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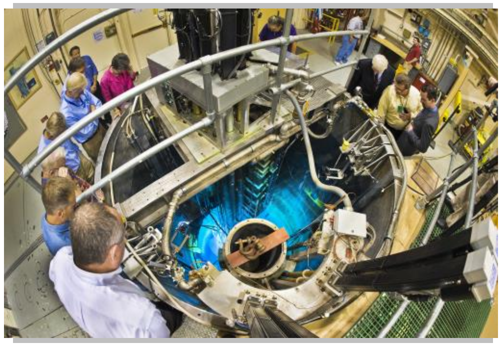
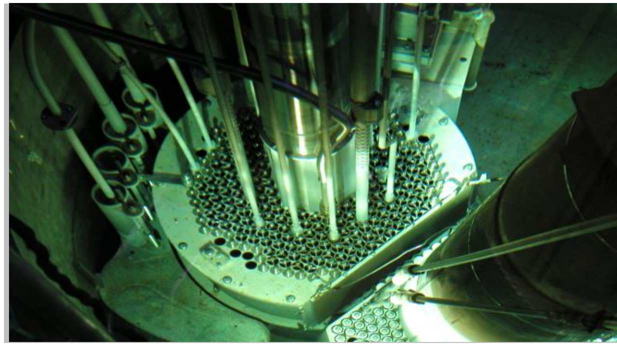
Annular Core Research Reactor (ACRR)





Considerations in the Analysis of a Large Rapid Reactivity Addition to a Natural Circulation Research Reactor

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Background and Motivation

- Safety analysis of a pulse reactor must address large rapid reactivity addition events
  - High fuel temperatures
  - Transient flow development
- DOE safety analysis methodology requires addressing "unmitigated" scenarios (i.e., no protective action)
  - System is stressed beyond what is typically analyzed
    - Thermal-hydraulic response
    - Thermomechanical response
    - Reactor kinetics response
  - Analysis code must deal with all of these factors

Analysis Codes

- The RAZORBACK code was applied to analyze this event and its various phenomena
    - RAZORBACK was discussed at last year's conference
    - Couples reactor kinetics, thermal-hydraulics, and thermomechanical effects
- MCNP was applied to determine the various neutronic analysis inputs
    - Regulating rod reactivity worth curves
    - ***Reactivity feedback coefficients (more discussion to follow)***
    - Fission energy deposition profiles
    - n/γ energy deposition profiles
    - Neutron generation time
- These neutronic analyses provide the framework for the RAZORBACK analysis

Reactivity Feedback

- Assume a fundamental relationship for the reactivity effects due to changes in the fuel

$$\rho = f(R_o, R_i, \rho_f, T_f)$$

- Use MCNP to compute

$$\rho = f(R_o, R_i = const, \rho_f = const, T_f = const)\ \text{, etc.}$$

  - Assume the effects are separable

$$d\rho = \left(\frac{\partial\rho}{\partial R_o}\right) dR_o + \left(\frac{\partial\rho}{\partial R_i}\right) dR_i + \left(\frac{\partial\rho}{\partial \rho_f}\right) d\rho_f + \left(\frac{\partial\rho}{\partial T_f}\right) dT_f$$

- Compute the feedback coefficients from the derivatives

$$\alpha_{F\_Ro} = \left(\frac{\partial\rho}{\partial R_o}\right) \qquad \alpha_{F\_Ri} = \left(\frac{\partial\rho}{\partial R_i}\right) \qquad \alpha_{F\_\rho f} = \left(\frac{\partial\rho}{\partial \rho_f}\right) \qquad \alpha_{F\_Tf} = \left(\frac{\partial\rho}{\partial T_f}\right)$$

Doppler

Reactivity Feedback – (cont'd)

- Repeat the general process using MCNP for other feedback mechanisms
  - Cladding thermal expansion
  - Coolant temperature and density

- MCNP reactivity vs. "parameter" can be curve fit to compute derivatives
  - Has generally resulted in a linear dependence (resulting in a constant reactivity coefficient) except for coolant density and fuel temperature
  - Fuel temperature has a $\sqrt{T}$ dependence (which gives Doppler coefficient the expected $\frac{1}{\sqrt{T}}$ dependence)

Reactivity Feedback (cont’d)

- Computing reactivity feedback coefficients for use in Reactor Kinetics-Thermomechanical-Thermal-Hydraulics code is not the end of the story
  - Code computes temperature, density, and dimensional changes as a function of fuel element radial position and axial position

- How do you weight these local changes to get the impact on core reactivity?
  - Weighting function w(r,z,“R”) where “R” refers to element location in the core

Rapid Reactivity Addition

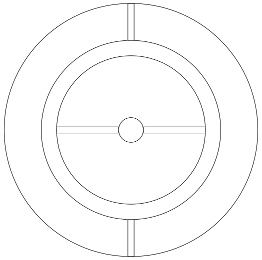
- Rapid internal heating of fuel
  - Thermal stresses
  - Potential for gap closure
  - Reactivity feedback impacts pulse response

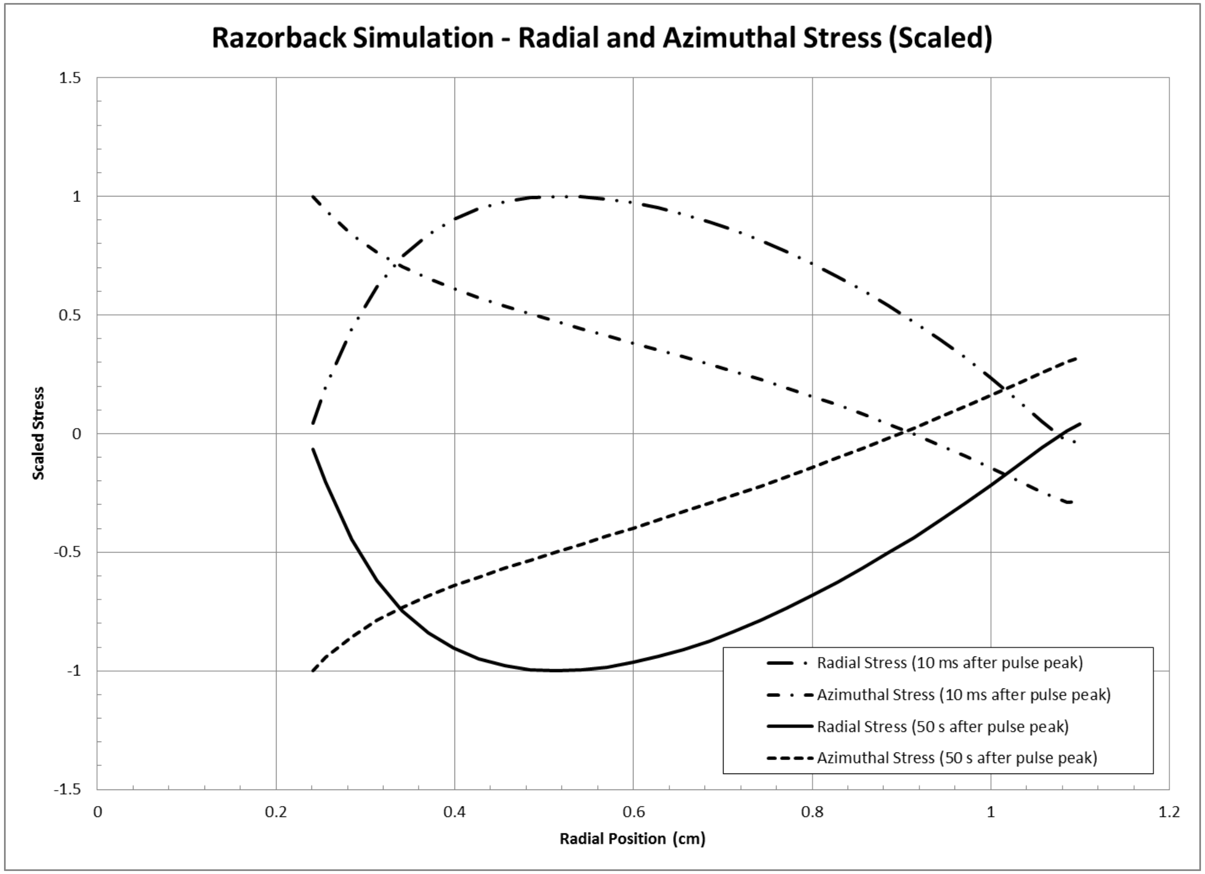
- Rapid internal heating of coolant
  - Coolant pressurization
  - Two-phase conditions develop near axial center of flow channel

- Two-phase flow oscillations
  - Critical heat flux implications

Thermal Stresses

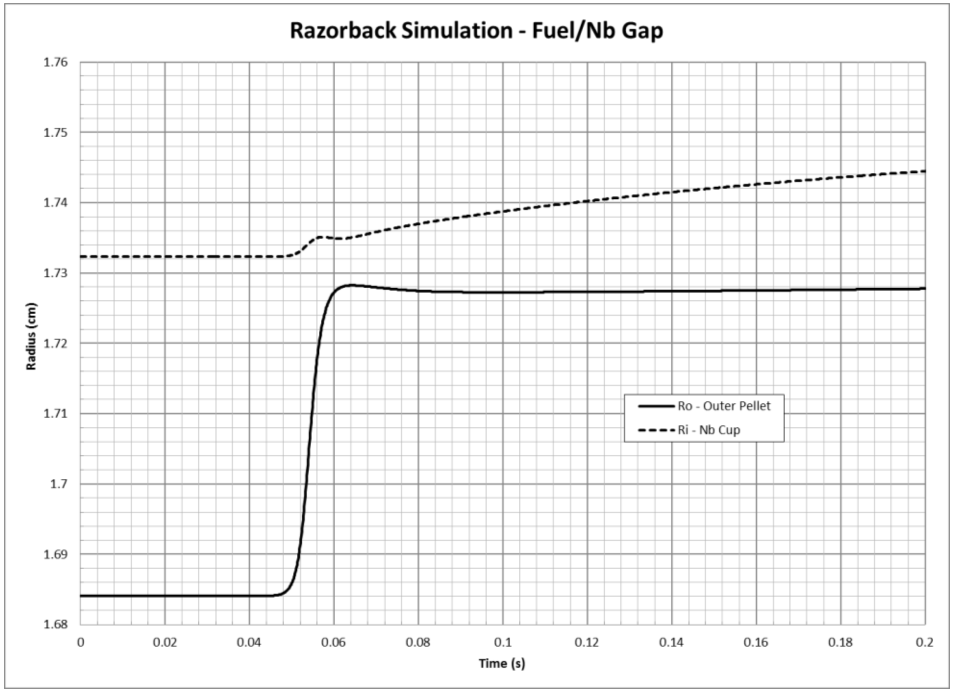
- Strong outer edge peaking of temperature profile early in pulse
- At longer times, heat transfer moves the temperature distribution to the typical equilibrium shape
- Developed stresses can be fairly high early in the pulse

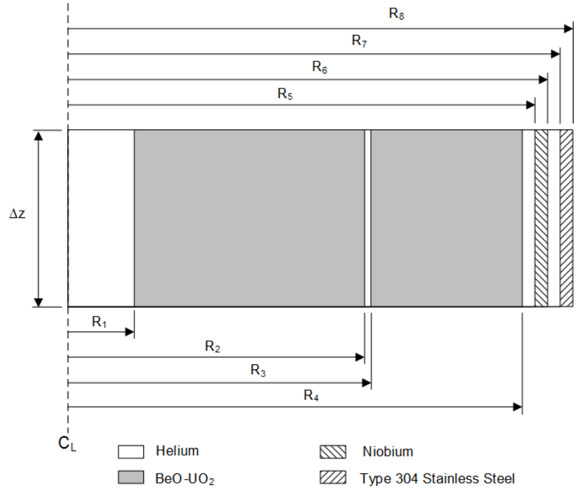




Potential Gap Closure

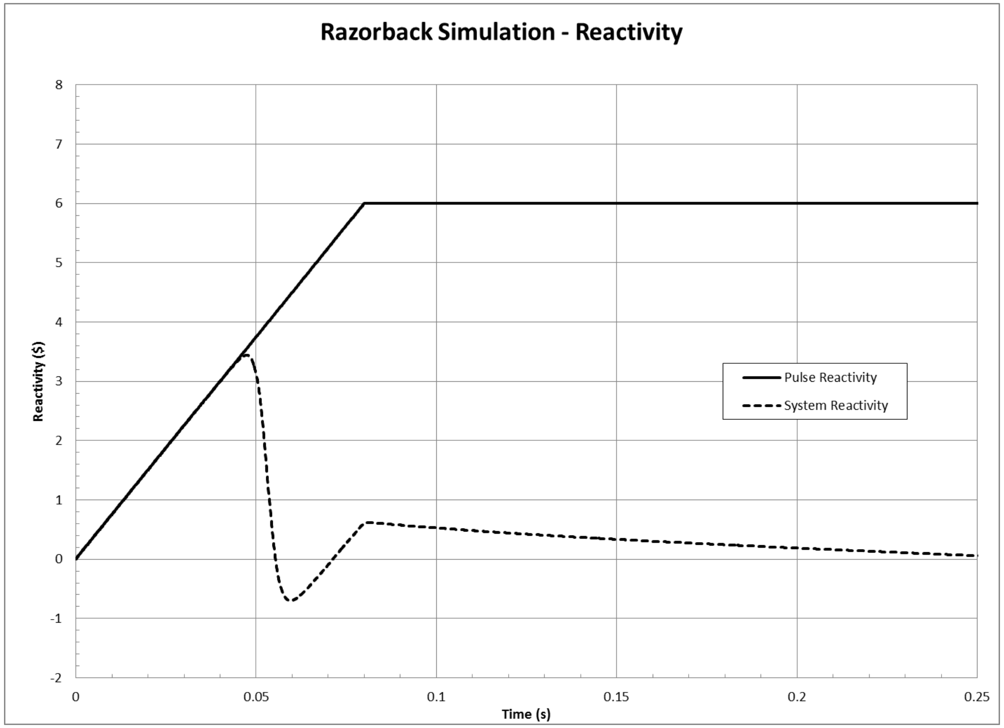
- Outer fuel pellet's outer edge experiences higher temperatures
- Gap between outer pellet and fuel cup decreases dramatically
    - Enhances heat transfer rate
- Potential for gap to completely close for sufficiently large pulse
    - Contact stresses





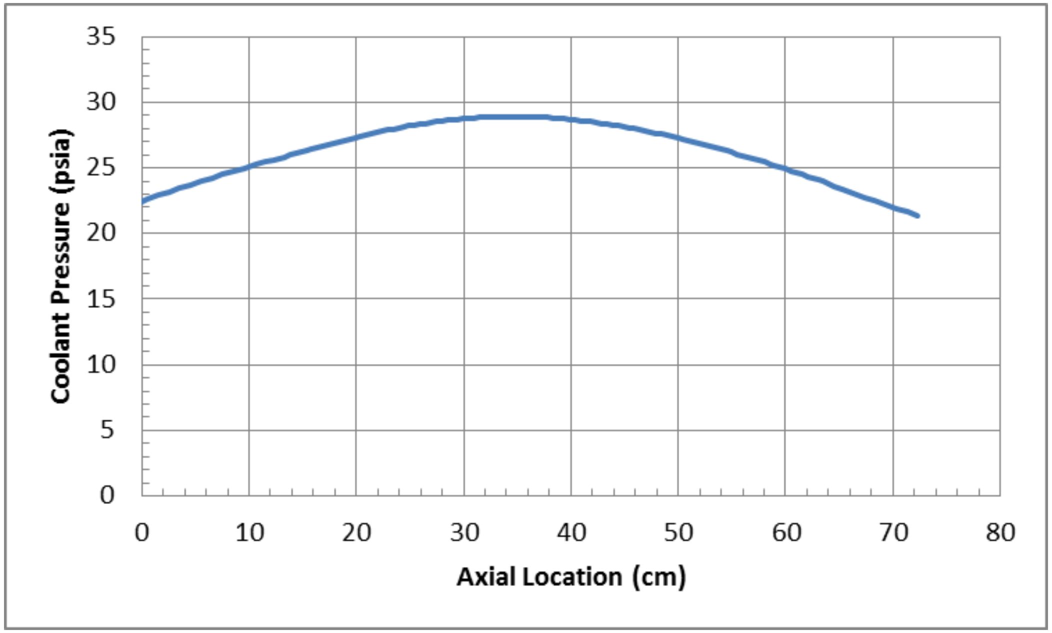
Reactivity Feedback Impacts Pulse

- Feedback can "terminate" a pulse before the rods are fully withdrawn
  - "Walking on the rods"
- Relevant factors include:
  - Withdrawal rate
  - Initial power level
- Importance of adequate feedback models



Coolant Channel Pressurization

- Internal n/γ heating of the coolant channel is significant for large rapid reactivity additions
  - ~1 MW at pulse peak
- Pressure can rise several psi above ambient
  - Transient external loading on fuel cladding
  - Potential for lateral loads on fuel elements where significant core radial peaking factors occur



Transient Two-Phase Flow Development

- Bounded two-phase flow region develops near the axial center of the flow channel
  - Axial center peaked n/γ heating of the coolant
  - Axial center peaked fission heating of the fuel

- Natural circulation characteristics such that oscillating two-phase flow development occurs

- Negative void reactivity feedback produces reactor power response

- Transient flow development raises questions for critical heat flux determination

- **Disclaimer**: Two-phase flow model implementation required a factor to reduce the void fraction resulting from a given static quality

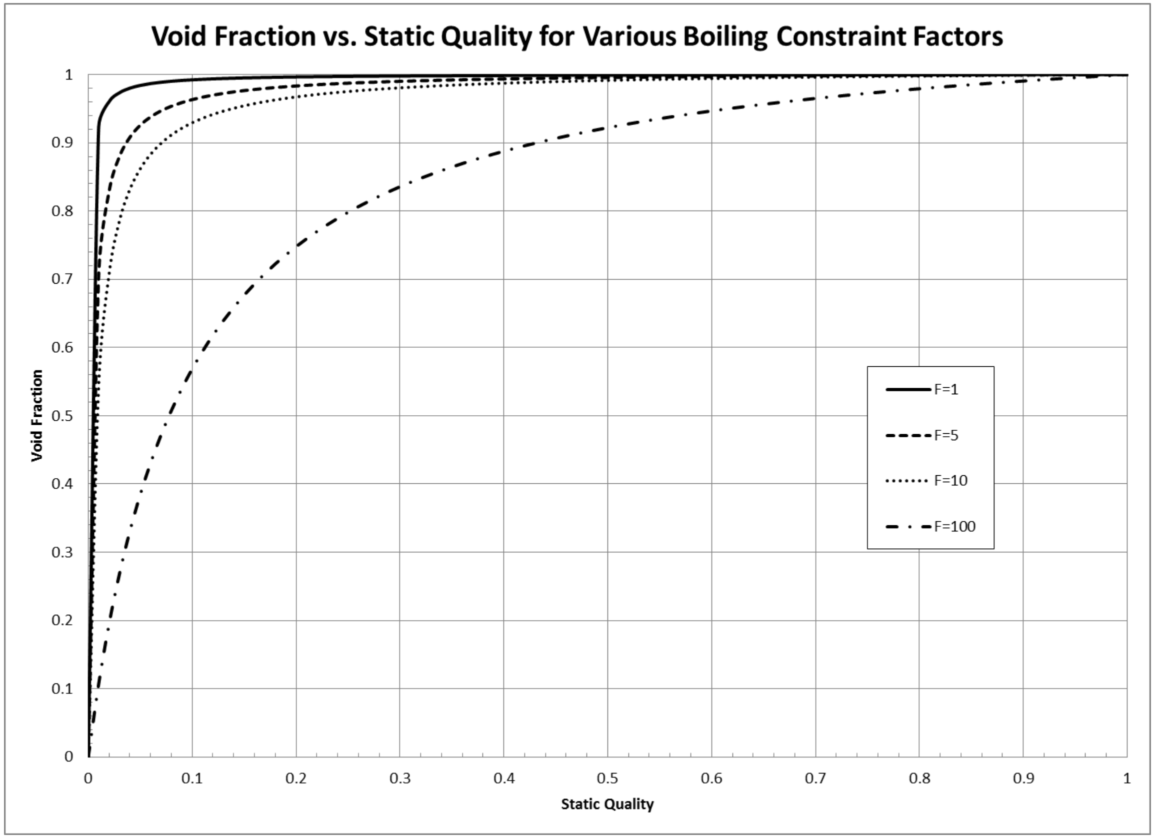
Void Fraction Relationship

- Code will crash if unmodified $\alpha=\alpha(\chi_s)$ relationship is used

- Added a factor (F) which effectively suppresses the expansion of the vapor phase
  - Use smallest "F" which doesn't crash the code

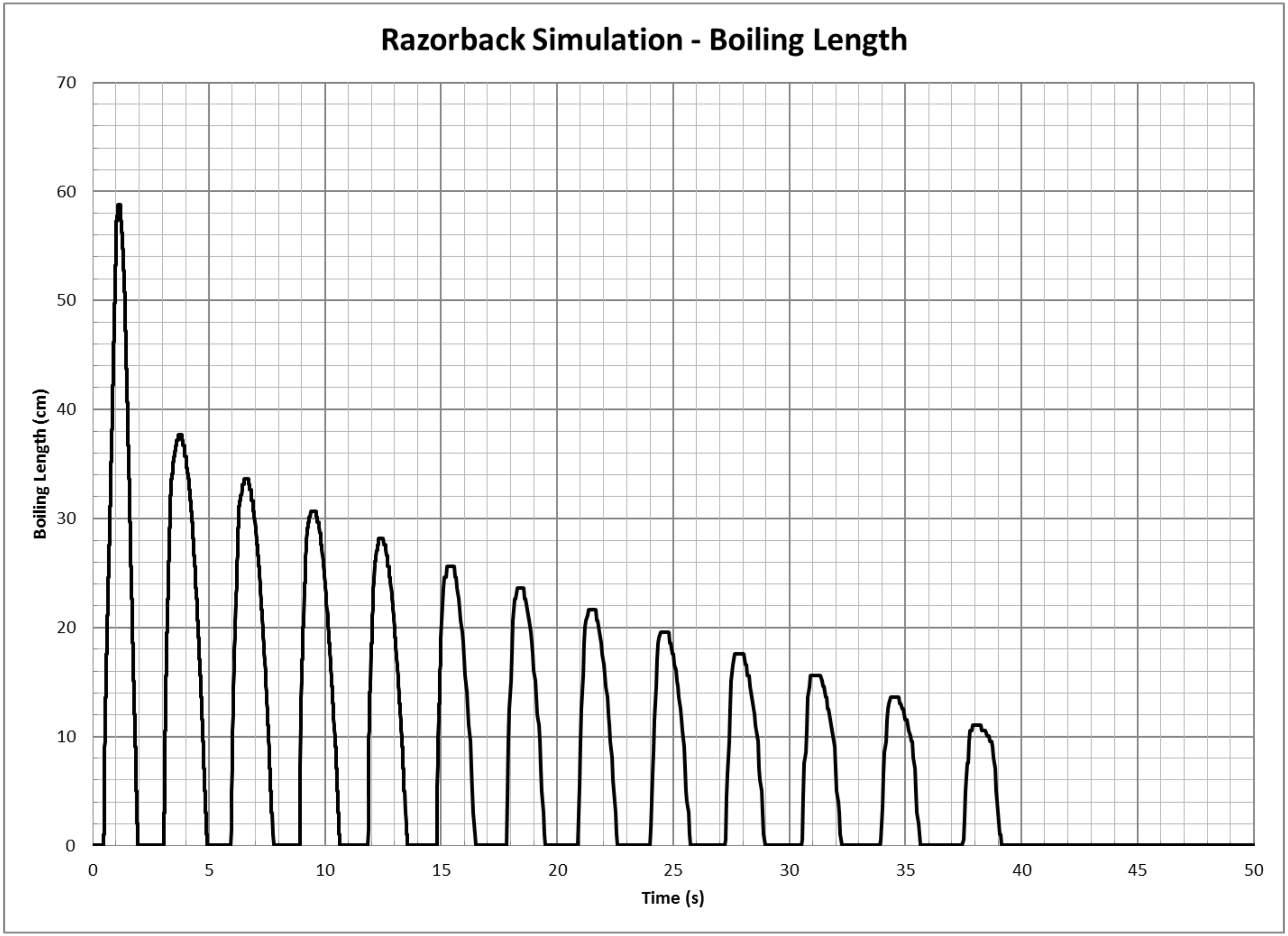
$$\alpha = \frac{\chi_s \frac{\rho_f}{\rho_g} \frac{1}{F}}{1 + \chi_s\left(\frac{\rho_f}{\rho_g} \frac{1}{F} - 1\right)}$$

- Approach appears to give reasonable results

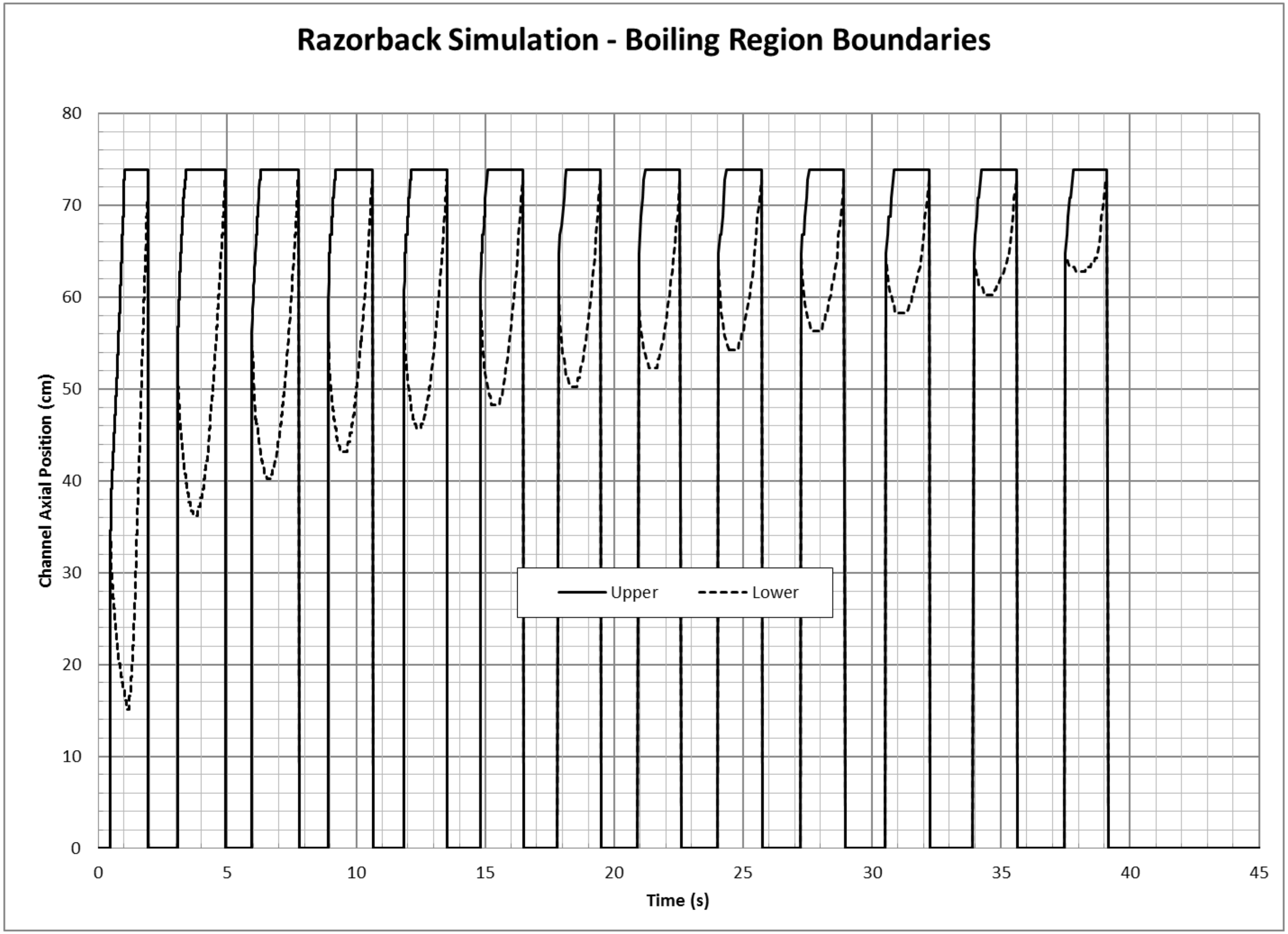


P = 20.5 psia

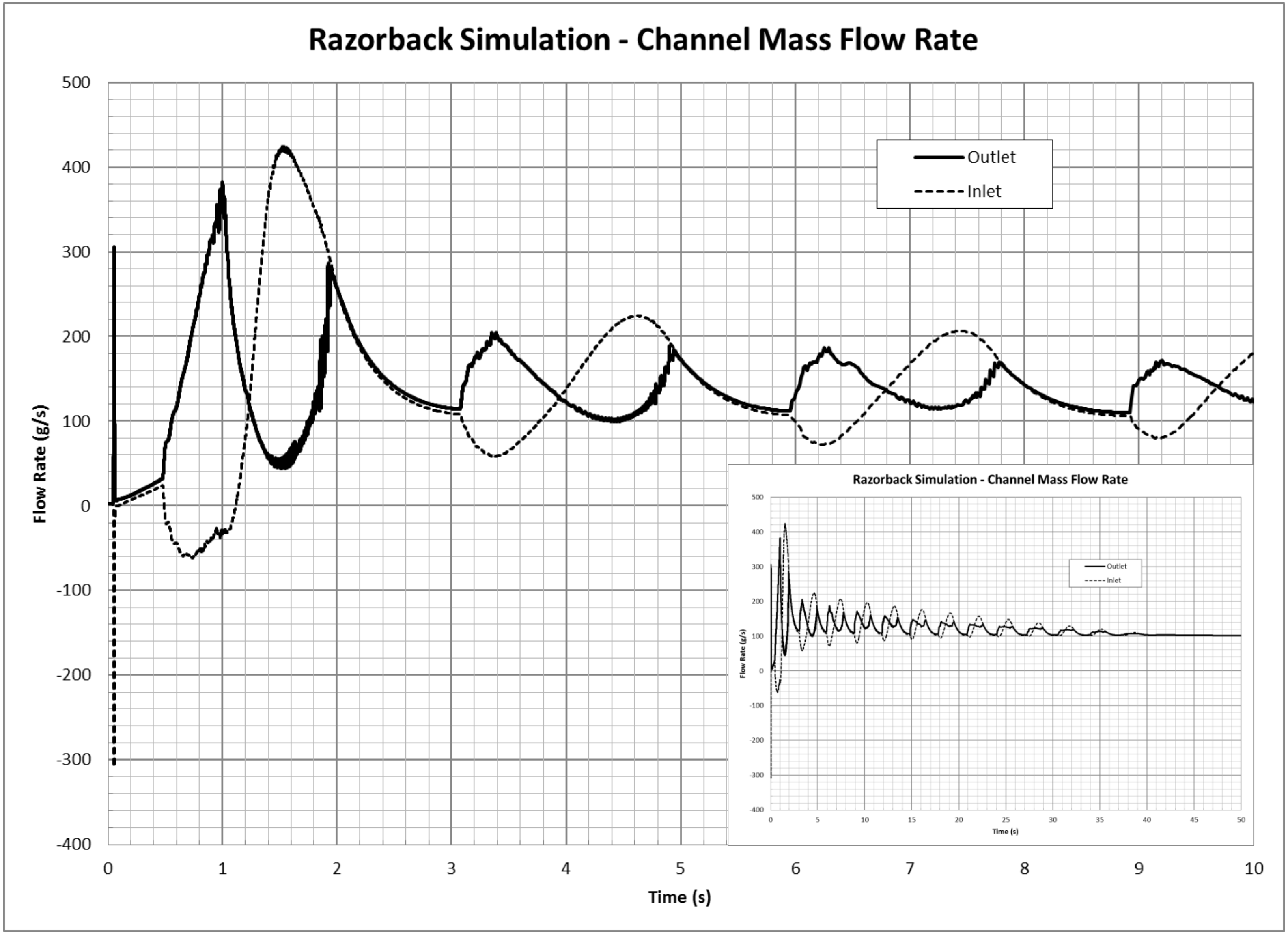
Two-Phase Flow Oscillations
Boiling Length



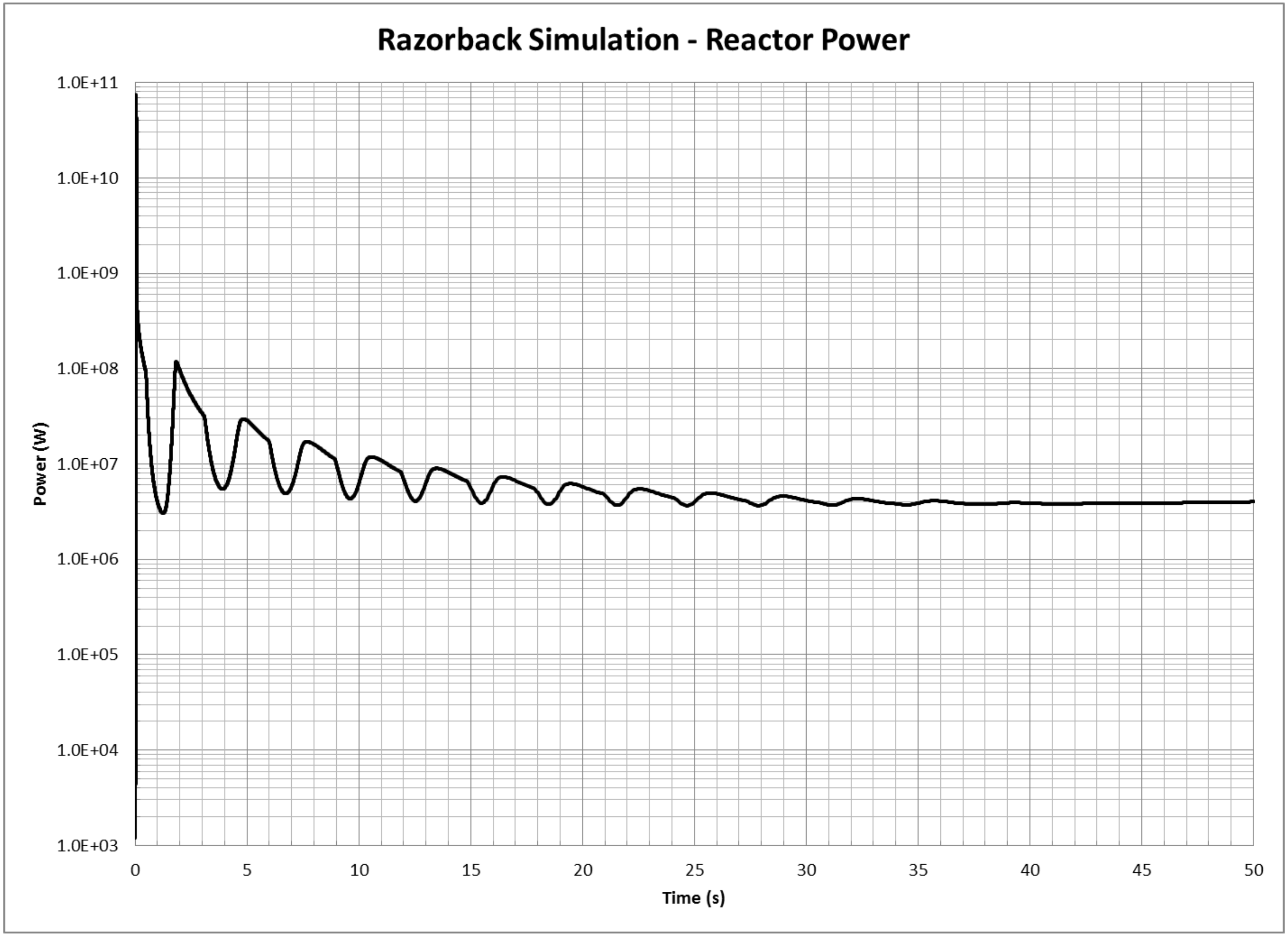
Two-Phase Flow Oscillations
Boiling Boundaries



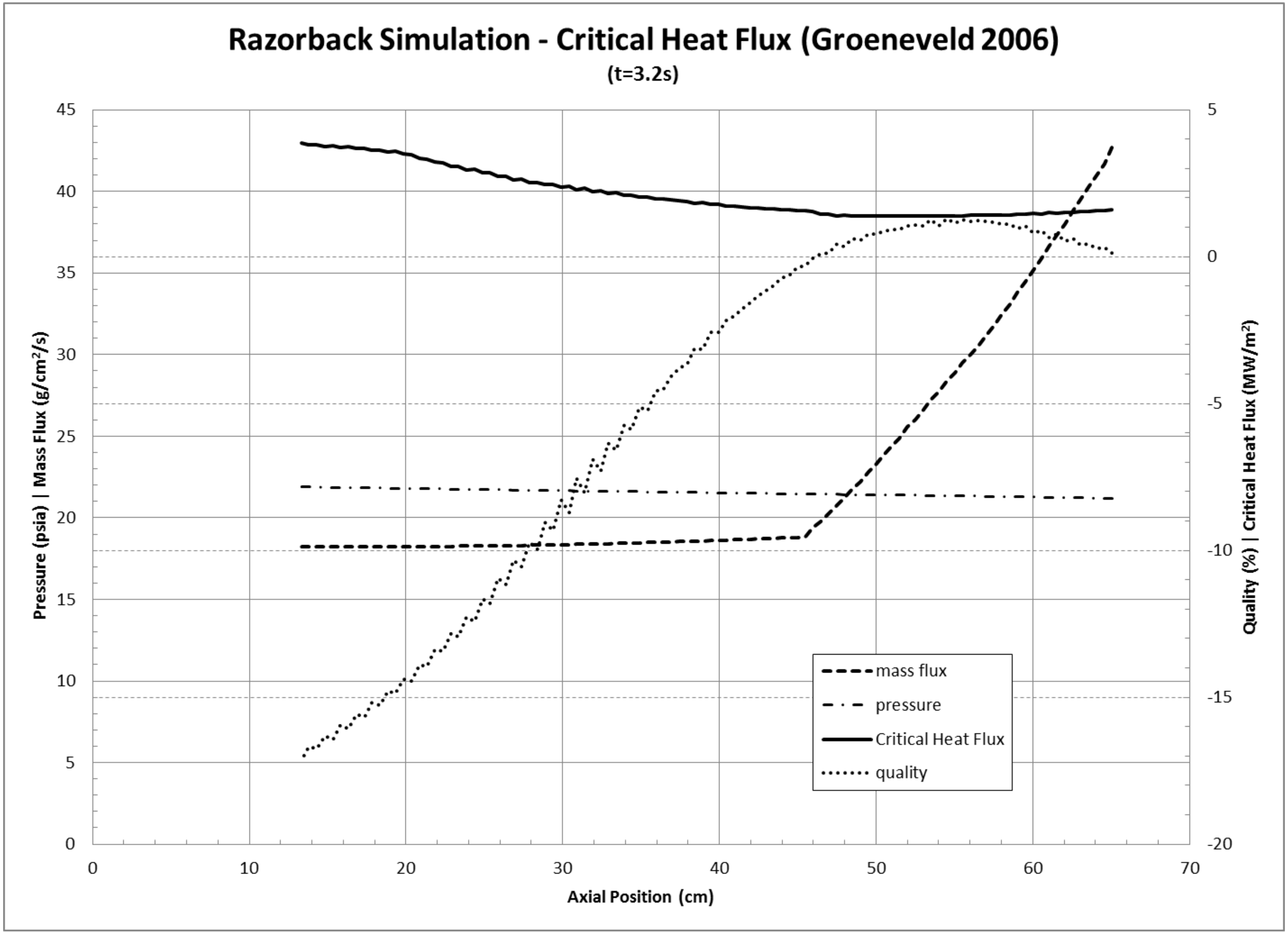
Two-Phase Flow Oscillations
Mass Flow Rate



Two-Phase Flow Oscillations
Reactor Power Response



Critical Heat Flux



Critical Heat Flux Questions

- Critical Heat Flux (CHF)
  - Departure from Nucleate Boiling (PWR) or Dryout (BWR)
  - Near atmospheric pressure pool-type reactor more akin to a BWR
- What type of "approach" is best?
  - Local conditions (e.g., $CHF(z) = f[\chi(z),G(z),P(z)]$)
  - Global conditions (e.g., $\chi_c = f(L_B)$)
- How does one assess CHF under transient conditions?
  - Application of some steady-state correlation/database/test may be the only available option
- What does CHF Ratio (CHFR) mean?
  - Typically: Power would have to increase by a factor of CHFR ***at constant mass flux*** to attain the CHF (*for flat axial heating profile*)
  - Mass flux and power are not independent in a natural circulation system

Concluding Remarks

- Analyses of large rapid reactivity additions in natural circulation reactor systems present interesting challenges and phenomena

- Thorough neutronic analyses key to addressing the various phenomena

- Validation data in these regimes would be of great help
  - Two-phase flow
  - CHF

- Exploring other approaches to the void fraction suppression

BACKUP SLIDES

RAZORBACK Description

- Coupled point reactor kinetics, fuel heat transfer, fuel element thermal expansion, and coolant thermal-hydraulics code designed to address ACRR operation (steady-state, pulse, and transient rod withdrawal)
  - Multiple radial fuel pin regions to address ACRR BeO-UO_2 fuel pellets, fuel cans, and cladding
  - Quasi-2D heat transfer from fuel to coolant, and 1D ***natural circulation*** coolant flow
  - Models to simulate ACRR control rods, safety rods, and transient rods (including pneumatic ejection)
  - Multiple reactivity feedback mechanisms modeled
- Also designed to simulate abnormal and accident scenarios
  - Scram system model
  - Basic reactor pool and cooling system models
    - Loss of heat sink (cooling system coastdown)
    - Loss of pool water (pool drain)

Modeling the ACRR