NUCL 511
Nuclear Reactor Theory and Kinetics

Lecture Note 11

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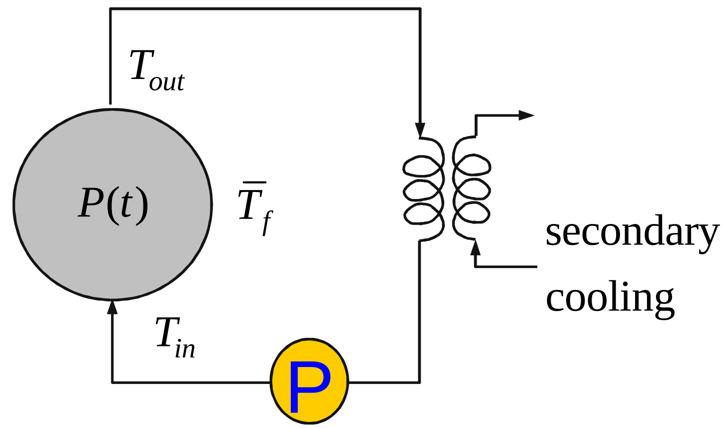
Point Reactor Model for T/H Feedback

- Reactor power with point kinetics model

$$P(t) = P_n p(t)$$

$p(t) =$ power or flux amplitude in PKE

$P_n =$ nominal power level (Watts)



- Heat balance in fuel

$$C_f \frac{d\bar{T}_f}{dt} = P_n p(t) - Q_{out} = P_n p(t) - U(\bar{T}_f - \bar{T}_c)$$

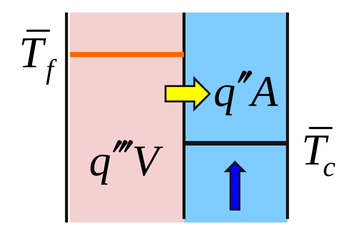
$C_f = \rho_f c_p V_f =$ total heat capacity of fuel

$U = hA =$ overall heat transfer coefficient

  – Steady state heat balance

$$0 = P_n p_0 - U(\bar{T}_{f0} - \bar{T}_{c0})$$

Average Coolant Channel



$$q'' = h(\bar{T}_f - \bar{T}_c)$$

- Change in average fuel temperature

$$C_f \frac{d}{dt}\delta T_f = P_n \delta p - U(\delta T_f - \delta T_c) \qquad \delta p = p - p_0, \quad \delta T_f = \bar{T}_f - \bar{T}_{f0}, \quad \delta T_c = \bar{T}_c - \bar{T}_{c0}$$

Point Reactor Model for T/H Feedback

- Change in average fuel temperature

$$\frac{d}{dt}\delta T_f = \frac{P_n}{C_f}\delta p(t) - \frac{U}{C_f}(\delta T_f - \delta T_c) = C_{IT}\delta p(t) - \lambda_H(\delta T_f - \delta T_c)$$

$C_{IT} = P_n / C_f =$ rate of temperature rise per second (K/s) of nominal power application

$\lambda_H = U / C_f =$ time constant for heat transfer from fuel to coolant (1/s)

- Rapid transients where $\delta T_f >> \delta T_c$

$$\frac{d}{dt}\delta T_f(t) = -\lambda_H \delta T_f(t) + C_{IT}\delta p(t), \quad \delta T_f(0) = 0$$

$$\frac{d}{dt}[\delta T_f(t) e^{\lambda_H t}] = C_{IT} e^{\alpha_H t}\delta p(t) \quad \Rightarrow \quad \delta T_f(t') e^{\lambda_H t'}\Big|_0^t = \delta T_f(t) e^{\lambda_H t} = C_{IT}\int_0^t e^{\lambda_H t'}\delta p(t')dt'$$

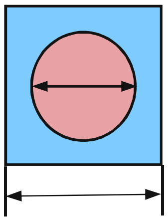
$$\delta T_f(t) = C_{IT}\int_0^t e^{-\lambda_H(t-t')}\delta p(t')dt' = \frac{P_n}{C_f}\int_0^t e^{-\lambda_H(t-t')}\delta p(t')dt' = \frac{P_n}{C_f}\int_0^t e^{-\lambda_H(t-t')}[p(t') - p_0]dt'$$

- Adiabatic boundary condition (very rapid transient, $\lambda_H = 0$)

$$\delta T_f(t) = C_{IT}\int_0^t \delta p(t')dt' = \frac{P_n}{C_f}\delta I(t) = \frac{\delta Q(t)}{C_f} = \frac{P_n}{C_f}\int_0^t [p(t') - p_0]dt'$$

Typical PWR Data

- Power density
  - Core average power density: ~100 kW/ℓ (cf. ~50 kW/ℓ for BWR)
  - Power density in fuel: 100/0.32 ≈ 300 kW/ℓ



Pellet dia = 0.8 cm

Cell pitch = 1.25 cm

Fuel Volume Fraction ≈ 0.32

- Heat capacity of fuel: 0.32 kJ/kg-K
  - Fuel density: ~10 g/cc = ~10 kg/ℓ
  - Volumetric heat capacity: ~3.2 kJ/ℓ-K (cf. 4.2 kJ/ℓ-K for H_2O)
- Fuel temperature rise per full-power-second

$$\delta T_f = \frac{300 \text{ kw}/\ell \times 1\text{sec}}{3.2 \text{ kJ}/\ell\text{-K}} = 94 \text{ K/fp-s}$$

- Reactivity change per full-power-second

$$\delta\rho / \text{fp-s} = 94 \text{ K/fp-s} \times (-3)\text{pcm/K} = -280 \text{ pcm/fp-s}$$
$$= -0.4 \ \$ / \text{fp-s} \equiv \gamma \text{ (full power coefficient, 1/s)}$$

PKE with Prompt Reactivity Feedback

- Reactivity with feedback (induced by fuel temperature change)

$$\rho(t) = \rho_e(t) + \gamma \int_0^t e^{-\lambda_H (t-t')} [p(t') - p_0] dt'$$

$$\gamma = C_{IT} \alpha_F = \frac{P_n}{C_f} \alpha_F$$

- If γ is constant, then reactivity change is proportional to energy deposit
  - Linear energy feedback model for rapid transients
- Point kinetics equations with reactivity feedback

$$\Lambda \dot{p}(t) = \left[\rho_e(t) - \beta + \gamma \int_0^t e^{-\lambda_H (t-t')} [p(t') - p_0] dt' \right] p(t) + \sum_{k=1}^{K} \lambda_k \zeta_k(t)$$

$$\dot{\zeta}_k(t) = -\lambda_k \zeta_k(t) + \beta_k p(t)$$

- Sub-prompt critical transients
  - Transient with step reactivity insertion, $\rho_1 < 1\$$
  - Prompt jump approximation with pseudo initial condition

$$p(0^+) = p^0 = \frac{1}{1 - \rho_{1\$}} p_0$$

Short-Time Transient with Step Reactivity Insertion

- Prompt jump approximation
  - Adiabatic approximation: heat confined in fuel for short time
  - One group of delayed neutrons

$$0 = \left[\rho_1 + \gamma \int_0^t [p(t') - p_0] dt' - \beta \right] p(t) + \bar{\lambda} \zeta(t)$$

$$\dot{\zeta}(t) = -\bar{\lambda} \zeta(t) + \beta p(t)$$

- Taylor expansion for relatively slow change after prompt jump

$$p(t) = p^0 + p' t + p'' t^2 + \cdots$$

$$\zeta(t) = \zeta_0 + \zeta' t + \zeta'' t^2 + \cdots$$

- Reactivity derivative in terms of power

$$\dot{\rho}(t) = \frac{d}{dt} \left[\rho_1 + \gamma \int_0^t [p(t') - p_0] dt' \right] = \gamma [p(t) - p_0] = \gamma (p^0 - p_0 + p' t + p'' t^2 + \cdots)$$

$$\Rightarrow \quad \dot{\rho}(0) = \gamma (p^0 - p_0)$$

- Precursor equation

$$\zeta' + 2\zeta'' t + \cdots = -\bar{\lambda} (\zeta_0 + \zeta' t) + \beta (p^0 + p' t + \cdots) \quad \Rightarrow \quad \zeta'(0) = -\bar{\lambda} \zeta_0 + \beta p^0 = \beta (p^0 - p_0)$$

Short-Time Transient with Step Reactivity Insertion

- Power equation

$$\left[\rho_1-\beta+\gamma\int_0^t [p^0-p_0+p't']dt'\right](p^0+p't)+\bar{\lambda}(\zeta_0+\zeta' t)=0$$

  - Constant term

$$p^0(\rho_1-\beta)+\bar{\lambda}\zeta_0=0 \quad\Rightarrow\quad p^0=\frac{\bar{\lambda}\zeta_0}{\beta-\rho_1}=\frac{\beta p_0}{\beta-\rho_1}=\frac{1}{1-\rho_{1\$}}p_0 \text{ (prompt jump)}$$

  - 1st order term

$$(\rho_1-\beta)p'+\gamma(p^0-p_0)p^0+\bar{\lambda}\beta(p^0-p_0)=0 \quad\Rightarrow\quad p'=\frac{p^0-p_0}{\beta-\rho_1}(\gamma p^0+\bar{\lambda}\beta)$$

$$p^0=\frac{\beta p_0}{\beta-\rho_1} \quad\Rightarrow\quad \frac{1}{\beta-\rho_1}=\frac{p^0}{\beta p_0} \quad\Rightarrow\quad p'=\frac{p^0}{\beta p_0}(p^0-p_0)(\gamma p^0+\bar{\lambda}\beta)$$

- Condition for $p'=0$

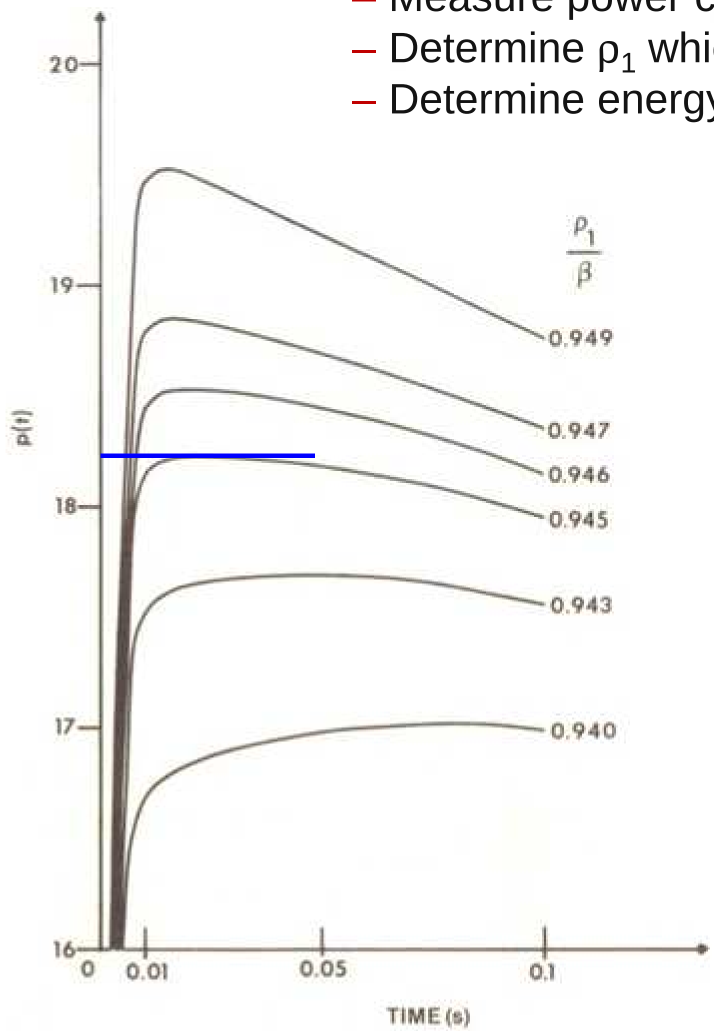
$$\gamma p^0+\bar{\lambda}\beta=0 \quad\Rightarrow\quad p^0=\frac{\bar{\lambda}\beta}{-\gamma}\equiv p^{00}$$

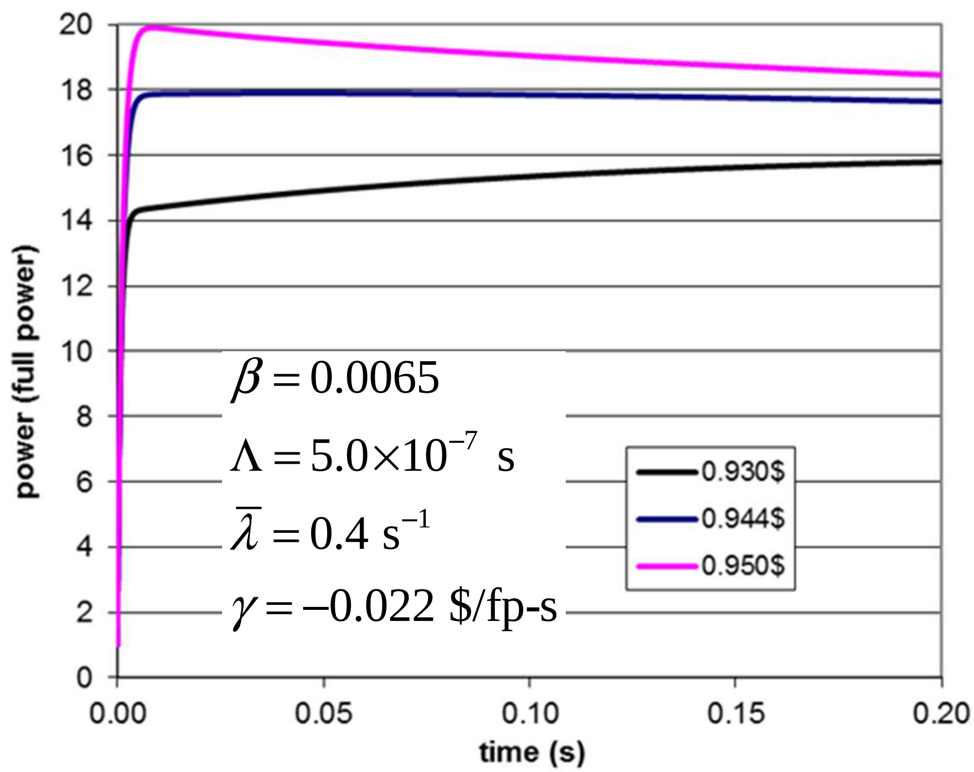
$$\frac{1}{1-\rho_{1\$}}p_0=\frac{\bar{\lambda}\beta}{-\gamma} \quad\Rightarrow\quad \rho_{1\$}=1+\frac{\gamma p_0}{\bar{\lambda}\beta}$$

  - When the prompt jump is p^{00}, the power change after the prompt jump vanishes
  - The influence of feedback and delayed neutrons on the power change after the prompt jump is cancelled

Experimental Determination of Energy Coefficient

– Measure power change vs. time for different values of ρ_1
– Determine ρ_1 which gives p'=0
– Determine energy coefficient γ





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Asymptotic Solution of Sub-Prompt Critical Transient

- Asymptotic state with adiabatic approximation

$$p\uparrow \;\Rightarrow\; T\uparrow \;\Rightarrow\; \rho\downarrow \;\Rightarrow\; \rho = 0 \text{ @ what power?}$$

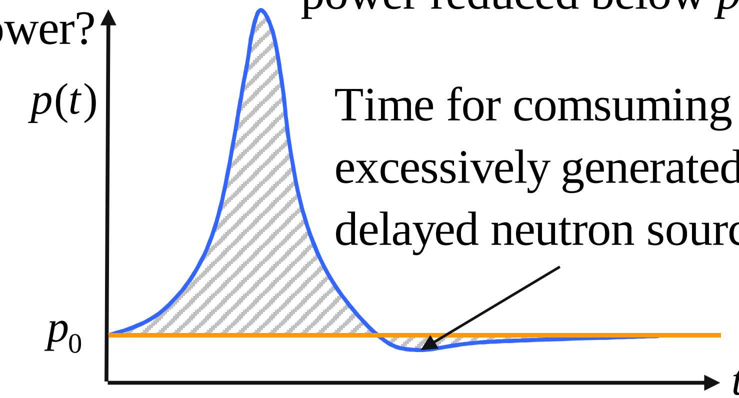
$$\dot{p}_{as} = \frac{\lambda\rho_{as}(t)+\dot{\rho}_{as}(t)}{\beta-\rho_{as}(t)}p_{as} = 0 \quad (\Leftarrow \text{ PJA})$$

$$\dot{\rho}_{as} = \gamma(p_{as}-p_0) = 0 \;\Rightarrow\; p_{as} = p_0 \text{ as } t\to\infty$$

$$\rho_{as} = \rho_1 + \gamma\int_0^\infty [p(t')-p_0]dt' = 0 \;\Rightarrow\; I_{as} = \frac{\rho_1}{-\gamma}$$

$$\delta Q = P_n I_{as} \;\Rightarrow\; \text{Heat added} \;\Rightarrow\; T_f^{as} > T_{f0}$$

Too strong feedback $\rightarrow$ power reduced below p_0



– External reactivity insertion is compensated for by increased fuel temperature

- Asymptotic state with first-order heat transfer $(\lambda_H \neq 0)$

$$0 = \lim_{t\to\infty}\left\{\rho_1 + \gamma\int_0^t [p(t')-p_0]\exp[-\lambda_H(t-t')]dt'\right\}$$

$$\approx \rho_1 + \gamma\int_{-\infty}^t (p_{as}-p_0)\exp[-\lambda_H(t-t')]dt' = \rho_1 + \frac{\gamma}{\lambda_H}(p_{as}-p_0)$$

$$p_{as} = p_0 + \frac{\rho_1\lambda_H}{-\gamma}$$

– Asymptotic power is higher than the initial power to maintain a high temperature to compensate for the external reactivity insertion with heat transfer to coolant

Super-Prompt Critical Excursion by Step Reactivity

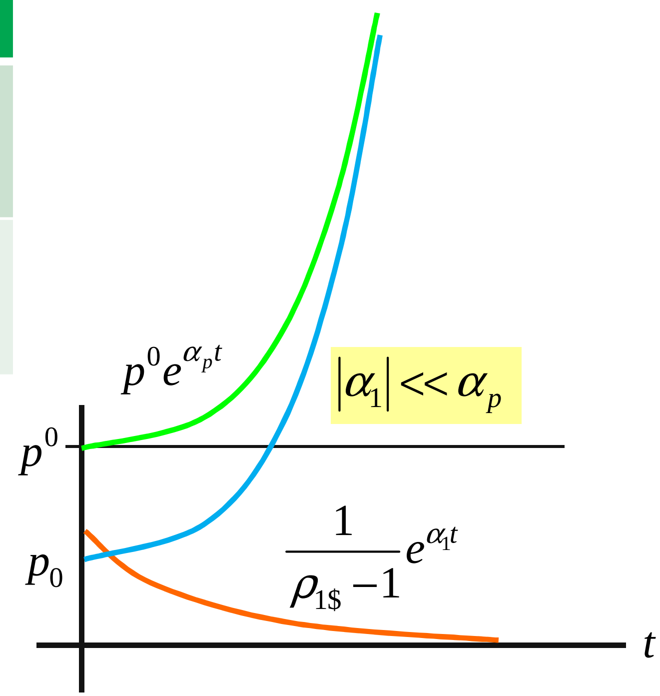
- Step reactivity insertion $\rho > \beta$
- Solution with one delayed neutron group

$$p(t) = p_0\left(\frac{1}{1-\rho_{1\$}}e^{\alpha_1 t} - \frac{\rho_{1\$}}{1-\rho_{1\$}}e^{\alpha_p t}\right), \quad \alpha_p = \frac{\rho_1 - \beta}{\Lambda}, \quad \alpha_1 = \frac{\rho_{1\$}}{1-\rho_{1\$}}\bar{\lambda}$$

ρ	α_p	α_1	*Prompt jump*	Asymptotic solution
$<\beta$	<0	>0	$p^0 = \frac{p_0}{1-\rho_{1\$}}$	$p^0 e^{\alpha_1 t}$
$>\beta$	>0	<0	$p^0 = \frac{\rho_{1\$} p_0}{\rho_{1\$}-1}$	$p^0 e^{\alpha_p t}$

– Solution of prompt kinetics equation with pseudo initial condition

$$p(t) \approx \frac{p_0 \rho_{1\$}}{\rho_{1\$}-1}e^{\alpha_p t} = p^0 e^{\alpha_p t}$$



Super-Prompt Critical Excursion with Prompt Feedback

- Linear energy model with adiabatic boundary condition

$$\rho(t) = \rho_1 + \gamma \int_0^t [p(t') - p_0] dt' \cong \rho_1 + \gamma \int_0^t p(t') dt'$$

$$\Leftarrow \quad p(t) >> p_0 \text{ for prompt critical transient}$$

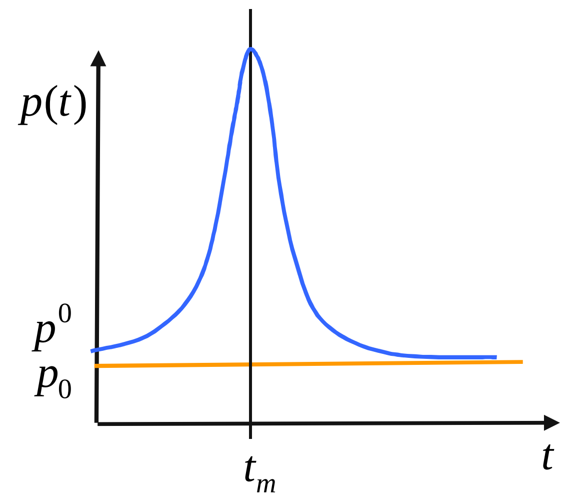
- At maximum power

$$\Lambda \dot{p} = [\rho(t_m) - \beta] p(t_m) = 0$$

$$\Rightarrow \quad \rho(t_m) = \rho_1 + \gamma \int_0^{t_m} p(t') dt' = \beta$$

$$I(t_m) = \int_0^{t_m} p(t') dt' = \frac{\rho_1 - \beta}{-\gamma}$$

$$\delta Q = P_n I(t_m) = P_n \frac{\rho_1 - \beta}{-\gamma} = \frac{\rho_1 - \beta}{-\gamma / P_n} = \frac{\rho_1 - \beta}{-\gamma_E}$$



The energy released untill the power reaches its maximum is dependent only on ρ_1, but independent of Λ

- Fuel temperature rise for $\rho_1 = 1.2\$$

$$\frac{0.2\$}{0.4\$/\text{fp-s}} = 0.5 \text{ fp-s} \quad \Rightarrow \quad \delta T_f \sim 50\text{K} \quad (1\text{fp-s} \rightarrow \sim 94\text{K})$$

Solution of Prompt Kinetics Equation

- System of first order ODEs

$$\dot{p}(t)=\frac{\rho(t)-\beta}{\Lambda}p(t) \quad \text{(prompt kinetic equation)}$$

$$\rho(t)=\rho_1+\gamma\int_0^t p(t')dt' \quad \text{(reactivity feedback)} \quad \Rightarrow \quad \dot{\rho}(t)=\gamma p(t)$$

- Second order ODE for reactivity

$$\ddot{\rho}(t)=\gamma\dot{p}(t)=\gamma\frac{\rho(t)-\beta}{\Lambda}p(t)=\frac{\rho(t)-\beta}{\Lambda}\dot{\rho}(t) \quad \Rightarrow \quad \Lambda\ddot{\rho}_p(t)=\rho_p(t)\dot{\rho}_p(t), \quad \rho_p=\rho(t)-\beta$$

Initial conditions: $\rho_p(0)=\rho(0)-\beta=\rho_1-\beta, \quad \dot{\rho}_p(0)=\gamma p(0)=\gamma p^0$

- Maximum power

$$\Lambda[\dot{\rho}_p(t)-\dot{\rho}_p(0)]=\frac{1}{2}[\rho_p^2(t)-\rho_p^2(0)] \quad \Rightarrow \quad \gamma\Lambda[p(t)-p^0]=\frac{1}{2}[\rho_p^2(t)-\rho_{1p}^2]$$

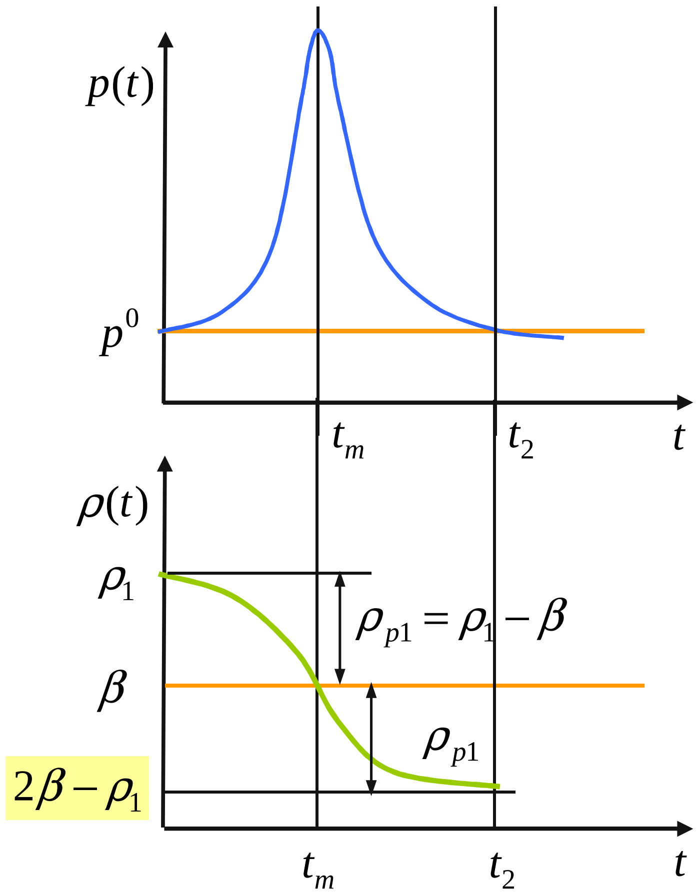
  - At maximum power, $p(t_m)=p_m, \quad \rho(t_m)=\beta \quad \Rightarrow \quad \rho_p(t_m)=0$

$$\gamma\Lambda(p_m-p^0)=-\frac{1}{2}(\rho_1-\beta)^2 \quad \Rightarrow \quad p_m=p^0+\frac{(\rho_1-\beta)^2}{2\Lambda(-\gamma)}$$

$$p_m=\frac{1.2}{0.2}p_0+\frac{0.2^2\times 0.007^2}{2\times 10^{-5}\times(0.4\times 0.007)}=6p_0+35$$

PKA Solution beyond the Power Peak

- After the power peak, the reactivity is reduced below β, and the neutron flux of the super-prompt reactor dies away rapidly, and the flux is eventually determined by the source multiplication factor of the delayed neutrons
- When the power is back to the initial jump level



$$p(t) - p^0 = \frac{1}{2}[\rho_p^2(t) - \rho_{p1}^2] = 0$$

$$\rho_p^2(t) = \rho_{p1}^2 \quad \Rightarrow \quad \rho_p(t) = \pm\rho_{p1}$$

$$\Rightarrow \quad \rho_p(t_2) = -\rho_{p1}$$

$$\Delta\rho(t_2) = \rho(t_2) - \rho(0) = -2\rho_{p1} = -2(\rho_1 - \beta)$$

$$\Delta\rho(t_2) = \gamma I(t_2)$$

$$I(t_2) = 2\frac{\rho_1 - \beta}{-\gamma} = 2I(t_m)$$

Two times the energy release to the power peak

Solution of Prompt Kinetics Equation

- First integral of second order ODE for reactivity

$$\Lambda[\dot{\rho}_p(t) - \dot{\rho}_p(0)] = \frac{1}{2}[\rho_p^2(t) - \rho_p^2(0)] \qquad \rho_{p1} = \rho_p(0) = \rho_1 - \beta, \quad \dot{\rho}_p(0) = \gamma p^0$$

$$2\Lambda\dot{\rho}_p(t) = \rho_p^2(t) - \rho_{p1}^2 + 2\Lambda\gamma p^0 = \rho_p^2(t) - \rho_b^2$$

$$\rho_b^2 = \rho_{p1}^2 + 2\Lambda(-\gamma)p^0 > \rho_{p1}^2$$

$$\frac{\dot{\rho}_p(t)}{[\rho_p(t)+\rho_b][\rho_p(t)-\rho_b]} = \frac{1}{2\Lambda} \quad \Rightarrow \quad \left(\frac{1}{\rho_p(t)+\rho_b} - \frac{1}{\rho_p(t)-\rho_b}\right)\frac{\dot{\rho}_p(t)}{(-2\rho_b)} = \frac{1}{2\Lambda}$$

$$\left(\frac{1}{\rho_p - \rho_b} - \frac{1}{\rho_p + \rho_b}\right)\frac{d\rho_p}{\rho_b} = \frac{dt}{\Lambda}$$

- Integrate over (0,t)

$$\frac{t}{\Lambda} = \frac{1}{\rho_b}\left[\ln\frac{\rho_b + \rho_{p1}}{\rho_b - \rho_{p1}} - \ln\frac{\rho_b + \rho_p(t)}{\rho_b - \rho_p(t)}\right] \qquad \rho_p(t) \le \rho_b$$

Solution of Prompt Kinetics Equation

- At peak power, $\rho_p(t_m) = 0$

$$\frac{t_m}{\Lambda} = \frac{1}{\rho_b}\left[\ln\frac{\rho_b + \rho_{p1}}{\rho_b - \rho_{p1}} - \ln\frac{\rho_b + \rho_p(t_m)}{\rho_b - \rho_p(t_m)}\right] \Rightarrow \quad t_m = \frac{\Lambda}{\rho_b}\ln\frac{\rho_b + \rho_{p1}}{\rho_b - \rho_{p1}}$$

$$\frac{t}{\Lambda} = \frac{t_m}{\Lambda} - \frac{1}{\rho_b}\ln\frac{\rho_b + \rho_p(t)}{\rho_b - \rho_p(t)} \quad \Rightarrow \quad \frac{1}{-\rho_b}\ln\frac{\rho_b + \rho_p(t)}{\rho_b - \rho_p(t)} = \frac{t - t_m}{\Lambda}$$

- Reactivity and power

$$\rho_p(t) = \rho_b\,\frac{e^{-\rho_b(t-t_m)/\Lambda} - 1}{e^{-\rho_b(t-t_m)/\Lambda} + 1} = \rho_b \tanh\left[-\frac{\rho_b}{2\Lambda}(t - t_m)\right] \quad \Rightarrow \quad \rho_p(\infty) = -\rho_b \quad \text{(background)}$$

$$p(t) = \frac{\dot{\rho}_p(t)}{\gamma} = \frac{p_m}{\cosh^2\left[-\frac{\rho_b}{2\Lambda}(t - t_m)\right]}$$

Symmetric around t_m!

$$p_m = \frac{\rho_b^2}{2\Lambda(-\gamma)} = \frac{\rho_{p1}^2 - 2\Lambda\gamma p^0}{2\Lambda(-\gamma)} = \frac{\rho_{p1}^2}{2\Lambda(-\gamma)} + p^0$$

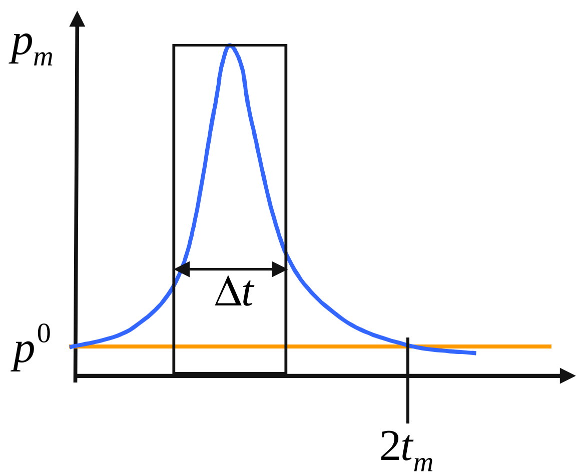
Equivalent Width of Power Burst

- At t = $2t_m$ (when the power returns to the initial jump)

$$\rho_p(2t_m) = \rho_b \frac{e^{-\rho_b t_m/\Lambda} - 1}{e^{-\rho_b t_m/\Lambda} + 1} \qquad e^{-\rho_b t_m/\Lambda} = e^{-\frac{\rho_b}{\Lambda}\frac{\Lambda}{\rho_b}\ln\frac{\rho_b+\rho_{p1}}{\rho_b-\rho_{p1}}} = \frac{\rho_b - \rho_{p1}}{\rho_b + \rho_{p1}}$$

$$\rho_p(2t_m) = \rho_b \frac{\frac{\rho_b - \rho_{p1}}{\rho_b + \rho_{p1}} - 1}{\frac{\rho_b - \rho_{p1}}{\rho_b + \rho_{p1}} + 1} = \rho_b \frac{-2\rho_{p1}}{2\rho_b} = -\rho_{p1} \quad \Rightarrow \quad 2t_m = t_2$$

- Equivalent width (of power burst)



$$p_m \Delta t = \int_0^{2t_m} p(t)dt = \frac{2\rho_{p1}}{-\gamma}$$

$$\Delta t = \frac{2\rho_{p1}}{-\gamma p_m} = \frac{2\rho_{p1}}{-\gamma} \frac{1}{\frac{\rho_{p1}^2}{2\Lambda(-\gamma)} + p^0}$$

$$\Delta t \sim \frac{4\Lambda}{\rho_{p1}} \propto \Lambda \quad \text{for } p_0 << 1$$

Example of Burst Estimate

- ρ_1 = 1.1$ in PWR

$$\gamma = -0.4\$/\text{fp-s}, \quad \beta = 0.007, \quad \Lambda = 2.5\times 10^{-5} \text{ sec}$$

$$p^0 = \frac{\rho_{1\$}}{\rho_{1\$}-1} p_0 = \frac{1.1}{0.1} p_0 = 11 p_0$$

$$p_m - p^0 = \frac{(\rho_1-\beta)^2}{2\Lambda(-\gamma)} = \frac{\beta(\rho_{1\$}-1)^2}{2\Lambda(-\gamma/\beta)} = \frac{0.007\times 0.1^2}{2\times 2.5\times 10^{-5}\times 0.4} = 3.5 \text{ fp}$$

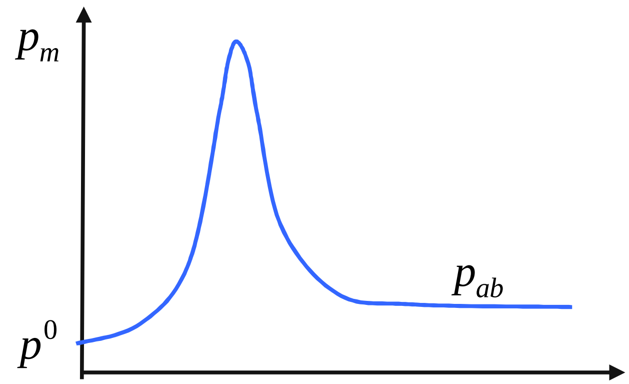
$$p_m = 11 p_0 + 3.5 \approx 3.5 \text{ fp} \ \text{ if } \ p_0 << 1$$

$$\Delta t = \frac{4\Lambda}{0.1\beta} = \frac{4\times 2.5\times 10^{-5}}{0.1\times 0.007} = 14.3 \text{ ms}$$

Precursor Accumulation Solution After Burst

- After the reactivity is reduced below β, PKA is not valid, and the flux is determined by the source multiplication factor of the delayed neutrons
  – A first approximation can be obtained by using the initial value of the delayed neutron source and the reactivity after the burst

$$p_{ab} = \frac{s_{d0}}{\beta - \rho(2t_m)} = \frac{\beta p(2t_m)}{\beta - \rho(2t_m)} = \frac{\beta p^0}{\rho_0 - \beta} = \frac{\beta \rho_0 p_0}{(\rho_0 - \beta)^2}$$



  – An improved estimate of the delayed neutron source multiplication requires accounting for the increase of the precursor population during the flux burst
    • *Precursor accumulation model*

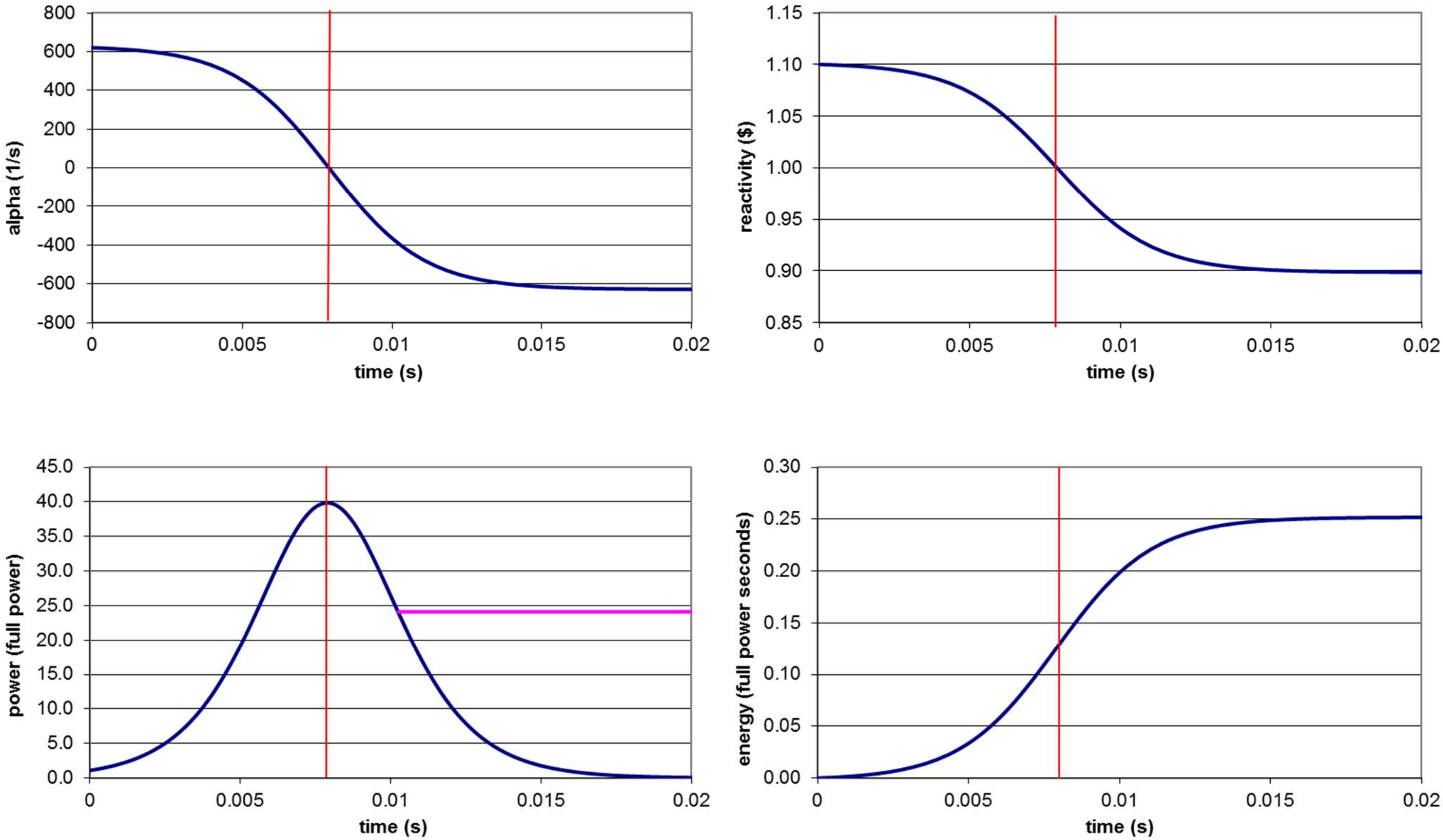
$$\lambda \zeta_2 = \beta p_0 \left(1 + \frac{2 \times 0.4 \times 0.1}{0.4 \times 10^{-4}}\right) = 2000 \beta p_0$$

$$\zeta(2t_m) \approx \zeta_0 + \beta \int_0^{2t_m} p(t)dt = \zeta_0 + \beta \frac{2\rho_{p1}}{-\gamma}$$

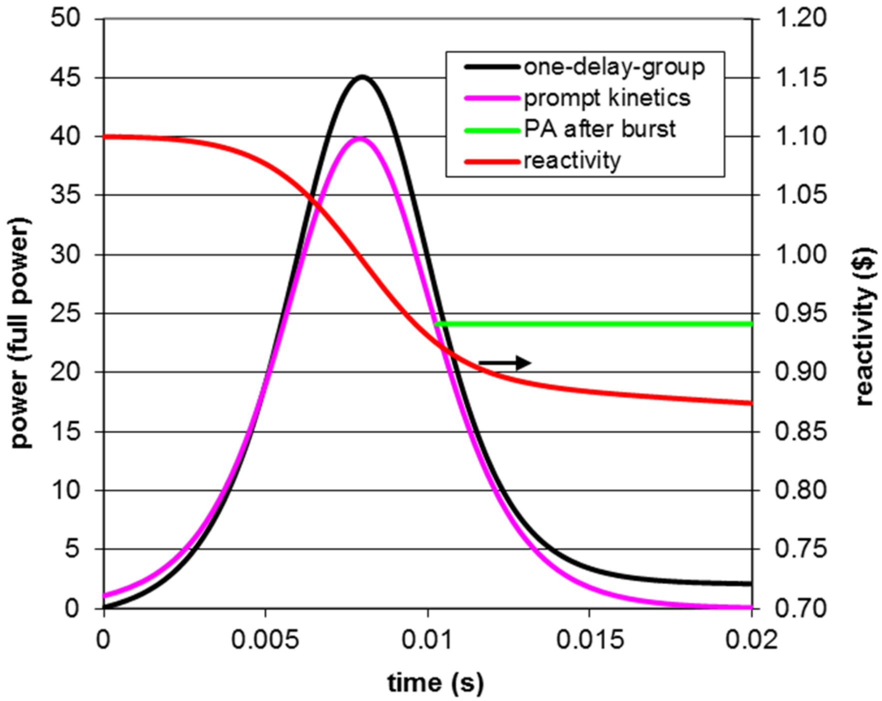
$$\lambda \zeta_2 = \lambda \zeta_0 + \lambda \beta \frac{2\rho_{p1}}{-\gamma} = \beta p_0 \left(1 + 2\frac{\lambda \rho_{p1}}{-\gamma p_0}\right) = \frac{1}{\rho_{p1\$}} \left(1 + 2\frac{\lambda \rho_{p1}}{-\gamma p_0}\right) p_0$$

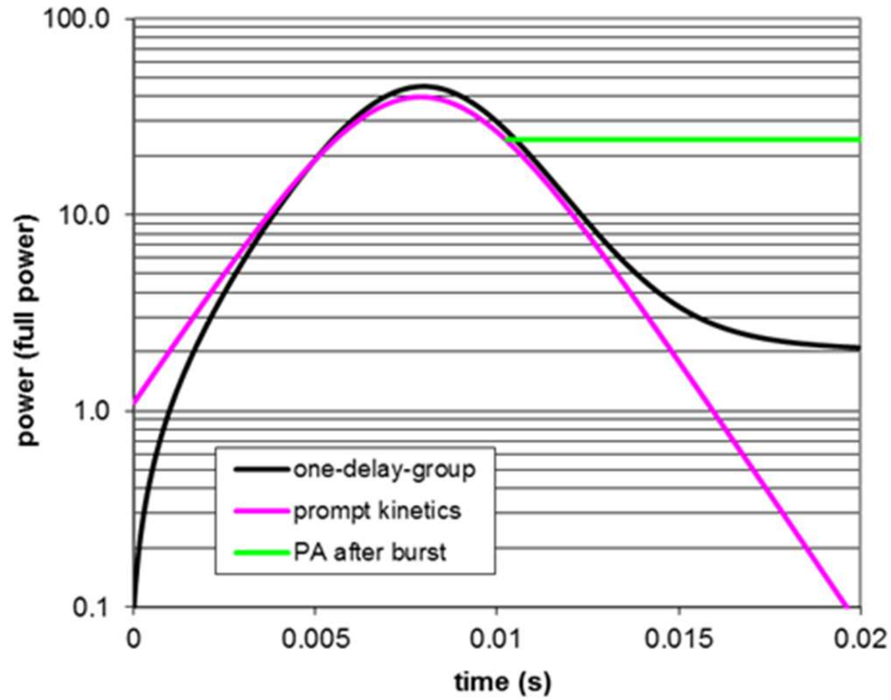
$$p_{ab} = \frac{s_d}{\beta - \rho} = \frac{\beta p_0}{\rho_{p1}} \left[1 + 2\frac{\lambda \rho_{p1}}{(-\gamma) p_0}\right]$$

PKA Solutions of Super-prompt Critical Transient

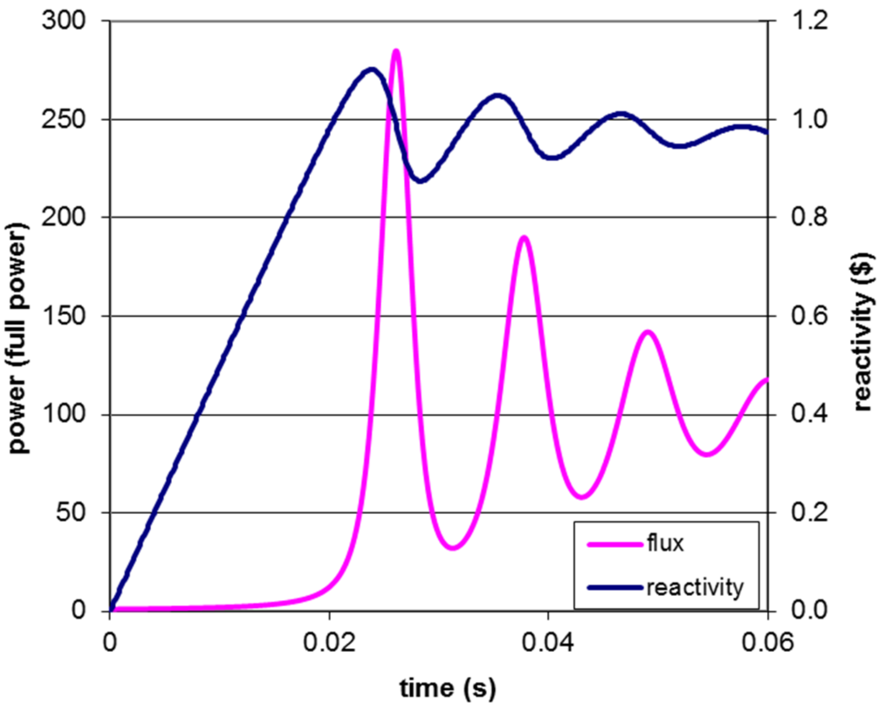


Solutions of Super-prompt Critical Transient

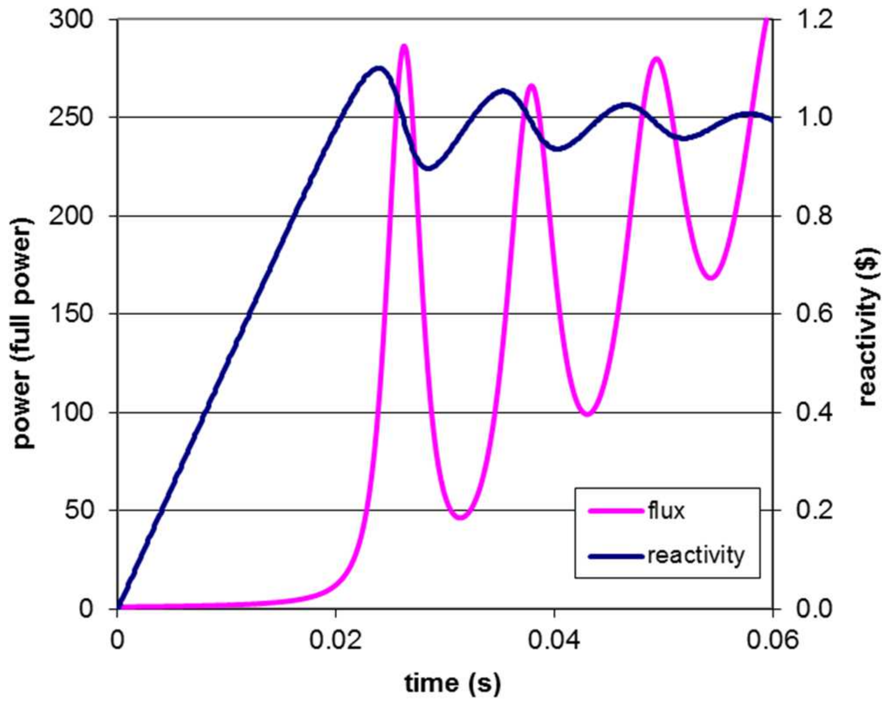




Super-prompt Critical Transient by Reactivity Ramp

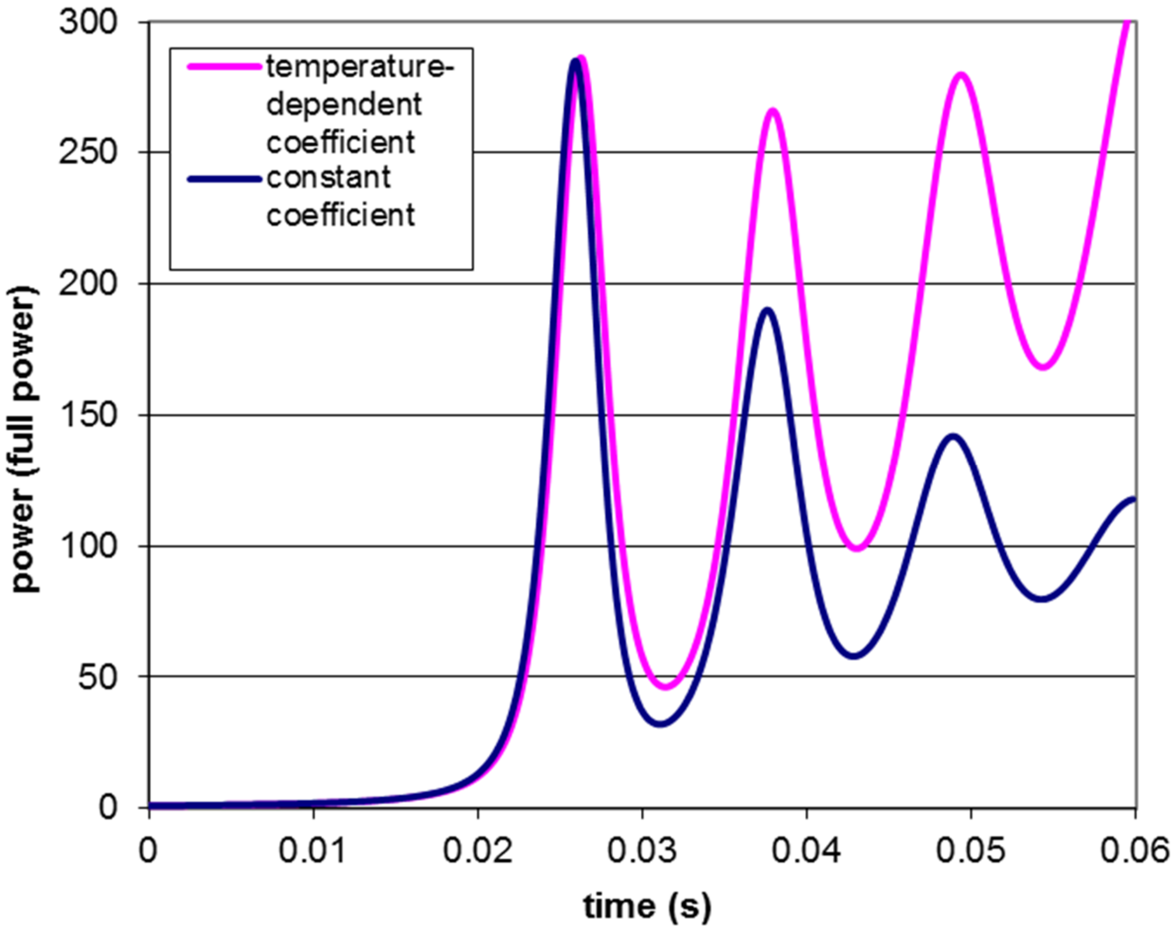


Super-prompt Critical Transient Induced by Reactivity Ramp with Constant Feedback Coefficient



Super-prompt Critical Transient Induced by Reactivity Ramp with Energy Coefficient Proportional to 1/T

Super-prompt Critical Transient by Reactivity Ramp



Comparison of Flux Transients between Constant and Temperature-Dependent Feedback Coefficients