Status of System-Code Development and Needs of Additional V&V

C. Parisi

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Outline

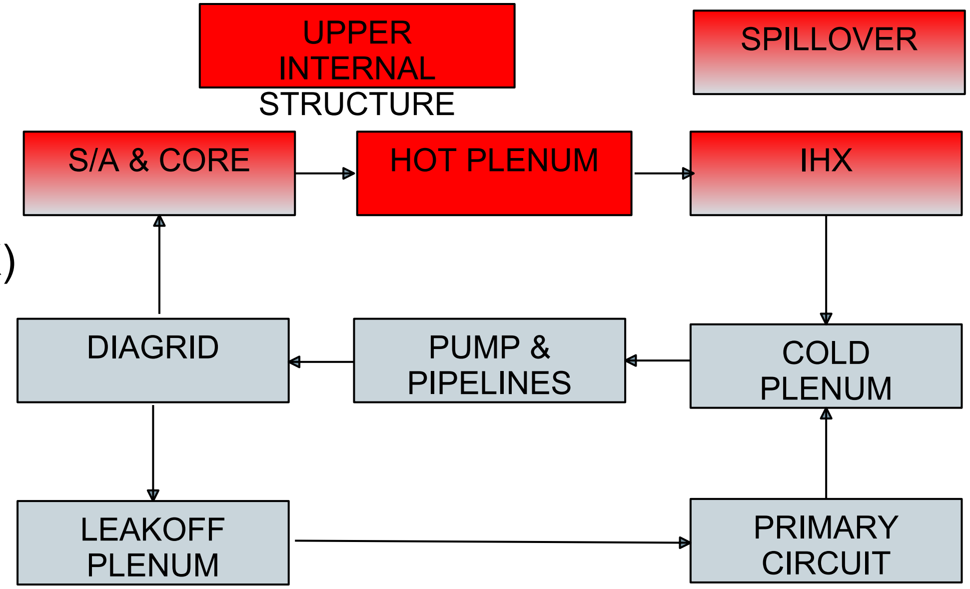
- Liquid Metals reactors TH challenges for system TH codes
- Status of System TH codes development
  - Suitability of RELAP5-3D for SFR simulation
- Needs of Additional V&V
- Conclusions

TH challenges

- Scope of thermal-hydraulic (TH) analyses of the LM system determine **thermal** and **hydraulic** loads for the main components
- Knowledge of the   and fundamental for mechanical design of the components and for safety analyses
  - TH induced stresses
  - Thermal expansions of safety components (e.g. CR) during steady state and transients
- LM operating with steep temperature gradients (~ 150 ˚C) and fast temperature changes (~7 ˚C/s) can happen
  - Mixed convection flows
  - Flow velocities from ΔP and $\Delta\rho$

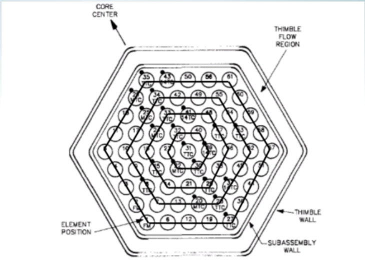
TH challenges for system TH codes

- Imperative need for next-generation LM systems: minimize costs ($), improve safety
  - Optimization of LM and structural materials masses
  - New designs Structural simplification and compactness detailed knowledge of TH fields and
- Some TH challenges for system TH codes…
  - Subassembly (S/A)
  - Core
  - Hot Plenum
  - Cold Plenum
  - Intermediate Heat Exchangers (IHX)
  - Decay Heat Removal
  - Gas entrainment



Primary circuit flows

TH challenges

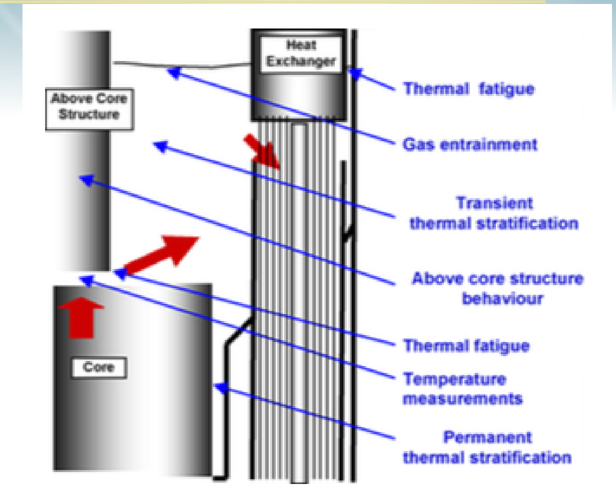


XX09 S/A (from Messick et al., Nuclear Engineering & Design 101 (1987))

- Sub-Assembly (S/A) and Core Simulations
  - S/A pressure drops in all the S/A regions
  - Maximum Clad temperature
  - Hexagonal Can temperature
  - Core flow distribution
  - Inter-wrapper flows
- Tools:
  - SYS TH: modeling the different core regions with 1D channels, including inter-wrapper/bypass flows
  - Sub-channel + CFD (3D flows) detailed design analyses and boundary conditions (BC) for SYS TH
- Need of experimental facilities (water and Na) for validation

TH challenges

- Hot Plenum
  - Hot/Cold Na mixing
  - Upper Internal Structure porosity
  - Thermal stratification
  - Thermal fatigue
  - Gas entrainment
  - Transient behaviors
- Tools:
  - CFD (3D flows) □ detailed design analyses and boundary conditions (BC) for SYS TH
  - SYS TH: nodalization strategies needed for 1D/3D components; feedback from CFD and experiments
- Need of experimental facilities (water and Na) for validation



Hot Plenum Phenomena
(from F. Tenchine, Nuclear Engineering & Design **240** (2010))

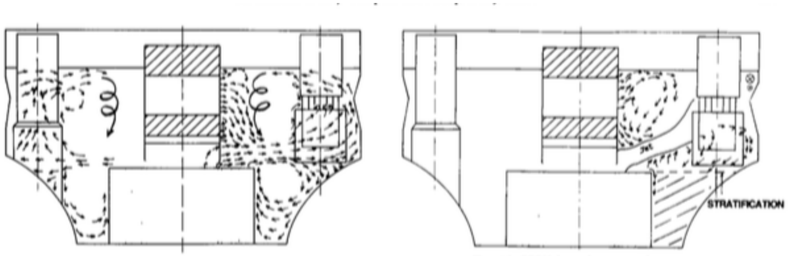


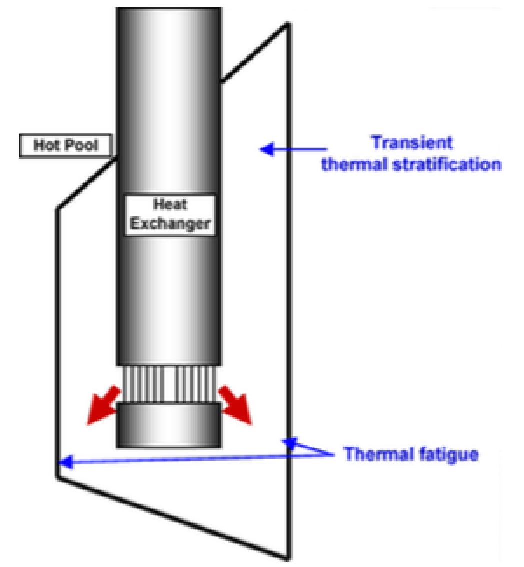
Fig. 9. SPX2 hot plenum.

Fig. 10. SPX2 hot plenum with rising jet.

SPX2 Hot Plenum at HFP and NC (from M. Azarian, et al., Nuclear Engineering & Design **124** (1990))

TH challenges

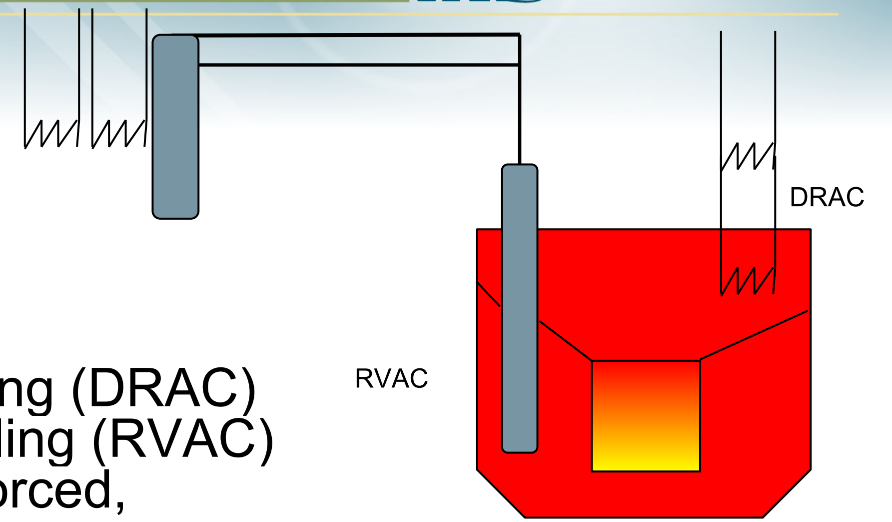
- Cold Plenum
  - Thermal Stress/Fatigue
  - Thermal stratification
  - IHX outlet window (cold/hot Na mixing)
    - ~10s ◦C gradients
  - Non-symmetrical temperature field (loss of one or more IHX)
    - Hot and cold shocks possible
  - Thermal loads on Core support structure
- Tools:
  - CFD (3D flows) detailed design analyses and boundary conditions (BC) for SYS TH
  - SYS TH: nodalization strategies needed for 1D/3D components; feedback from CFD and experiments
- Need of experimental facilities (water and Na) for validation



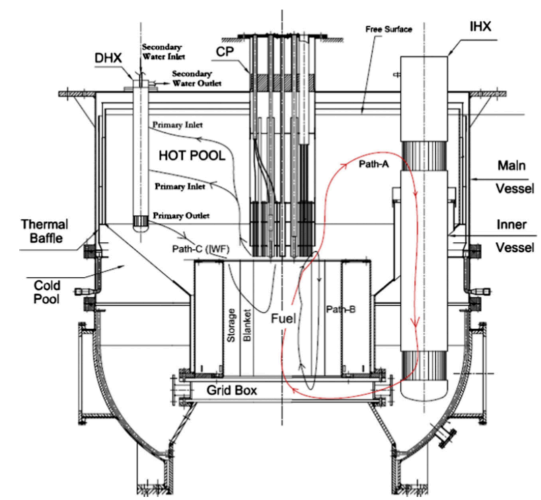
Cold Plenum Phenomena
(from F. Tenchine, Nuclear Engineering & Design **240** (2010))

TH challenges

- Decay Heat Removal
  - Different strategies available
    - Indirect Reactor Cooling
    - Direct Reactor Auxiliary Cooling (DRAC)
    - Reactor Vessel Auxiliary Cooling (RVAC)
  - Different flow regimes possible (forced, natural circulation)
  - Thermal Stratification in the pools
- Tools:
  - SYS TH: modeling the Decay HX or vessel walls
  - CFD (3D flows) □ mixing in the hot plenum, flow paths in the core inter-wrapper, spillover, etc.
- Need of experimental facilities (air/sodium, air, air/water)



Possible Decay Heat Removal Strategies

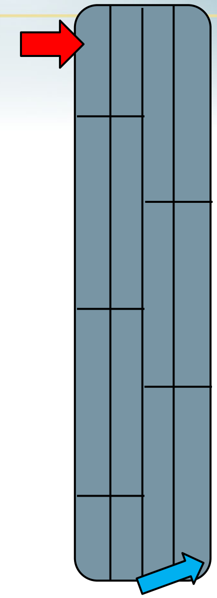


Decay Heat Removal for PBFR (from V.M. Mente et al., Annals of Nuclear Energy **65** (2014))

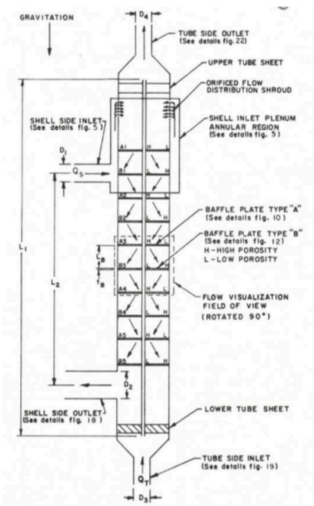
TH challenges

- Intermediate Heat Exchangers (IHX)
  - Sodium-sodium Shell & tube HX
  - Bundle Flow and temperature fields
  - Inlet/outlet window flow distribution
  - Flow-patterns during low-flow conditions (thermal buoyancy)

- Tools:
  - CFD (3D flows) detailed design analyses and BC for SYS TH
  - SYS TH: nodalization strategies needed for 1D components; feedback from CFD and experiments
- Need of experimental facilities (water, sodium)



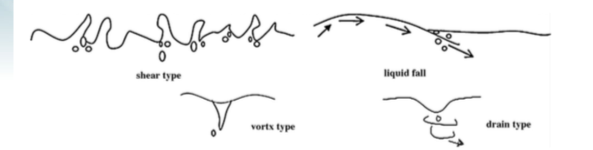
IHX flow paths



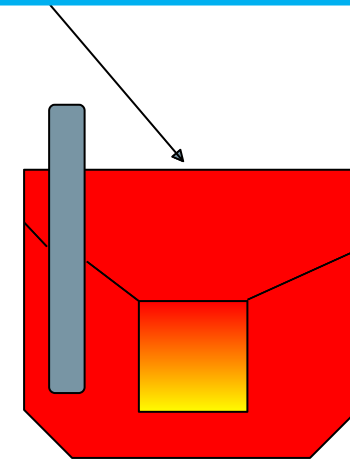
ANL 360° glass IHX test article (from K. Kasza, ANL/NE-07/21, 2007)

TH challenges

- Gas Entrainment
  - Transport of cover gas through the core
    - Compactness □ UP velocities increase □ free surface disturbed
  - Nucleation of Dissolved Gas
  - Leakage at gas seal
- Tools:
  - SYS TH: 2 phases, 2 or >2 fields codes for tracking transport and core effects
  - CFD □ free surface/vortex studies
- Need of experimental facilities (water, sodium)



Main types of gas entrainment (from Patwardhan, A.W, et al., Nuclear Engineering and Design, **249**, (2012))



Entrained Gas flow

Status of System TH codes development

- Several tools available, with different level of qualifications for LM systems analyses
  - E.g.: CATHARE, SAS4A/SASSYS-1, RELAP5-3D, TRACE, ATHLET, SPECTRA, ASTEC-Na
- SAS4A/SASSY-1 is the reference code for VTR safety analyses (see next presentation for V&V status)
- The RELAP series of codes have been developed at the INL for more than 40 years
  - RELAP5-3D is the flagship of nuclear reactor system analysis tools
  - Development still ongoing (e.g., integration in the INL "MOOSE" framework □ exploit new framework capabilities)
  - Capability to model LM systems added in 2000s'
    - Several libraries available (Na, Na-K, Pb, Pb-Bi, Li)
    - Specific correlations for LM Heat Transfer (Shimazaki, Westinghouse)
    - 3D hydraulic components

Status of System TH codes development

- Suitability of RELAP5-3D to LM reactor analyses possible and demonstrated in several studies, including international benchmarks, e.g.:
  - T. Sumner, S.M. Ghiaasiaan, "Effects of fuel type on the safety characteristics of a sodium cooled fast reactor. Part II: Simulation results", *Annals of Nuclear Energy,* **38**, pp. 1760-1768 (2011).
  - A. Del Nevo, et al. "Validation of a 3D Model of EBR-II and Assessment of RELAP5-3D Based on SHRT-17 Test", *Nuclear Technology* (2017).
  - M. Memmott, et al., "On the use of RELAP5-3D as a subchannel analysis code", *Nuclear Engineering and Design* (2010).
  - A. Lazaro et al., "Code assessment and modelling for Design Basis Accident Analysis of the European sodium fast reactor design. Part I: System description, modelling and benchmarking", *Nuclear Engineering and Design*, **266**, (2017).
  - V. Narcisi et al., "System thermal-hydraulic modelling of the Phenix dissymmetric test benchmark", *Nuclear Engineering and Design,* **353**, (2019).

Status of System TH codes development

- Suitability of RELAP5-3D to LM reactor analyses
  - Main possible code improvements identified:
    1) Cheng-Todreas correlation for wire-wrapped S/A
    2) Orifice pressure drop correlations at low flow conditions
    3) Reactivity components
    4) Decay Heat for fast reactor fuels
    5) Axial conduction
    6) EM pump model
    7) Thermal stratification model
    8) Na Boiling
  - 1) to 5) can already be implemented using **dedicated control variables/general tables**
  - 7) require coupling to CFD (available) or porous-media tool (MOOSE) or specific a-posteriori nodalization strategy
  - 6) and 8) require non-trivial code modifications

Needs of additional V&V

- RELAP5-3D validation for LWRs carried out on several separate-effect tests (SETF) and integral test facilities (ITF)
  - Decades long effort, budget ~ B$
- For LM systems, several RELAP5-3D basic validation cases should be also systematically included and documented

Phenomena/Components	Needs of Additional V&V for RELAP5-3D	Comments
0D NK	Low	Partially completed
Pressure Drop and Heat Transfer correlation for all flow regimes	Low	Partially completed. Need of final design for components.
2D/3D Phenomena (e.g. thermal stratification, flow jets, structure porosity)	Medium	Partially completed. Need of final design for components. Derived best-practice guidelines for modeling from experiments/reactors (benchmarks). Possible improvements using advanced coupling (MOOSE, CFD)
Asymmetric flows (consequences of pump trip or IHX fault)	Medium	Same as above
Limited Sodium Boiling	High	To be completely developed

Conclusions

- TH challenges for LM reactors are well-known
- Design and Safety Analyses strategies needs to include dedicated experiments, 3D advanced TH tools (CFD, subchannel) and advanced System TH tools
- INL RELAP5-3D code is being developed and implemented in the MOOSE framework
- Possibility to study LM systems with some approximation demonstrated
- Priorities for additional V&V tasks identified