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A point dynamic model for stability analysis of the PGSFR

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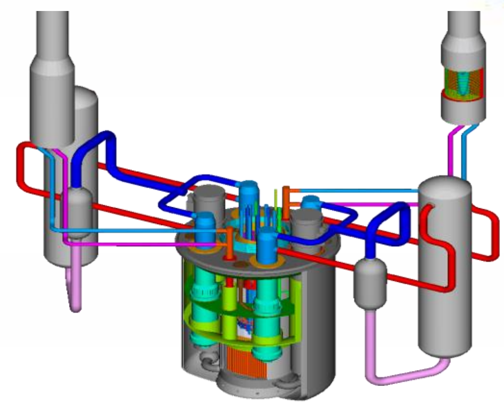


Presentation outline

I. Introduction

II. Model development

- Point-kinetics coupled w/ T-H feedbacks
- Transfer functions & characteristic equation

III. Stability analysis results

- *PGSFR w/ and w/o reactivity feedbacks*
- *Impact of the sodium density coefficient, initial core power, and fuel bowing*

IV. Concluding remarks

Introduction

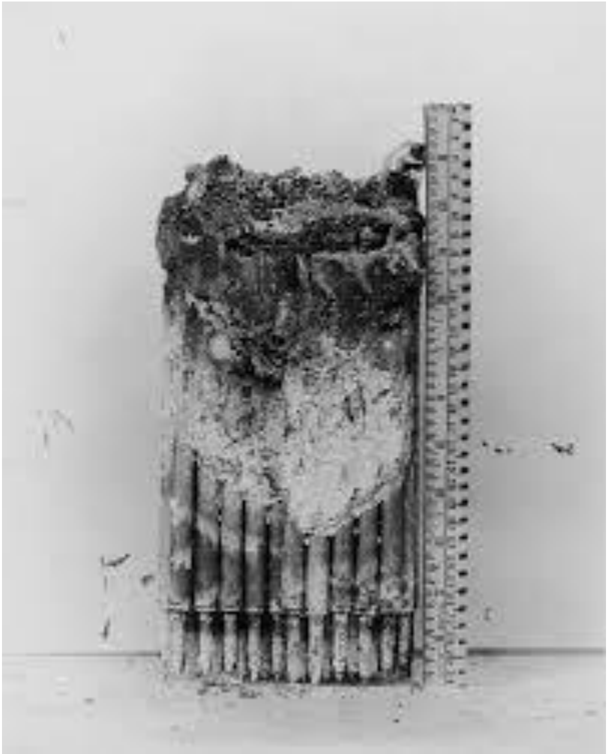
◆ **Instability and safety of fast power reactors:**

- Power oscillations occurring in a reactor during power operation can make it become unstable.

➢ **Standard practice has been to design reactors with only negative reactivity coefficients.**

— Limitation on reactor design which may require additional trade-off studies on the design features.

— Absence of positive reactivity coefficients does not itself ensure stability. In fact, a single negative reactivity coefficient which is delayed because of a coolant transport effect may result in instability at some power.

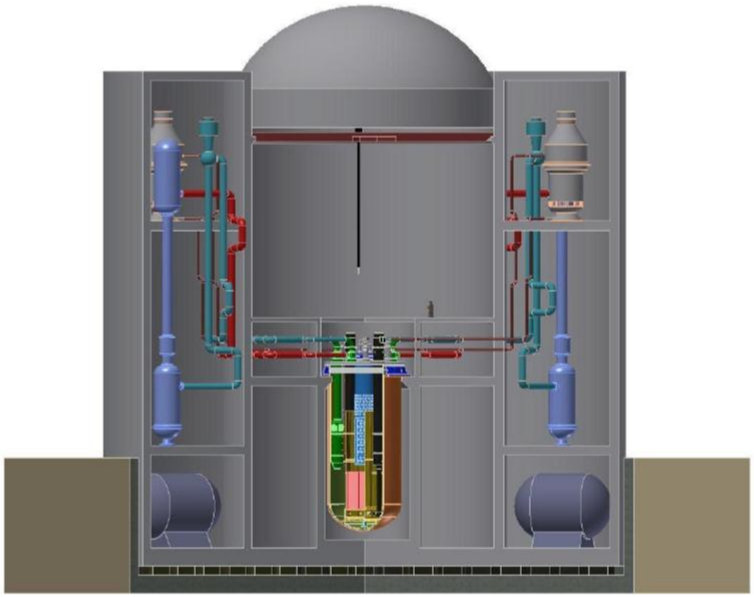


Partial core meltdown accident of EBR-I in 1955

Introduction (cont'd)

Prototype Gen-IV Sodium-cooled Fast Reactor (PGSFR)	
Designer	Korea Atomic Energy Research Institute (KAERI)
Reactor type	Sodium-cooled Fast Reactor (SFR)
Thermal/electric capacity	392 MWth/150 MWe
Coolant	Sodium
Primary circulation	Pool
System pressure	~1 bar
System temperature	390–545 ºC
Metal fuel	U-Zr (initial core) → U-TRU-Zr (reload core)
Fuel cycle	~10 months
Emergency safety systems	Hybrid (passive and active)
Residual heat removal systems	Hybrid (passive and active)
Design life	60 years

PGSFR (KAERI, Korea)



Schematic view of PGSFR

- **PGSFR's mission is to test and demonstrate the performance of the TRU containing metal fuel for commercial SFRs and the TRU transmutation capability of a burner as a part of an advance fuel cycle system.**

Introduction (cont'd)

● Necessity of stability analysis:

- To provide designers the conditions under which the reactor may become unstable.
  - ➢ *ensure the stability and safety of the reactor during power operation.*

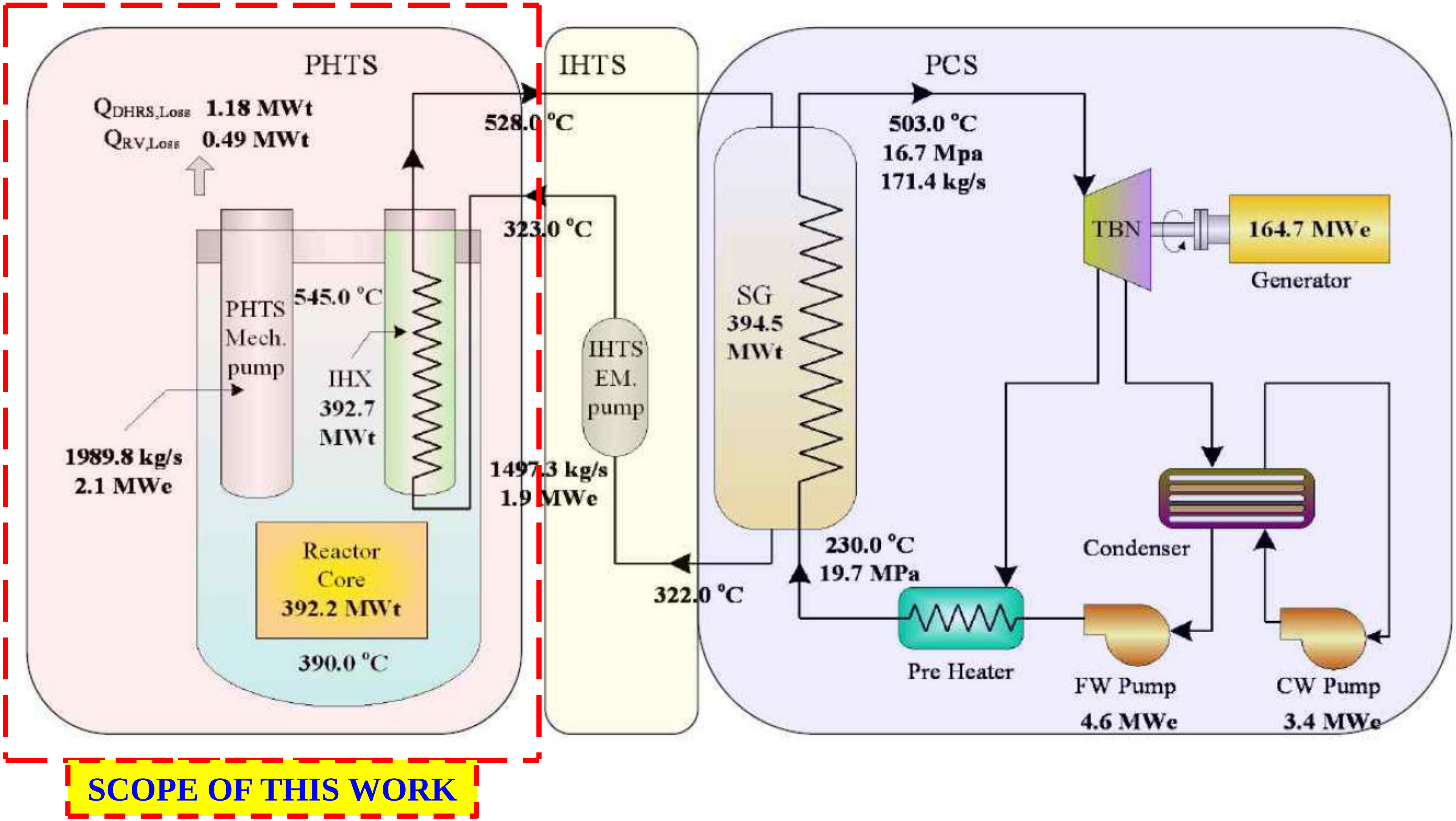
● THIS WORK:

- **Point dynamic model for stability analysis of PGSFR:**
  - Consider inherent reactivity feedbacks *such as the Doppler, fuel bowing, axial and radial thermal expansion, and sodium density effects*.
  - Consider *the relation between core outlet and inlet coolant temperatures via IHXs*.
  - Account for power oscillations caused by small perturbations of *either external reactivity, core inlet coolant temperature, or primary coolant mass flow rate*.

➢ **Frequency domain approach is applied:**

- Linearized point kinetics and lumped heat transfer model are coupled.
- *Reactor transfer functions are derived for evaluating the stability of PGSFR.*
- Impact of sodium density coefficient, initial core power, and fuel bowing is examined.

Introduction (cont'd)



Configuration of heat transport system in PGSFR

Point dynamic model - small perturbations

❖ Linearized point kinetics:

r_D	fuel Doppler coeff. (pcm/K)
r_Z	axial expansion coeff. (pcm/K)
r_M	sodium density coeff. (pcm/K)
r_R / r_{Min}	sub-assembly / grid plate radial expansion coeff. (pcm/K)

$$\frac{d\delta P}{dt} = \frac{P_0}{\Lambda}\delta\rho - \frac{\beta}{\Lambda}\delta P + \sum_j \lambda_j \delta c_j$$

$$\frac{d\delta c_j}{dt} = \frac{\beta_j}{\Lambda}\delta P - \lambda_j \delta c_j$$

Reactor kinetics

$$\delta\rho = \delta\rho_{ex} + r_D \delta T_F + r_Z \delta T_C + (r_M + r_R)\delta T_M + r_{Min}\delta T_{Min}$$

Reactivity change

❖ Lumped heat transfer model in fuel, cladding, and coolant:

$$\frac{d\delta T_F}{dt} = b_1 \delta P + b_2 \delta T_F + b_3 \delta T_C$$

Change in fuel temperature

$$\frac{d\delta T_C}{dt} = b_4 \delta T_F + b_5 \delta T_C + b_6 \delta T_M$$

Change in cladding temperature

$$\frac{d\delta T_M}{dt} = b_7 \delta T_C + b_8 \delta T_M + b_9 \delta T_{Mout} + b_{10} \delta T_{Min} + b_{11} \delta W_M$$

Change in coolant temperature

$$\delta T_{Mout} = b_{12} \frac{d\delta T_{Min}}{dt} + b_{13} \delta T_{Min} + b_{14} \delta W_M$$

Relation between core outlet and inlet coolant temperatures via IHX

Point dynamic model - Laplace transform

- Laplace images:

$$s\delta P(s) = \frac{P_0}{\Lambda}\delta\rho(s) - \frac{\beta}{\Lambda}\delta P(s) + \sum_j \lambda_j \delta c_j(s)$$

$$s\delta c_j(s) = \frac{\beta_j}{\Lambda}\delta P(s) - \lambda_j \delta c_j(s)$$

$$\delta\rho(s) = \delta\rho_{ex}(s) + r_D \delta T_F(s) + r_Z \delta T_C(s) + (r_M + r_R)\delta T_M(s) + r_{Min}\delta T_{Min}(s)$$

$$s\delta T_F(s) = b_1 \delta P(s) + b_2 \delta T_F(s) + b_3 \delta T_C(s)$$

$$s\delta T_C(s) = b_4 \delta T_F(s) + b_5 \delta T_C(s) + b_6 \delta T_M(s)$$

$$s\delta T_M(s) = b_7 \delta T_C(s) + b_8 \delta T_M(s) + b_9 \delta T_{Mout}(s) + b_{10}\delta T_{Min}(s) + b_{11}\delta W_M(s)$$

$$\delta T_{Mout}(s) = (b_{12}s + b_{13})\delta T_{Min}(s) + b_{14}\delta W_M(s)$$

where *Y(s)* = Laplace image of the quantity *Y(t)*

– Expressing $\delta T_{Mout}(s)$ in terms of $\delta T_{Min}(s)$ and $\delta W_M(s)$ yields:

$$s\delta T_M(s) = b_7 \delta T_C(s) + b_8 \delta T_M(s) + (b_{15} + b_{16}s)\delta T_{Min}(s) + b_{17}\delta W_M(s)$$

– Express the Laplace images of the fuel, cladding, and coolant temperatures in terms of the images of the power, core inlet coolant temperature, and primary coolant mass flow rate:

$$\delta T_F(s) = A_1(s)\delta P(s) + A_2(s)\delta T_{Min}(s) + A_3(s)\delta W_M(s)$$

$$\delta T_C(s) = A_4(s)\delta P(s) + A_5(s)\delta T_{Min}(s) + A_6(s)\delta W_M(s)$$

$$\delta T_M(s) = A_7(s)\delta P(s) + A_8(s)\delta T_{Min}(s) + A_9(s)\delta W_M(s)$$

⇒ Substitute into the image of the reactivity change

Point dynamic model - reactivity change

❖ Laplace image of total reactivity change:

$$\begin{aligned}\delta\rho(s) &= \delta\rho_{ex}(s) + r_D A_1(s)\delta P(s) + r_Z A_4(s)\delta P(s) + (r_M + r_R)A_7(s)\delta P(s) \\ &\quad + [r_D A_2(s) + r_Z A_5(s) + (r_M + r_R)A_8(s) + r_{Min}]\delta T_{Min}(s) \\ &\quad + [r_D A_3(s) + r_Z A_6(s) + (r_M + r_R)A_9(s)]\delta W_M(s) \\ &= \delta\rho_{ex}(s) + \delta\rho_F(s) + \delta\rho_C(s) + \delta\rho_M(s) + \delta\rho_u(s) + \delta\rho_w(s)\end{aligned}$$

— Image of total reactivity change is contributed from the following six terms:

(1) external reactivity perturbation (e.g. control rods): $\delta\rho_{ex}(s)$

(2) feedback from fuel temperature: $\delta\rho_F(s) = r_D A_1(s)\delta P(s)$

(3) feedback from cladding temperature: $\delta\rho_C(s) = r_Z A_4(s)\delta P(s)$

(4) feedback from coolant temperature: $\delta\rho_M(s) = (r_M + r_R)A_7(s)\delta P(s)$

(5) inlet coolant temperature perturbation: $\delta\rho_u(s) = [r_D A_2(s) + r_Z A_5(s) + (r_M + r_R)A_8(s) + r_{Min}]\delta T_{Min}(s)$

(6) coolant mass flow rate perturbation: $\delta\rho_w(s) = [r_D A_3(s) + r_Z A_6(s) + (r_M + r_R)A_9(s)]\delta W_M(s)$

❖ Equation for the image of reactivity change can be rewritten as:

$$\frac{\delta P(s)}{P_0 G(s)} = \delta\rho_{ex}(s) + K_u(s)\delta T_{Min}(s) + K_w(s)\delta W_M(s) + H_F(s)\delta P(s) + H_C(s)\delta P(s) + H_M(s)\delta P(s)$$

where $H_F(s) = \frac{\delta\rho_F(s)}{\delta P(s)} = r_D A_1(s)$; $H_C(s) = \frac{\delta\rho_C(s)}{\delta P(s)} = r_Z A_4(s)$; $H_M(s) = \frac{\delta\rho_M(s)}{\delta P(s)} = (r_M + r_R)A_7(s)$

$$K_u(s) = \frac{\delta\rho_u(s)}{\delta T_{Min}(s)} = r_D A_2(s) + r_Z A_5(s) + (r_M + r_R)A_8(s) + r_{Min}$$

$$K_w(s) = \frac{\delta\rho_w(s)}{\delta W_M(s)} = r_D A_3(s) + r_Z A_6(s) + (r_M + r_R)A_9(s)$$

Point dynamic model - transfer functions

- We will consider one perturbation at a time, assuming other perturbations equal to zero, to find the following transfer functions (the system is linear, thus superposition of perturbations can be used).
  - The external-reactivity-to-power transfer function is obtained by assuming that $\boldsymbol{\delta T_{Min}} = \boldsymbol{\delta W_M} = 0$.

$$H(s) = \frac{\delta P(s)}{\delta \rho_{ex}(s)} = \frac{P_0 G(s)}{1 - P_0 G(s)[H_F(s) + H_C(s) + H_M(s)]}$$

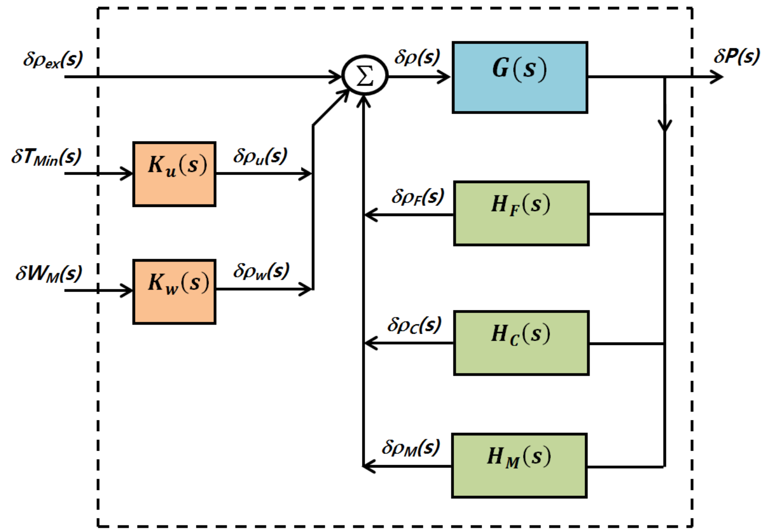
  - The core-inlet-coolant-temperature-to-power transfer function is obtained by assuming that $\boldsymbol{\delta \rho_{ex}} = \boldsymbol{\delta W_M} = 0$.

$$L(s) = \frac{\delta P(s)}{\delta T_{Min}(s)} = K_u(s) H(s)$$

  - The coolant-mass-flow-rate-to-power transfer function is obtained by assuming that $\boldsymbol{\delta \rho_{ex}} = \boldsymbol{\delta T_{Min}} = 0$.

$$M(s) = \frac{\delta P(s)}{\delta W_M(s)} = K_w(s) H(s)$$

- The poles of *H(s)*, *L(s)*, and *M(s)* are found to be the same. Thus, stability property is independent of forcing functions.



Block diagram of the reactor dynamics

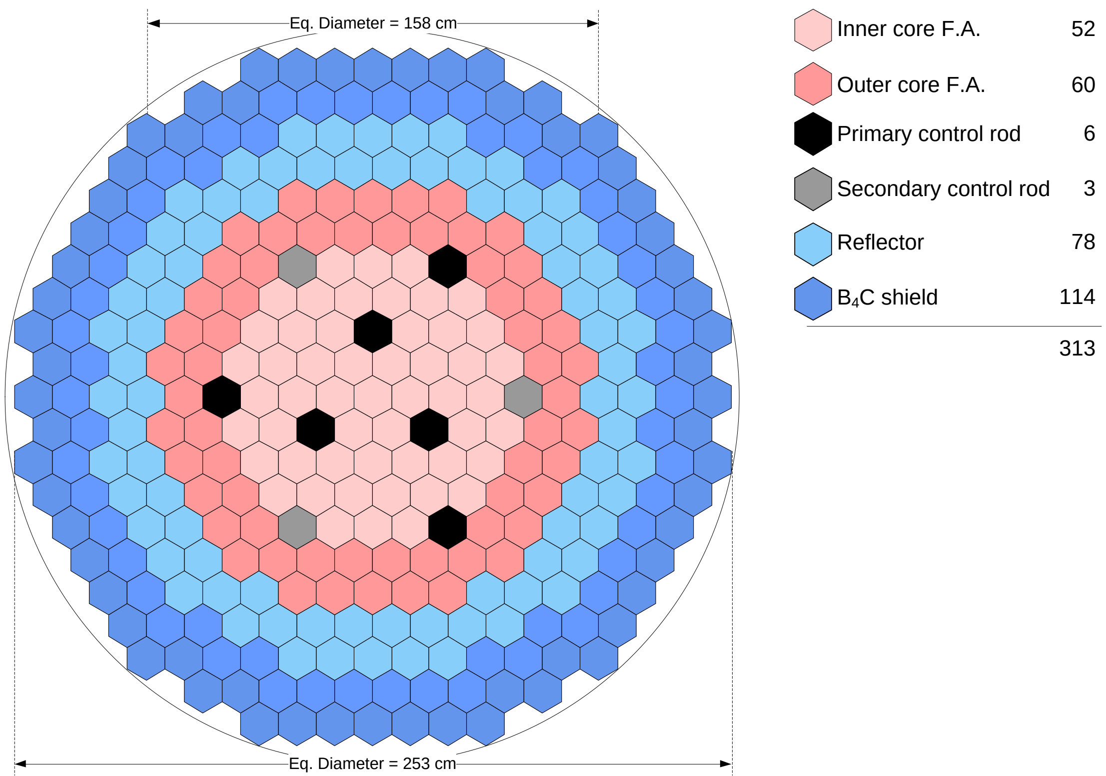
Judge the reactor stability based on the poles of *H(s)*, *L(s)*, and *M(s)* <u>i.e., roots of the characteristic equation:</u>

$$1 - P_0 G(s)[H_F(s) + H_C(s) + H_M(s)] = 0$$

PGSFR U-Core (Initial Core) Configuration

◆ **Initial uranium-loaded & final TRU-loaded cores:**

– PGSFR will be initially loaded and operated with uranium fuel owing to the insufficiency of TRU fuel irradiation databases; *As the practical performance of the TRU fuel is demonstrated, the initial uranium-loaded core will be gradually changed into the final TRU-loaded core.*



Radial layout of U-Core

Core design/performance parameters	U-Core
Power, MWth	392.6
Coolant temperature, ^{o}C (inlet/outlet)	390 / 545
Fuel form	U-10%Zr
Cladding/Reflector material	HT9M
Enrichment, wt.%	19.53
Cycle length(EFPD), day	290
Active core height, cm	90
Fuel pin diameter, cm	0.74
Number of fuel pins per assembly	217
Heavy metal loading, MT	7.33
Ave. power density, W/cm^3	218.3
Burnup reactivity swing, pcm	2235
Peak fast neutron fluence, x10^{23} #/cm^2	2.88

PGSFR U-Core - lumped kinetics and T-H data

BOEC/EOEC kinetics data						
β_j	0.000197/ 0.000190	0.001103/ 0.001069	0.001086/ 0.001048	0.002605/ 0.002511	0.001245/ 0.001208	0.000514/ 0.000496
λ_j	0.01337	0.03239	0.12105	0.30783	0.86964	2.91800
β = 0.00675/ 0.00652		λ = 0.0995/ 0.0994		Λ = 3.30429 E-07/ 3.44076 E-07 sec		

BOEC/EOEC reactivity coefficients, pcm/K				
r_D	r_Z	r_M	r_R	r_{Min}
-1269.5 $T^{-1.19834}$/ -1198.0 $T^{-1.18282}$	-0.21876/ -0.22633	-0.21200/ -0.19700	-0.65654/ -0.68027	-1.10490/ -1.14459
Assuming fuel temp. raised to ~900 °C gives $r_D \cong$ -0.36597/ -0.38381				

Steady state T-H data					
m_F (U-10%Zr), kg	7330	m_C (HT9M), kg	1804	m_M (Na), kg	1803.5
c_{pF}, J/kg/K	500	c_{pC}, J/kg/K	750	c_{pM}, J/kg/K	1269.5
h_{FC}, W/K	1.14 E11	h_{CM}, W/K	1.14 E8	W_{M0}, kg/sec	1991.2
T_{Min0}, °C	390	T_{Mout0}, °C	545	m_X, kg	2784.8
h_X, W/K	2334524	T_{Xin0}, °C	545	T_{Xout0}, °C	390

Zero power transfer function

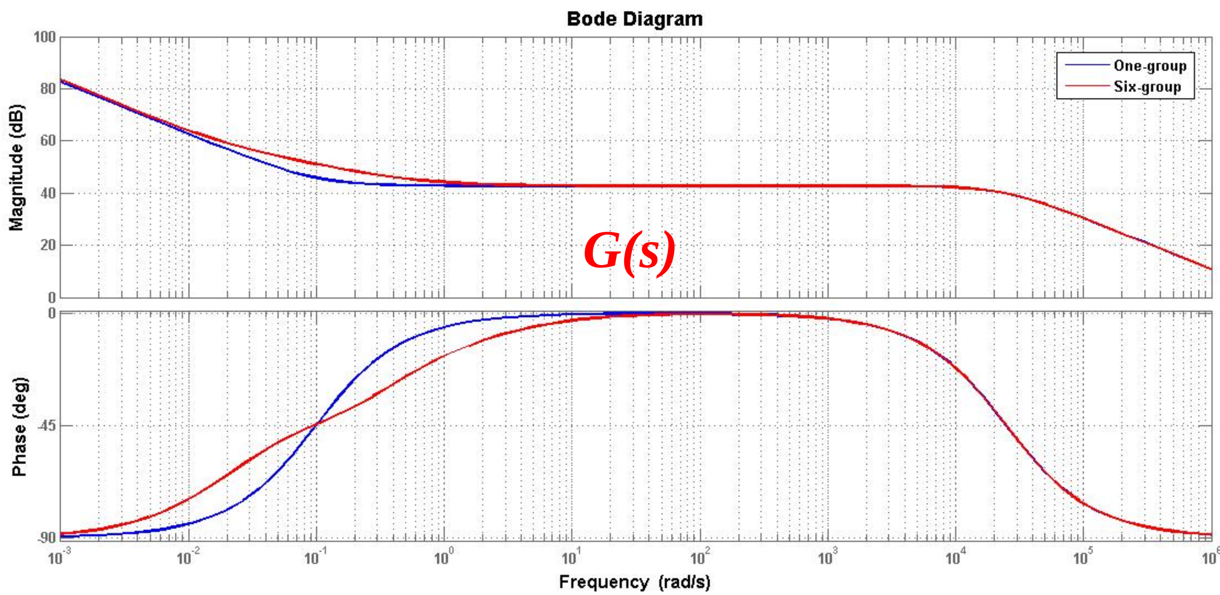
$$G(s) = \frac{\delta P(s)}{P_0 \delta\rho(s)} = \frac{1}{s\left(\Lambda + \sum_{j=1}^{6} \frac{\beta_j}{s+\lambda_j}\right)}$$

$\Rightarrow$ one-group approx. gives:

$$G(s) = \frac{1}{s\left(\Lambda + \frac{\beta}{s+\lambda}\right)}$$

where $$\frac{1}{\lambda} = \frac{1}{\beta}\sum_{j=1}^{6} \frac{\beta_j}{\lambda_j}$$

- One-group and six-group approx. show the same behavior of the zero power TF.
  - As the frequency approaches zero, the magnitude becomes infinite.
    - PGSFR w/o reactivity feedbacks is intrinsically unstable.



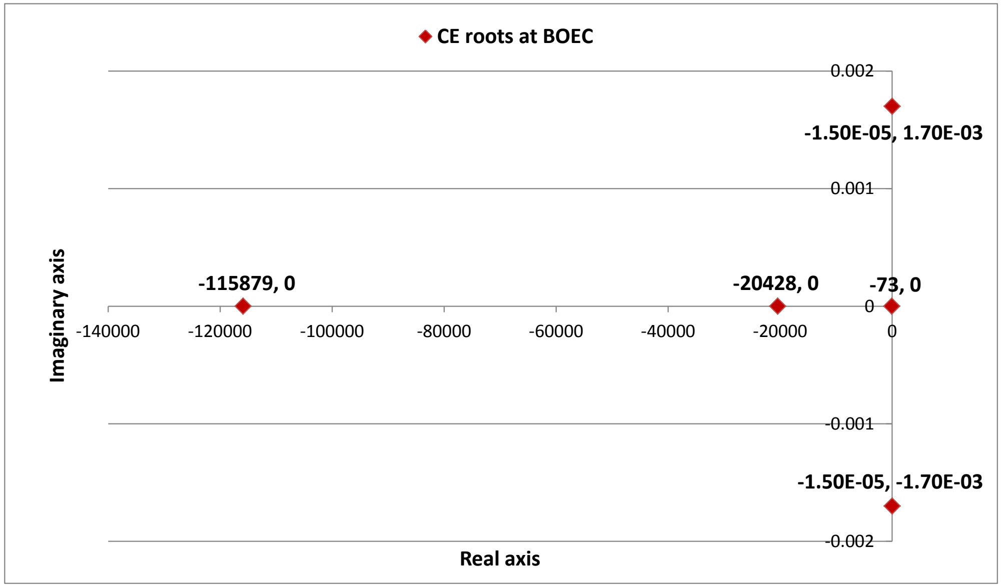
Bode diagram of the zero power TF

Roots of characteristic equation

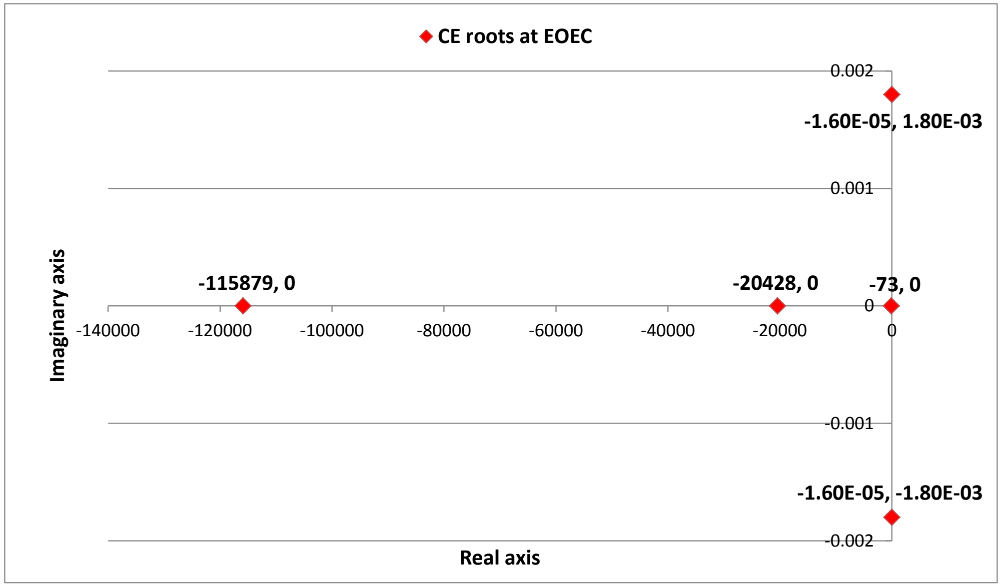
The necessary and sufficient condition for the closed-loop system (system w/ feedbacks) to be stable to small perturbations is that:

— all the roots of the characteristic equation have negative real parts.

- ❖ PGSFR is inherently stable at BOEC/EOEC because the real parts of the roots are all negative.
- ❖ Its stability is independent of the fuel burnup in the equilibrium cycle.



Roots of characteristic equation at BOEC (P_0 = 1.0)



Roots of characteristic equation at EOEC (P_0 = 1.0)

Impact of sodium density coefficient

- Under certain circumstances, r_M can be positive and thus the reactor can be unstable.
- As r_M becomes positive and approaches $|r_D + r_Z + r_R|$ from the left, the real part of one root becomes positive and thus the reactor becomes unstable.
  - r_M should be kept somewhat lower than $|r_D + r_Z + r_R|$.
  - PGSFR becomes increasingly stable with fuel burnup.

r_M	$r_D + r_Z + r_M + r_R$	Real parts of the roots at BOEC				
$P_0 = 1.0$ ($r_D + r_Z + r_R = -1.2413$)						
-0.212	-1.453	-115879	-20428	-73	-1.5 E-05	-1.5 E-05
1.238	-0.003	-115879	-20428	-73	-7.4 E-09	-7.4 E-09
1.239	-0.002	-115879	-20428	-73	2.7 E-09	2.7 E-09
1.240	-0.001	-115879	-20428	-73	1.3 E-08	1.3 E-08
1.242	7.3 E-04	-115879	-20428	-73	-3.8 E-05	3.8 E-05
1.245	0.004	-115879	-20428	-73	-8.7 E-05	8.7 E-05

Varying r_M at BOEC

r_M	$r_D + r_Z + r_M + r_R$	Real parts of the roots at EOEC				
$P_0 = 1.0$ ($r_D + r_Z + r_R = -1.2904$)						
-0.1970	-1.4874	-115879	-20428	-73	-1.6 E-05	-1.6 E-05
1.2875	-0.003	-115879	-20428	-73	-2.8 E-09	-2.8 E-09
1.2885	-0.002	-115879	-20428	-73	7.7 E-09	7.7 E-09
1.2895	-0.001	-115879	-20428	-73	1.8 E-08	1.8 E-08
1.2910	5.8 E-04	-115879	-20428	-73	-3.5 E-05	3.5 E-05
1.2945	0.004	-115879	-20428	-73	-9.2 E-05	9.2 E-05

Varying r_M at EOEC

Impact of initial power level

❖ The higher the initial power level, the more unstable the reactor can be.

r_M	$r_D + r_Z + r_M + r_R$	Real parts of the roots at BOEC				
P_0 = 0.1						
-0.212	-1.453	-115879	-20428	-73	-1.5 E-06	-1.5 E-06
1.238	-0.003	-115879	-20428	-73	-7.4 E-10	-7.4 E-10
1.239	-0.002	-115879	-20428	-73	2.7 E-10	2.7 E-10
1.242	7.3 E-04	-115879	-20428	-73	-1.2 E-05	1.2 E-05
P_0 = 0.5						
-0.212	-1.453	-115879	-20428	-73	-7.4 E-06	-7.4 E-06
1.238	-0.003	-115879	-20428	-73	-3.7 E-09	-3.7 E-09
1.239	-0.002	-115879	-20428	-73	1.4 E-09	1.4 E-09
1.242	7.3 E-04	-115879	-20428	-73	-2.7 E-05	2.7 E-05
P_0 = 1.0						
-0.212	-1.453	-115879	-20428	-73	-1.5 E-05	-1.5 E-05
1.238	-0.003	-115879	-20428	-73	-7.4 E-09	-7.4 E-09
1.239	-0.002	-115879	-20428	-73	2.7 E-09	2.7 E-09
1.242	7.3 E-04	-115879	-20428	-73	-3.8 E-05	3.8 E-05
P_0 = 1.5						
-0.212	-1.453	-115879	-20428	-73	-2.2 E-05	-2.2 E-05
1.238	-0.003	-115879	-20428	-73	-1.1 E-08	-1.1 E-08
1.239	-0.002	-115879	-20428	-73	4.1 E-09	4.1 E-09
1.242	7.3 E-04	-115879	-20428	-73	-4.7 E-05	4.7 E-05
P_0 = 3.0						
-0.212	-1.453	-115879	-20428	-73	-4.4 E-05	-4.4 E-05
1.238	-0.003	-115879	-20428	-73	-2.2 E-08	-2.2 E-08
1.239	-0.002	-115879	-20428	-73	8.2 E-09	8.2 E-09
1.242	7.3 E-04	-115879	-20428	-73	-6.6 E-05	6.6 E-05

Varying initial power level at BOEC

Impact of fuel bowing

- Positive reactivity due to fuel bowing in PGSFR has not yet been determined. But, the degree of fuel bowing coeff. (r_B) at which reactor may become unstable can be predicted.
  - reactivity change due to fuel temp. change will be $(r_B + r_D)\delta T_F$ instead of $r_D\delta T_F$.
- As r_B approaches $|r_D + r_Z + r_M + r_R|$, the reactor becomes unstable.
  - r_B should be kept somewhat lower than $|r_D + r_Z + r_M + r_R|$.

r_B	$r_B + r_D + r_Z + r_M + r_R$	Real parts of the roots at BOEC				
P_0 = 1.0						
0.0	-1.45327	-115879	-20428	-73	-1.5 E-05	-1.5 E-05
1.45317	-1.0 E-04	-115879	-20428	-73	-3.9 E-08	-3.9 E-08
1.45326	-1.0 E-05	-115879	-20428	-73	-3.9 E-08	-3.9 E-08
1.45327	0.0	-115879	-20428	-73	-1.6 E-07	8.3 E-08
1.45427	0.001	-115879	-20428	-73	-4.5 E-05	4.5 E-05
1.45527	0.002	-115879	-20428	-73	-6.4 E-05	6.4 E-05

Varying r_B at BOEC

r_B	$r_B + r_D + r_Z + r_M + r_R$	Real parts of the roots at EOEC				
P_0 = 1.0						
0.00000	-1.48741	-115879	-20428	-73	-1.6 E-05	-1.6 E-05
1.48731	-1.0 E-04	-115879	-20428	-73	-4.1 E-08	-4.1 E-08
1.48740	-1.0 E-05	-115879	-20428	-73	-4.0 E-08	-4.0 E-08
1.48741	0.0	-115879	-20428	-73	-1.6 E-07	8.4 E-08
1.48841	0.001	-115879	-20428	-73	-4.6 E-05	4.6 E-05
1.48941	0.002	-115879	-20428	-73	-6.5 E-05	6.5 E-05

Varying r_B at EOEC

Positive reactivity coefficients

- Sodium density and fuel bowing coefficients are both positive.
  - The reactor will become unstable as r_M > ~0.658/0.682 pcm/K at BOEC/EOEC, provided that the overall reactivity coefficient is kept at zero.

r_B	r_M	$r_B + r_D + r_Z + r_M + r_R$	Real parts of the roots (P_0 = 1.0)				
$r_B + r_M$ = 1.24126		at BOEC					
1.45326	-0.212	-1.0 E-05	-115879	-20428	-73	-3.9 E-08	-3.9 E-08
0.58326	0.658	-1.0 E-05	-115879	-20428	-73	-4.4 E-11	-4.4 E-11
0.58226	0.659	-1.0 E-05	-115879	-20428	-73	3.8 E-13	3.8 E-13
0.57226	0.669	-1.0 E-05	-115879	-20428	-73	4.4 E-10	4.4 E-10
$r_B + r_M$ = 1.29040		at EOEC					
1.48740	-0.197	-1.0 E-05	-115879	-20428	-73	-4.0 E-08	-4.0 E-08
0.60840	0.682	-1.0 E-05	-115879	-20428	-73	-3.3 E-11	-3.3 E-11
0.60740	0.683	-1.0 E-05	-115879	-20428	-73	1.2 E-11	1.2 E-11
0.59740	0.693	-1.0 E-05	-115879	-20428	-73	4.7 E-10	4.7 E-10

Varying both r_M and r_B

Concluding Remarks

- **Main findings for U-Core of PGSFR are:**
  - Stability property is the same for all the considered perturbations.
  - *U-Core is inherently stable & its stability is even more enhanced with fuel burnup.*
  - If a positive reactivity coefficient exists, *it must be kept somewhat lower than the magnitude of the overall negative reactivity coefficient.*
  - The higher the initial core power is, the more unstable the reactor can be.
  - If sodium density and fuel bowing coefficients are both positive, **U-Core is stable under the conditions that (i)** *overall reactivity coefficient is negative*, **(ii)** *sodium density coefficient must be kept lower than ~0.658/0.682 pcm/K at BOEC/EOEC.*
- **Further work:**
  - Consider time lag in the IHXs
  - Analyze the final TRU core of PGSFR

Thank you !