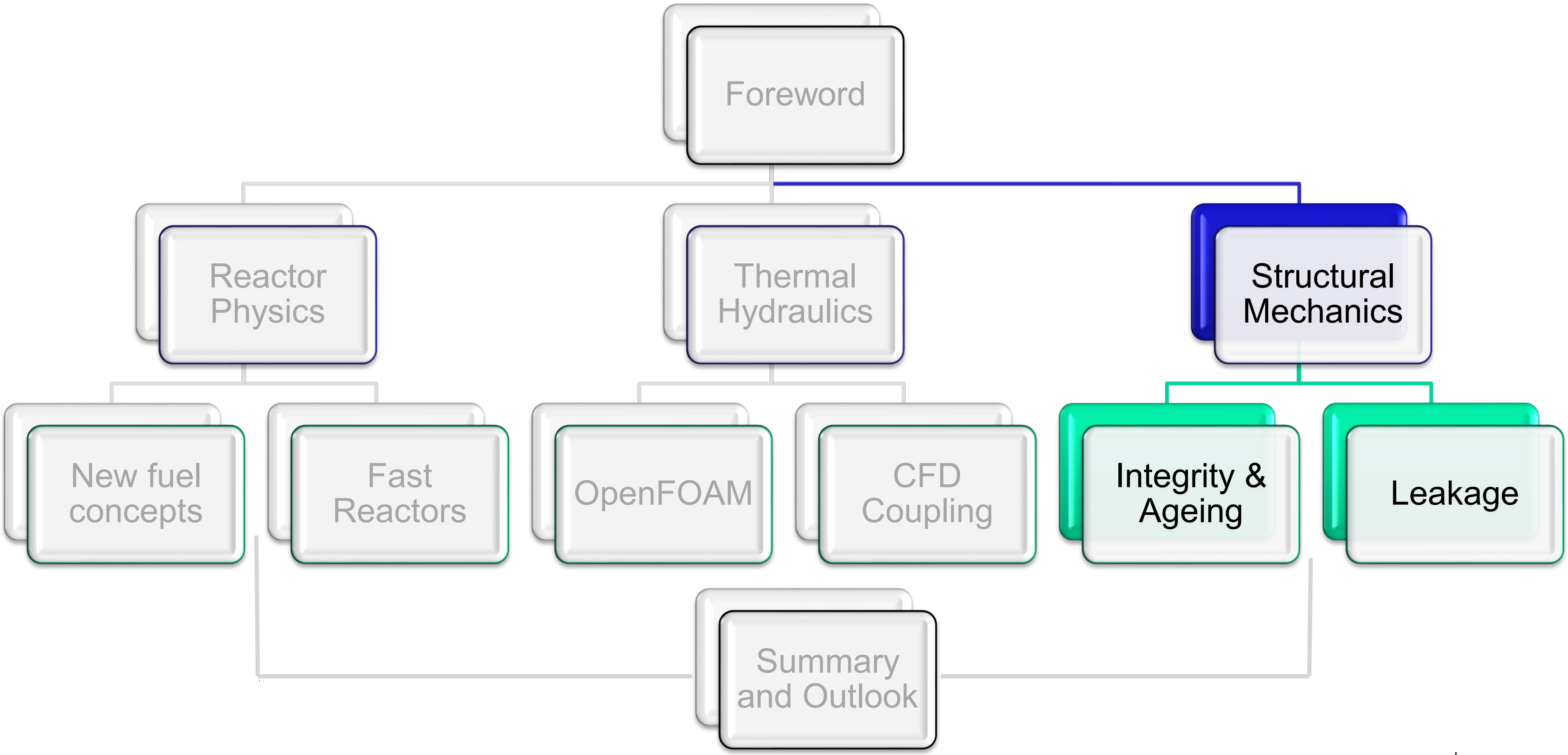
Presented research priorities:

- Ongoing and planned OpenFOAM activities on containment-specific issues
- Coupling of AC² system code with CFD codes

Additionally research priorities:

- Thermal radiation modelling
- Simulation of passive catalytic hydrogen recombiners
- Passive systems
- SMRs
- Sub-critical reactors

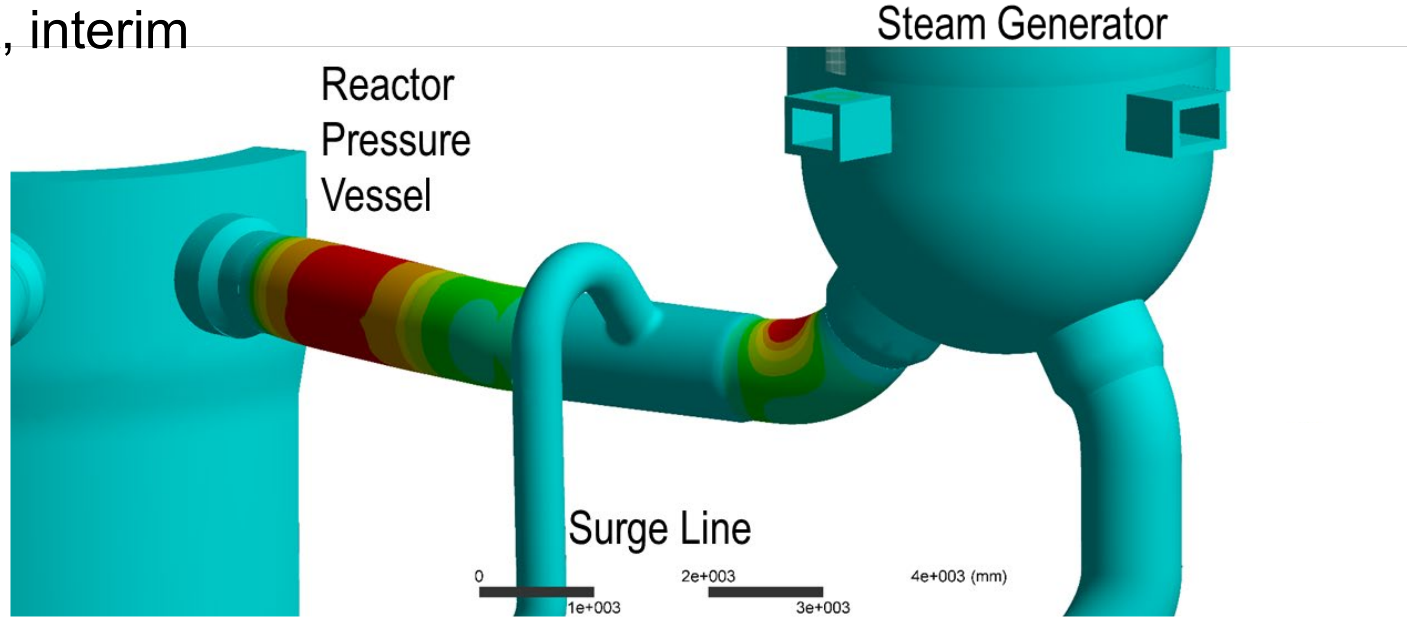
Structural Mechanics



Structural Mechanics

PROST WinLeck

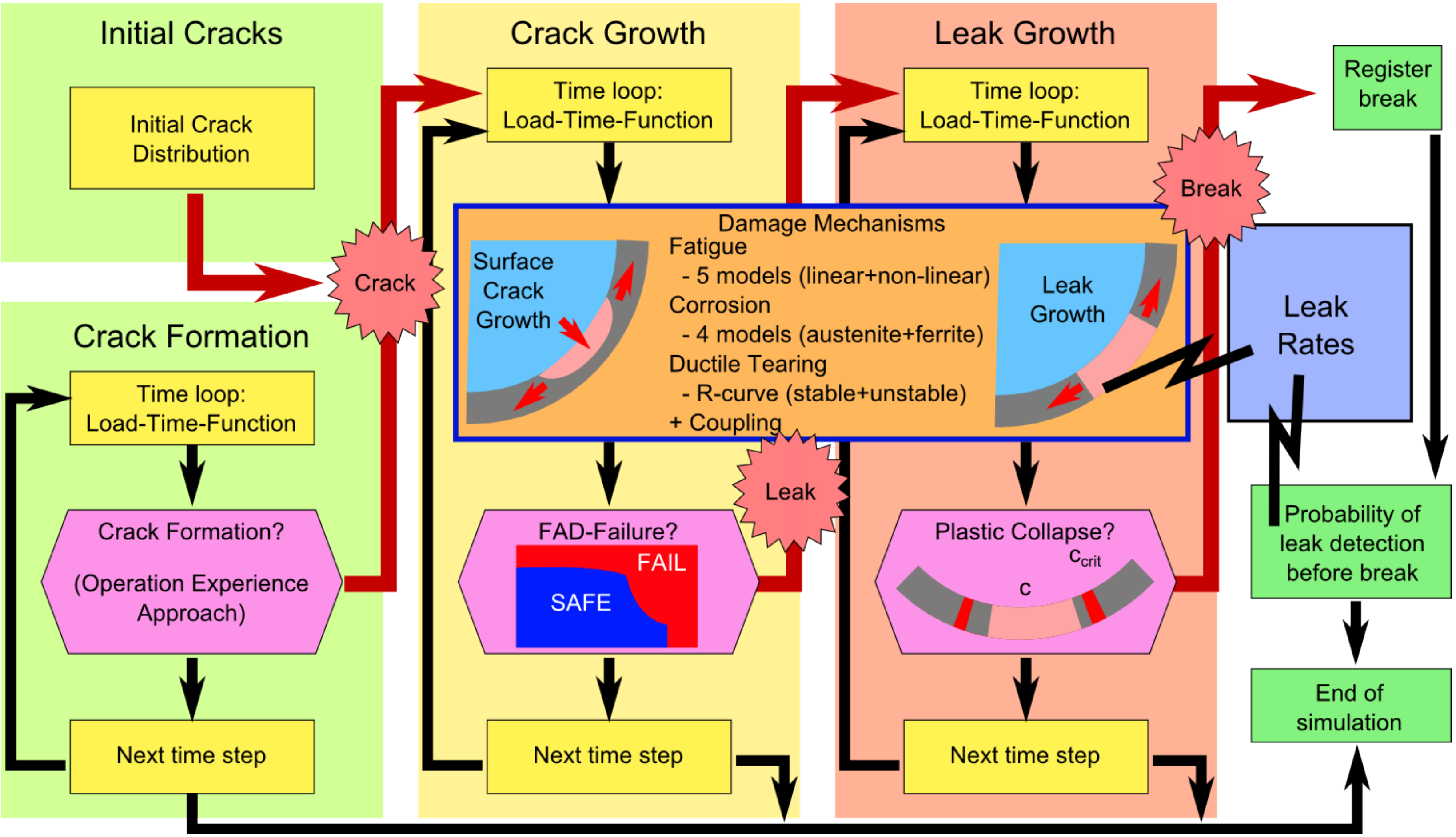
- Analysis methods for
  - Metal components (piping, RPV, fuel element, …)
  - Building structures (containment, interim storage, …)
- Based on
  - Finite-Element Analyses
  - Analytical methods
- Code development



PWR hot leg assessment under severe accident conditions

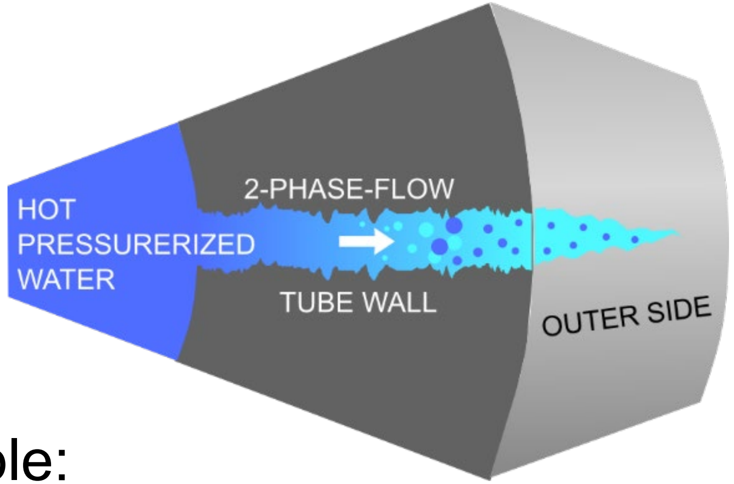
Integrity Assessment: Code PROST

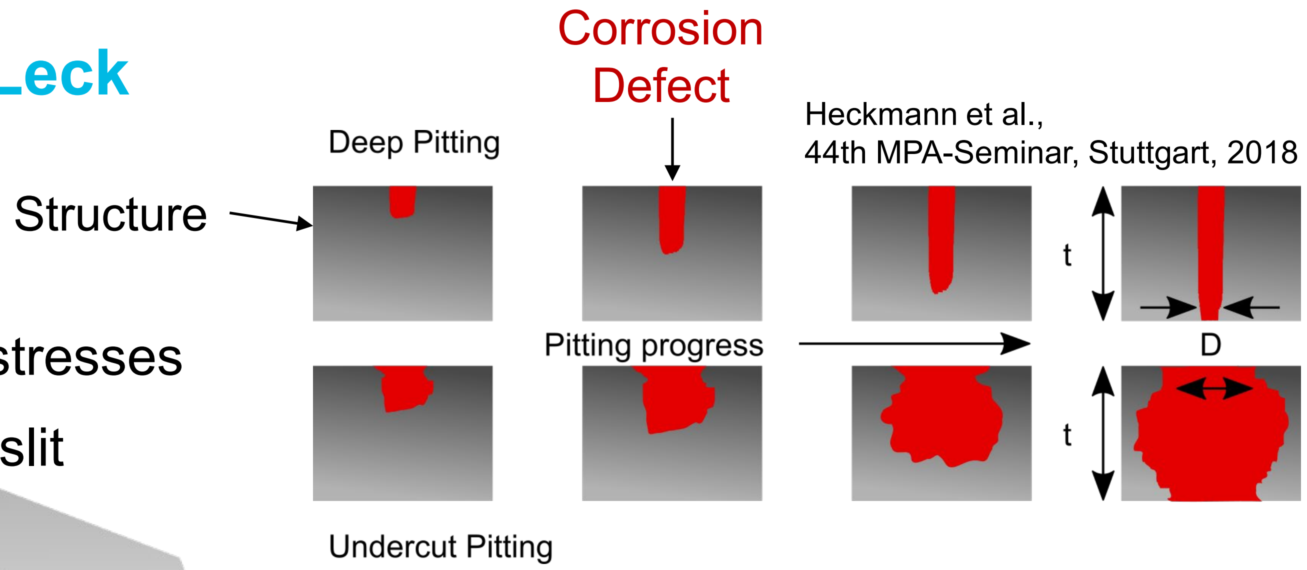
- Ageing and degradation
  - Crack initiation
  - Crack growth
  - Leak growth
- Integrity assess-ment
  - Leaking
  - Rupture
- Reliability
  - Probabilistic Fracture Mechanics (PFM)

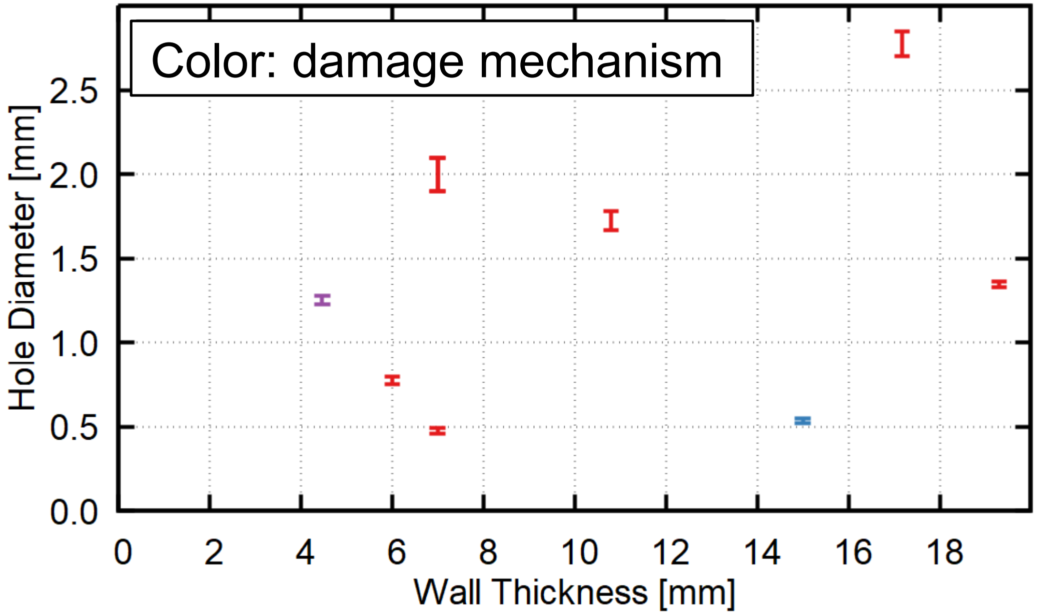


Leakage Assessment: Code WinLeck

- Leak assessment
  - Narrow slits, opened by operational stresses
  - Evaporation & two-phase flow in the slit
  - Critical flow
- Computation
  - Leak opening
  - Flow modeling
- Analysis example:
  - Pinhole leaks from operation experience
  - Deep pitting typical

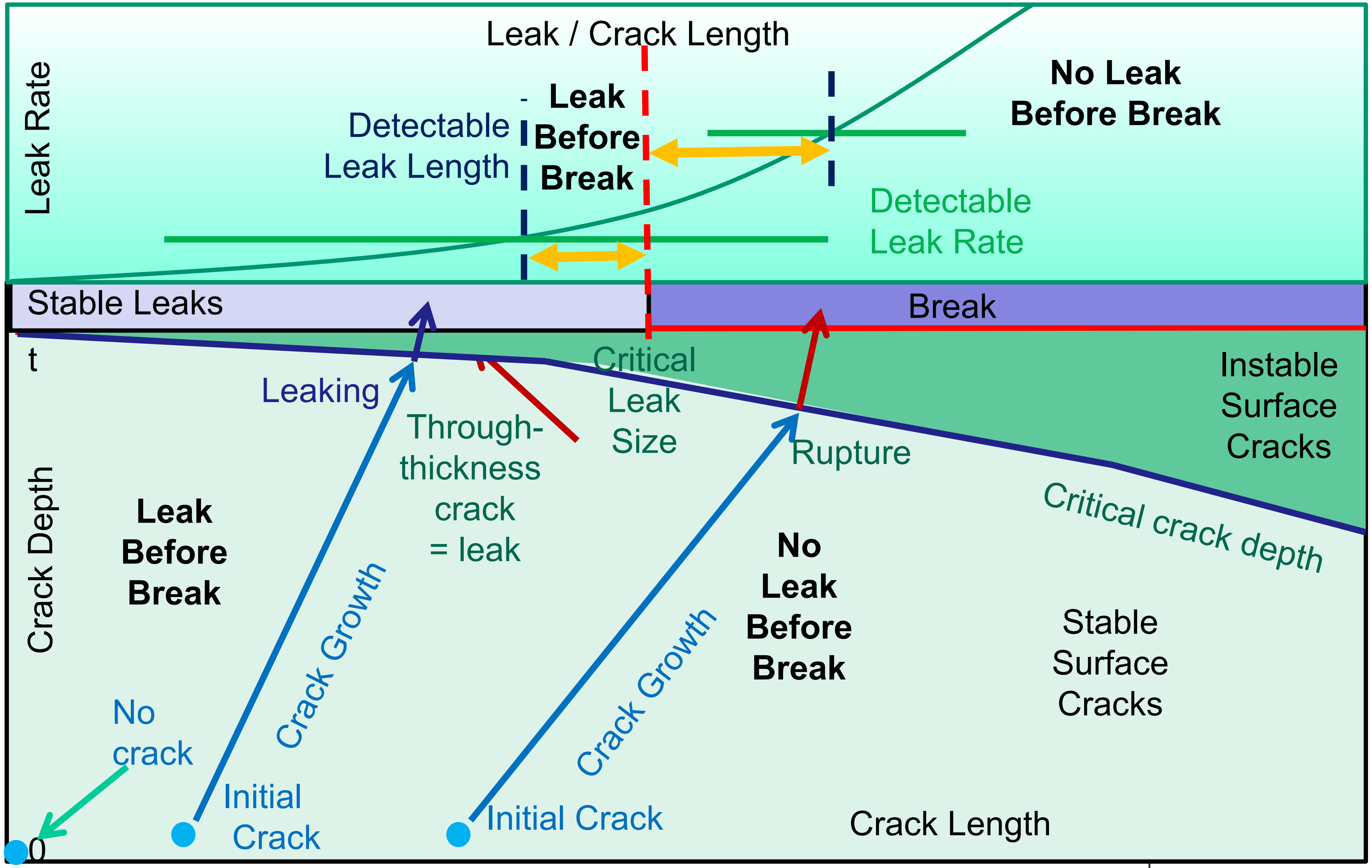






Leak-Before-Break Analysis

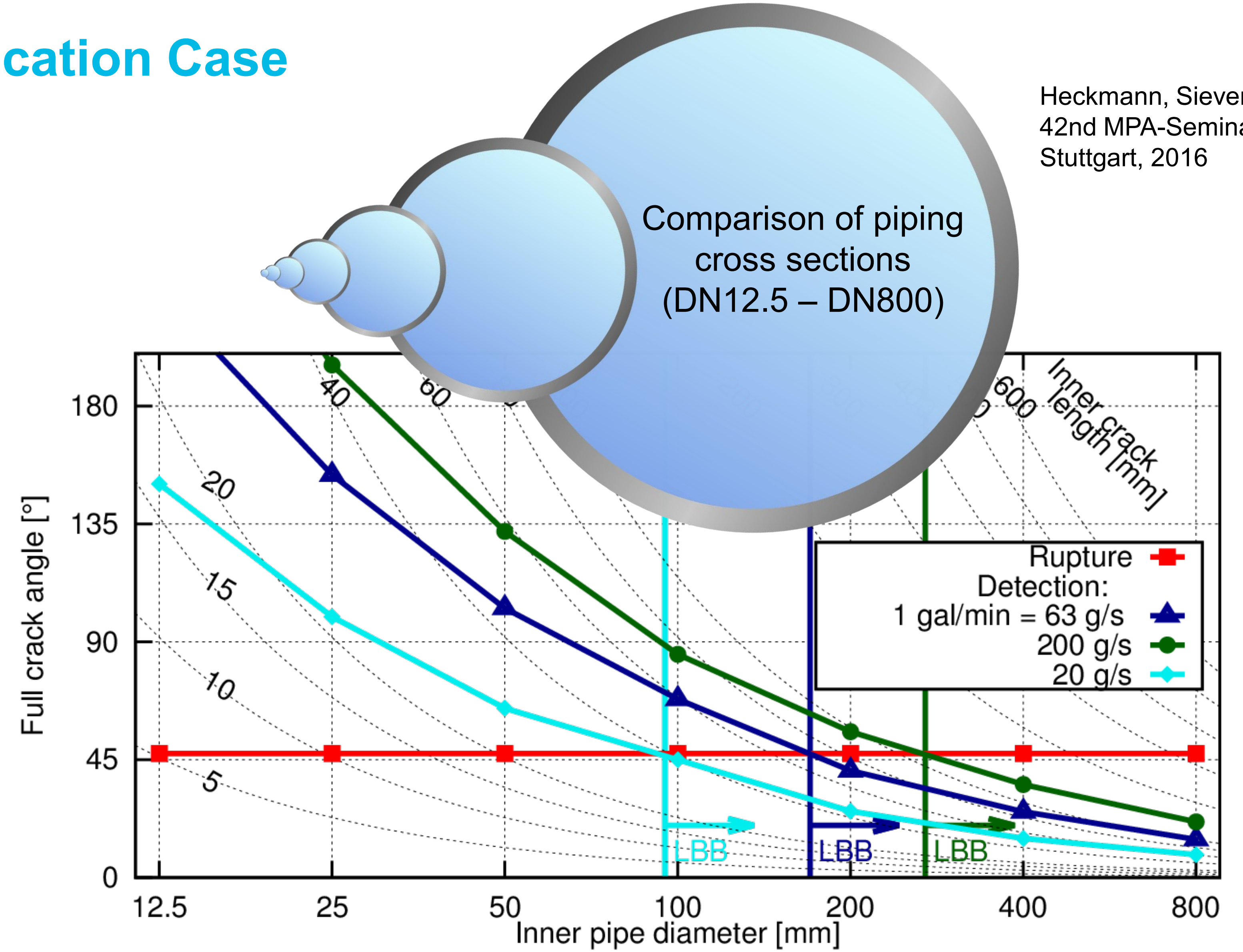
- Extended structural integrity diagram
- Computation of
  - critical size of postulated through-thickness cracks
  - Flow rates of postulated leaks
- Identification of local leak before large failure



Leak-Before-Break Application Case

Heckmann, Sievers,
42nd MPA-Seminar,
Stuttgart, 2016

- Variation of
  - Pipe size
  - Detection threshold
- Comparison
  - Detectable leak size
  - Critical leak size
- LBB favorable for
  - Large pipes
  - Low detection threshold



Structural Mechanics - Summary

Presented research priorities:

- Integrity assessment of piping and vessels with consideration of ageing mechanisms
- Assessment of leakage in piping and leak-before-break

Additionally research priorities:

- Components under severe accident loadings
- Aircraft impact
- Ageing of concrete structures
- Integrity assessment of reactor pressure vessels (RPV)

Summary & Outlook

- ~70 technical experts at GRS's Safety Research Division develop, validate and apply codes in various disciplines
- Selected activities presented from reactor physics, thermal hydraulics, and structure mechanics
- GRS remains stable partner in this area

- Future activities – national level
  - Retain and increase competence for currently operated reactors
  - Decommissioning, radioactive waste, (prolonged) interim storage
- Future activities – international level
  - Long-term operation
  - Build-up of competences for Gen III/III+ reactors, Gen IV, SMR

Conclusion & Acknowledgement

In future GRS will have the necessary staff, competences, know-how and validated evidence tools for safety assessments for currently operated, advanced and innovative reactors and SMRs.

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