METHODOLOGY TO ENHANCE NEGATIVE REACTIVITY

T. Sathiyasheela, G. S. Srinivasan,

K. Devan, S.C.Chetal

Indira Gandhi Centre for Atomic Research

INDIA

- Negative reactivity feedbacks are essential for inherent safety of reactors along with engineered safety.
- There has been continuous attempt to enhance negative reactivity feedbacks in the reactor core to ensure enhanced safety.
- Higher magnitude of negative reactivity does not necessarily ensure safe shutdown in all accidents.
- Effort was made to find out the methodologies to enhance the negative reactivity which will be effective in Unprotected Loss of Flow (ULOF) and Unprotected Transient over Power (UTOP) transients.

Contents

- Overview of Liquid Metal Fast Breeder Reactor (LMFBR) Accidents.
- Components of Reactivity Feedbacks.
- Analogy of Reactivity Feedbacks.
- Methodology to Enhance Negative Reactivity in LMFBR.
- Discussions

Overview of (LMFBR) Accidents.

- Design Basis Events.
- Unprotected Transients-
  - *	Unprotected Transient Over Power Accidents.
  - *	Unprotected Loss of Flow Accidents.
- How Unprotected Accidents are mitigated.

Components of Reactivity Feedbacks

- Fuel Doppler Feedback .
- Coolant Density.
- Fuel Axial Expansion.
- Core Radial Expansion.
- Control Rod Drive Line Expansion.
- Vessel Expansion.
- Fuel Extrusion.

Fuel Doppler

- Fuel Doppler Feedback.
    - Increase in fuel temperature – Increase in Neutron absorption – Negative Reactivity.
    - Decrease in fuel temperature – Decrease in Neutron absorption – Positive Reactivity.
- Doppler co-efficient –Spectrum Dependent.
- Doppler feedback – Thermal Conductivity.

Coolant Density

- Increment in coolant temperature reduces coolant density.
- Reduction in coolant density harden the neutron spectrum.
- Reactivity effect-
  - Core Centre - Positive due to Spectral Hardening.
  - Core Boundaries - Negative due to Leakage.
- Large commercial reactor – Positive Feedback.
- Height to Diameter- Negative Feedback.

Fuel Axial Expansion

- Fuel Axial Expansion,
  - Increment in fuel temperature.
  - Free Fuel axial Expansion - gap open.
  - Bound Fuel axial Expansion fuel - gap closed.

- Reactivity Effect
  - Negative- Axial Expansion.
  - Positive - Fuel Contraction.

Core Radial Expansion

- Increment in inlet coolant temperature-

  - Grid Plate Expansion.
- Increment in coolant temperature

  - Flowering of Sub-assemblies.
- Reactivity Effect- Negative

  - ❖ Neutron Leakage.
  - ❖ Core Boundary movement.

Control Rod Drive Line Expansion

- Increment in coolant outlet temperature.
- Relative motion between core and control rod drive line.
- Apparent Insertion of Control Rods.
- Reactivity Effect - Negative.

Fuel Extrusion

- Experimental results available in the literature.
- Transients progress beyond fuel melt may drive the fuel in the upward direction with the contribution of fission gas pressure.
- If only, there is path available to the fission gas plenum.
- Displacement of the fuel from the higher core mid plane introduce negative reactivity.

ULOF Transient Sequence

- Flow decreases.
- Coolant temperature increases.
- Coolant Expansion feedback +ve
- Radial Expansion Feedback –ve.
- Net Reactivity –ve.
- Power decreases.
- Fuel temperature decreases (oxide)/
  increases (metal)
- Doppler feedback Positive (oxide)/
  Negative or zero (metal)

ULOF – Transient Sequence

- Reduction in reactor flow f
- Increase in p/f ratio
- p/f increase, core temperature increases inducing negative reactivity
- Positive reactivity of power reduction balanced by the negative reactivity of core heat up by ratio p/f

Reactivity Balance

$$\delta\rho = (p-1)A + (p/f-1)B + C\delta T_i + \Delta\rho_{ext} = 0$$

$$p/f = 1 + \frac{A}{B} \quad , \qquad \delta T_{out} = \left(A/B\right)\Delta T_c$$

Inherent safety is promoted, when

A - Small

B - Large

$A/B \leq 1$

UTOP- Transient Sequence

- Single rod withdrawal positive reactivity $\Delta\rho_{TOP}$
- No change in coolant flow
- No change in inlet coolant temp
- External positive reactivity is compensated by power increase negative reactivity
- p / f ratio increases
- p / f ratio increase causes T_{out} increase

UTOP-Reactivity Balance

$$\delta\rho = (p-1)A + (p/f-1)B + C\delta T_i + \Delta\rho_{ext} = 0$$

$$f = 1$$

$$P = 1 - \frac{\Delta\rho_{TOP}}{(A + B)}$$

$$\delta T_{out} = \left(\delta\left(p/f \right)\right)\Delta T_c$$

$$\delta T_{out} = -\frac{\Delta\rho_{TOP}}{(A+B)}\Delta T_c$$

Inherent Safety

- ULOF A - Small, $A/B \leq 1$
  B - Large

- UTOP A+B - Large $\frac{\Delta\rho_{TOP}}{|A+B|} \leq 1$

Inherent Safety Parameters

$$A=\left\{\left[\frac{\delta\rho_D}{\delta T}+\Delta k_f^{j,i}\alpha_f+\Delta z\alpha_f C^i\right]\left(\frac{1}{h_{sc}}+\frac{1}{h_{fs}}\right)+\Delta k_s^{j,i}\alpha_s\frac{1}{h_{sc}}\right\}q^{j,i}$$

$$B=\left[\frac{\delta\rho_D}{\delta T}+\Delta k_f^{j,i}\alpha_f+\Delta z\alpha_f C^i+\Delta k_s^{j,i}\alpha_s+3\Delta\Delta_c^{j,i}\alpha_{Na}\right]\sum_{k=1}^{j}\frac{\Delta z}{C_c\rho A_f}\frac{q^{k,i}}{v(i)}$$

$$+\left[\begin{array}{l}2\alpha_s\Delta k_f^{j,i}W^j+2\alpha_s\Delta k_s^{j,i}W^j+2R_1(R^{i+1}-R^i)\alpha_s W^j\dfrac{E_j}{2R_1+1}\\ +2R_c(R^{i+1}-R^i)\alpha_s W^j\dfrac{D_j}{2R_c+1}\end{array}\right]\sum_{k=1}^{jsp}\frac{\Delta z}{C_c\rho A_f}\frac{q^{k,i}}{v(i)}$$

Co-efficient A

- Doppler Worth.
- Fuel & clad removal worth.
- Axial boundary movement worth.
- Linear Power.
- Linear expansion co-efficient of fuel and steel
- Effective heat transfer.

Co-efficient B

- Doppler Worth.
- Fuel & clad removal worth.
- Linear Power to flow ratio.
- Linear expansion co-efficient of fuel and steel
- Bulk coolant expansion.
- Effective heat transfer.
- Axial boundary movement worth.
- Fuel axial and radial boundary movement worth.

Enhance Inherent Safety

- Doppler Reactivity - ????
- Linear expansion co-efficient of fuel - ????
- Effective heat transfer- Good
  - High fuel thermal conductivity.
  - Better gap conductance.
- Enhancing negative reactivity through axial and radial boundary movement.
  - Fixing the boundary worth difference appropriately.
- Decrease the gap between spacer pads.
  - Enhance the flowering effect.

Perturbation Worth of 500 MWe LMFBR

Component	Worth (in pcm) -Core only	
	Oxide	Metal
Fuel worth	-35776 (100.7 $)	-38228 (98.5 $)
Steel worth	3181 (8.9 $)	4190 (10.8 $)
Coolant worth	620 (1.75 $)	2050 (5.3 $)
Doppler worth	-748 (2.1$)	-470 (1.2 $)

The Isothermal Temperature Reactivity Coefficients of 500 MWe LMFBR

Component	Reactivity Co-efficient (pcm/C)	
	Oxide	**Metal**
Doppler	-0.971	-0.624
Fuel Axial expansion	-0.236	-0.504
Clad axial expansion	0.064	0.084
Coolant expansion	0.177	0.584
Spacer pad expansion	-0.869	-1.039
Total	**-1.835**	**-1.499**

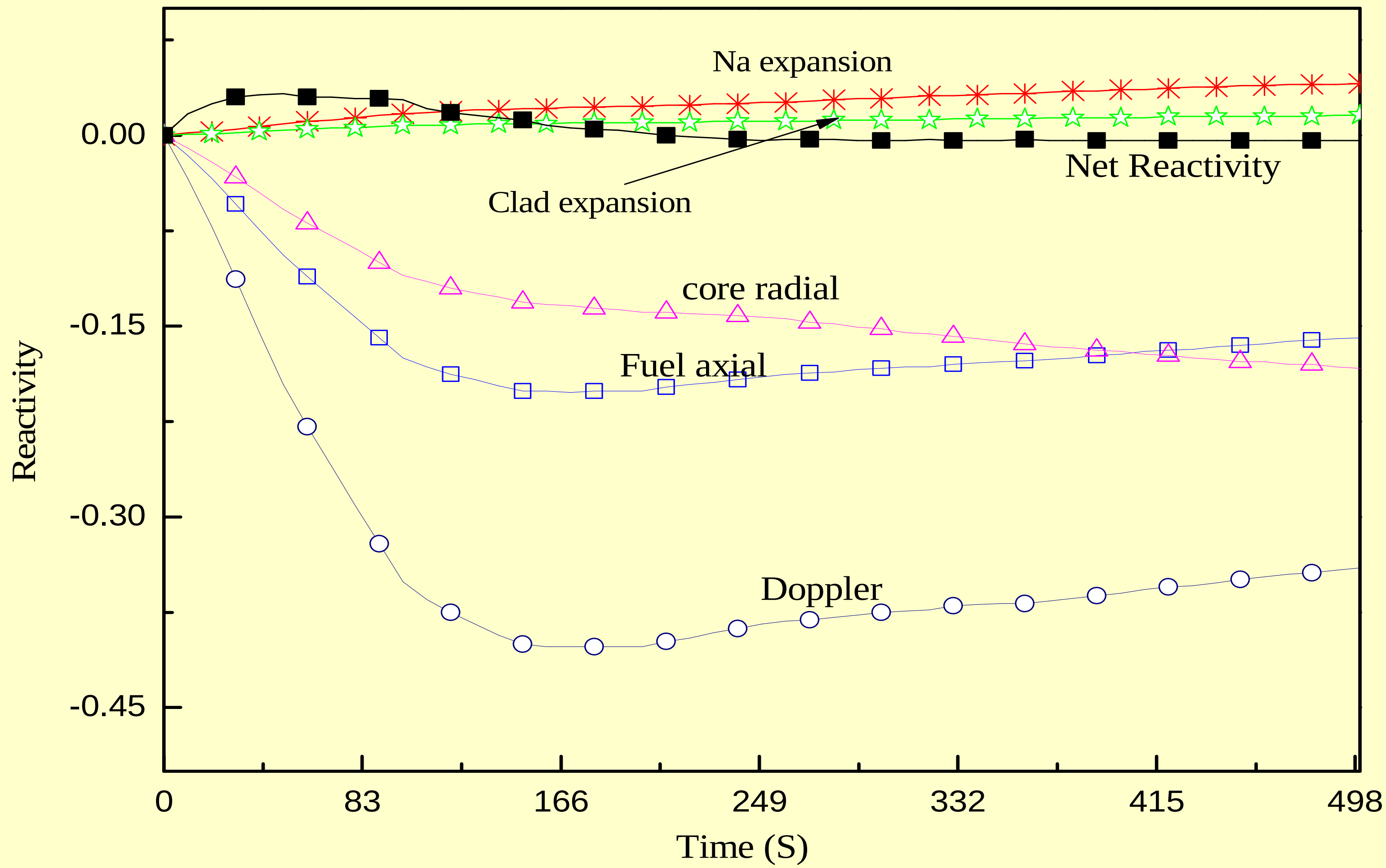
Static Power coefficients of 500 MWe LMFBR (Averaged over Zero to Full Power)

Reactivity Component	**Reactivity coefficient (pcm/MWt)**	
	Oxide	**Metal**
Doppler	-0.479	-0.093
Fuel Axial expansion	-0.161	-0.079
Clad & sheath axial expansion	0.007	0.008
Coolant expansion	0.014	0.042
Spacer pad expansion	-0.092	-0.092
Total	**-0.711**	**-0.214**
Power Reactivity Decrement (pcm)	-848.7	-236.1

Power Reactivity Decrement of 500 MWe LMFBR (Averaged over Zero to Full Power)

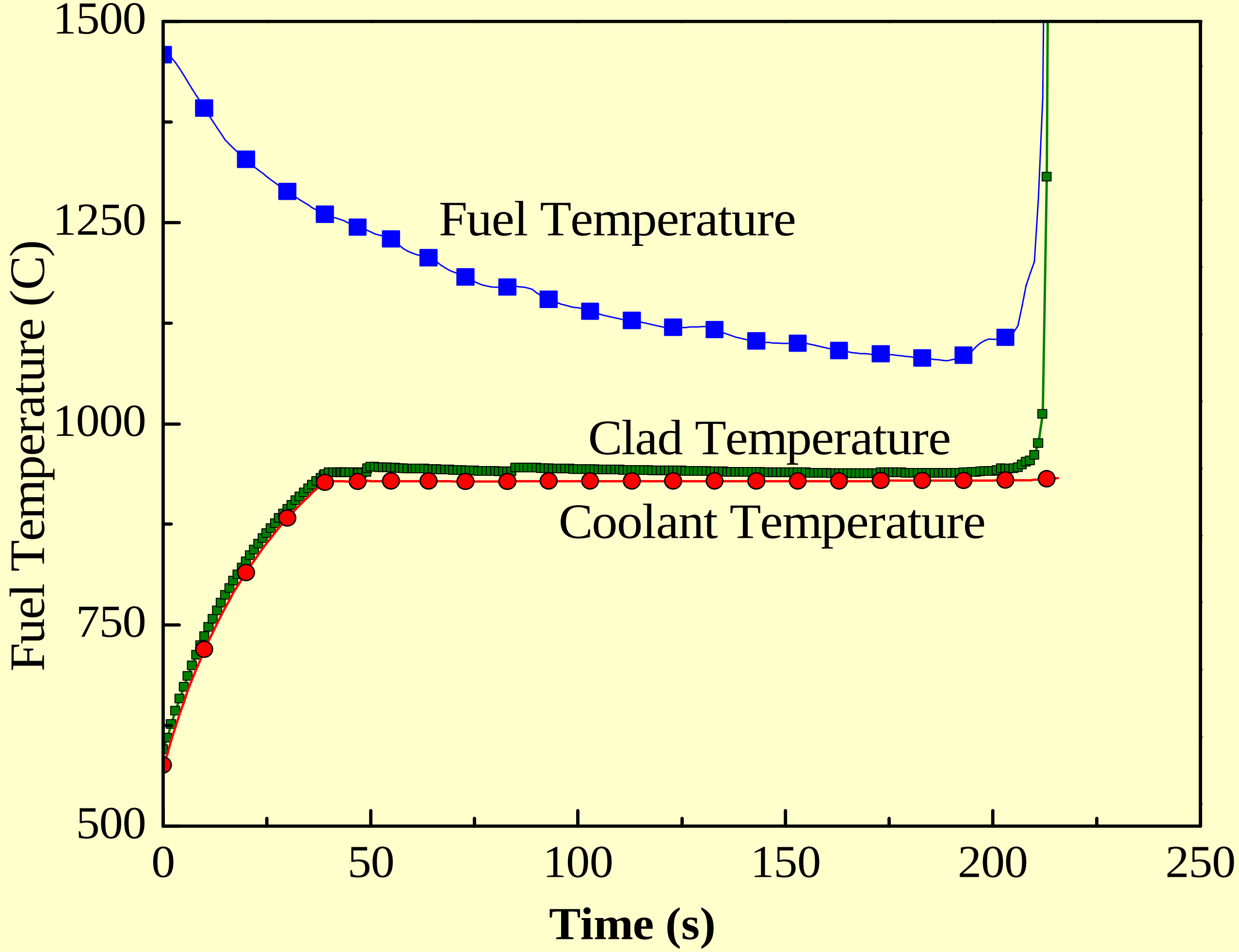
Reactivity Component	Reactivity coefficient (pcm/MWt)	
	Oxide	Metal
Vested from the fuel temperature rise (A)	-694.4	-112.0
Vested from the coolant temperature rise (B)	-154.36	-124.07
Power Reactivity Decrement (A+B)	-848.7	-236.1

UTOPA- Oxide fuel-PFBR

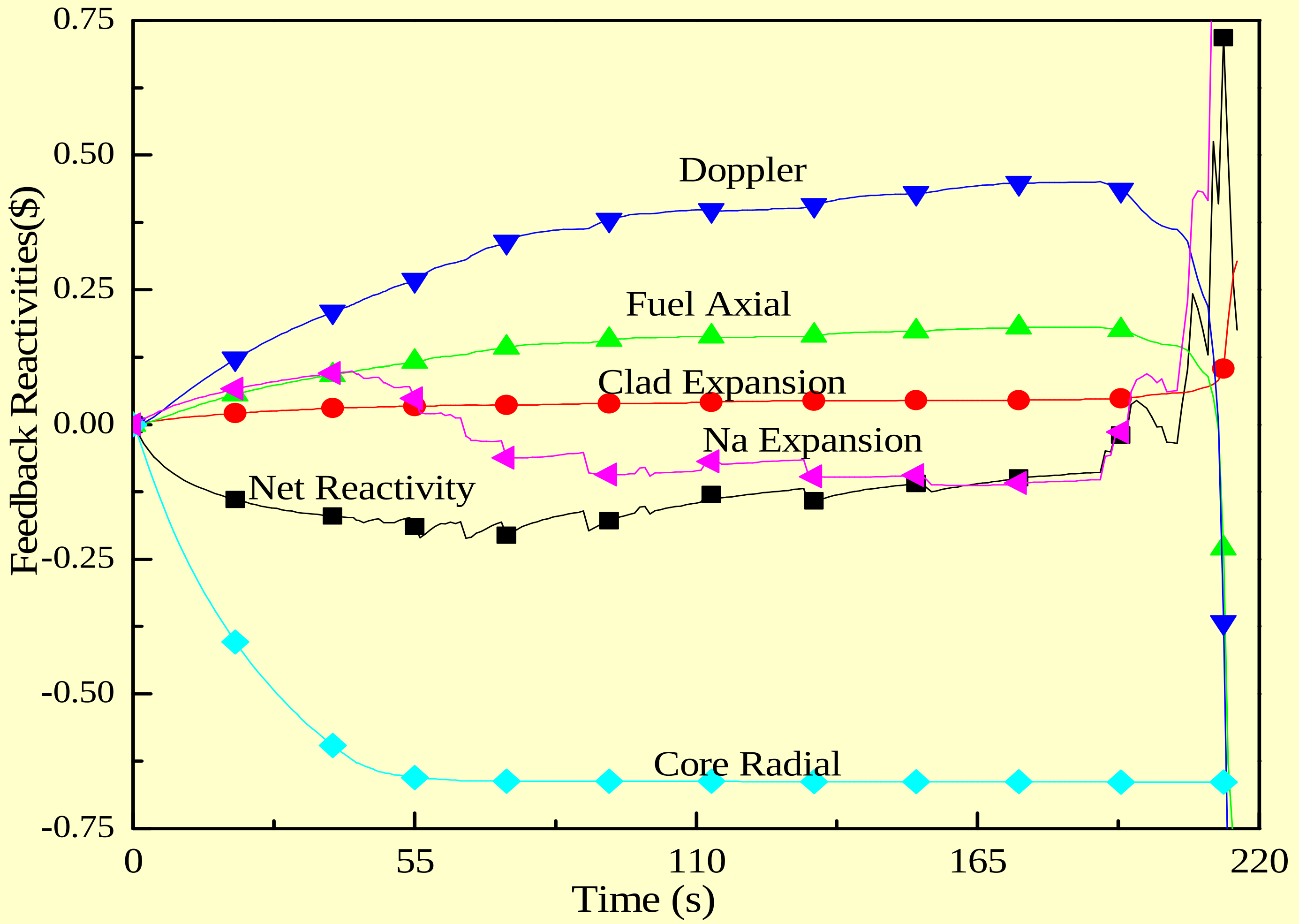


Uncontrolled withdrawal of one CSR (UTOPA)- PFBR

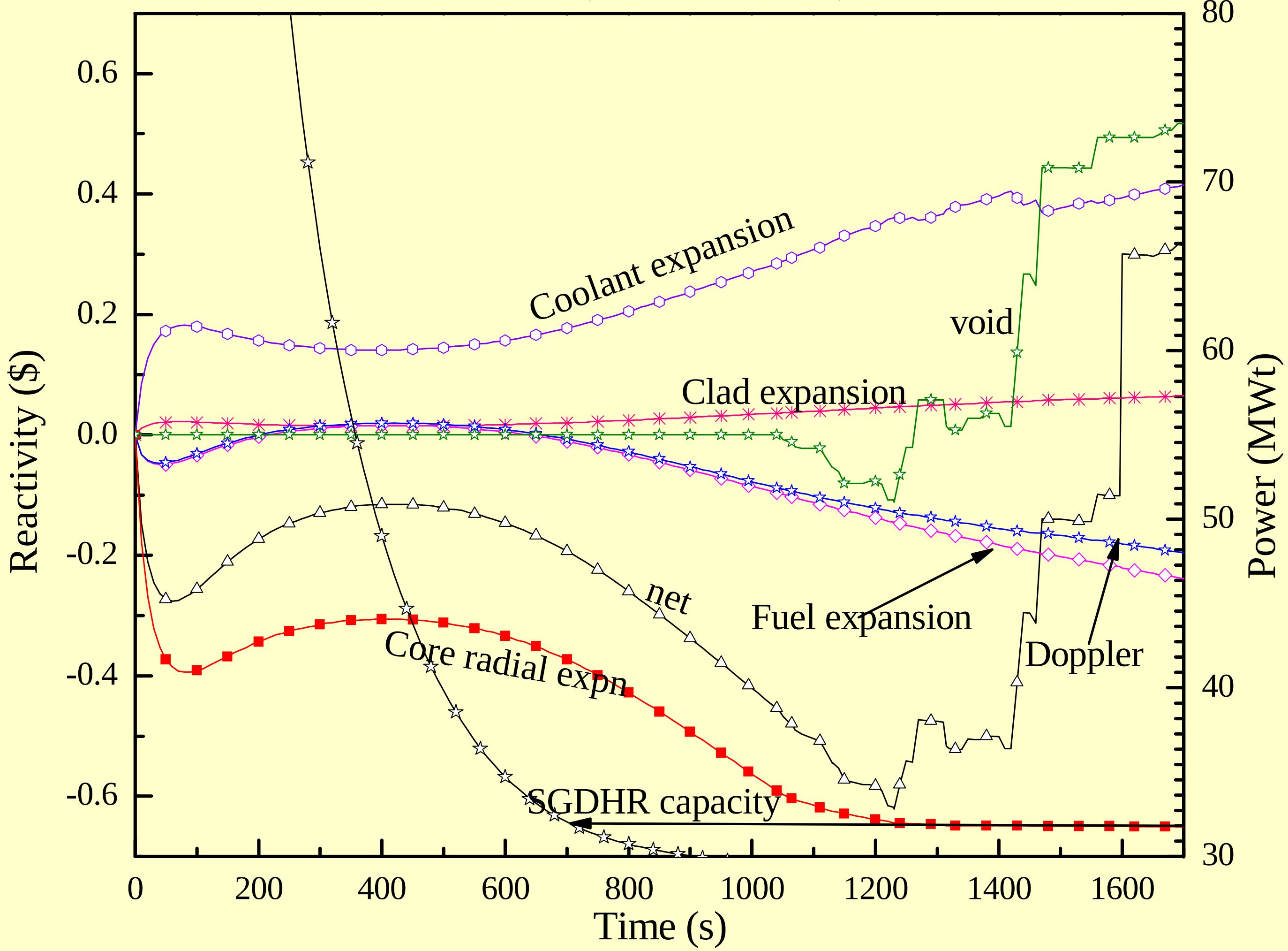
Temperatures of PFBR (ULOF analysis)



ULOFA- Oxide fuel-PFBR



Feedback reactivity of 500 MWe MFBR (ULOF)



Feedback Reactivity – Analogy

- Prompt Doppler is good, provided available during both ULOFA and UTOPA.
  - Increasing conductivity of the fuel.
- Methodology may be explored to increase the Doppler in metal fuel.
  - Addition of moderating material to soften the spectrum.
- Enhance negative reactivity through core radial expansion.
  - Decrease the gap between spacer pads.
  - Enhance the radial boundary movement contribution.

Enhancing negative Doppler

- Addition of moderating material in metal fuel reactors.
- Soften the spectrum and improves the Doppler feedback.
- Addition of diluents in coolant or replacing some fuel pins with pins having moderating properties.
- Replacing some fuel pins with ZrH – Literature

  Tsujimoto, K. et al, Annals of Nuclear Energy, V 28, P 831-855.
- Experiments conducted in FCA of JAERI shows hydrogenous material significantly improves the Doppler and sodium void reactivities.

Increasing Thermal conductivity of fuel

- This argument is more relevant to metallic fuel.
- Lower operating temperature, small rise in temperature during transient
- Reduced excess reactivity. Severity of the UTOP is reduced
- Thermal conductivity is enhanced by suitable alloying material.
- Expansion co-efficient of U-Pu-Al is good.(Ishizu, T.,et al, 2010, Journal of nuclear science and technology, Vol.47, P. 684.).
- Fuel axial expansion feedback expected to give negative reactivity contribution during ULOFA.

Decrease gap between spacer pads

- Delayed feedback, effective for both UTOPA and ULOFA .
- Space between spacer pads are less, gaps would have been closed already during the steady state.
- Coolant temperature and the adverse effect of positive feedback is more during ULOFA.
- Flowering of sub-assemblies provide negative reactivity feedback.

Enhancing negative reactivity through axial and radial boundary movement

- Expansion of inner core into outer core gives a negative boundary movement reactivity feedback.
- Outer core into radial blanket gives a positive boundary movement reactivity feedback.
- Expansion of core in the axial direction to the lower and upper axial blanket gives a positive boundary movement reactivity feedback.
- Reduce the positive reactivity feedback by adjusting the worth at the core–blanket boundaries.

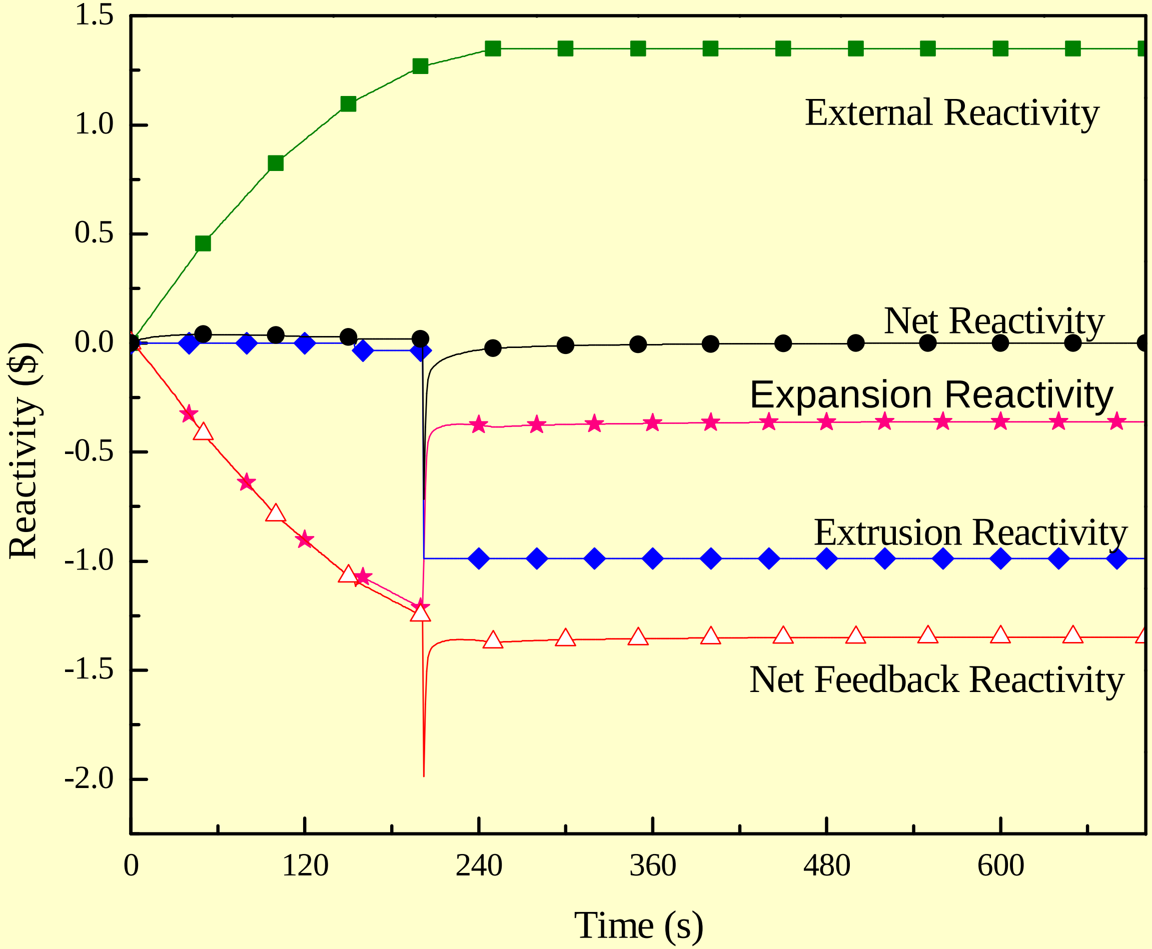
Enhancing negative reactivity through axial and radial boundary movement –contd.

- Reduce the difference in worth at the core–blanket boundaries.
- Enhance the negative reactivity feedback by adjusting the worth between core-1 and core-2 boundaries.
- Increase the difference in worth between core-1 and core-2 boundaries.

Enhancing negative reactivity through axial and radial boundary movement – contd.

- Boundary worth adjusted through enrichment.
- Boundary worth adjusted through enrichment
  - Number of sub-assemblies are increased.
  - Enhanced negative reactivity through flowering .
  - Increased axial leakage.
  - Reduced sodium void worth.

Fuel Extrusion-PFBR



Discussions and Conclusions

- Metal fuel shows superior inherent passive safety features for both ULOFA and UTOPA.
- Negative Doppler may be enhanced by addition of moderating material in metal fuel reactors to protect the reactor against UTOPA.
- Increase thermal conductivity of fuel by suitable alloy.

Discussions and Conclusions

- Better Expansion co-efficient of metal fuel to enhance negative reactivity.
- Decrease gap between spacer pads to enhance the flowering effect.
- Enhancing negative reactivity through axial and radial boundary movement by adjusting the enrichment.

Thank you