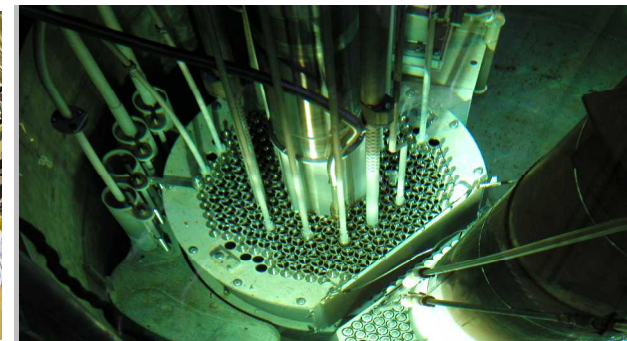
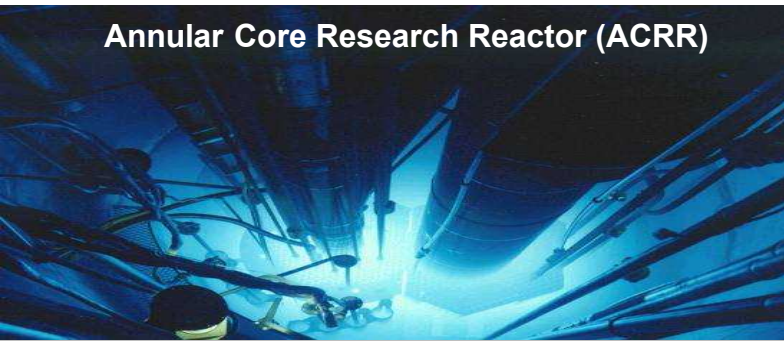


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Annular Core Research Reactor (ACRR)



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

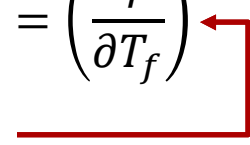
$$\rho = f(R_o, R_i = \text{const}, \rho_f = \text{const}, T_f = \text{const}) , \text{ etc.}$$

- 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

$$\alpha_{F_{R_o}} = \left(\frac{\partial \rho}{\partial R_o} \right) \quad \alpha_{F_{R_i}} = \left(\frac{\partial \rho}{\partial R_i} \right) \quad \alpha_{F_{\rho_f}} = \left(\frac{\partial \rho}{\partial \rho_f} \right) \quad \alpha_{F_{T_f}} = \left(\frac{\partial \rho}{\partial T_f} \right)$$

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

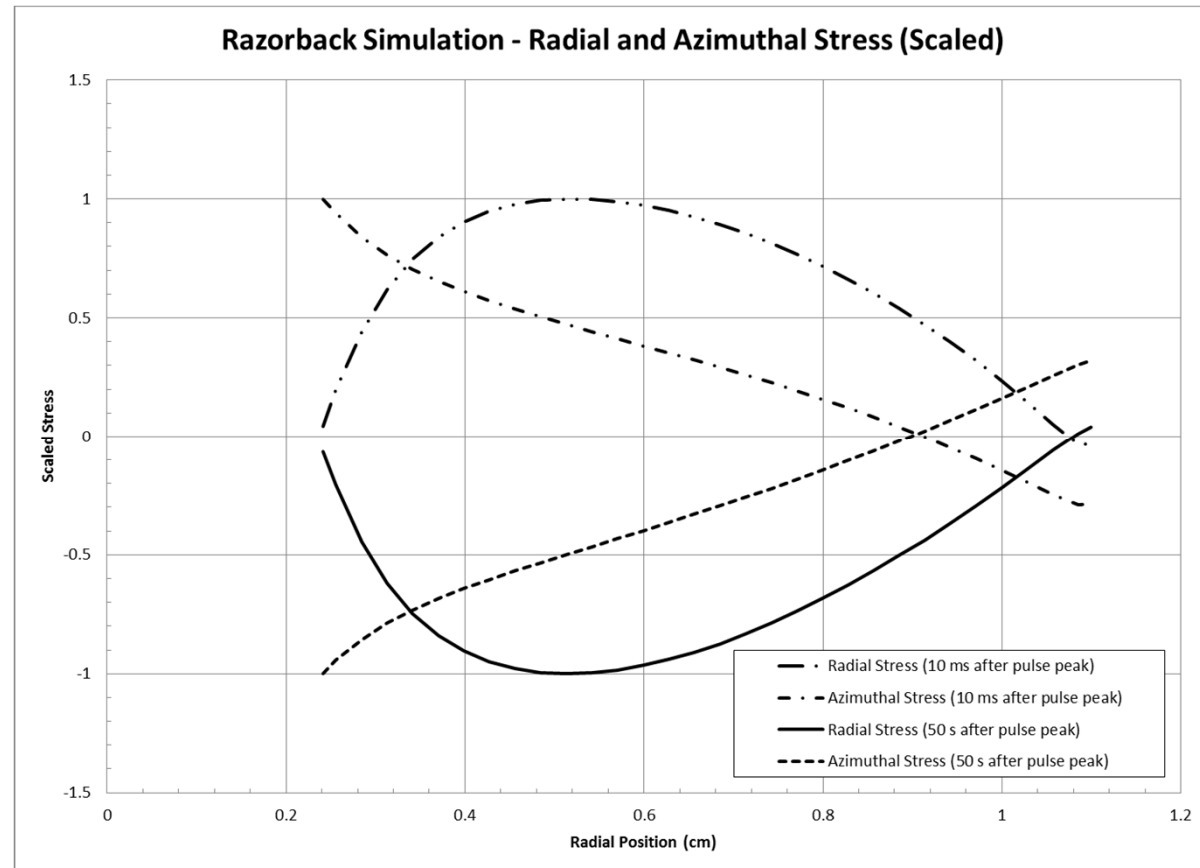
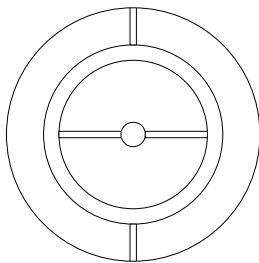
- Rapid internal heating of fuel
 - Thermal stresses
 - Potential for gap closure
 - Reactivity feedback impacts pulse response

- 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

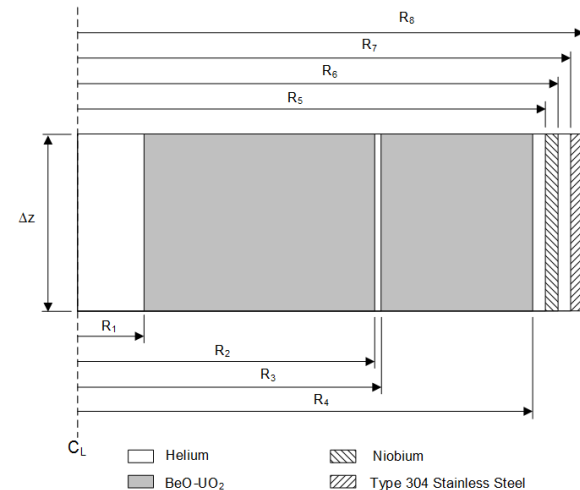
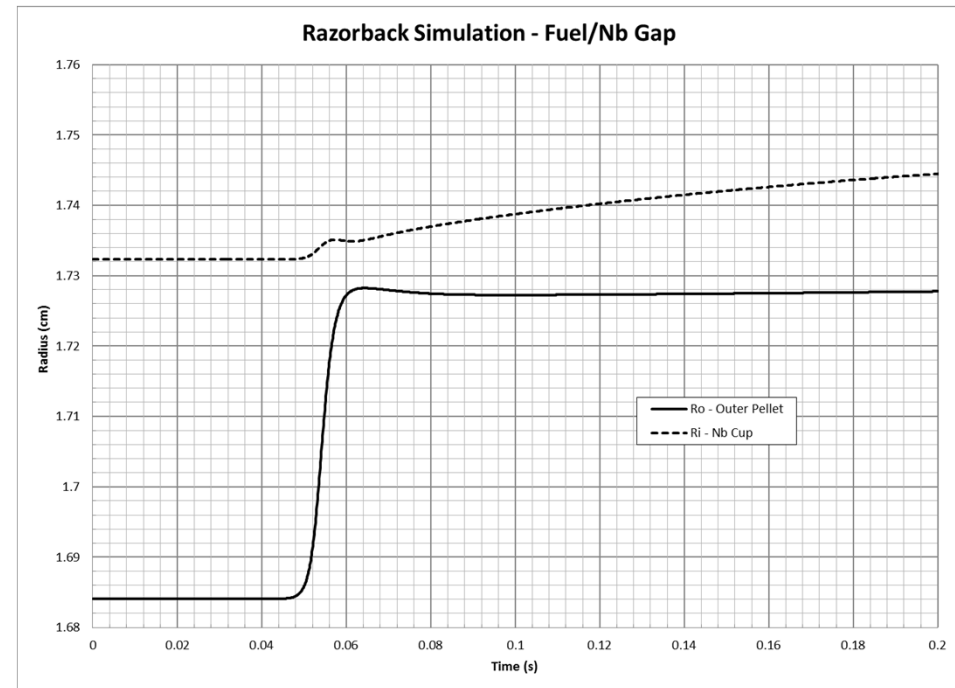
Thermal Stresses

- 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



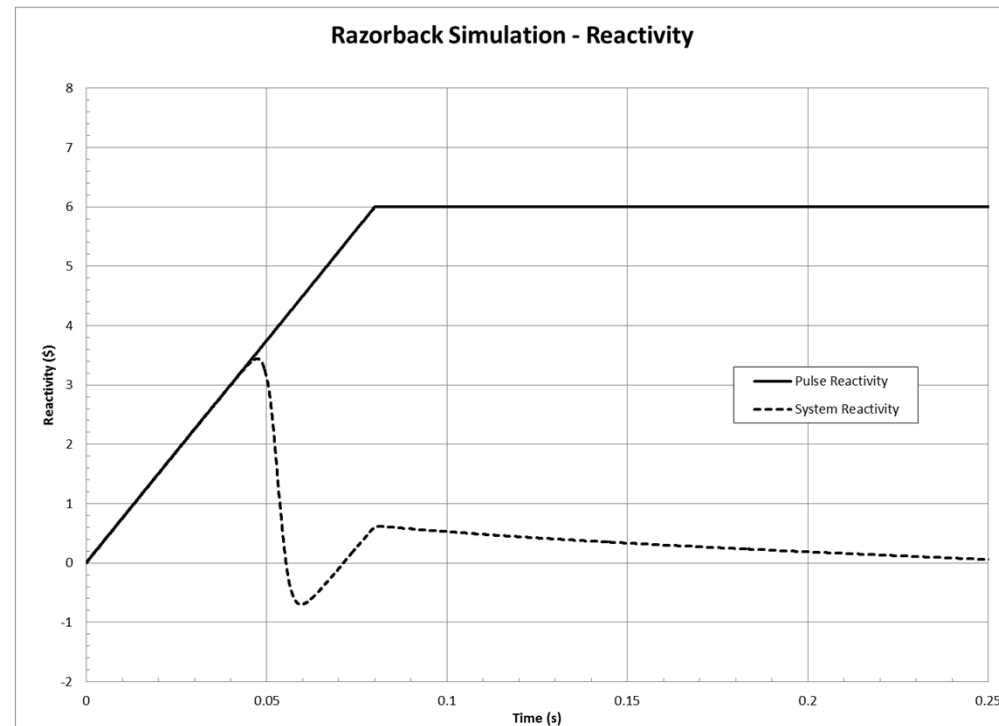
Potential Gap Closure

- 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



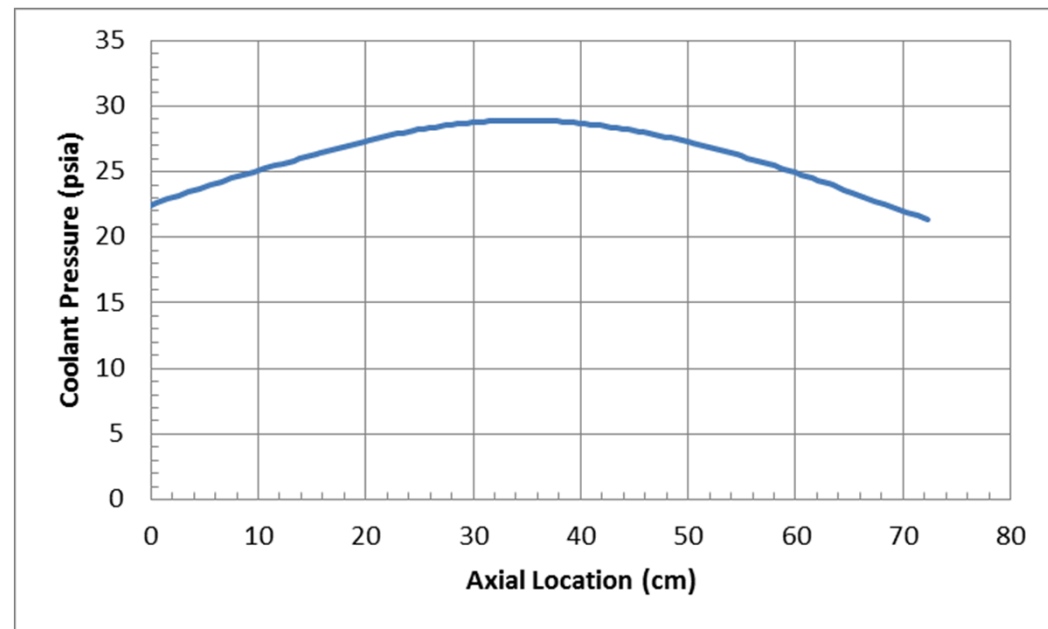
Reactivity Feedback Impacts Pulse

- 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

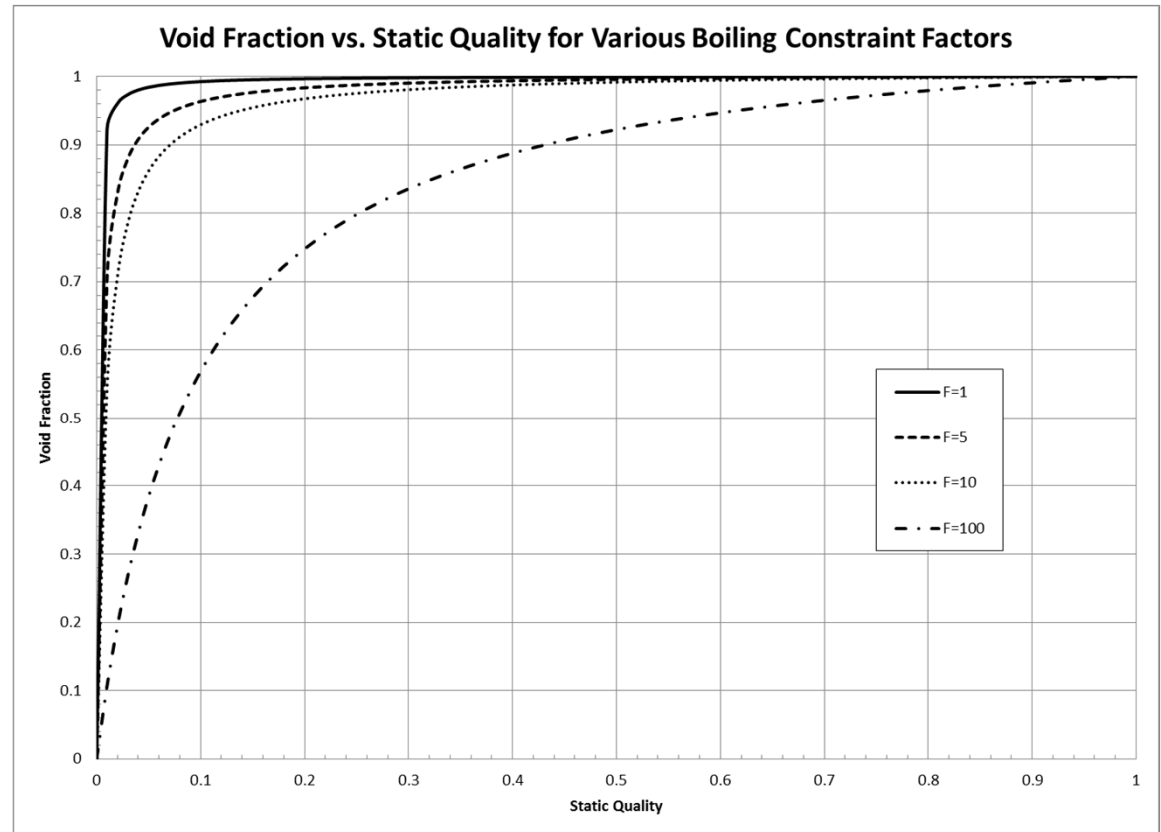
- Bounded two-phase flow region develops near the axial center of the flow channel
 - Axial center peaked n/γ heating of the coolant
 - Axial center peaked fission heating of the fuel
- Natural circulation characteristics such that oscillating two-phase flow development occurs
- Negative void reactivity 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

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

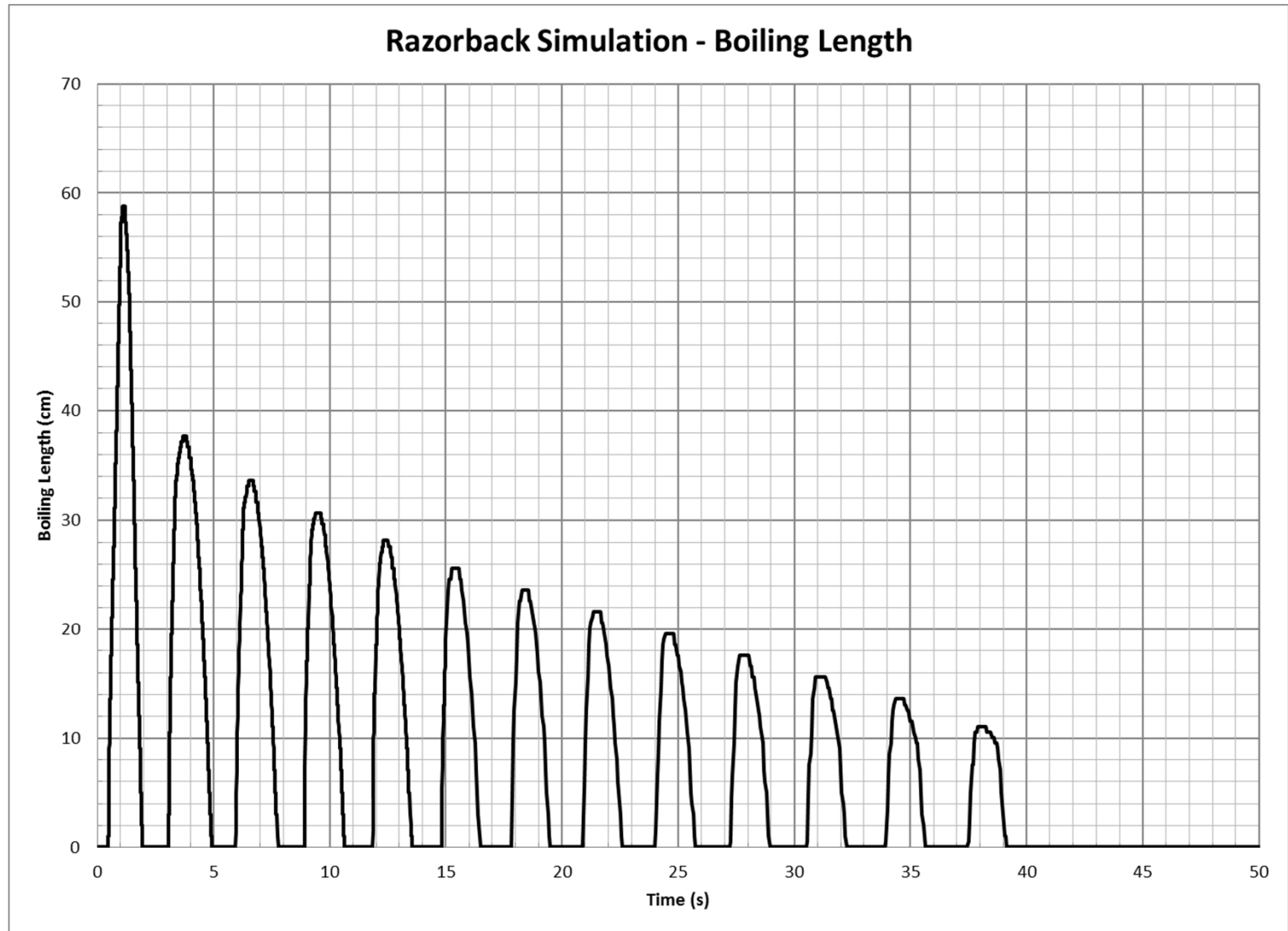
- Approach appears to give reasonable results



P = 20.5 psia

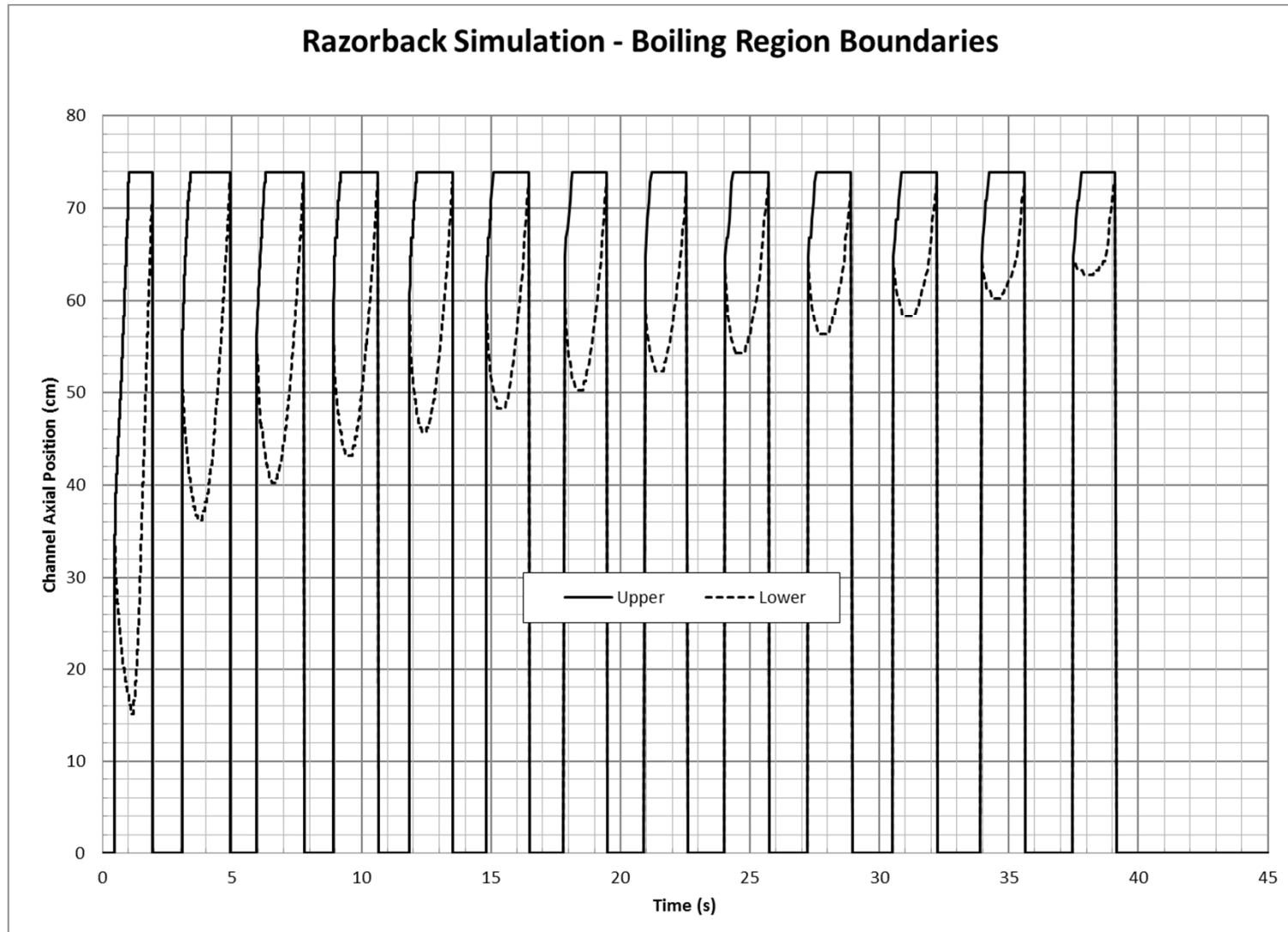
Two-Phase Flow Oscillations

Boiling Length



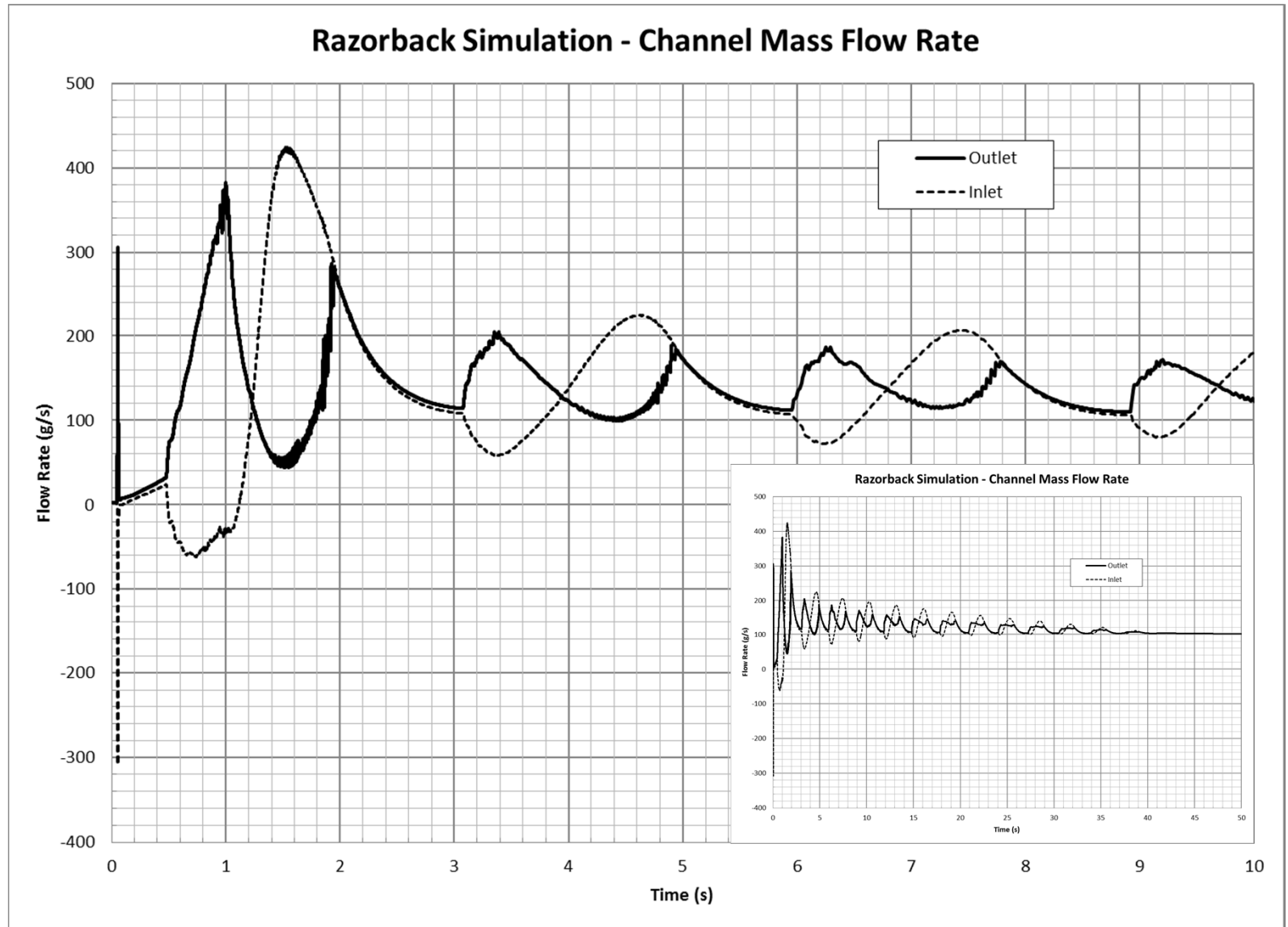
Two-Phase Flow Oscillations

Boiling Boundaries



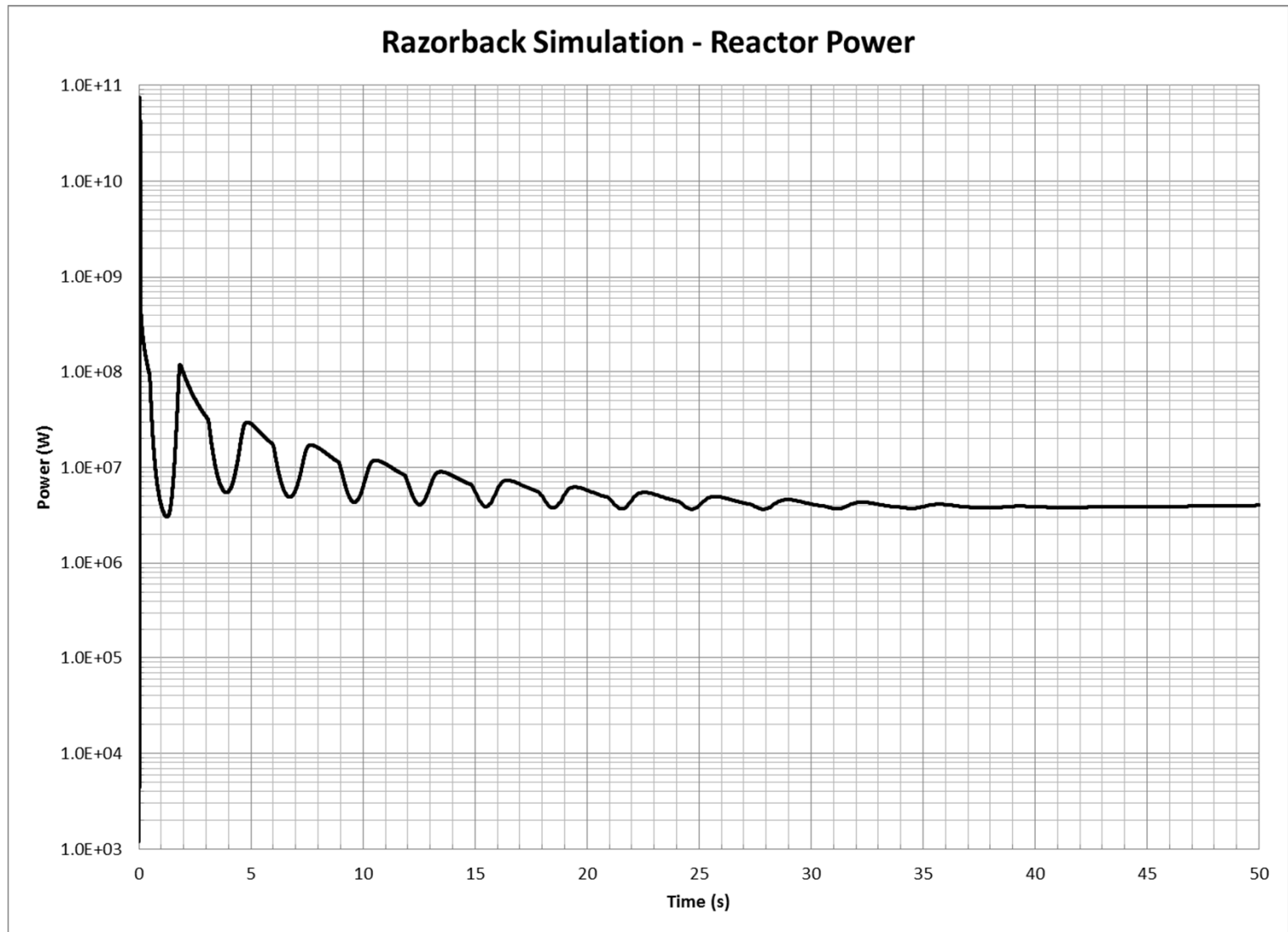
Two-Phase Flow Oscillations

Mass Flow Rate

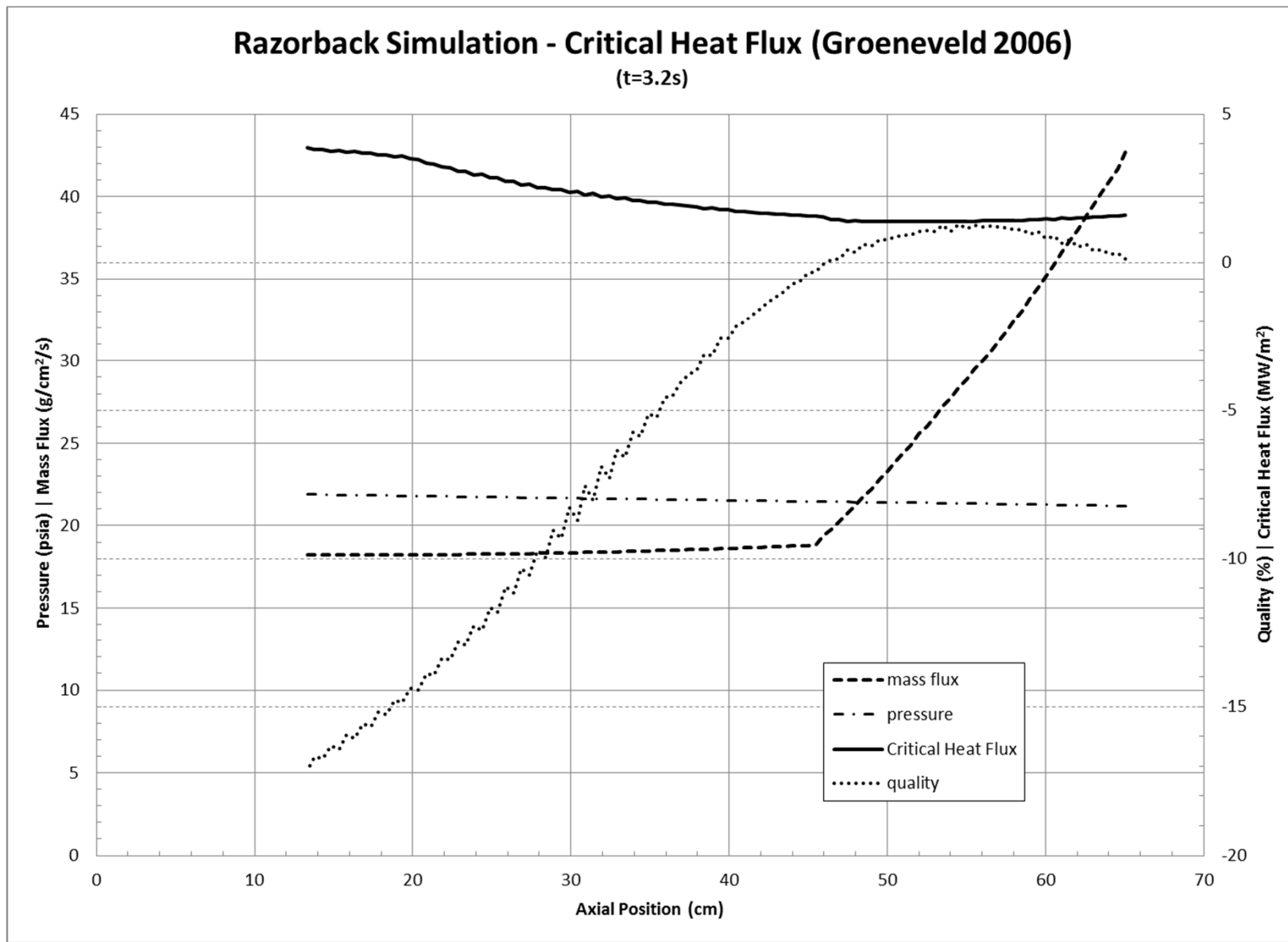


Two-Phase Flow Oscillations

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., $\text{CHF}(z) = f[\chi(z), G(z), P(z)]$)
 - 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-UO₂ 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

