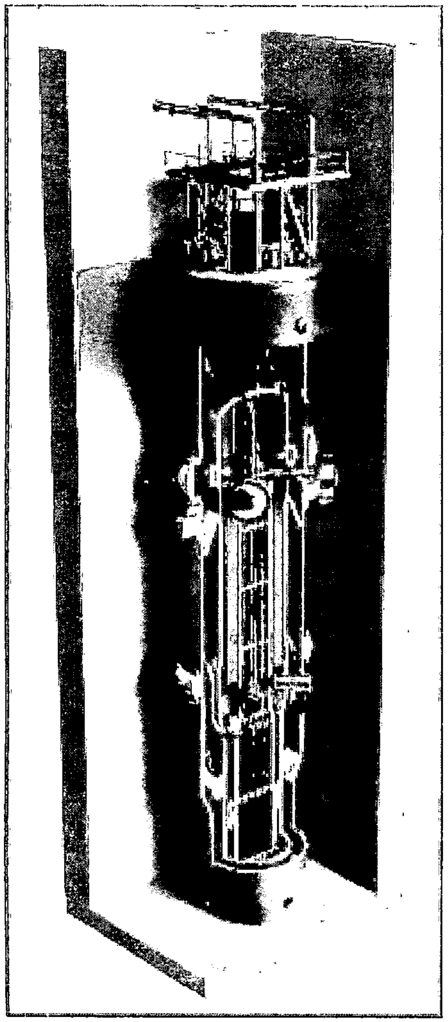
# ACRS Full Committee Presentation



## NuScale Topical Report

## Evaluation Methodology for Stability Analysis of the NuScale Power Module

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Template #: 0000-21727-F01 R5

# Presenters

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# Agenda

- Introduction and Main Message
- Stability Solution Type
- Stability Investigation Description
  - Theoretical
  - Numerical Using New Code PIM
  - Experimental Benchmark
- Procedure and Methodology
- Summary
- Questions and Discussions

# The Main Message

- The NuScale power module design was found to be stable in the entire range of normal operation
- Outside of normal operation, the reactor is destabilized when the riser flow is voided, however
  - Unstable flow oscillation amplitude is limited by nonlinear effects and the critical heat flux ratio actually improves
- The stability threshold is protected by scram upon loss of riser inlet subcooling
  - Conceptually equivalent to a "region exclusion" not a "detect and suppress" solution type
  - No action required to implement a stability solution hardware
- These conclusions are based on extensive first principles, experimental, and computational studies. Details next.

# Stability Evaluation

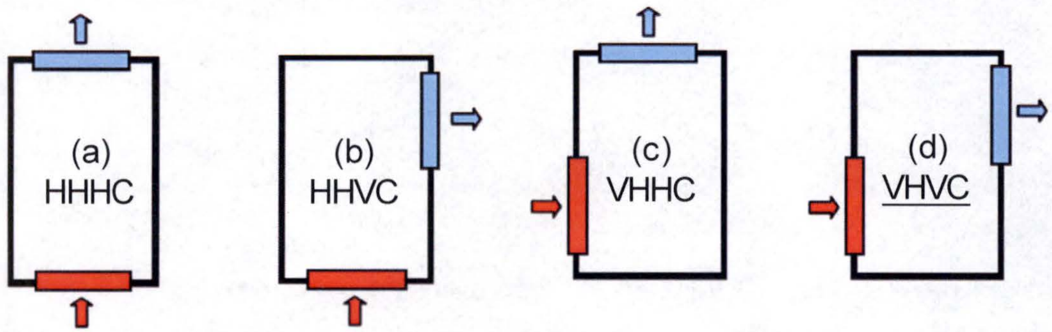
- Natural circulation instabilities were reported in literature
  - See for example D.S. Pilkhwal et al., "Analysis of the unstable behaviour of a single-phase natural circulation loop with one-dimensional and computational fluid-dynamic models," Annals of Nuclear Energy 34 (2007) 339–355.

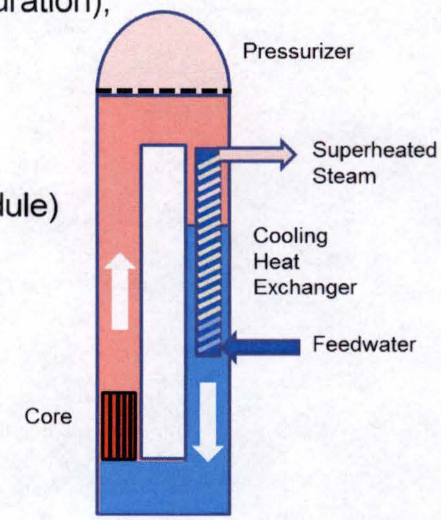
    a) HHHC: horizontal heater and horizontal cooler (the only unstable configuration);

    b) HHVC: horizontal heater and vertical cooler;

    c) VHHC: vertical heater and horizontal cooler;

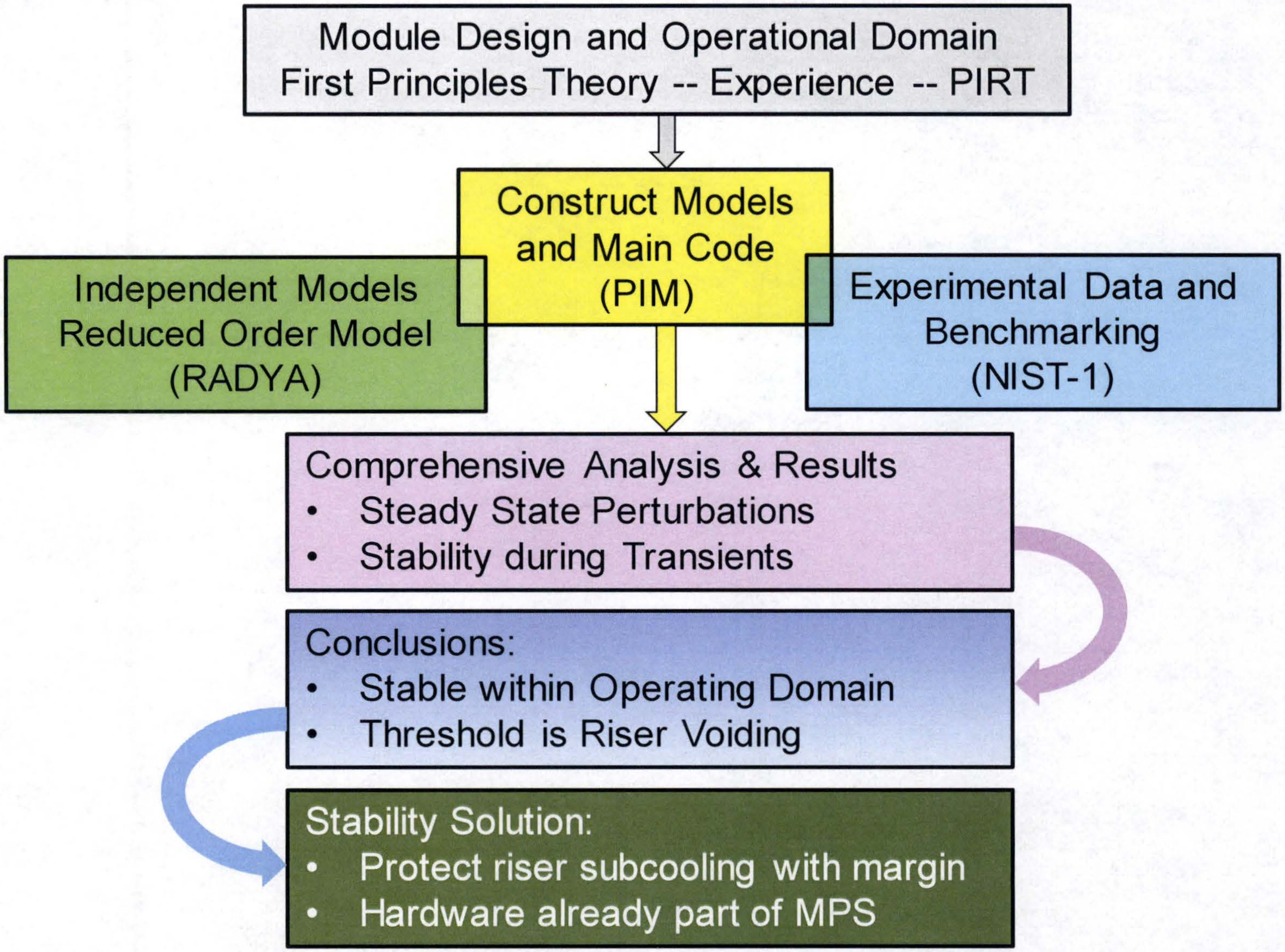
    d) VHVC: vertical heater and vertical cooler (qualitatively like NuScale module)




- Investigation of the NuScale module stability commenced to demonstrate stability, identify threshold conditions, and license stability protection methodology

# Stability Investigation Elements



# Theoretical Investigation

- Kick off with an expert committee to generate a first PIRT
- Scoping review of thermalhydraulic instability modes and contrasting with the NPM design features
- Identification of the possible instability mechanism
- Analysis from first principles
  - Riser-only mode (separate from cold leg)
  - Stability trend with power using a simple SG model
  - Shows decoupling of possible oscillations in SG tubes from primary flow and core
  - Informs design of stability experiments
- All medium ranked phenomena treated as highly ranked



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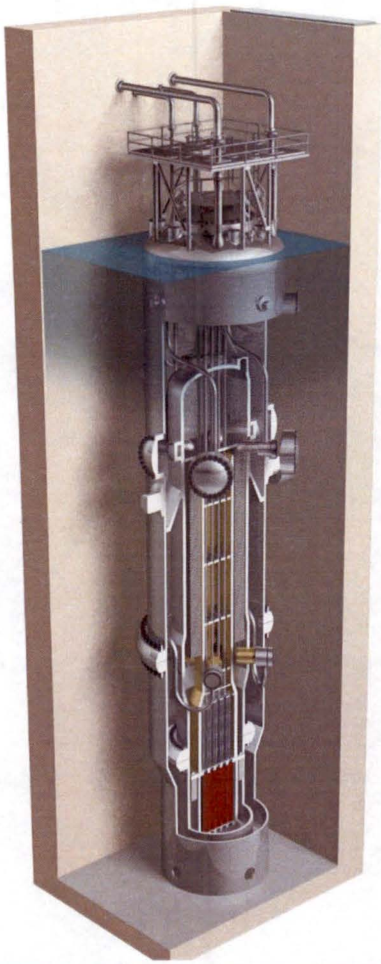
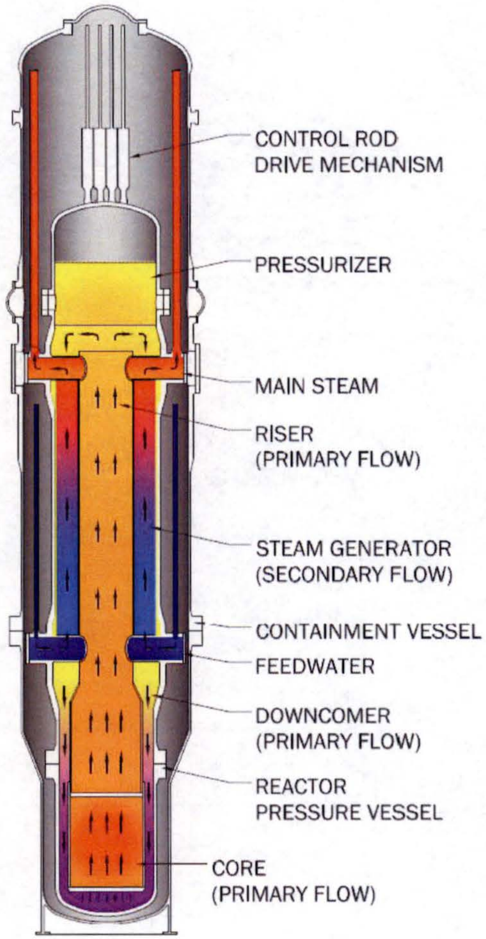
# Theoretical and First Principles

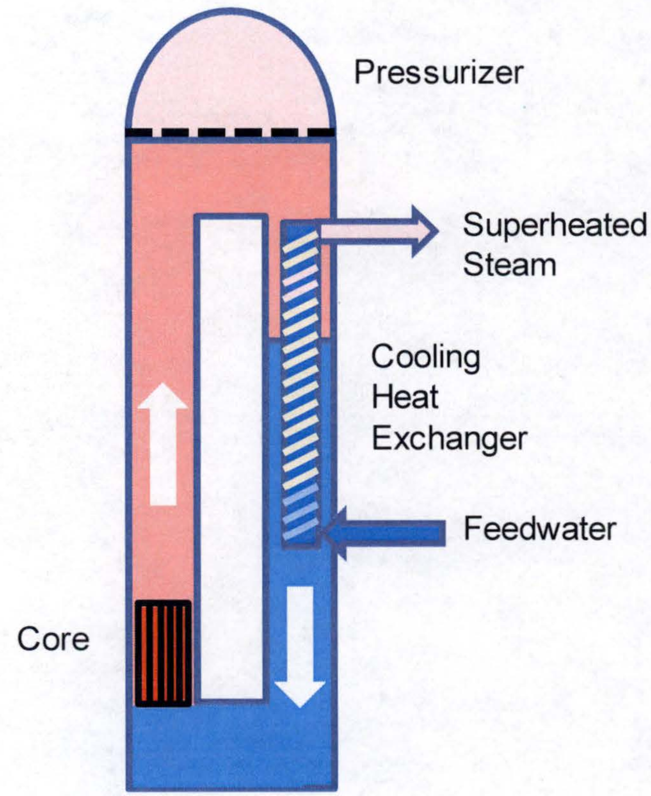
- A system with feedback processes may undergo oscillatory instability if the feedback is:
  - Negative (positive feedback is unconditionally unstable)
  - Delayed
  - Sufficiently strong
- NuScale natural circulation mode is examined
  - Feedback is negative. A perturbation increasing core flow decreases exit temperature thus decreases riser density head
  - Feedback is delayed. Transport delay for core exit condition to fill the riser and reach maximum density head effect.
  - Feedback strength is related to liquid thermal expansion and possibility of phase change, riser length, SG characteristics, reactivity feedback… Requires detailed modeling

# Main Stability Analysis Tool: PIM

- Transient 1-D 2-phase non-equilibrium primary loop flow





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# Model Equations of the PIM code

- Thermalhydraulic conservation equations
  - Liquid and vapor mass balance

$$\frac{dM_{l,n}}{dt} = \dot{m}_{l,n-1} - \dot{m}_{l,n} - \Gamma_n$$

$$\frac{dM_{g,n}}{dt} = \dot{m}_{g,n-1} - \dot{m}_{g,n} + \Gamma_n$$

  - Mixture momentum conservation with drift flux (integrated momentum)

$$\frac{dI}{dt} = \Delta P_{grav} - \Delta P_{friction} - \Delta P_{local} + \Delta P_{resid}$$

  - Energy conservation (assume saturated vapor)

$$\frac{d}{dt}\left(M_{l,n} h_{l,n}\right) = \dot{m}_{l,n-1} h_{l,n-1} - \dot{m}_{l,n} h_{l,n} - \Gamma_n h_{fg} + \dot{Q}_n$$

| | |
|---|---|
| $t$ | time |
| $M_l$ | liquid mass |
| $M_g$ | vapor mass |
| $\dot{m}_l$ | liquid mass flow rate |
| $\dot{m}_g$ | vapor mass flow rate |
| $\Gamma$ | rate of evaporation |
| $I$ | integrated momentum |
| $\Delta P_{grav}$ | gravitational press. drop |
| $\Delta P_{friction}$ | friction pressure drop |
| $\Delta P_{local}$ | local pressure drop |
| $\Delta P_{resid}$ | residual pressure drop |
| $h_l$ | liquid enthalpy |
| $h_{fg}$ | latent heat |
| $Q$ | power |
| $n$ | control volume index |
| $n-1$ | upstream index |

# Model Equations of the PIM code

- Point Nuclear Kinetics

$$\Lambda \frac{d\Phi}{dt} = \beta(\rho - 1)\Phi + \lambda C$$

$$\frac{dC}{dt} = \beta\Phi - \lambda C$$

| | |
|---|---|
| $C$ | Concentration of the delayed neutron precursors |
| $\lambda$ | Decay constant of the delayed neutron precursors |
| $\Phi$ | Neutron flux amplitude |
| $\beta$ | Delayed neutron fraction |
| $\Lambda$ | Prompt neutron lifetime |
| $\rho$ | Reactivity |

  - Thermalhydraulic model provides reactivity input
    - Moderator density reactivity feedback model (equivalent to moderator temperature reactivity under single-phase flow)
    - Doppler fuel temperature reactivity feedback
  - Heat source from neutron kinetics feeds back to thermalhydraulics
    - Energy deposited in fuel pellets (proportional to neutron flux)
    - Fraction of fission energy deposited directly in coolant
    - Decay heat: input by the user as fraction of initial power

# Model Equations of the PIM code

- Heat conduction in fuel rods
  - Pellet conductivity is function of temperature and burnup
  - Driven by energy deposited in fuel pellets
  - Heat flux at outer rod surface as power source to coolant
  - Pellet temperature needed for Doppler reactivity
- Heat transfer models for heat sink (steam generator)
  - Secondary side flow is driven by user-provided inlet forcing function
  - Secondary flow is subcooled, 2-phase equilibrium, and superheated
  - Primary flow parameters calculated from transient conservation equations
  - Heat transfer between primary and secondary flow
    - Heat transfer correlations
    - Transient heat conduction in tube walls

# Model Equations of the PIM code

- Closing Relations and Correlations
  - Frictional pressure drop (single- and two-phase friction and local losses)
  - Drift flux parameters
  - Non-equilibrium evaporation and condensation model
  - Thermodynamic properties for water
  - Physical material properties (pellets, cladding, SG tubes)
  - Pellet-clad gap conductance
  - Reactivity coefficients as functions of exposure and moderator density
- What is not modeled
  - Pressurizer; pressure is input provided constant or forcing function
  - Heat transfer through riser wall, adiabatic riser is default option
  - Heat capacity of structures; only ambient heat losses through vessel

# Flow Stability in Steam Generator Tubes

- Secondary side flow changes from single-phase liquid, to two-phase mixture, ultimately to superheated steam
- Flow in the tubes is subject to density wave instability
- Experiments demonstrate flow oscillations under certain conditions (generally low flow)
  - Oscillations in different tubes are not phase-locked
  - Effect on primary flow cancels out, confirming first-principle finding
- No impact on the primary flow and core stability
  - No feedback loop between primary and secondary oscillations

# PIM Results of Perturbing Steady State

- Purpose is to calculate stability parameters of decay ratio and period at different conditions of power and exposure
  - Following a user-applied small perturbation flow will oscillate
  - Oscillations will grow with time if system is unstable
  - Oscillations will decay eventually returning to the pre-perturbation state if the system is stable
- Stability parameters, decay ratio and period, are extracted from the transient output. Observations:
  - Unconditional stability in the entire operational range
  - DR decreases with power and exposure
  - Period also decreases with power
  - Observations agree with the independent Reduced Order Model

# PIM Application Methodology

- For perturbations of steady state to get DR
  - Vary power within 5-100% of rated
  - BOC and EOC, and any point in between if warranted
  - Conservative assumptions for MTC and decay heat fraction
- For a depressurization transient (scram not credited)
  - Verify that unstable oscillations limit cycle without CHFR decrease
- Stability conclusion is generic, but confirmation is needed
  - For plant upgrades such as power uprates
  - Plant operation changes such as operating temperatures and maximum boron concentration
  - Changes in fuel design that would change natural circulation flow

# Long Term Stability Solution

- Region Exclusion for NuScale
  - Unstable region defined by a single parameter (core exit subcooling)
  - Monitor and protect margin to riser exit subcooling (with temperature margin below saturation point at pressurizer pressure)
  - Operator alarm when subcooling margin is approached
  - Riser exit subcooling will be controlled by the reactor protection system as part of normal operating limits – not only for preventing instabilities
  - Generic solution: there are no fuel or cycle design elements

# Summary and Conclusions

- Stability of the NuScale module was evaluated using a dedicated code (PIM) and supported by first principles analysis and experimental data benchmarking
- The module was found unconditionally stable within normal operation domain using conservative criterion
- Stability boundary identified as associated with riser voiding (loss of riser inlet subcooling)
- Stability protection methodology protects riser inlet subcooling with a margin to define the exclusion region enforced by the module protection system with scram

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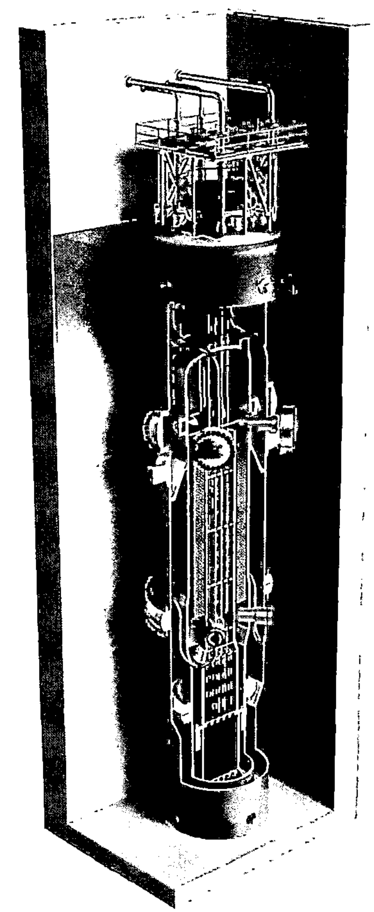

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