Analysis of the Stability of a SMR with Lyapunov Methods

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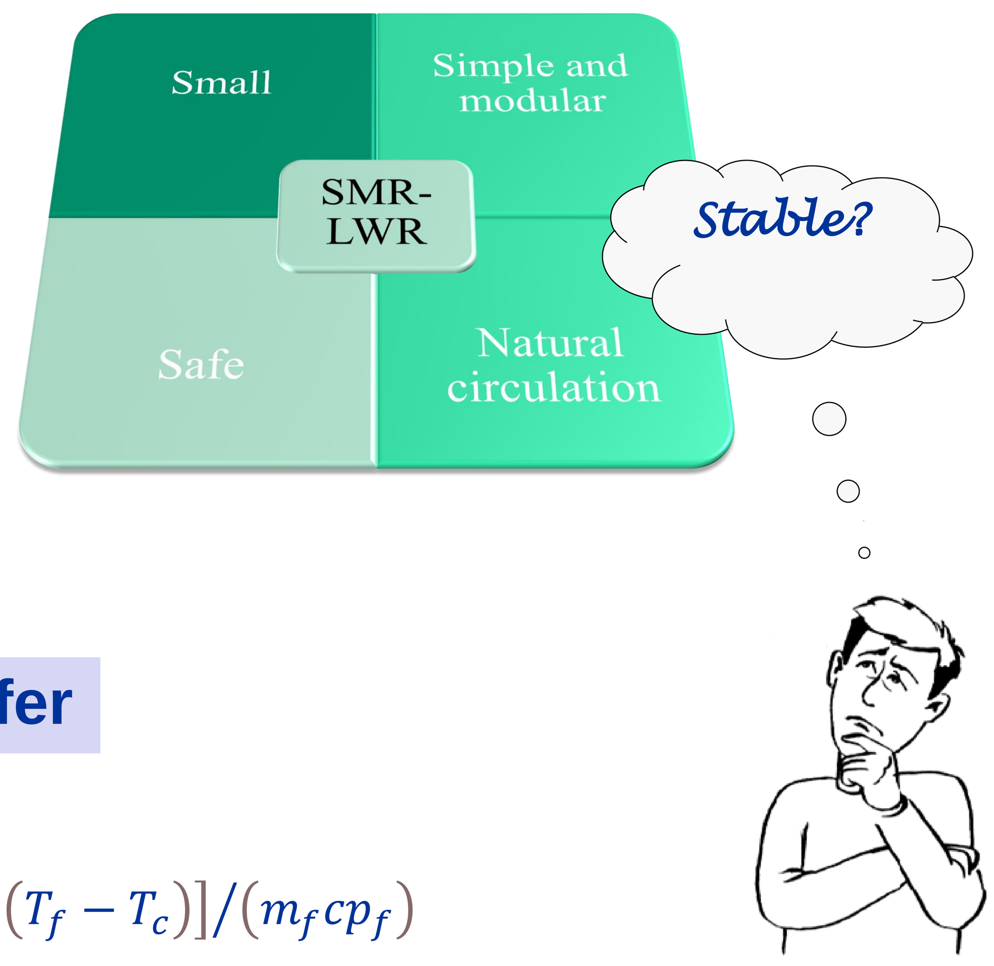
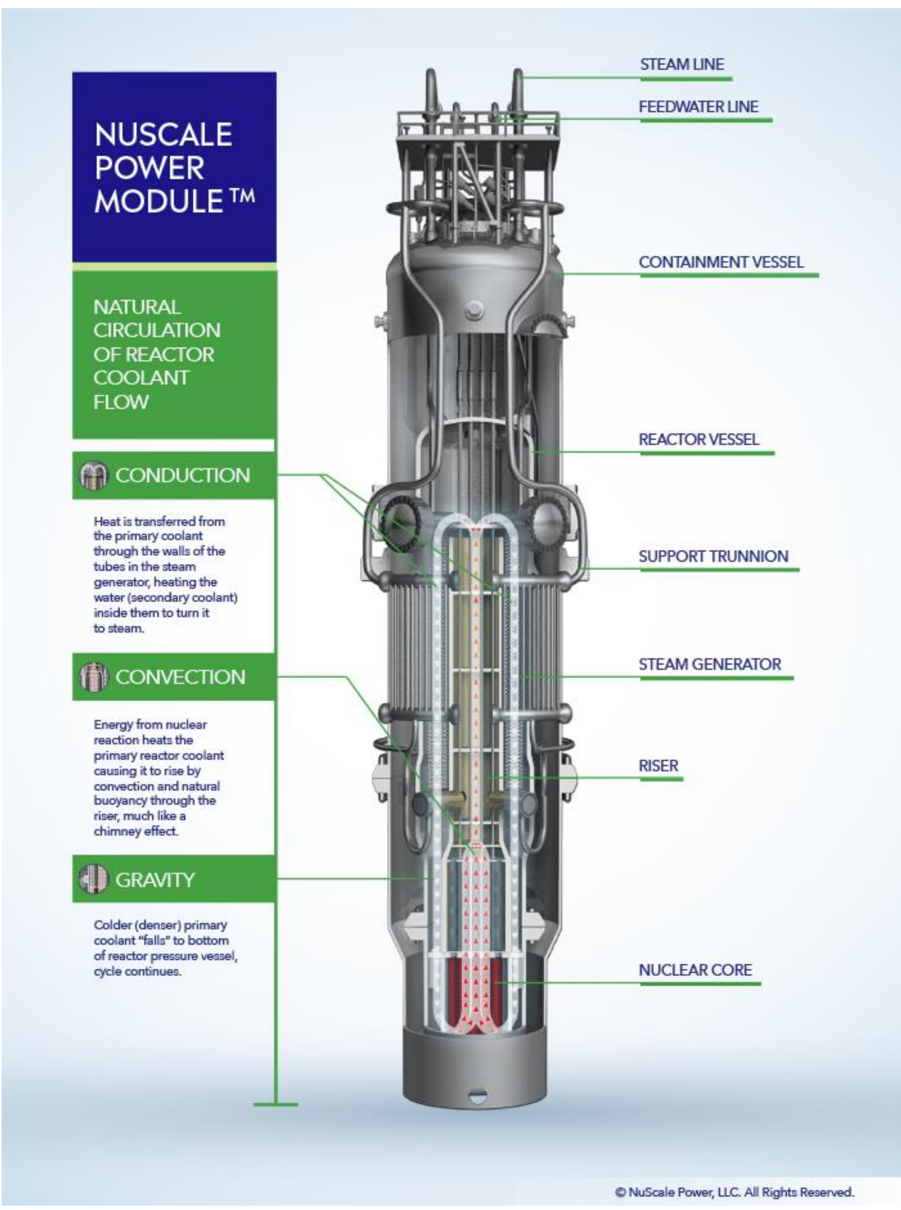
Javier Riverola Gurruchaga (jrg@enusa.es)
ENUSA, Industrias Avanzadas, S.A.

Introduction

- Light water SMRs offer numerous advantages such as transportability, availability, and operability compared to large Generation II reactors, and some designs additionally feature improved safety by natural convection cooling.
- This work addresses the study of the **neutronic-thermohydraulic stability** of these reactors using Lyapunov methods, as an alternative to conventional time-domain and frequency-domain methods.





An example of a stable SMR with natural circulation.
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Point Kinetics

$$\frac{dP}{dt} = \frac{\rho - \beta}{\Lambda} P + \sum_{1}^{6} \lambda_i C_i$$

$$\frac{dC_i}{dt} = \frac{\beta_i}{\Lambda} P - \lambda_i C_i \qquad i = 1, \dots, 6$$

$$\rho = \rho_{ext} + \alpha_f (T_f - T_{f0}) + \alpha_w (T_w - T_{w0})$$

Heat transfer

$$\frac{dT_f}{dt} = [P - UA_f(T_f - T_c)]/(m_f c p_f)$$

$$\frac{dT_c}{dt} = [UA_f(T_f - T_c) - \mu (T_c - T_w)^{1.33}]/(m_c c p_c)$$

$$\frac{dT_w}{dt} = [\mu (T_c - T_w)^{1.33} - 2 w_w c p_w (T_w - T_{win})]/(m_w c p_w)$$

Flow momentum

$$I \frac{dW_w}{dt} = \frac{g L \beta_v \rho_w Q_{cw}}{c p_w W_w (t - \tau)} - \xi W_w^2$$

Simplified Modeling

- Point kinetics is valid for relatively small reactivity perturbations. Besides, lumped parameter thermohydraulics allow for the qualitative description of transient behavior.
- The small size and simplicity of SMRs enable modeling their behavior with few equations and variables, allowing the use of Lyapunov's theorems for stability analysis.

ODE11

- 11 equations
- Response to an arbitrary step of reactivity?

= Stable and smooth response with some minor oscillations

∴ **stable behaviour!**

ODE5

- 5 equations: 1group PKE + Fuel HT + Coolant HT + Flow momentum
- First Method of Lyapunov (eigenvalues of Jacobian)

= All eigenvalues are real-negative

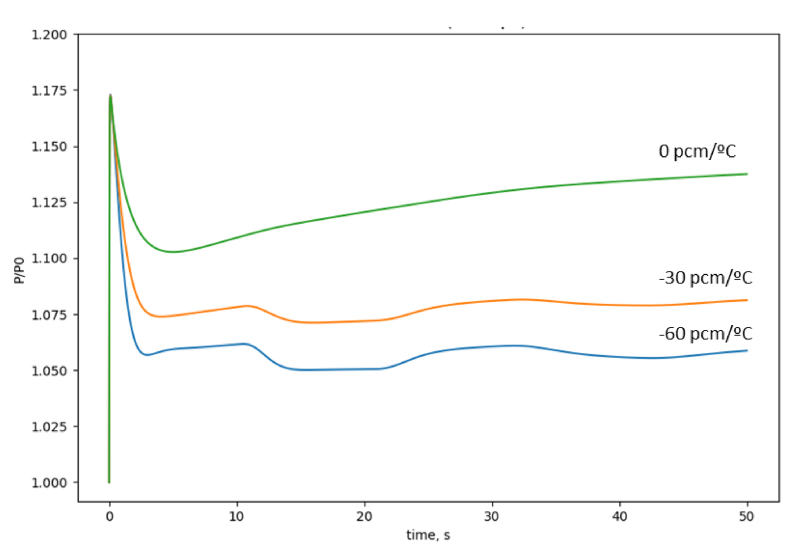
∴ **locally asymptotically stable!**

ODE2

- 2 equations: Prompt-jump point kinetics + Newton Law of Cooling
- Second Method of Lyapunov (surrogate of potential energy)

= V function is found so that V > 0, and dV/dt < 0 along solutions of the system

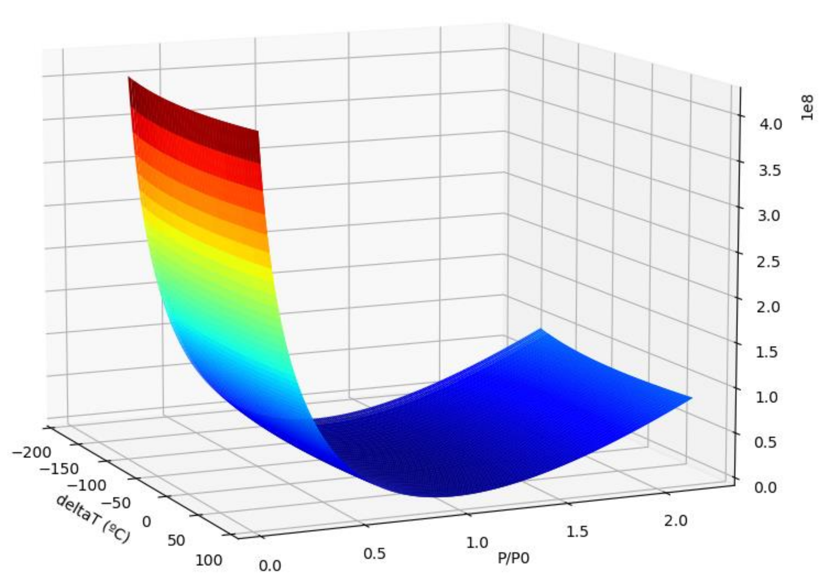
∴ **Regional asymptotic stability!**



☺ Smooth and stable response to a reactivity step

HFP	HZP (~ 1%)
αw = 0 pcm/ºC	*αw = +5 pcm/ºC*
-64.7550	-65.0734
-0.0422	-1.0743
-0.5492	**-0.00012**
-1.4711	-0.1521
-1.5	-1.5
αw = -60 pcm/ºC	*αw = -15 pcm/ºC*
(-64.7724+0j)	-65.0735
(-0.9909+0.9351j)	-1.0677
(-0.9909-0.9351j)	**-0.0031**
(-0.0634+0j)	-0.1557
(-1.5+0j)	-1.5

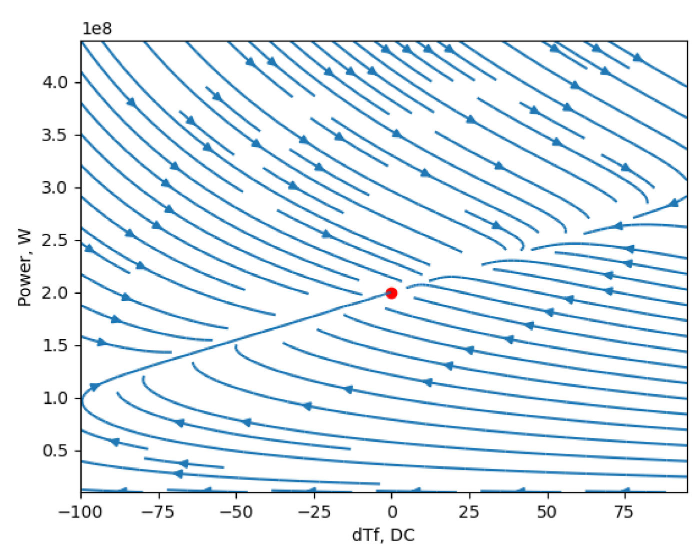
☺ All eigenvalues are real-negative



☺ A Lyapunov V function

Conclusions:

- **Lyapunov's Theorems** enable the characterization of stability zones and behaviors around nodes, complementing current methods in the frequency and time domains.
- **Result and extension of the Method**: This work concludes N-TH stability of these reactors and is consistent with previous studies. The method can be extended to other operational states and to other SMRs such as molten salt reactors or lead-cooled fast reactors, by using the appropriate equations.



☺ A stability valley and equilibrium saddle