Evaluation of Point Kinetics for NGNP VHTR Core Design

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February 24, 2009

Exact Point Kinetic Equations

- Exact Point Kinetic Equations

$$\frac{dp(t)}{dt} = \frac{\rho(t) - \beta^{eff}(t)}{\Lambda(t)} p(t) + \frac{1}{\Lambda_0} \sum_k \lambda_k(t)\zeta_k(t)$$

$$\frac{d\zeta_k(t)}{dt} = \frac{\Lambda_0}{\Lambda(t)} \beta_k^{eff}(t) p(t) - \lambda_k(t)\zeta_k(t), \quad k = 1, 2 \ldots$$

- Exact Point Kinetic Parameters

$$< \; > \equiv \sum_g \iiint_v dv$$

$$\beta_k^{eff}(t) = \frac{1}{p(t)F(t)} < \phi_g^*(\mathbf{r}) \chi_{dk,g}(\mathbf{r}) \beta_k(\mathbf{r}) S^F(\mathbf{r},t) >,$$

$$\Lambda(t) = \frac{1}{p(t)F(t)} < \phi_g^*(\mathbf{r}) \frac{1}{v_g} \phi_g(\mathbf{r},t) >$$

$$p(t)F(t) =< \phi_g^*(\mathbf{r}) \chi_g(\mathbf{r}) S^F(\mathbf{r},t) >,$$

$$S^F(\mathbf{r},t) = \frac{1}{k_{eff}^s} \sum_{g'} \nu\Sigma_{f,g'}(\mathbf{r},t) \phi_{g'}(\mathbf{r},t),$$

$$\rho(t) = \frac{1}{p(t)F(t)} < \phi^*(r)\left(F - M\right)\phi(r,t) >$$

$$\rho(t) = \frac{< \phi_g^*(\mathbf{r}) \left(-\nabla \bullet J_g(\mathbf{r},t) + \sum_{g'} \Sigma_{g,g'}(\mathbf{r},t) \phi_{g'}(\mathbf{r},t) - \Sigma_{tg}(\mathbf{r},t)\phi_g(\mathbf{r},t) + \chi_g(\mathbf{r}) S^F(\mathbf{r},t) \right) >}{p(t)F(t)}$$

Conventional Point Kinetic Equations

- Point Kinetic Equations

$$\frac{dp(t)}{dt}=\frac{\rho(t)-\beta^{eff}}{\Lambda}p(t)+\frac{1}{\Lambda}\sum_k \lambda_k\zeta_k(t)$$

$$\frac{d\zeta_k(t)}{dt}=\beta_k^{eff}p(t)-\lambda_k\zeta_k(t),\quad k=1,2...$$

* The betas, lambdas, and generation time are not time dependent

- Reactivity Feed Back Coefficient

$$\frac{\partial\rho}{\partial\alpha_i}\approx\frac{<\phi^*(r)\left(F(\alpha_1,\alpha_2,...\alpha_i+\Delta\alpha_i,...)-M(\alpha_1,\alpha_2,...\alpha_i+\Delta\alpha_i,...)\right)\phi(r,0)>}{\Delta\alpha_i p_0 F_0}$$

* Reactivity coefficients are normally evaluated with initial steady state flux and changing each parameter near its steady state value. It is hard to get feed back coefficients to represent the nonlinear dependency of reactivity on wide range of parameter changing, and the cross term effects between the coefficients.

PARCS Point Kinetics Options

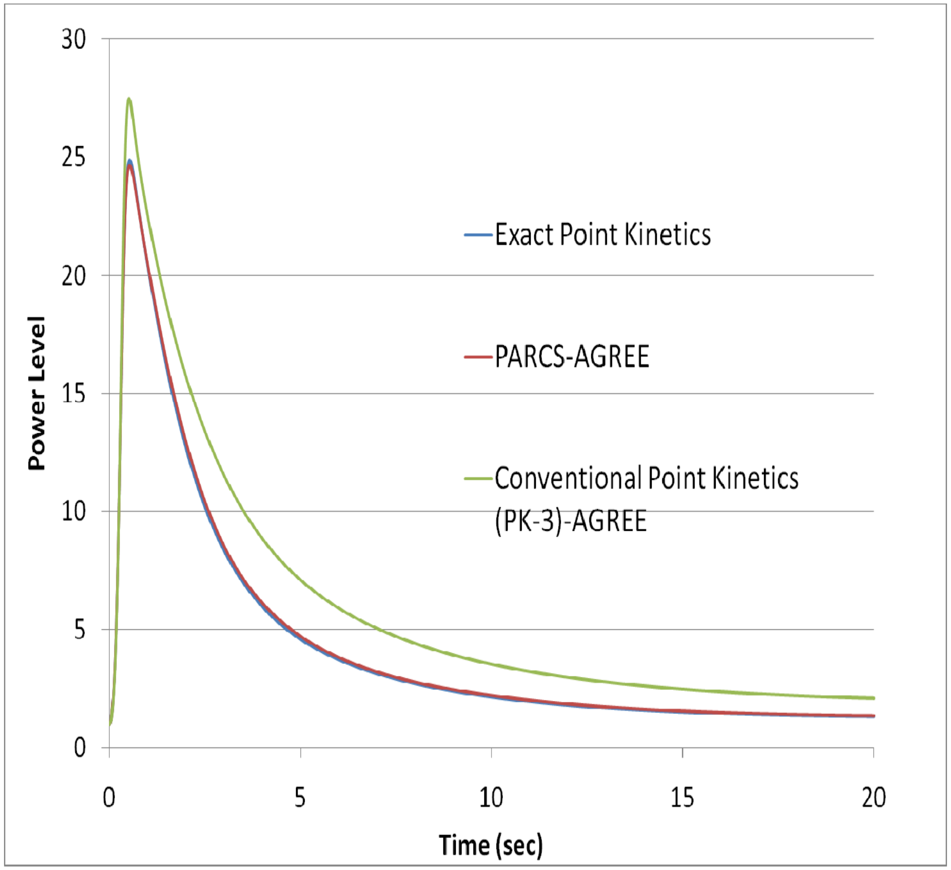
Kinetics Option	Description
0	3-D Spatial Kinetics
1	Point Kinetics with Adjoint weighted cross section change as reactivity excluding the control rod reactivity component
2	Point Kinetics with Adjoint weighted cross section change as reactivity
3	CONVENTIONAL Point Kinetics with Power weighted core average parameter feedback
4	Point Kinetics with Adjoint Fission weighted core average parameter feedback
5	Point Kinetics without feedback (user input reactivity)
6	No Kinetics (user input power levels)

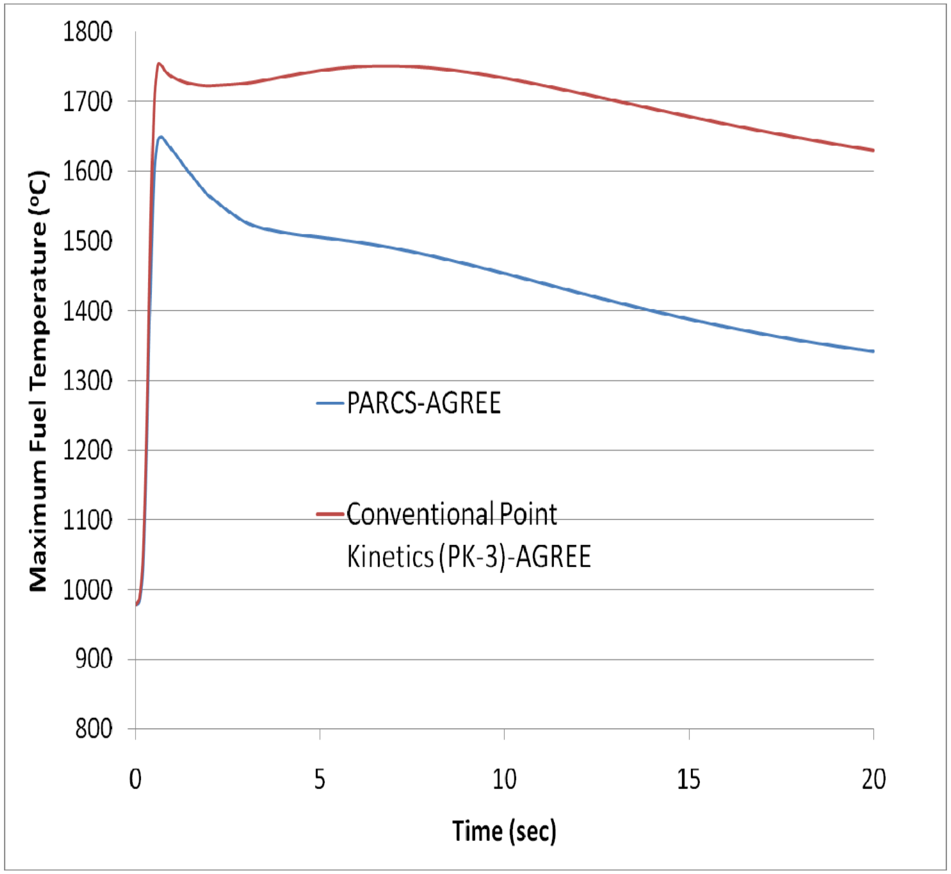
OECD PBMR-400 Benchmark

- STEADY STATE BENCHMARK CALCULATIONAL CASES
  - **CASE S-1**: Neutronics Solution with Fixed Cross Sections
  - **CASE S-2**: Thermal Hydraulic solution with given power / heat sources
  - **CASE S-3**: Combined neutronics thermal hydraulics calculation – starting condition for the transients

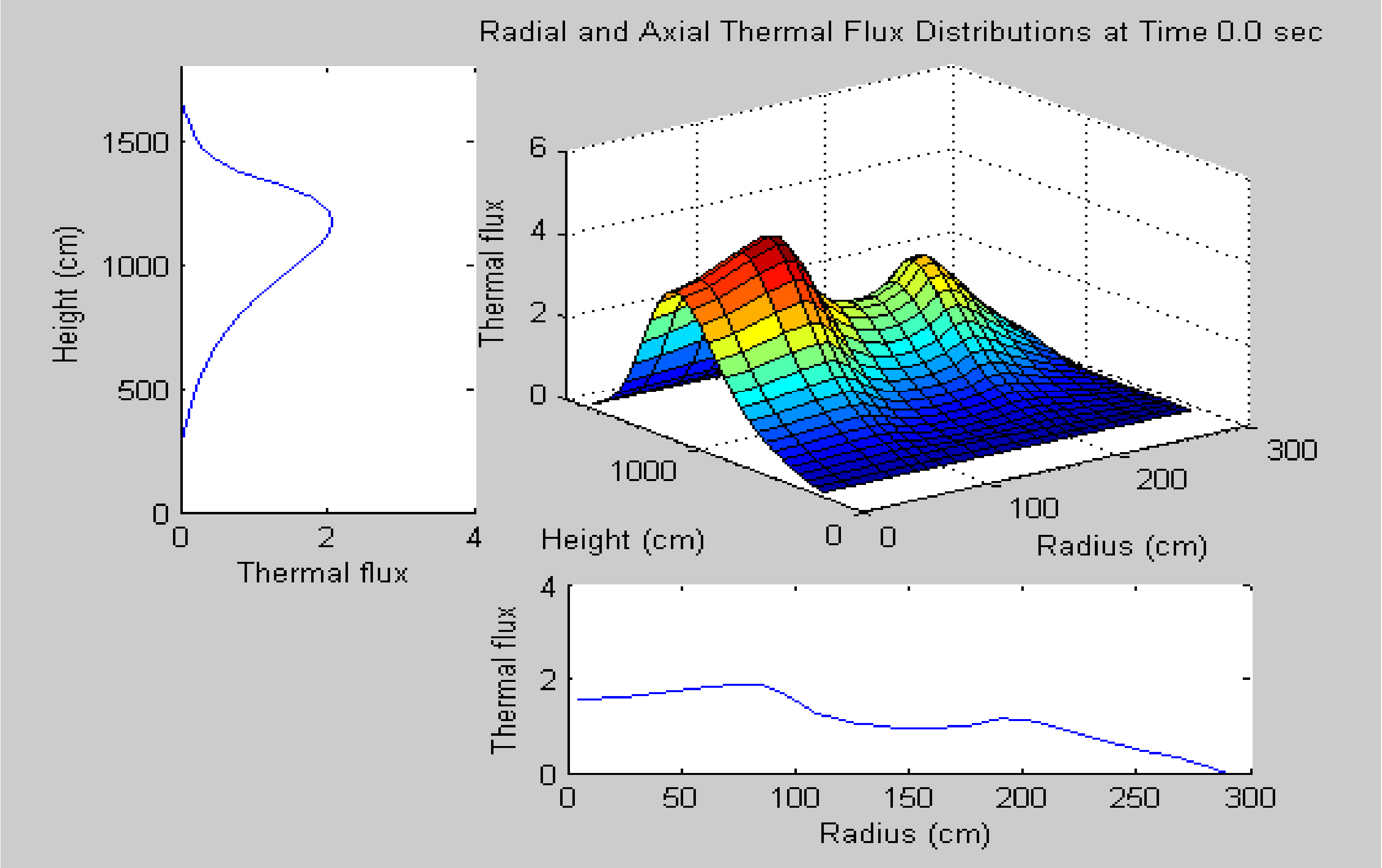
- TRANSIENT BENCHMARK CALCULATIONAL CASES
  - **CASE T-1**: Depressurised Loss of Forced Cooling (DLOFC) w/o SCRAM
  - **CASE T-2** : DLOFC with SCRAM
  - **CASE T-3** :Pressurised Loss of Forced Cooling (PLOFC) with SCRAM
  - **CASE T-4** : 100-40-100 Load Follow
  - **CASE T-5** : **Reactivity Insertions by CRE** ←
  - **CASE T-6** : Cold Helium Inlet

PBMR-400 CRE Transient

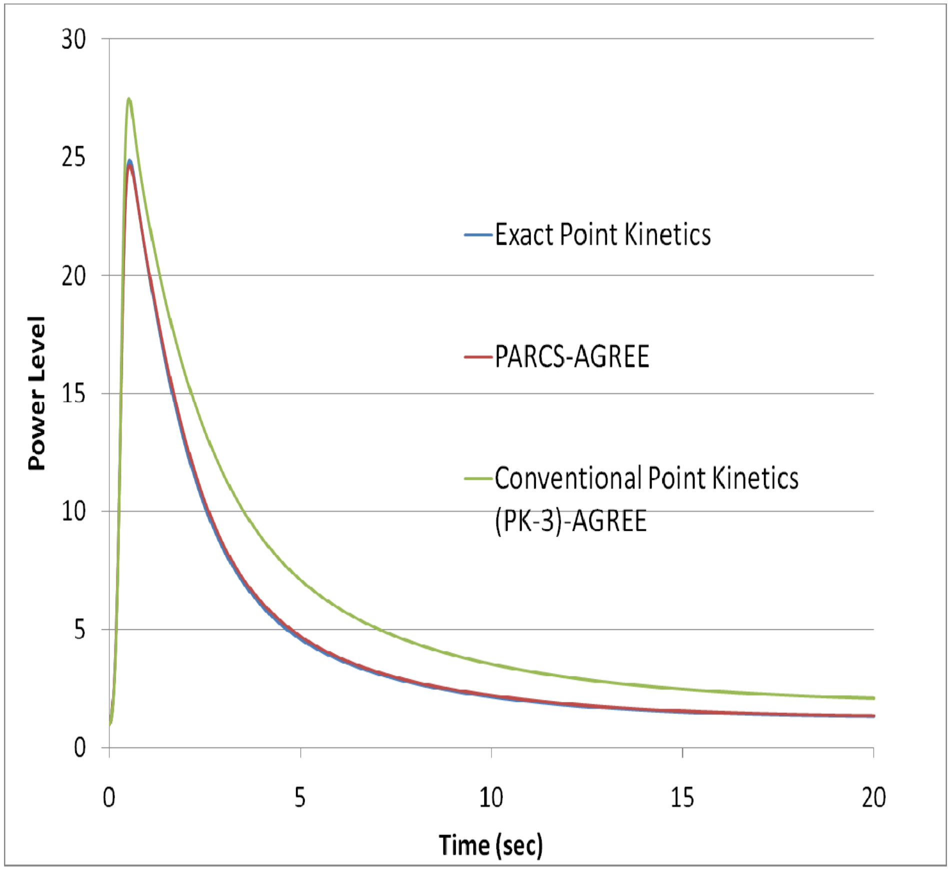


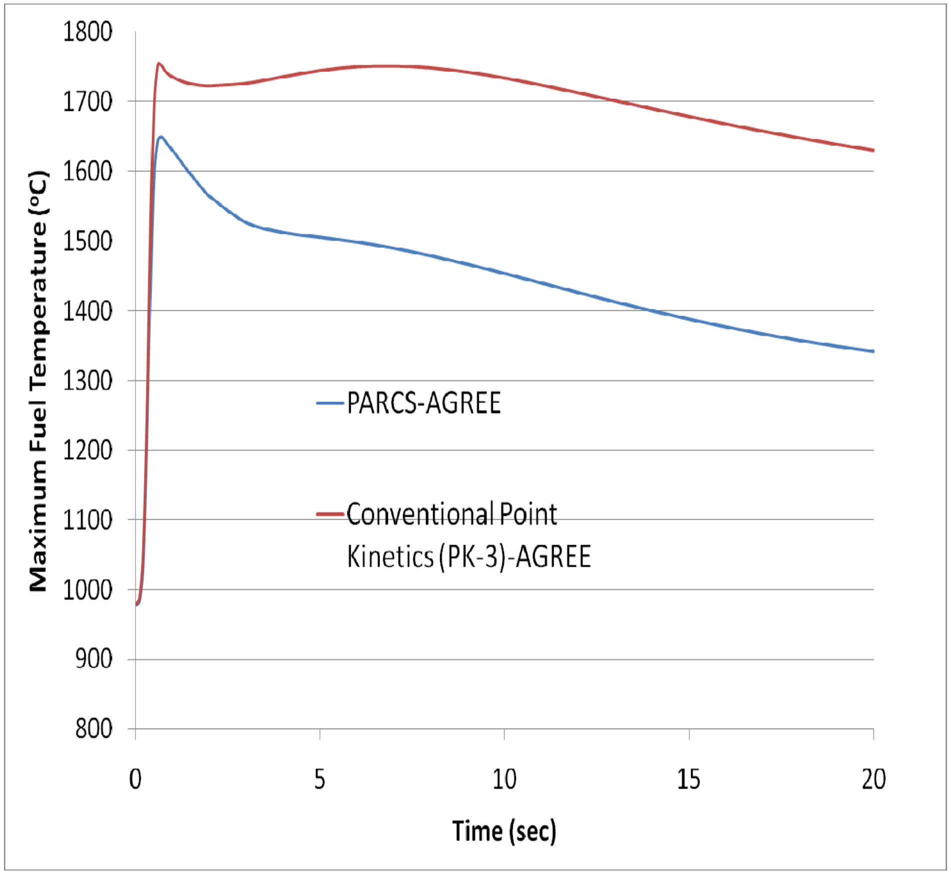


CRE Power Distribution vrs Time



PBMR-400 CRE Transient





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  - **CASE T-2** : DLOFC with SCRAM
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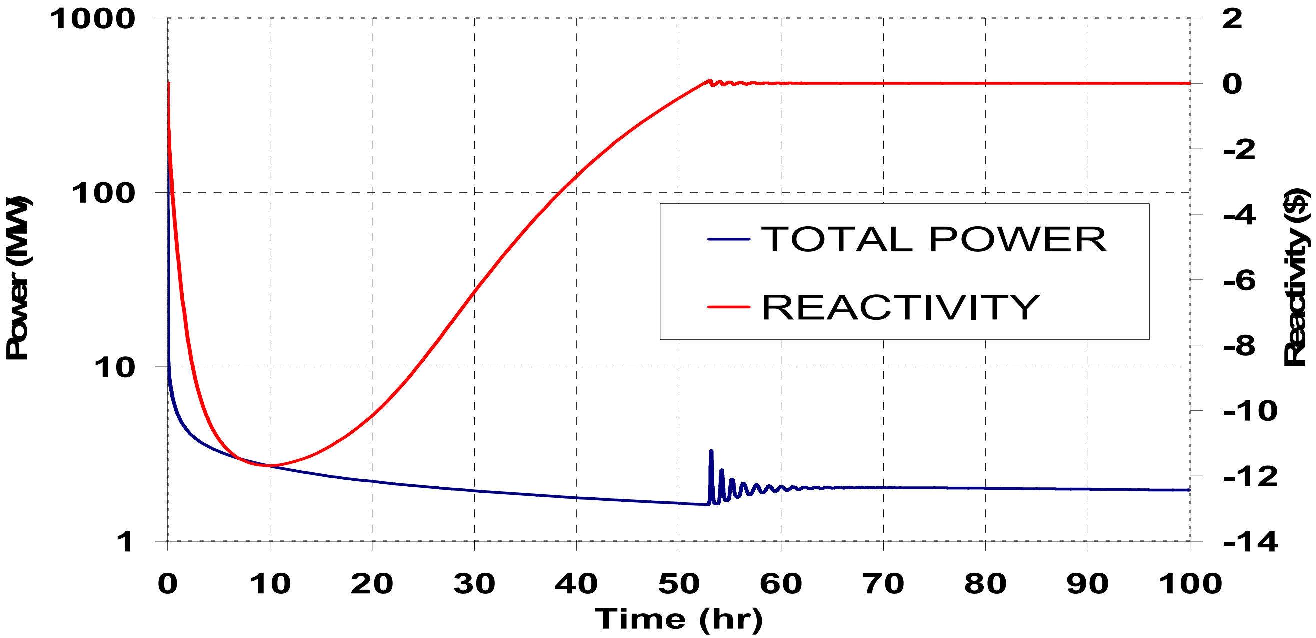
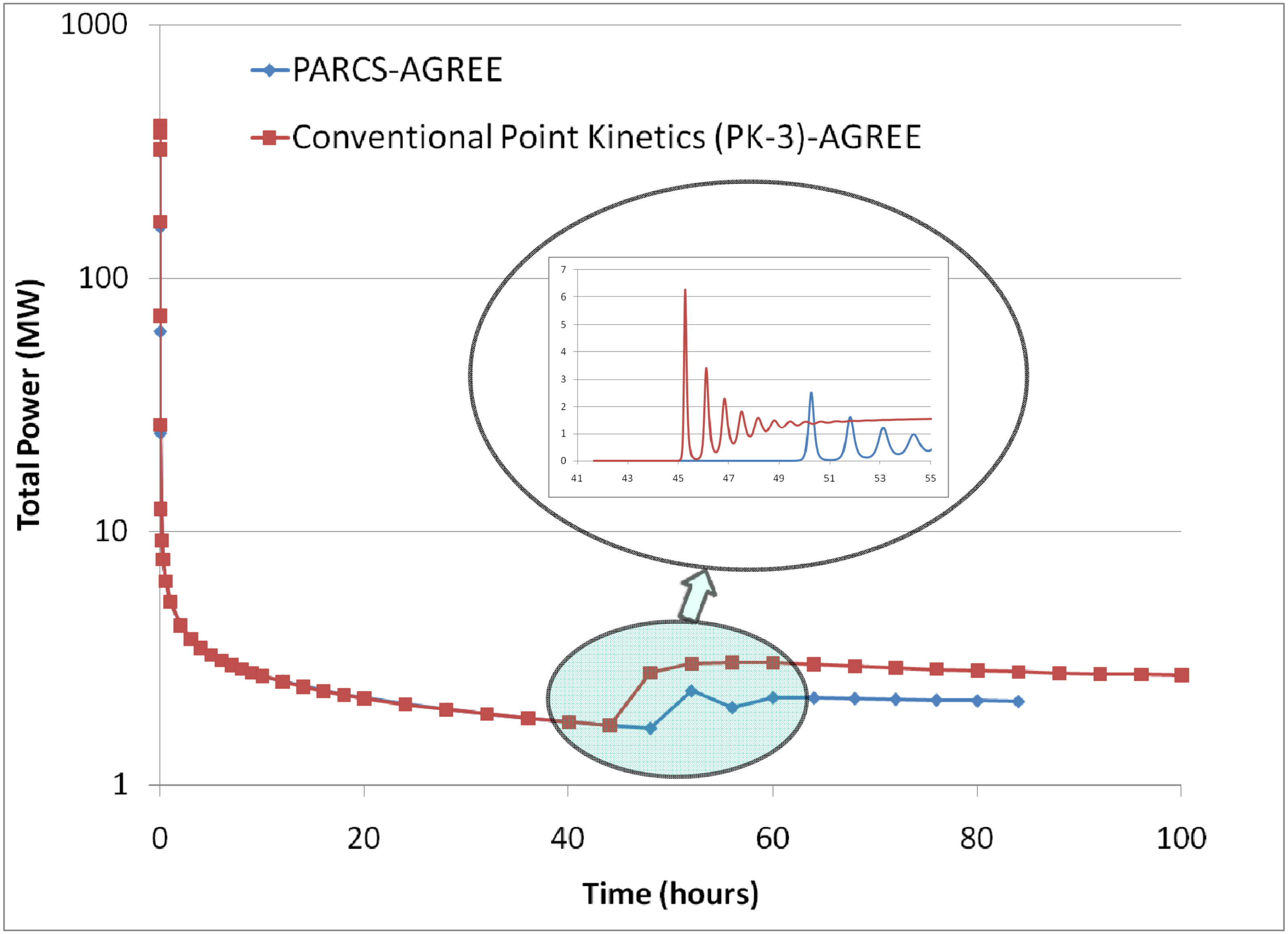
Case-T1 DLOFC w/o SCRAM
PARCS-AGREE Spatial Kinetics Solution

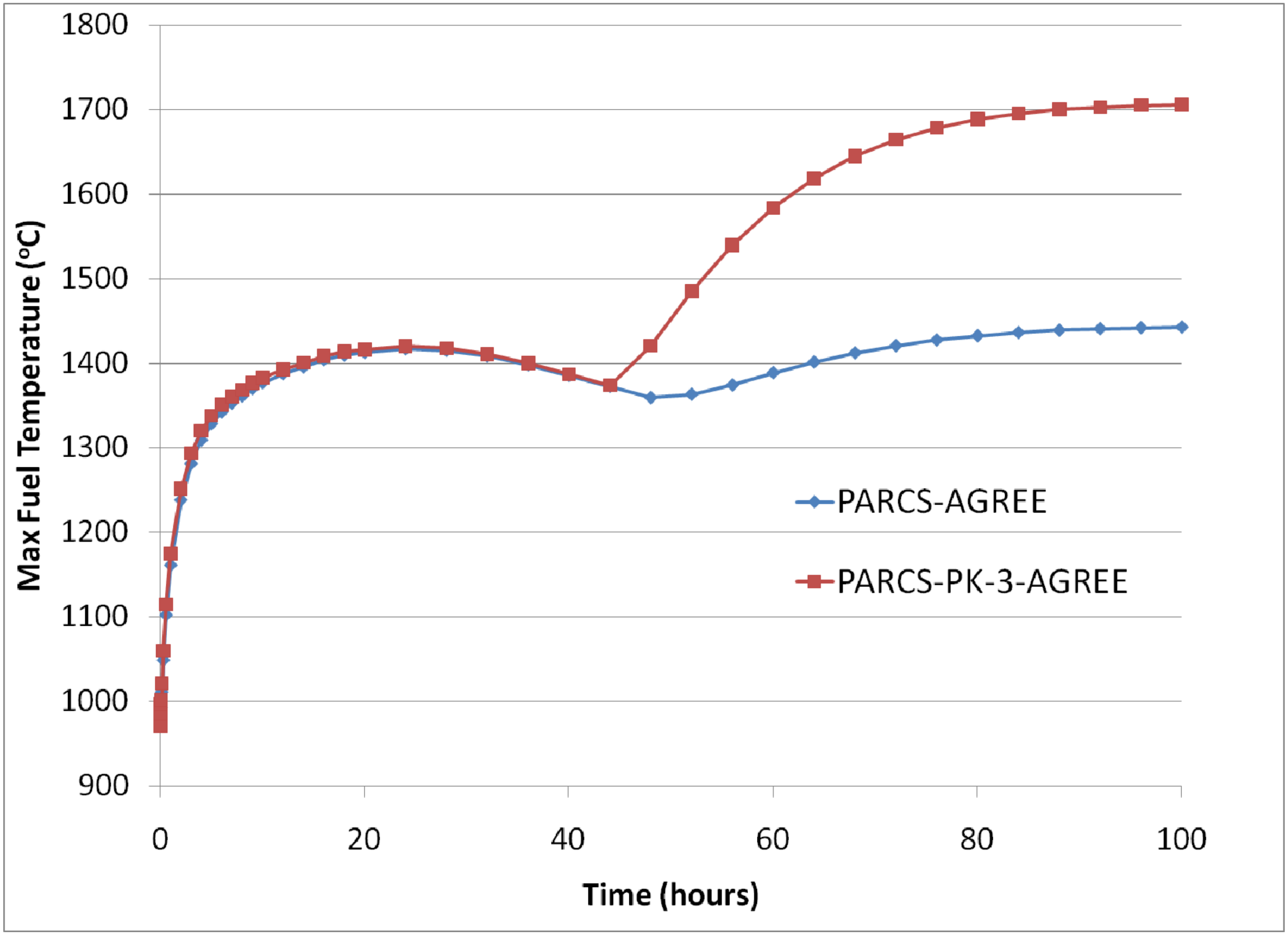
- Sequence of Events
  - 0 – 13 sec : Reduction in mass flow rate from 192.7 to 0.2 kg/s.
  - 0 – 13 sec : Reduction in helium outlet pressure from 90 to 1 bar.
  - No change in the input parameters
  - 13-360000 sec: Transient completed



DLOFC w/o SCRAM
Point Kinetics Solution



DLOFC - Maximum Fuel Temperature



Reactivity Coefficients for P.K.

- Conventional PK substantially mispredicts the time to recriticality and overpredicts the fuel temperature.
- This is not caused by reactivity coefficient which was found to relatively invariant with perturbation size.

$$\frac{\partial\rho}{\partial\alpha_i} \approx \frac{<\phi^*(r)\left(F(\alpha_1,\alpha_2,...\alpha_i+\Delta\alpha_i,...)-M(\alpha_1,\alpha_2,...\alpha_i+\Delta\alpha_i,...)\right)\phi(r,0)>}{\Delta\alpha_i p_0 F_0}$$

ΔT	DOPPLER	MODERATOR	XENON	ΔN_{Xe}
1	-5.285107E-03	-4.883649E-03	-6.336690E-14	0.000001
5	-5.280195E-03	-4.882987E-03	-6.336690E-14	0.00001
10	-5.273965E-03	-4.888493E-03	-6.336685E-14	0.0001
20	-5.261735E-03	-5.026924E-03	-6.336637E-14	0.001
50	-5.225919E-03	-5.525254E-03	-6.336162E-14	0.01
100	-5.168395E-03	-6.268374E-03	-6.331413E-14	0.1

Modified Conventional Point Kinetics (PK-2)

- Rather, the reason for the significant misprediction is a “cross term” effect in which the xenon worth strongly depends on the graphite temperature.

- This effect can be accurately treated by explicitly evaluating the graphite and xenon cross sections during the transient and evaluating the time dependent reactivity (and not using a reactivity coefficient precomputed at the initial time)

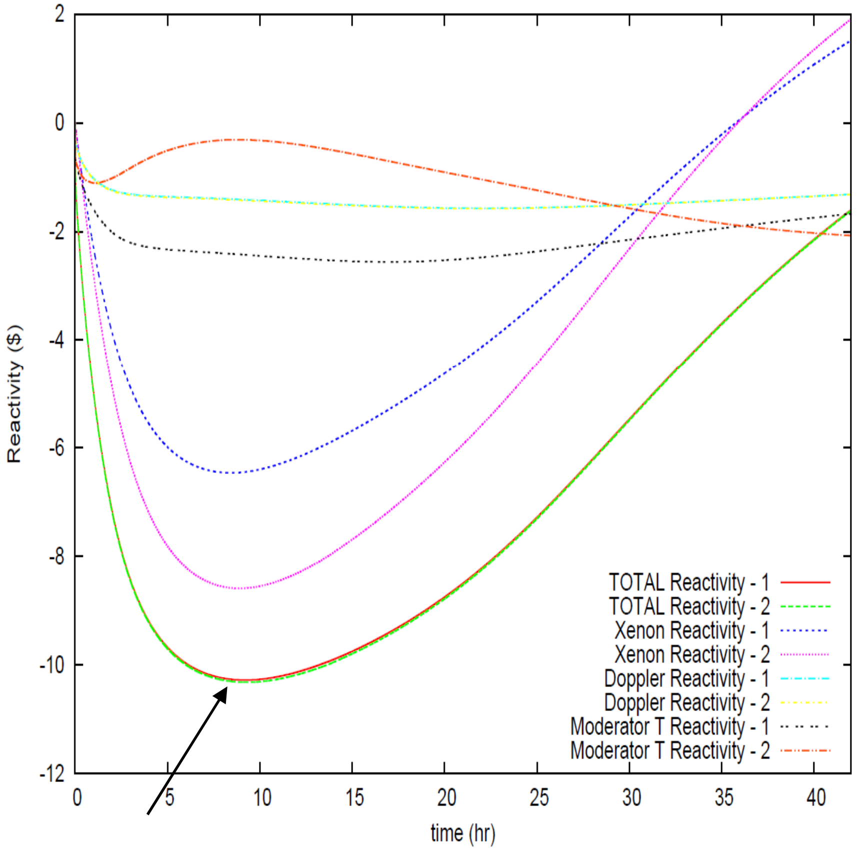
- Reactivity

$$\rho(t) = \frac{< \phi_g^*(\mathbf{r}) \left(-\nabla \bullet J_g(\mathbf{r},0) + \sum_{g'} \Sigma_{g,g'}\left(\mathbf{r},t\right) \phi_{g'}(\mathbf{r},0) - \Sigma_{tg}(\mathbf{r},t)\phi_g(\mathbf{r},0) + \chi_g\left(\mathbf{r}\right) S^F(\mathbf{r},0) \right) >}{p_0 F_0}$$

Evaluation of Reactivity for DLOFC PARCS PK-2

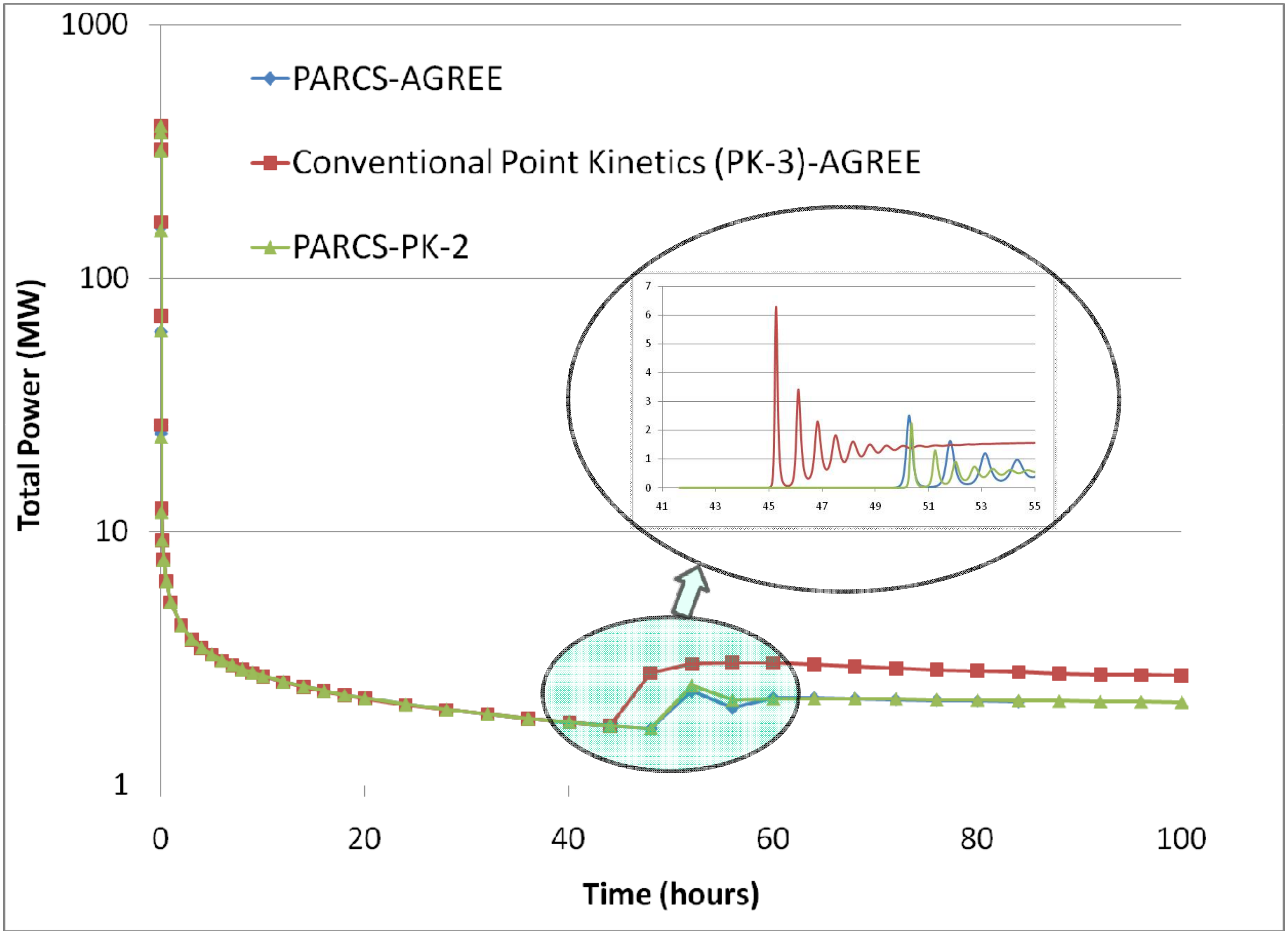
- The misprediction of reactivity can be demonstrated by evaluating the reactivity two ways:
  - Method 1: Reactivity calculation order is Xenon → Doppler → Moderator
  - Method 2: If we change this order to Doppler → Moderator → Xenon

- The essential point is that even though there are not large spatial flux variations during the transient, the HTR has some subtle physics effects that can not be easily described with conventional point kinetics

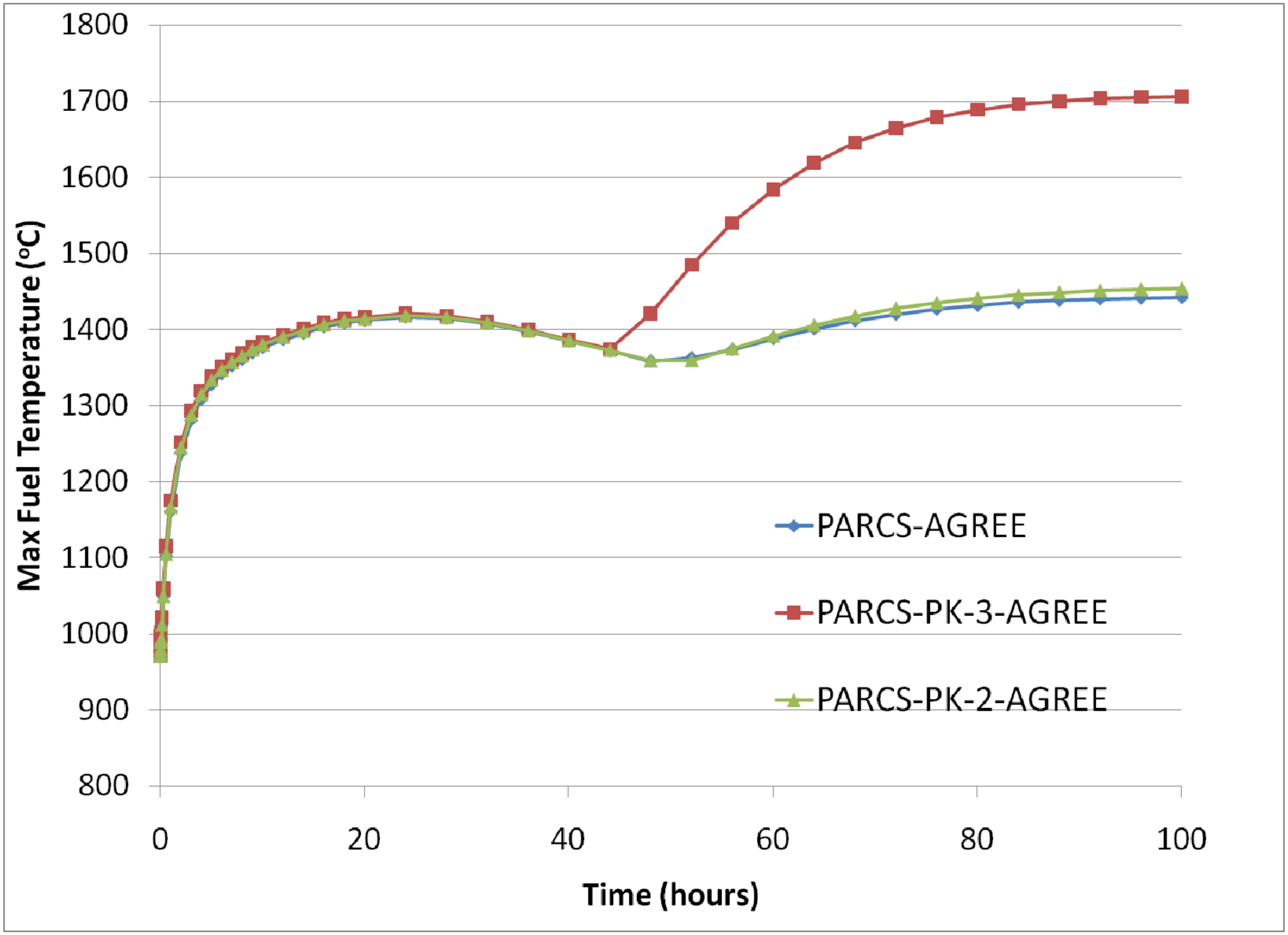


Exact Reactivity

DLOFC w/o SCRAM



DLOFC Maximum Fuel Temperature



Summary / Conclusions

- Several Point Kinetics Options have been implemented in PARCS
- Exact Point Kinetics reproduces exactly the spatial kinetics solution.
- As expected, for the Control Rod Ejection case with a significant flux variation, point kinetics is inadequate.
- Somewhat unexpected is that for the DLOFC, conventional point kinetics also substantially mispredicts the core power/temperature even though there is not a significant flux change during the transient
- Point Kinetics can only accurately predict the core power/temperature during a DLOFC if the evaluation of the reactivity explicitly treats the “cross term” dependence of the xenon worth on the graphite temperature rise during the transient.