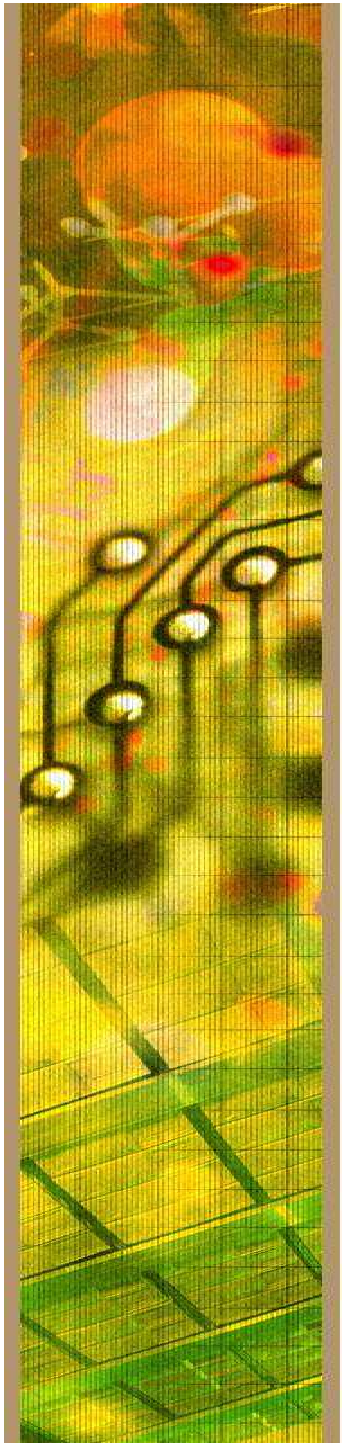

NUCL 511
Nuclear Reactor Theory and Kinetics

Lecture Note 12

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School of Nuclear Engineering

Spatial Kinetics Equation and Solution Method

- Neutron and precursor balance equation

$$\frac{1}{v}\frac{\partial \varphi}{\partial t} = (F_p - M)\varphi + S_d$$

$$\frac{\partial C_k}{\partial t} = -\lambda_k C_k + \beta_k \psi$$

where $\psi = \sum_{g=1}^{G} \nu\Sigma_{fg}\varphi_g$ is the total fission source

- Implicit temporal differencing

$$\frac{\varphi_l - \varphi_{l-1}}{v\Delta t_l} = \left(F_p^l - M_l\right)\varphi_l + S_d^l \quad \Rightarrow \quad \left(M_l + \frac{I}{v\Delta t_l} - F_p^l\right)\varphi_l = \frac{\varphi_{l-1}}{v\Delta t_l} + S_d^l$$

- Analytic solution of precursor balance equation

$$C_k^l = C_k^{l-1} e^{-\lambda_k \Delta t_l} + \beta_k \int_{t_{l-1}}^{t_l} \psi(t') e^{-\lambda_k (t-t')} dt'$$

Spatial Kinetics Solution Method

- Assumption of linear variation of fission source within the interval

$$\psi_l(t) = \psi_{l-1} + \frac{\psi_l - \psi_{l-1}}{\Delta t_l}\left(t - t_{l-1}\right)$$

- Delayed neutron source after integration of fission source in the analytical precursor solution

$$S_d^l = \tilde{S}_d^{l-1} + \alpha\psi_l$$

- Neutron balance equation in terms of flux only

$$\left[M_l + \frac{I}{v\Delta t_l} - (1+\tilde{\alpha})F_p^l\right]\varphi_l = \frac{\varphi_{l-1}}{v\Delta t_l} + \tilde{S}_d^{l-1}$$

  – Fixed source problem that can be solved by a steady-state solver which employs suitable spatial discretization method

Incorporation of Thermal Feedback

- Cross section functionalization

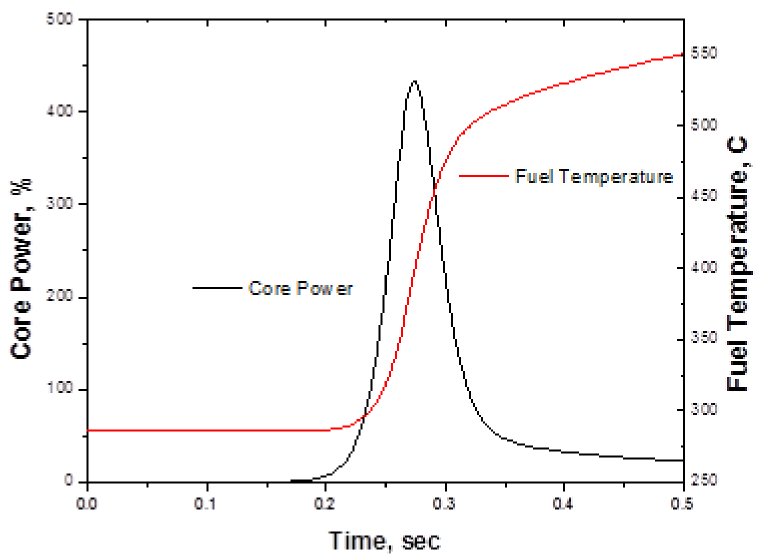
$$\Sigma(\text{ppm}, T_f, \rho_m) = \Sigma(\text{ppm}_0, T_{f0}, \rho_{m0}) + \frac{\partial \Sigma}{\partial \text{ppm}}(\text{ppm - ppm}_0) + \frac{\partial \Sigma}{\partial \sqrt{T_f}}(\sqrt{T_f} - \sqrt{T_{f0}})$$

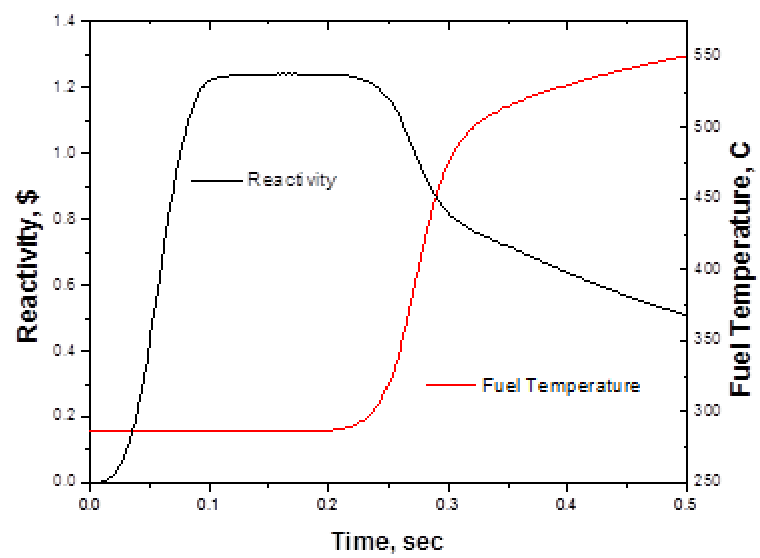
$$+ \frac{\partial \Sigma}{\partial \rho_m}(\rho_m - \rho_{m0})$$

- Iterative update of cross sections
  1) Use the current temperature first and evaluate cross sections
  2) Solve the FSP for flux with partial convergence
  3) Update Power
  4) Determine new temperature
  5) Update cross section
  6) Repeat steps 2 through 5 until convergence

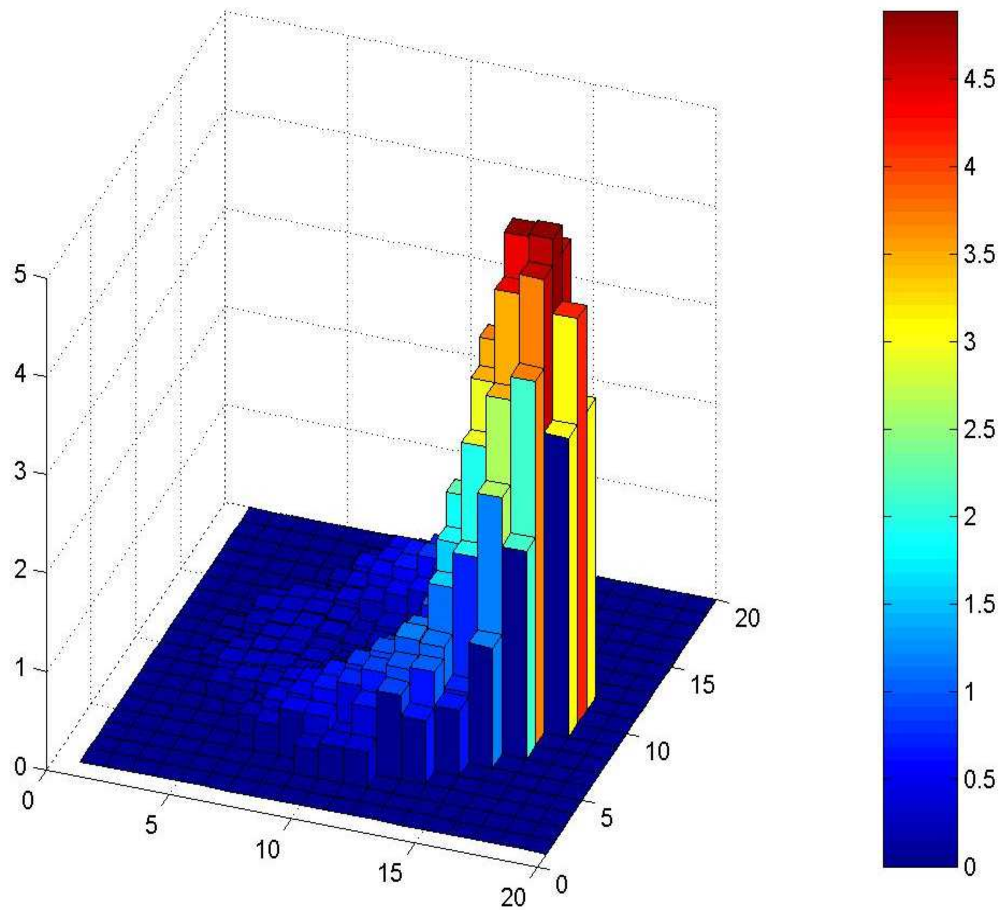
Control Rod Ejection

- Cause
  - Rupture in control rod derive housing on the reactor vessel head
  - Ejection of control rod due to high pressure of vessel
- Consequence
  - Super-prompt critical reactivity insertion
  - Rapid power rise and formation of power peak by Doppler
- Results (for 1.2$ reactivity insertion in 0.1 sec, NEACRP C1)
  - Initial power: 0.0001%

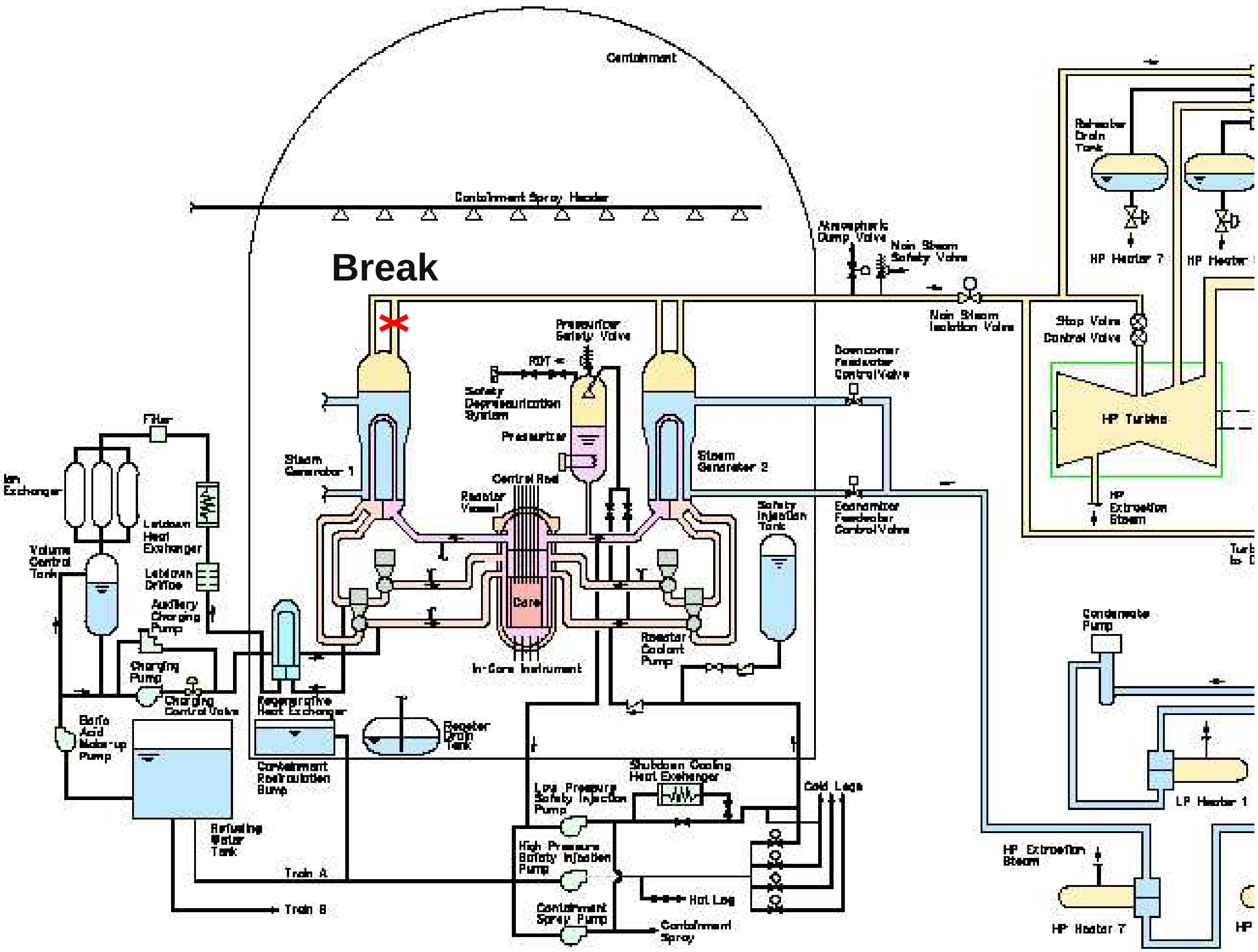




Power Distribution After Rod Ejection (NEACRP C1)



Main Steam Line Break (MSLB)



MSLB Progress Scenario – 1/2

- Break in one of the main steam lines (four or more)
  - Leak of high pressure steam through the break (critical flow)
  - Depressurization of SG and rapid evaporation
- Cool-down of primary coolant causing depressurization of primary loop
  - Initially coolant density decrease in the core
  - Core power decrease due to less moderation
- Transport of chilled coolant to core
  - Core reactivity increase due to negative MTC
  - Core power increase
- Overpower or low pressure trip
  - Control rod inserted, but with one control rod stuck out
  - Core power decrease to shutdown level
  - Turbine stop valve close
  - Feedwater block valve close

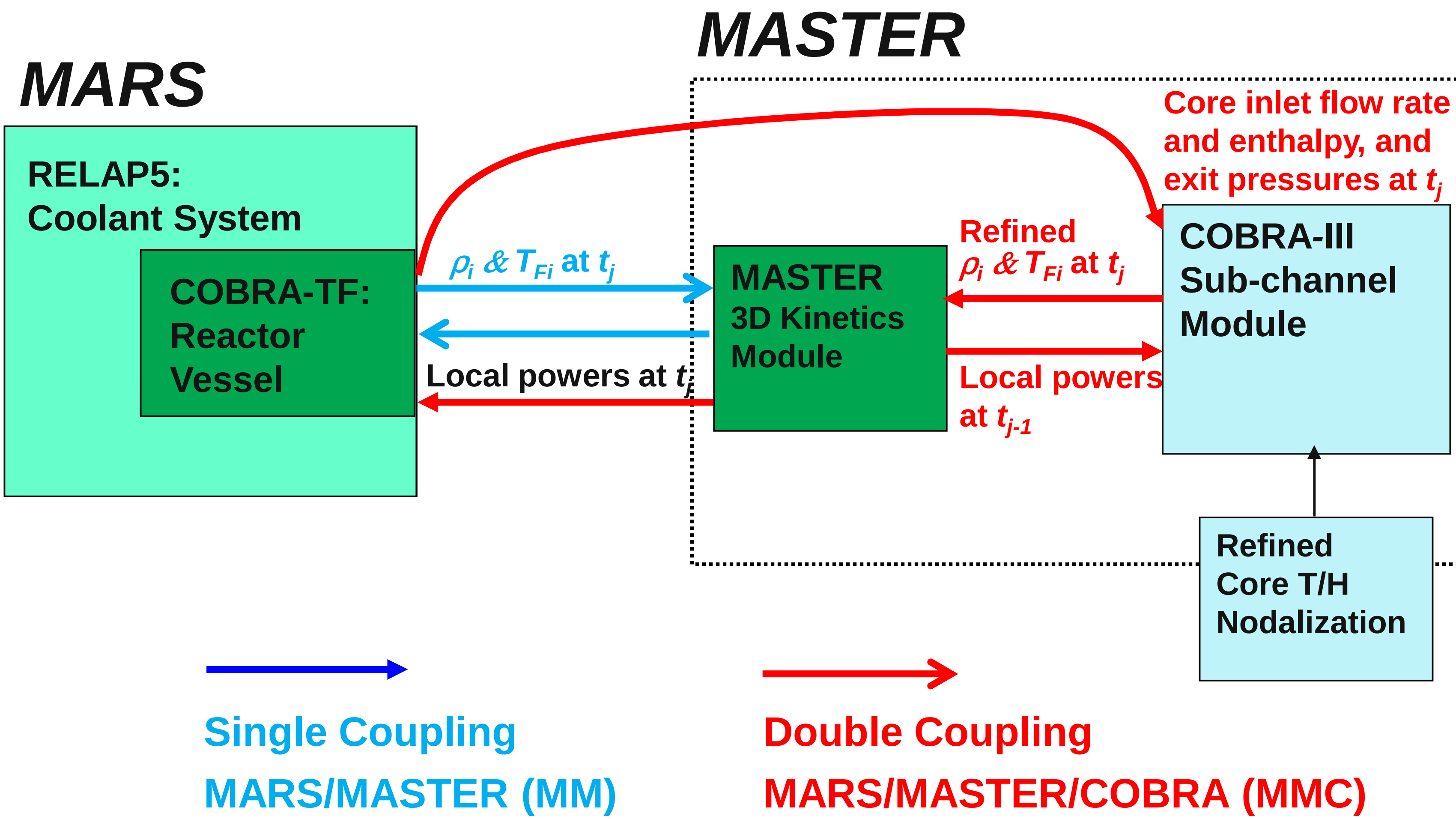
MSLB Progress Scenario – 2/2

- Continued evaporation of secondary coolant and overcooling of primary coolant in one loop
  – Asymmetric flow inlet flow
- Continued core reactivity increase
  – Subcritical neutron multiplication
  – Core power increase
  – Possibility of return-to-critical or return-to-power
- Dry-out of feedwater in broken side SG
  – No further decrease in coolant temperature
  – Core power decreases due to negative temperature coefficients

Considerations on MSLB

- Break flow rate → rate of evaporation
- Magnitude of moderator temperature coefficient (MTC)
  - Positive reactivity insertion due to negative MTC
  - Most limiting at end of cycle (least boron, most negative MTC)
- Shutdown margin
  - Total rod worth – largest stuck rod worth
  - Power defect
- Asymmetric flow condition
  - Flow mixing in lower plenum
  - Asymmetric radial coolant temperature distribution
- Localized power peaking
  - Stuck rod condition
  - Asymmetry due to asymmetric flow
- 3-D kinetics
  - Severe flux shape change during transient

MARS/MASTER Coupling Options



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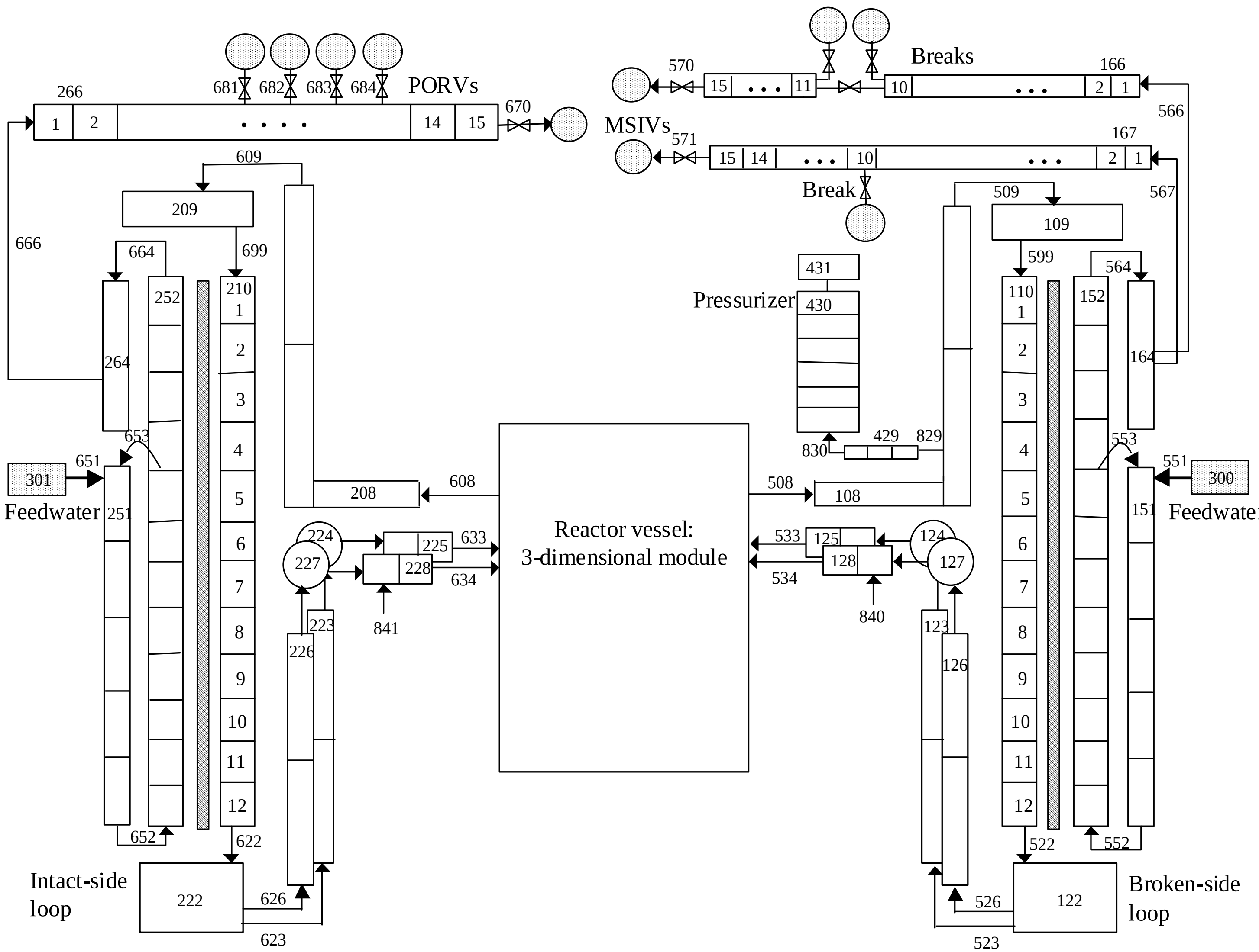
OECD MSLB Benchmark

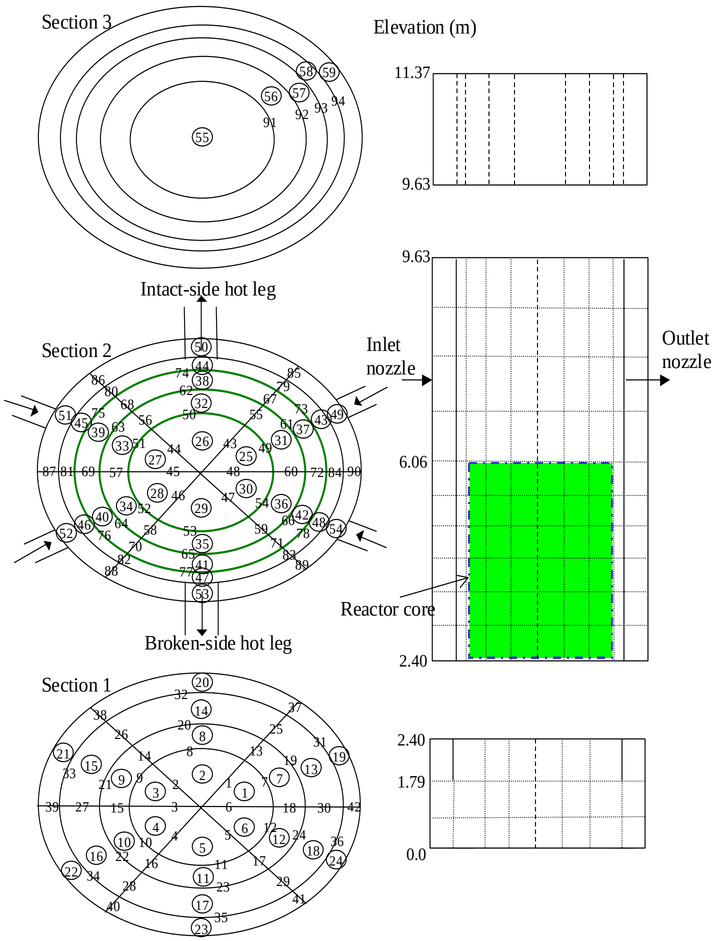
- Assess performance of system T-H/spatial kinetics coupled codes
- Model plant: TMI-1
  - B&W designed TMI-1, 2772 MWth
  - Two once-through steam generators
    - *Superheated vapor*
    - *Less feedwater inventory in SG*
- Provided data
  - Neutronics data
    - *Geometry, cross section*
  - T/H component data
    - *Dimension, volume, material properties*
  - Initial operating conditions
  - Trip set points
    - *Over power trip at 114%*
    - *Low pressure trip at 13.41 Mpa*

MARS System Model of OECD MSLB

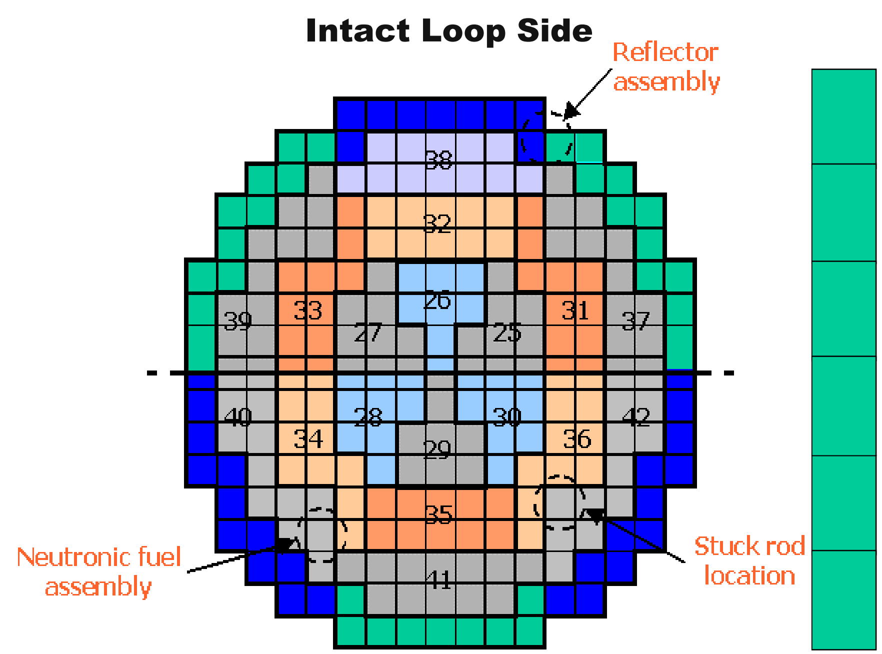


Core Modeling

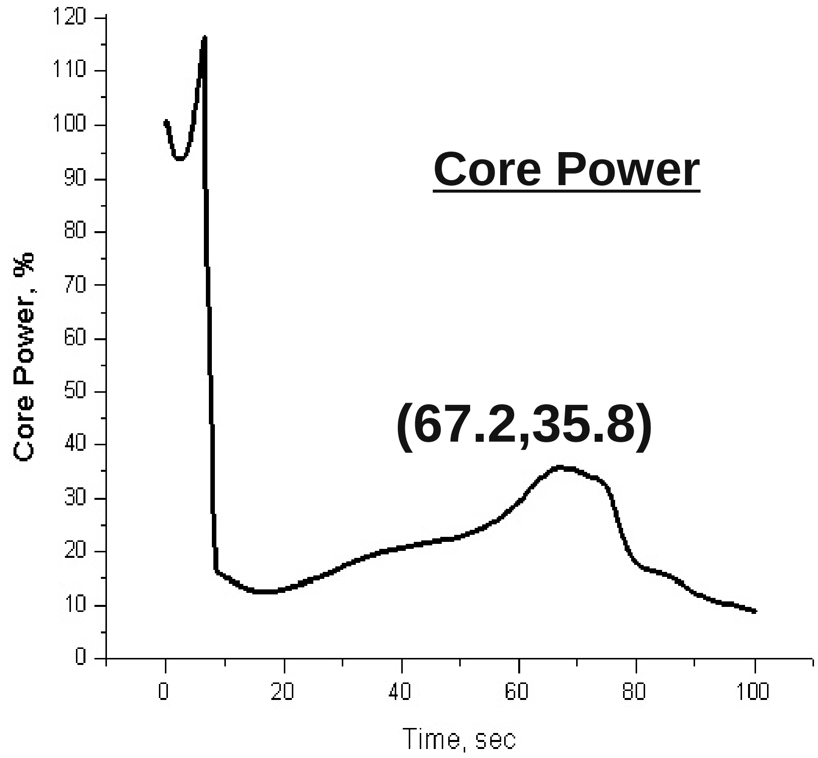
Vessel Modeling

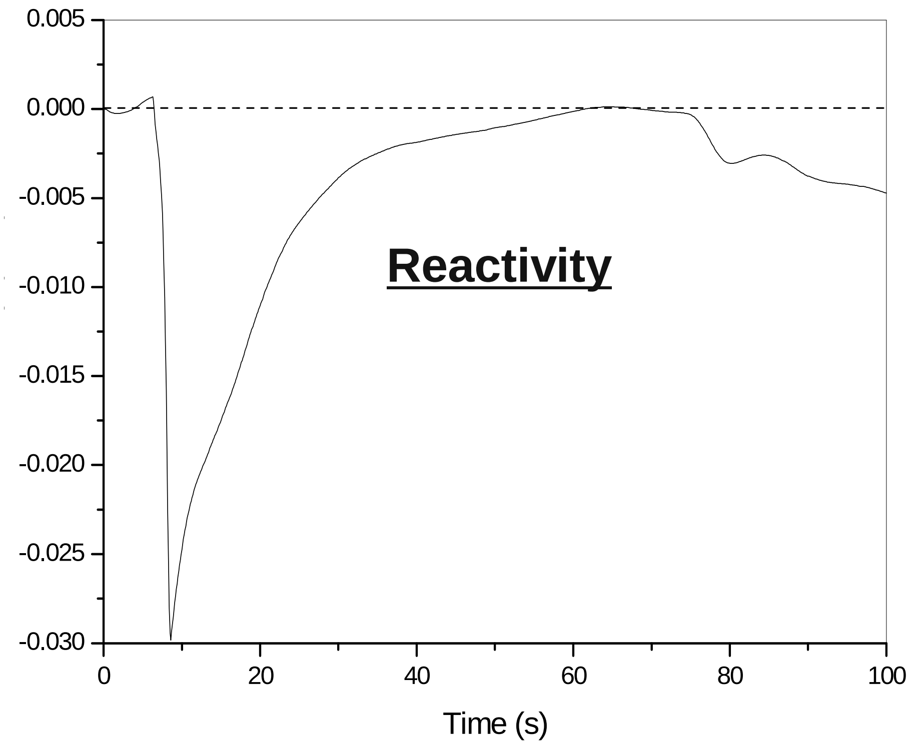


Core Modeling



Core Power and Reactivity





Subcritical Multiplication

- Prompt Jump Approximation solution with ρ in \$ ($\rho_\$ = \rho/\beta$)

$$\dot{p}(t) = \frac{\lambda\rho_\$(t) + \dot{\rho}_\$(t)}{1-\rho_\$(t)} p(t)$$

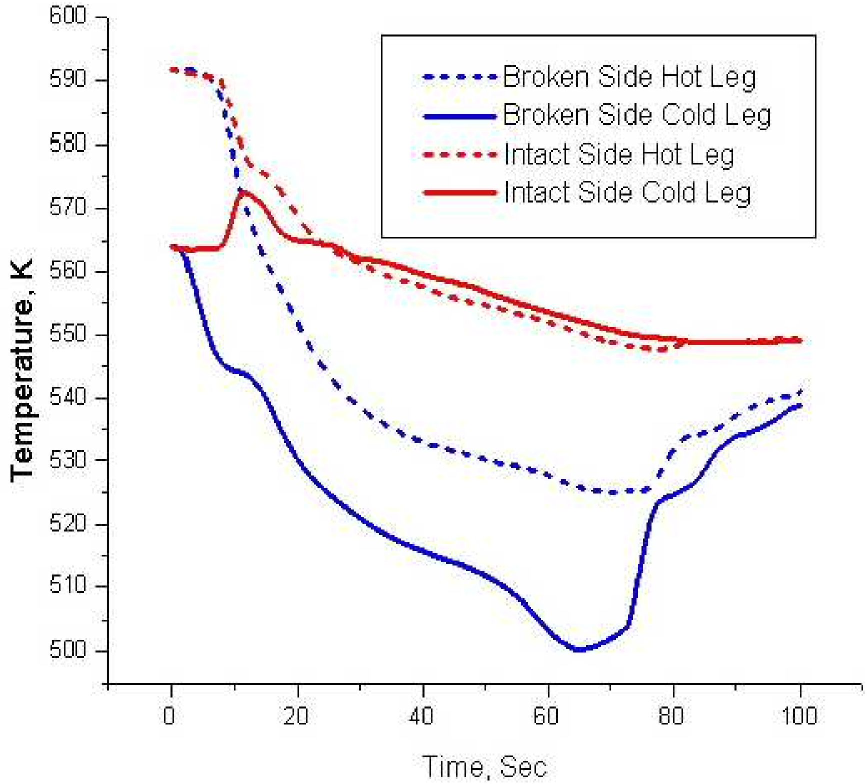
- The sign of power change is determined by numerator
  - Denominator always positive in the PJA application range ($\rho_\$ << 1\$$)
- If $\rho_\$ < 0$ (Subcritical)

$$\dot{p}(t) > 0 \text{ if } \frac{\dot{\rho}_\$(t)}{|\rho_\$(t)|} > \lambda$$

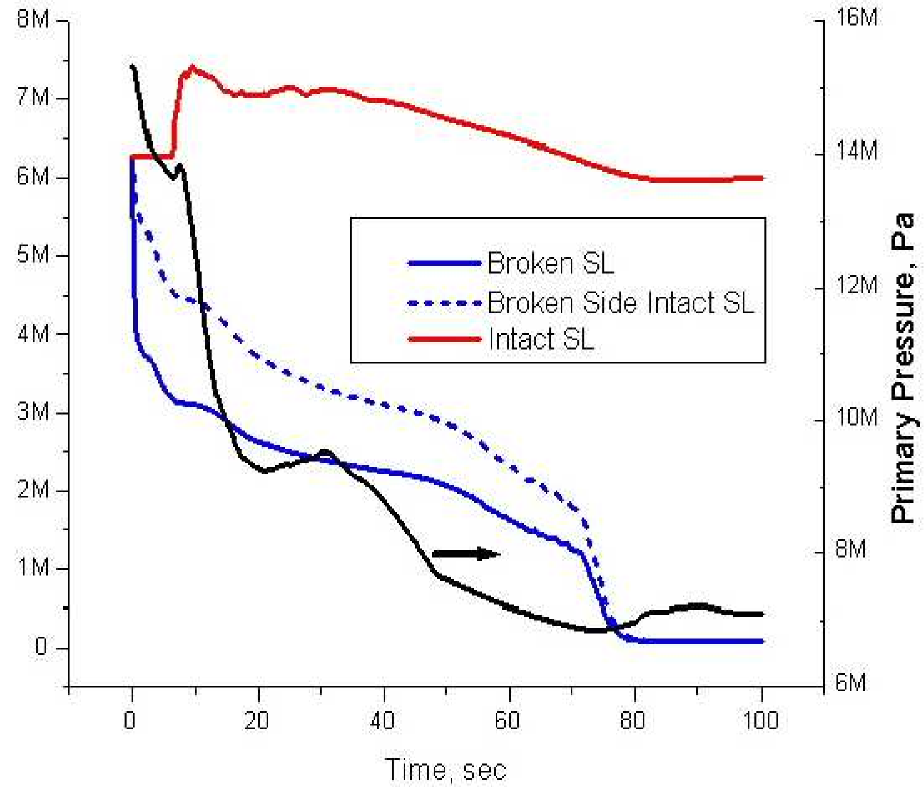
  - Reactor power can increase under subcritical condition if the logarithmic derivative of reactivity is larger than precursor decay constant
  - Because the increase rate of prompt neutrons is greater than the reduction rate of delayed neutrons
  - Or source multiplcation factor increases faster than delayed neutron source decreases

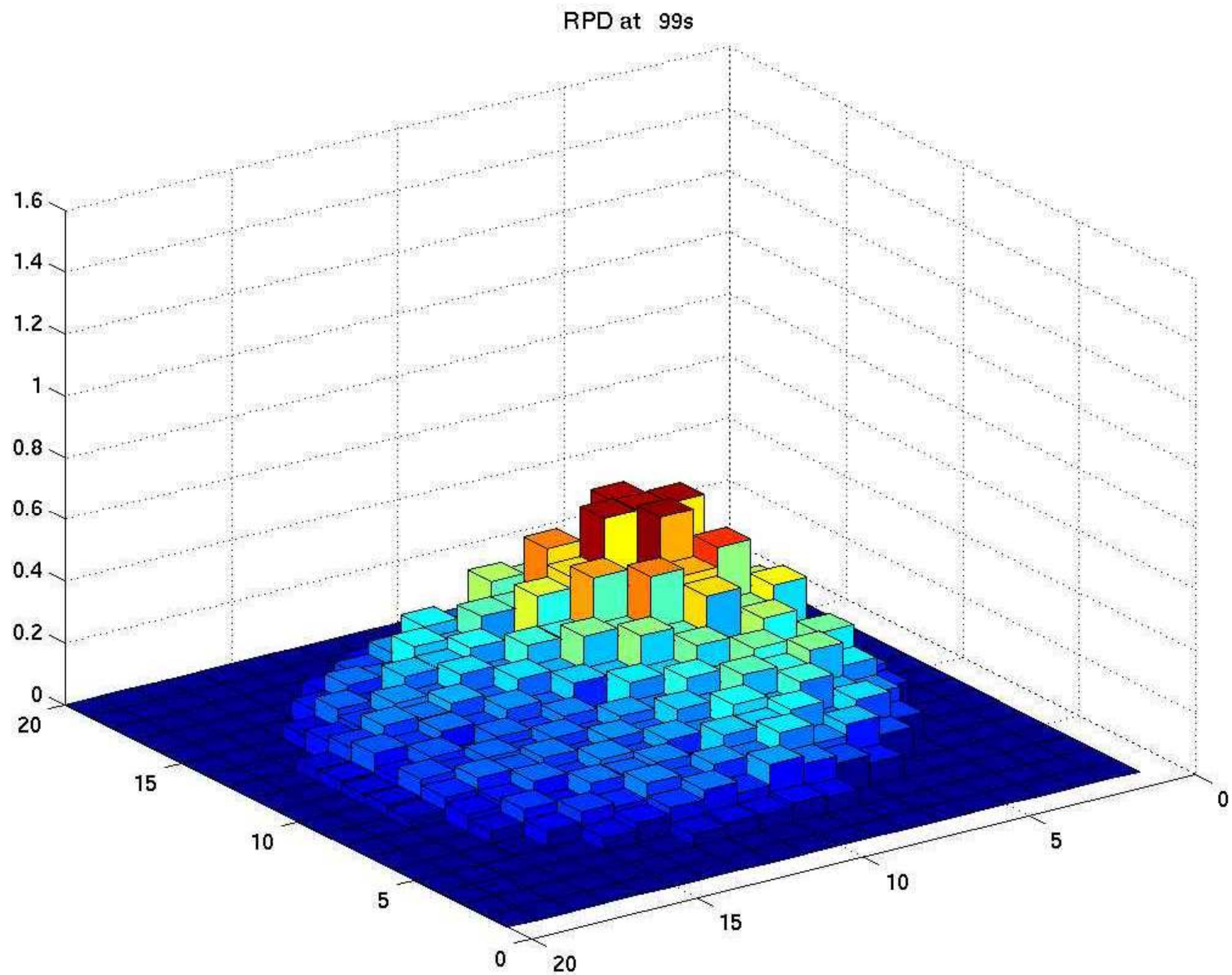
Transient Results - II

Temperature



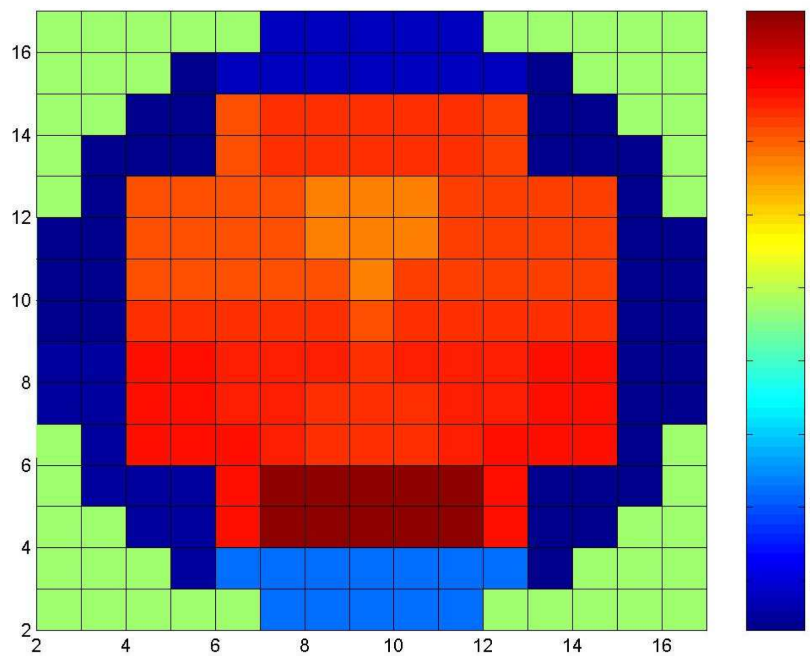
Pressure



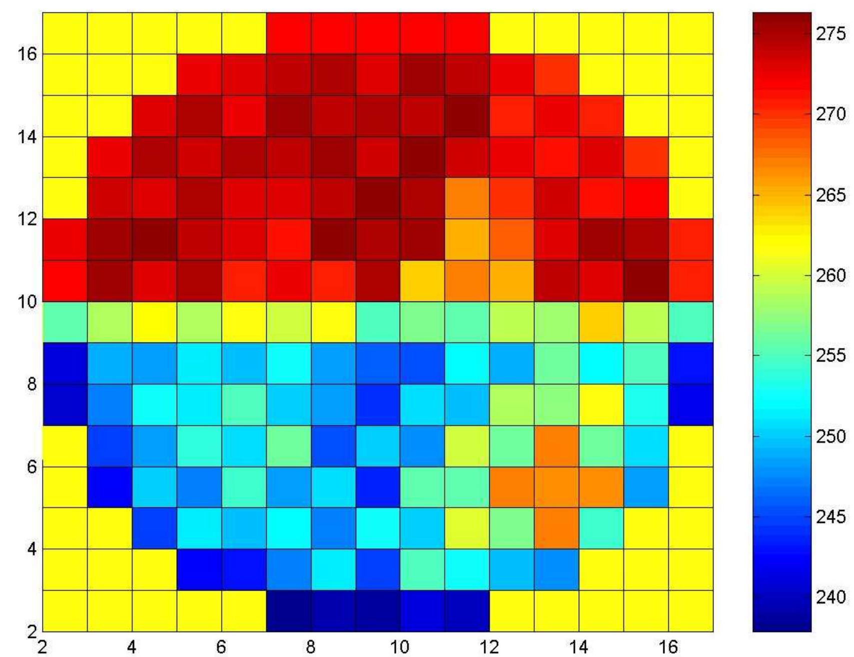

RPD at 99s
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
20
15
10
5
0
20
15
10
5
0

Flow Condition near 60 sec

Inlet Flow Rate

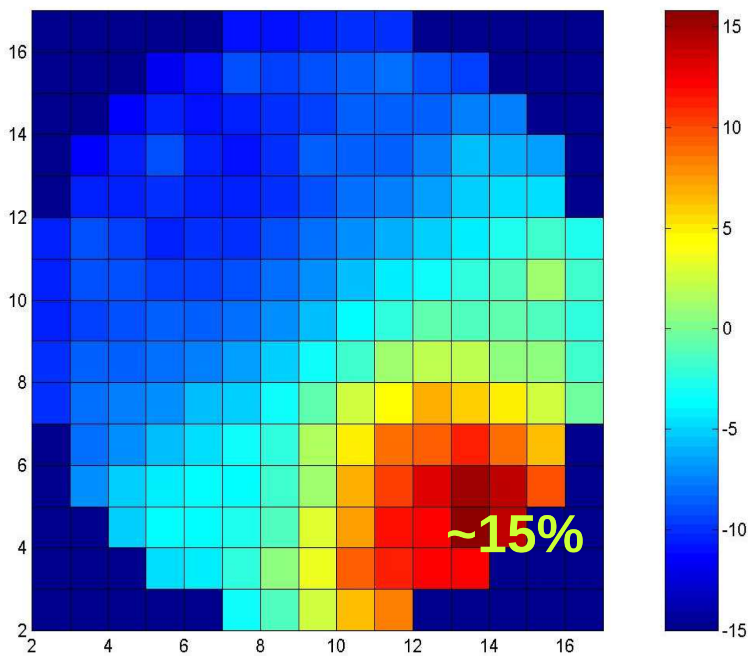


Outlet Temperature



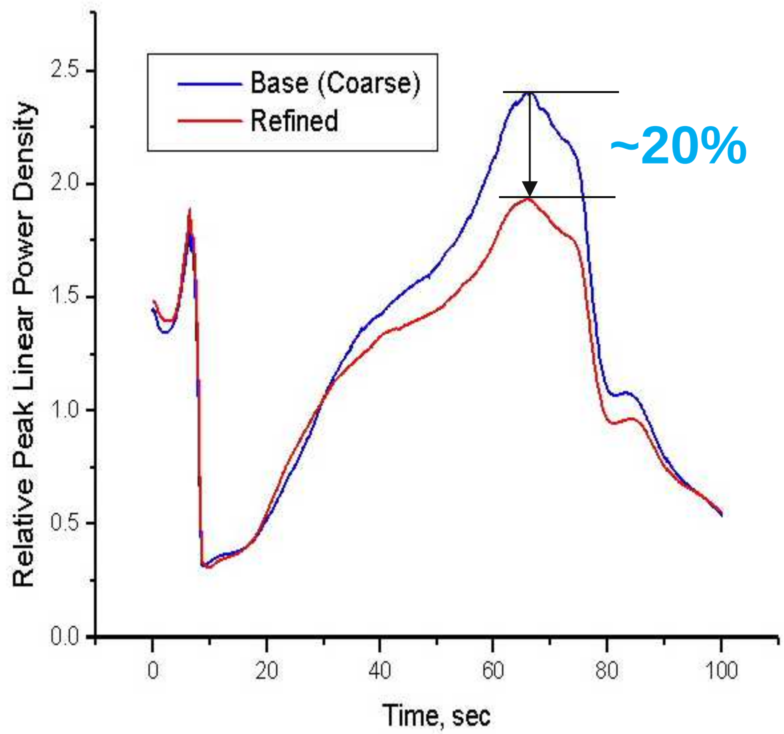
Transient Power Distribution Comparison

Coarse-Fine Difference, %



*at the time of max. return-to-power

Peak Linear Power Density



- Peak LPD is normalized to the nominal average value at full power