Multiscale analysis for Reactor Safety

Antoine Gerschenfeld

CEA - DM2S/STMF

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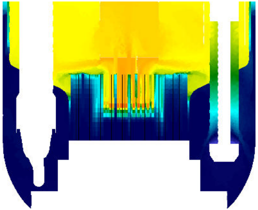
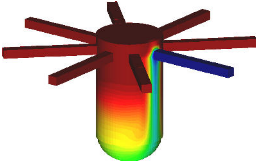
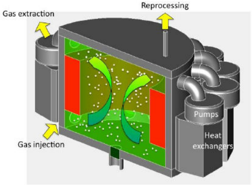
Introduction



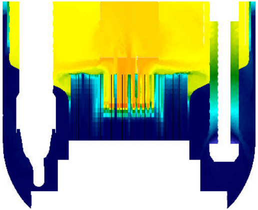


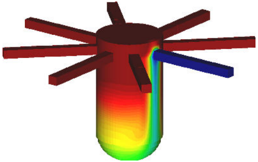


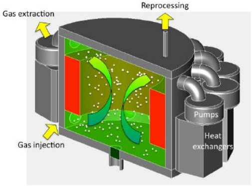
Why go beyond the system scale?

- All reactor safety reports up to now have relied on STH/system-scale codes for thermal-hydraulics analysis
  → 0D/1D(/3D) pipe networks : RELAP, CATHARE, TRACE...
- this approach predicts loop-type LWRs quite well...
  .. but can run in trouble with 3D effects :
  - PWR : mixing in inlet/outlet plena during SGTR/LOCA
  - SFR / LFR : stratification / natural convection in large plena
  - SMRs : stratif. / NC in containment, large pools!
  - MSRs : the fuel itself is a pool...

Introduction



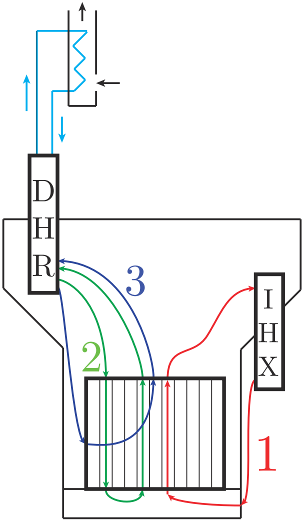




Why go beyond the system scale?

- Standard approach :
  - identify conservative hypotheses on phenomena
    → construct coarse, but conservative model at STH scale
  - → high margins in the final result
- but this is increasingly undesirable :
  - need to study longer transients (72h)
    - conservatism accumulates with time
    - sometimes, there is no clear conservative hypothesis!
  - for new designs : high margins have a cost
    → if they are reduced : potential for design optimization
  - for existing reactors : fixed designs, but increasing requirements
    → fresh air if margins can be recovered

Example phenomenon

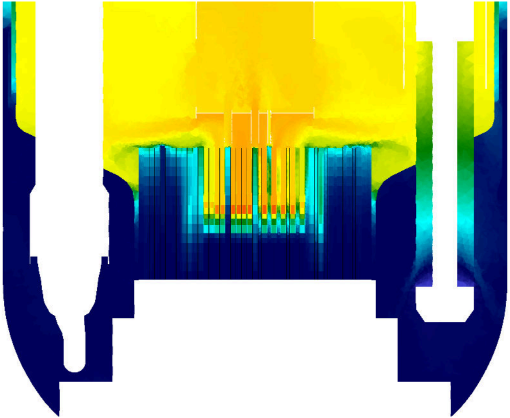


Long-term cooling in a Sodium Fast Reactor

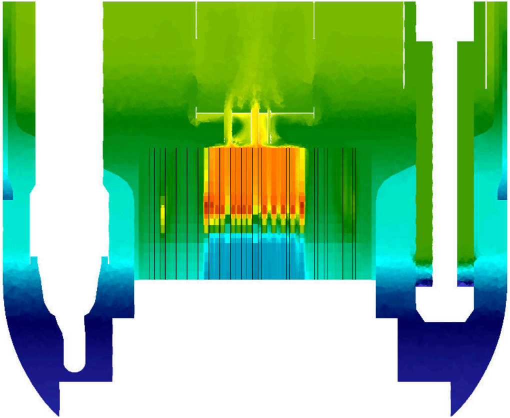
- passive heat removal to air by DHX in hot pool
- competition between three paths :
  1. normal primary circuit flow
  2. convection loops between S/As
  3. flow in the inter-wrapper gaps
- only (1) can be modeled in STH :
  (2) miscalculated, (3) neglected
  $\Rightarrow$ T_{core} overestimated (conservative)
  Q_{prim} overestimated (bad: wrong pool temps)
- but can we at least design a conservative approach?

Example: SFR long-term cooling

Overview

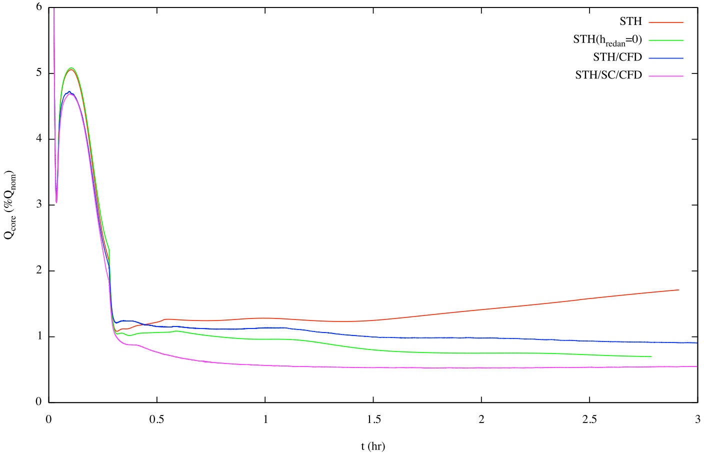


Nominal state



Long-term natural convection

Example: SFR long-term cooling

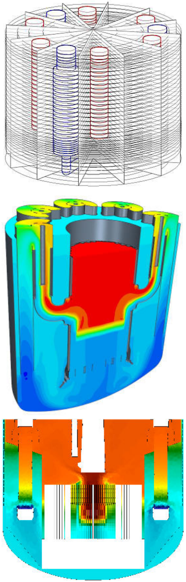


Flow rate

- 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% !

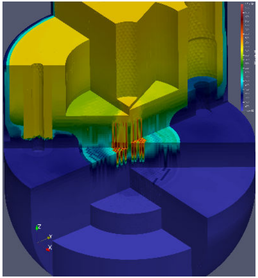
Predicting 3D phenomena

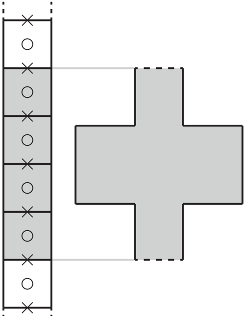


Alternatives

1. 3D modules in STH codes:
   - + turn-key! (everything is already there)
   - + mature for single-phase and two-phase
   - – but limited resolution (no HPC):
     - often rather good for stratification
     - but rarely enough for jet behavior
2. CFD codes for full reactor:
   - + enough resolution for all phenomena
   - + high maturity for single-phase; in progress for two-phase
   - – need to re-implement/validate models from STH: pumps, exchangers, core with point kinetics…
   - – CFD resolution everywhere, not just in areas of interest
3. coupling between STH and finer codes:
   - + can reuse STH models
   - + only use fine resolution where needed
   - – need to develop/validate a coupling algorithm

Predicting 3D phenomena





CEA approach: domain overlapping

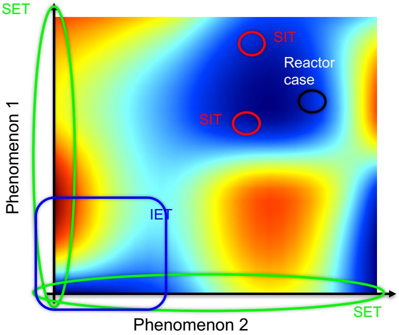
Need for : subchannel (in the core), CFD (in plena), STH (elsewhere)

1. unify subchannel and CFD within the same solver : TRUST
   - subchannel code implemented as porous-body CFD
2. keep the full-reactor STH model : CATHARE
   but overlap part of it with the subchannel+CFD fine domain
3. implement data exchanges between the two:
   - STH→SC/CFD: boundary conditions
   - SC/CFD→STH: forcing terms → keep the two domains consistent
   - code-to-code iterations → converge at each time step

⇒ within a generic coupling tool: MATHYS

- Practical experience:
  - works well in single-phase → small overhead compared to CFD
  - but insufficient for two-phase flows!

Qualification for safety



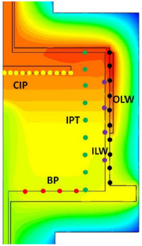
SET : Separate Effect Tests

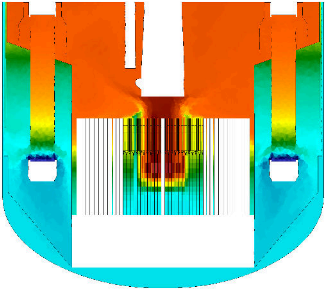
IET : Integral Effect Tests

SIT : System and Industrial Tests

- code development is a small part of the work: reactor safety studies require qualification
- Typical steps (e.g. in ASN "Guide n°28"): Verification, Validation, Uncertainty Quantification
- for STH codes, validation relies on an experimental database where:
  - each phenomenon can be validated in isolation $\rightarrow$ Separate Effect Tests
  - interactions between phenomena can be quantified $\rightarrow$ Integral Effect Tests (for PWRs : BETHSY, ROSA, ATLAS...)
  - everything can be validated together $\rightarrow$ on integral validation : System and Industrial Tests
- STH does not simulate 3D effects $\rightarrow$ geometrical similarity is needed (IETs are scaled-down reactor circuits)

Qualification





Multiscale codes

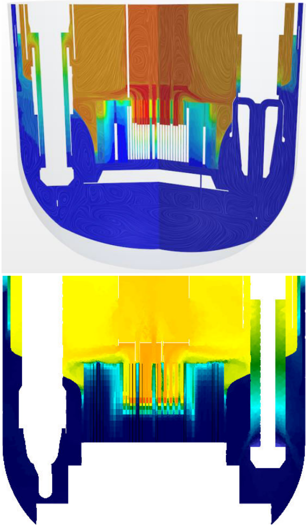
- for multiscale, the approach is the same!
  "a multi-scale coupling is qualified as a single code"

but the validation work differs:

- SETs → depend on one code → already covered
- each phenomenon predicted by the coupling must be validated → need for IETs. For SFRs at CEA:
  - natural convection in presence of stratified pools
  - cooling by inter-wrapper flow within the core

  but CFD simulates geometrical effects
  → complete similarity not needed:
  less need for new experiments
  For SFRs at CEA: TALL-3D for NC
  PLANDTL-2/THEADES for IWF
- also applies to integral validation:
  can use PHENIX (pool-type), FFTF (loop-type)

Conclusion



multi-scale is practical for single-phase reactor analysis

- (-) numerical cost compared to STH, but:
- (+) improved predictions → reduced margins
  → allows for optimized designs
- (+) no need for direct similarity during validation:
  - better use of existing databases
  - less need for (time-consuming) new experiments

⇒ At CEA, multiscale is now the reference option for transients involving 3D effects in SFRs (and MSRs)

Conclusion

For two-phase flows, significant work remains:

- CFD itself is less mature than in single-phase
- numerical costs are higher, esp. for long transients
- two-phase multi-scale coupling is more difficult:
  - no clear overlapping algorithm
  - domain decomposition (the alternative) have stability drawbacks

  → the only solution may be a monolithic coupling
  (where both codes contribute to a single pressure system)

There should be interesting developments in the next few years!