Stability Evaluation for Flowing-Fuel Reactors using System Dynamics Analysis Tool

Michael Parnell, Thabit Abuqudaira, Dr Pavel Tsvetkov

Introduction

All reactor systems require accurate modeling predictions to maintain safe operation, but flowing-fuel reactors, such as molten salt reactors (MSRs), present unique challenges in stability analysis:

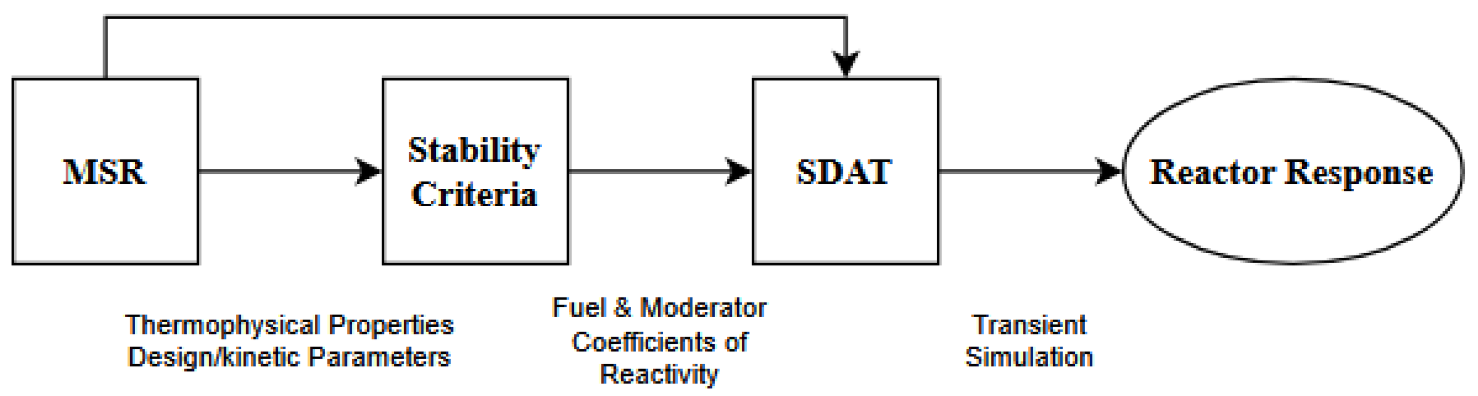
- Continuous fuel movement introduces complicated reactor dynamics
- Movement of fuel can impact reactivity feedback mechanisms
- Delayed Neutron Precursors (DNPs) flowing in and out of core complicate reactor response to reactivity changes

Analytical stability criteria can be developed through a transfer function approach that relates perturbations in the neutron population (or power level) to reactivity insertions. These equations depend on key design parameters, especially temperature coefficients of reactivity. This approach allows for the study of the dynamic behavior of the reactor under transient conditions by using transfer functions to consider the interactions between neutron flux, temperature, and reactivity feedback. These analytical stability predictions can be checked with reactor simulation models (such as the SDAT), to verify the expected behavior of the reactor during transients.

The purpose of this work is to provide a summary of a stability evaluation of a thermal-spectrum MSR though two complementary methods; first through analytical stability calculations, followed by transient simulations to verify the theoretical predictions.

Analysis Approach

- The reactor of interest was a thermal-spectrum MSR operating at $8MW_{th}$. The reactor's design and kinetic parameters, and thermophysical properties were fed into the Stability Criteria.
- The criteria were used to estimate the boundaries of different stability regions based on the values of the fuel and moderator temperature coefficients of reactivity.
- SDAT was then employed to verify the theoretical predictions by analyzing the power excursions following reactivity insertion transients, utilizing the fuel and moderator temperature reactivity coefficients generated from the stability model.

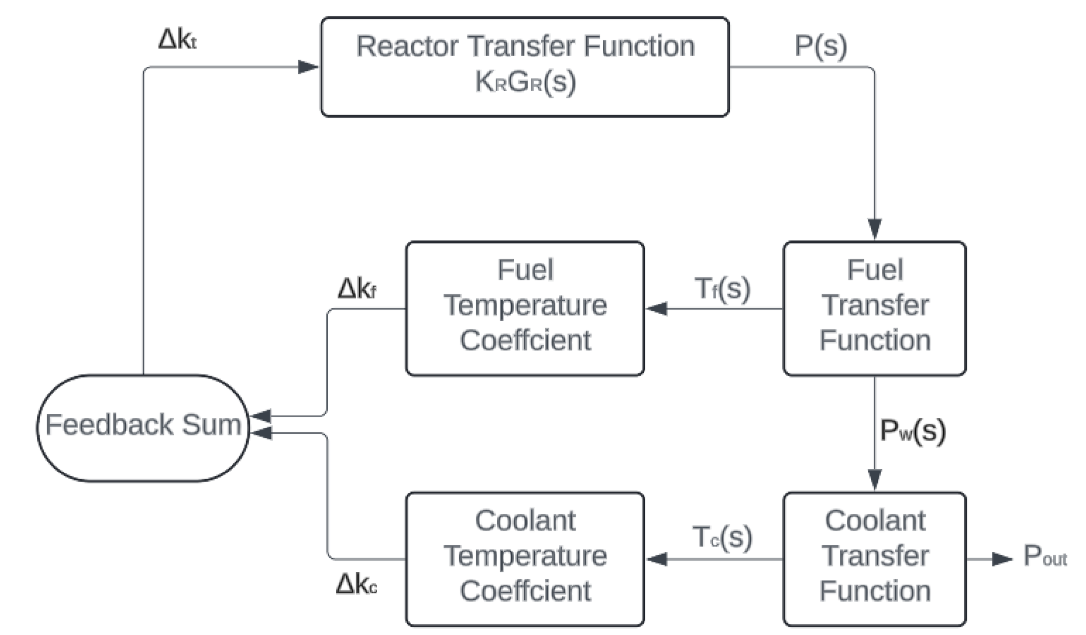


System Dynamics Analysis Tool (SDAT)

SDAT is a computational framework developed for the dynamic analysis of advanced reactor systems, with a particular focus on MSRs. Designed to support safety evaluations and emerging research topics, SDAT integrates physics-based models to assess reactor stability, transient behavior, and control strategies. It features real-time simulation capabilities, allowing rapid assessment of operational scenarios and reactivity feedback effects. Additionally, SDAT includes a user-friendly interface for intuitive model configuration and result visualization, enabling efficient parametric studies and decision support for reactor design and safety analysis.

Stability Criteria

The analytical stability criteria were developed via a transfer function approach between perturbations in the neutron population (or power level) and reactivity insertions for the separate fuel and moderator regions, considering closed-loop feedback of the neutron population. A block diagram representation of the closed-loop transfer function is provided:



The first transfer function computes the change in neutron population given a change in reactivity. This function was derived using the PKEs, with a few additional terms to account for the loss and reentry of DNPs passing through the loop. The second transfer function represents feedback via the temperature coefficients of reactivity and computes the reactivity insertion given a change in neutron population. This transfer function is based on two differential equations governing heat transfer between the fuel and moderator regions.

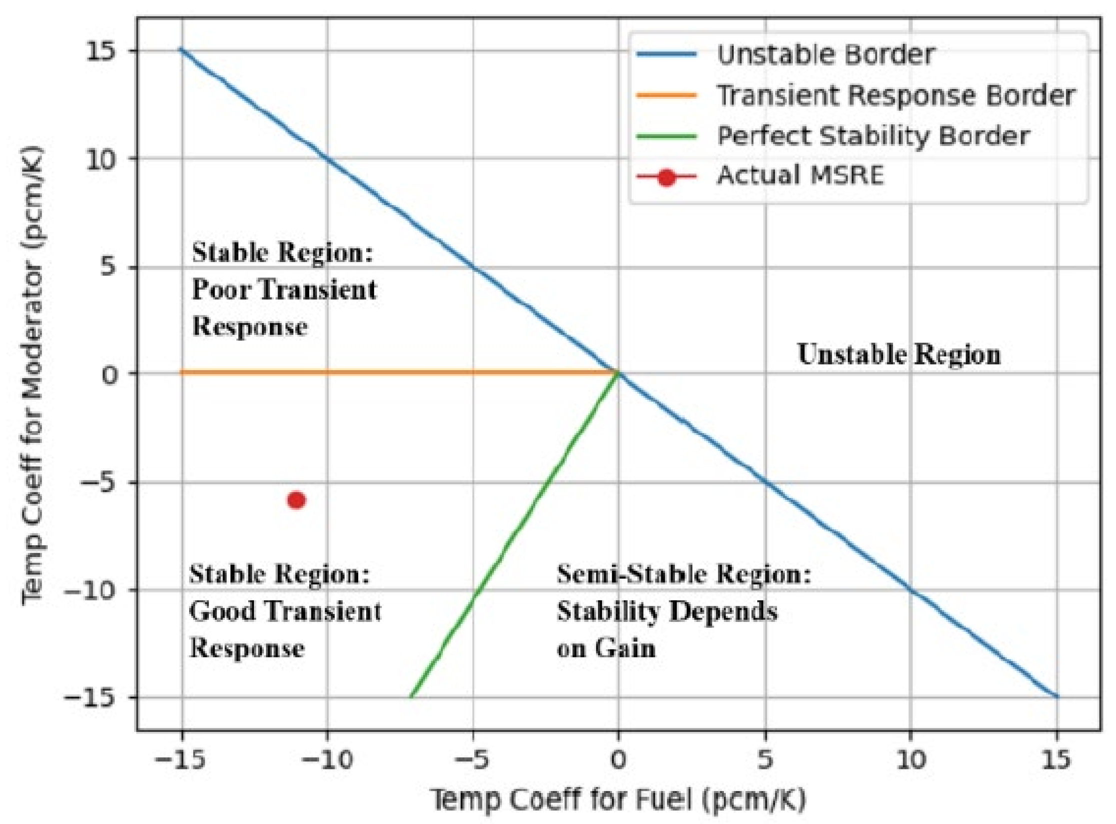
$$\frac{\Delta n(s)}{\Delta\rho(s)} = \frac{n_0}{sl}\,\frac{s+\frac{\lambda}{\eta X_0}}{s+\frac{\lambda}{\eta X_0}+\frac{\beta\eta}{l}} \qquad\qquad \frac{\Delta\rho(s)}{\Delta n(s)} = \frac{\alpha_f}{M_f c_f s}\,\frac{C_1+s}{C_2+s}$$

Based on closed-loop stability criteria, the product of the two transfer functions must be greater than -1. This relation can be simplified to form an inequality that must be satisfied for the system to be stable at all power levels.

$$\frac{\alpha_m}{\alpha_f} < \left(\frac{M_f c_f}{M_f c_f + M_m c_m} - \frac{\xi}{M_m c_m}\,\frac{\left(\frac{\eta X_0}{\lambda}\right)^2\left(\frac{\beta\eta}{l}\right)}{\left(\frac{\eta X_0}{\lambda}\right)\left(\frac{\beta\eta}{l}\right)+1}\right)^{-1} - 1$$

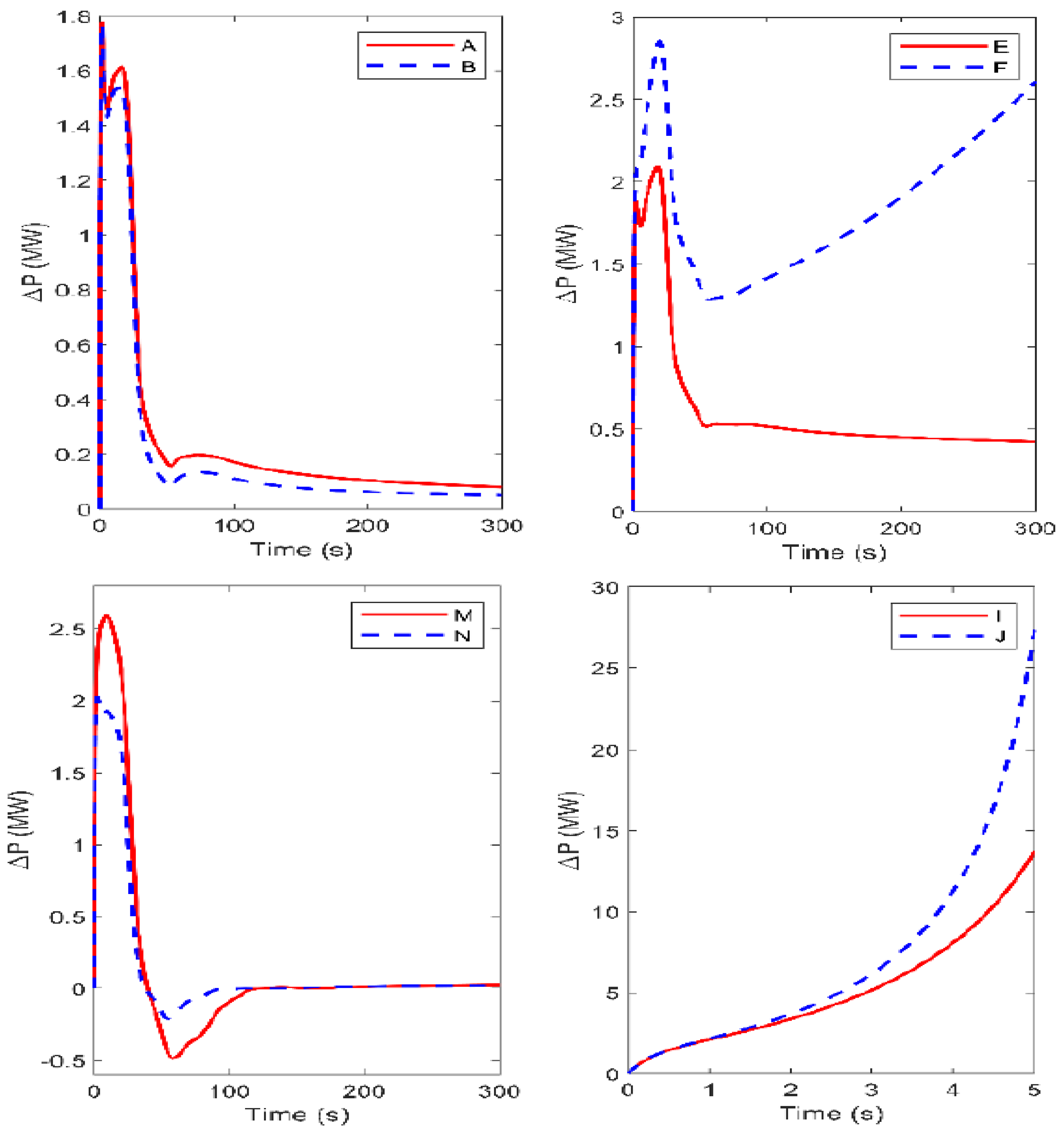
Results and Discussion

The analytical stability model was used to determine the combinations of (α_f, α_m) that govern the stability of the Molten Salt Reactor Experiment. As a result, four different stability regions were obtained, as shown below in the plot. The stability of each region depends on specific combinations of α values. The green line corresponds to the inequality above.



SDAT transient simulations are shown below. Transient simulations were performed for a partial control rod withdrawal, introducing a positive reactivity insertion of $0.1\beta_{eff}$. Each simulation utilized a different pair of (α_f, α_m). These pairs were carefully chosen to lie near the boundary of a stability region, allowing for an assessment of system behavior near the stability limits. For demonstration purposes, pairs of (α_f, α_m) at the boundary of each stability region were simulated. The change in power for each reactor configuration is provided:

- Top Left Figure: Border between stable region with poor transient response (containing Point A) and stable region with good transient response (containing Point B). Both points show power stability, but Point A takes longer to overcome the transient.
- Top Right Figure: Border between stable region with poor transient response (containing Point E) and unstable region (containing Point F). Point E is stable, but not Point F.
- Bottom Left Figure: Border between gain-dependent stability region (containing Point M) and stable region with good transient response (containing Point N). Both points show power stability, but Point M has greater power fluctuations.
- Bottom Right Figure: Border between gain-dependent stability region (containing Point I) and unstable region (containing Point J). Both points are unstable at this power.



Conclusions and Acknowledgements

In summary, this study highlights the effectiveness of coupling analytical stability predictions with the System Dynamics Analysis Tool (SDAT) in evaluating the stability of MSRs. SDAT simulations verified the analytical model's findings regarding effects of the temperature coefficients on reactor stability during transient events. Future research will incorporate the simulation of more complex transients and further analyze the stability in the gain-dependent region. We would like to acknowledge that this poster is based upon work supported by the project funded by the Idaho National Laboratory.

References:

[1] T. Kerlin, J. Ball, and C. Steffy, "Theoretical Dynamics Analysis of the Molten-Salt Reactor Experiment," *Nucl Technol*, **10**, 118 (1971).

[2] J. Wang, Q. Wang, and M. Ding, "Review on neutronic/thermal-hydraulic coupling simulation methods for nuclear reactor analysis," *Ann of Nuc Ener*, **137** (2020).

[3] M.A. Shultz, *Control of Nuclear Reactors and Power Plants,* 2nd Ed., Westinghouse Electric Corporation, Pittsburgh, Pennsylvania (1961).

[4] T. Abuqudaira, P. Tsvetkov, and P. Sabharwall, "Dynamics of Molten Salt Reactor with Operating Heaters," *Nucl Scie and Engi*, pp. 1-22, (2024).

TEXAS A&M UNIVERSITY
Department of Nuclear Engineering