Department of Nuclear Engineering

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MSR system dynamic modeling

Thorium Energy Alliance Conference 10

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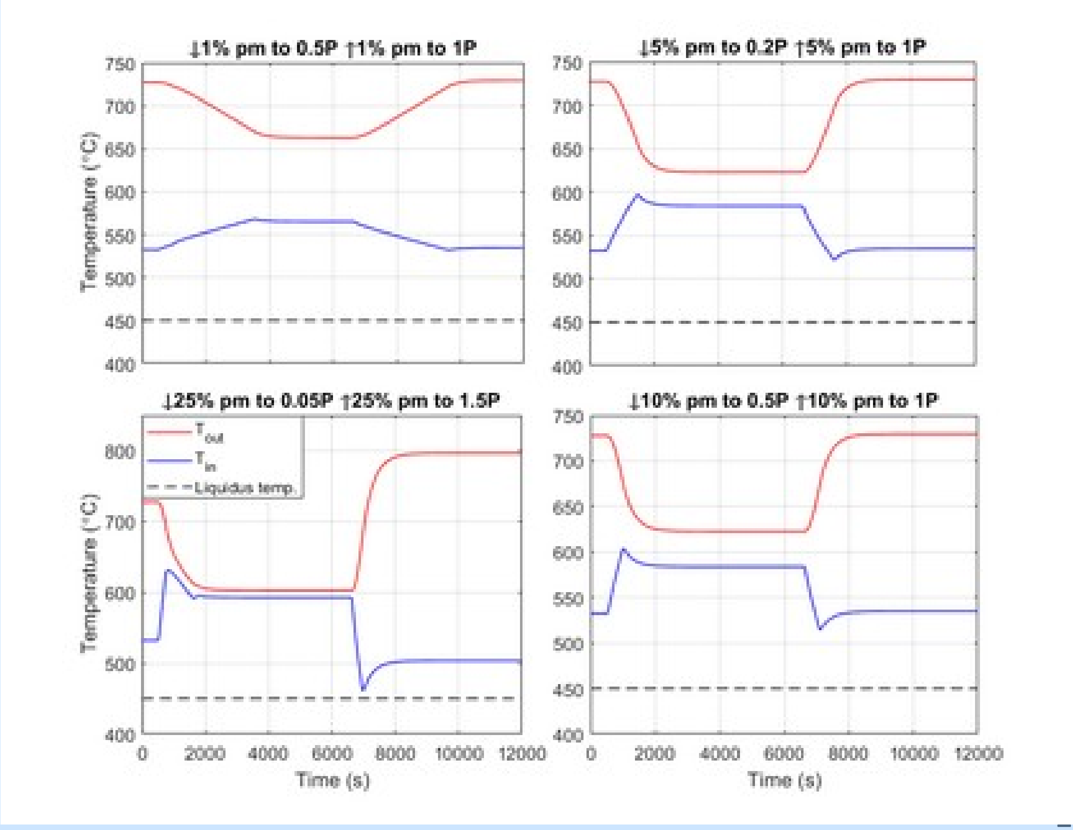
Overview

- UTK MSR research
- Why dynamic modeling?
- Available Simulink models of
  - MSRE, MSBR ORNL-4528
  - MSDR full powerplant with Rankine BOP
- Safeguards
- Decay heat



Acknowledgments: Thank you sponsors!

Flibe Energy Inc., Huntsville, AL

ORNL/UT-Battelle

U.S. Department of Energy

Terrestrial Energy Inc., Oakville, Canada

MSR research & student involvement

- Research topics
  - Core modeling: neutronics, fuel cycles
  - Safeguards
  - Dynamic modeling
  - Xenon behavior
- Students
  - ~100 undergraduates graduated with some MSR knowledge.
  - Graduate students in areas of dynamic modeling, nuclear material safeguards, Xenon behavior in MSRs.
  - Most of this work by Vikram Singh, Alex Wheeler, and Visura Pathirana.
  - https://msr.ne.utk.edu/~o/UTK_MS_thesis_Singh_final.pdf

Recent publications

1. G. Ridley, O. Chvala: “A method for predicting fuel maintenance in once-through MSRs,” Annals of Nuclear Energy 110 (2017) 265–281.
2. O. Chvála, M.R. Lish, V. Singh, and B.R. Upadhyaya, “Dynamic Analysis of the Next Generation Molten-Salt Breeder Reactor System,” Transactions of the American Nuclear Society, San Francisco, CA, USA, 116, pg. 1177-1180 (2017).
3. V. Singh, M.R. Lish, O. Chvála, and B.R. Upadhyaya, “Dynamics and Control of Molten-Salt Breeder Reactor,” Nuclear Engineering and Technology, 49, 5, pg. 887-895 (2017).
4. A.M. Wheeler, V. Singh, O. Chvála, and B.R. Upadhyaya, “Analysis of Operational Anomalies for the Molten-Salt Reactor Experiment,” Transactions of the American Nuclear Society, Washington, D.C., USA, 117, (2017).
5. V. Singh, A.M. Wheeler, M.R. Lish, O. Chvála, and B.R. Upadhyaya, “Nonlinear Dynamic Model of Molten-Salt Reactor Experiment – Validation and Operational Analysis,” Annals of Nuclear Energy, 113, pg. 177-193 (2018).
6. V. Singh, M.R. Lish, A.M. Wheeler, O. Chvála, and B.R. Upadhyaya, “Dynamic Modeling and Performance Analysis of a Two-Fluid Molten-Salt Breeder Reactor System,” Nuclear Technology, 202, 1, pg. 15-38 (2018).
7. V. Singh, A.M. Wheeler, O. Chvála, and B.R. Upadhyaya, “Exploring Molten-Salt Reactor Dynamic Behavior and Control Strategies,” 61st Annual ISA POWID Symposium Proceedings, Knoxville, TN, USA (2018).
8. V. Singh, A.M. Wheeler, B.R. Upadhyaya, and O. Chvála, “Load-following Operation and Transient Behavior of Molten Salt Demonstration Reactor,” Proceedings of 11th ANS NPIC&HMIT Conference, Orlando, FL, USA (2019).
9. V. Singh, A.M. Wheeler, B.R. Upadhyaya, O. Chvála, and M.S. Greenwood, “Plant-Level Dynamic Modeling of a Commercial-Scale Molten Salt Reactor System,” Nuclear Engineering and Design (in review).
10. T. Price, O. Chvala, Z. Taylor: “Molten Salt Reactor Xenon Analysis: Review and Decomposition,” ASME J of Nuclear Rad Sci. 5(4) (2019) 041210
11. T. Price, O. Chvala: "A Review of Molten Salt Reactor Xenon Analysis Literature," ASME J of Nuclear Rad Sci. (2019) doi: https://doi.org/10.1115/1.4044746
12. T. Price, O. Chvala, Z. Taylor: “A Review of Circulating Voids and Gaseous Fission Product Behavior In Molten Salt Reactors,” under review in ASME J of Nuclear Rad Sci. (2019)
13. T. Price, O. Chvala, Z. Taylor: “Xenon Behavior in Molten Salt Reactor Graphite: Modeling and a Method To Model The Distribution of Xenon Within The Graphite,” under review in ASME J of Nuclear Rad Sci. (2019)
14. T. Price, O. Chvala: "A Theory and Model of Molten Salt Reactor Xenon Behavior After the Solubility Limit,” under review in ASME J of Nuclear Rad Sci. (2019)
15. T. Price, O. Chvala, Z. Taylor: “Xenon in Molten Salt Reactors: The Effects of Solubility, Circulating Particulate, Ionization, and the Sensitivity of the Circulating Void Fraction,” under review in Nuclear Engineering Technology (2019

Dynamic system modeling

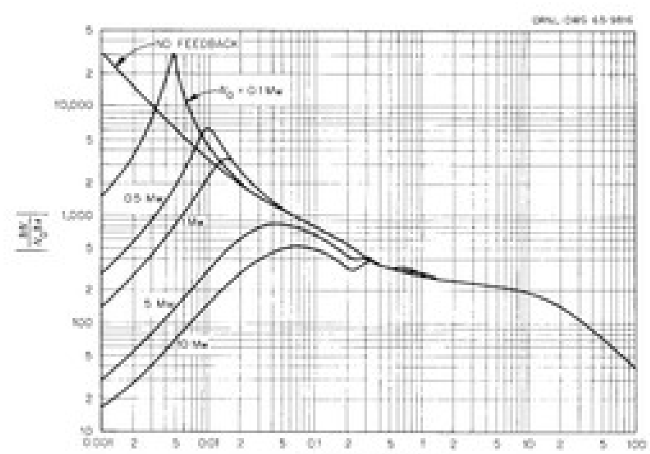
- Simple and adaptable modeling approach that captures underlying physics.
- Ascertain transient behavior during normal operation and accident scenarios. Useful for I&C development.
- Determine safety limits and parameter sensitivities.
- Develop a validated open-source tool with accessible computational requirements.
- Modern version of ORNL's MSRE dynamic modeling by Syd Ball and Tom Kerlin (ORNL-TM-1070, 1965).

STABILITY ANALYSIS OF THE MOLTEN-SALT
REACTOR EXPERIMENT

S. J. Ball   T. W. Kerlin

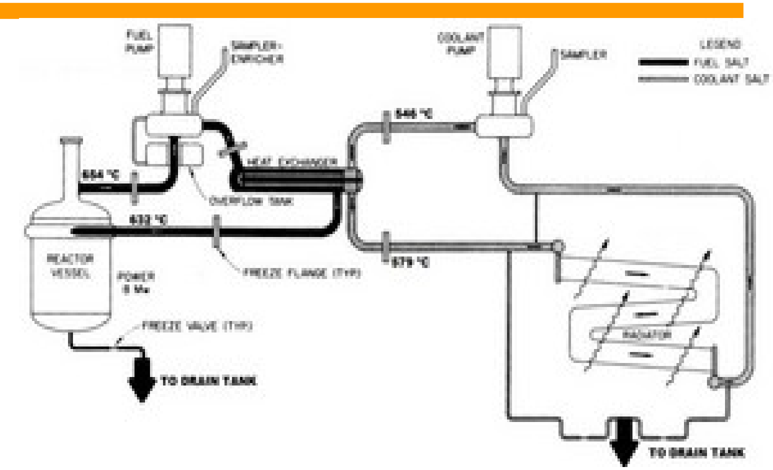
Abstract

A detailed analysis shows that the Molten-Salt Reactor Experiment is inherently stable. It has sluggish transient response at low power, but this creates no safety or operational problems. The study included analysis of the transient response, frequency response, and pole configuration. The effects of changes in the mathematical model for the

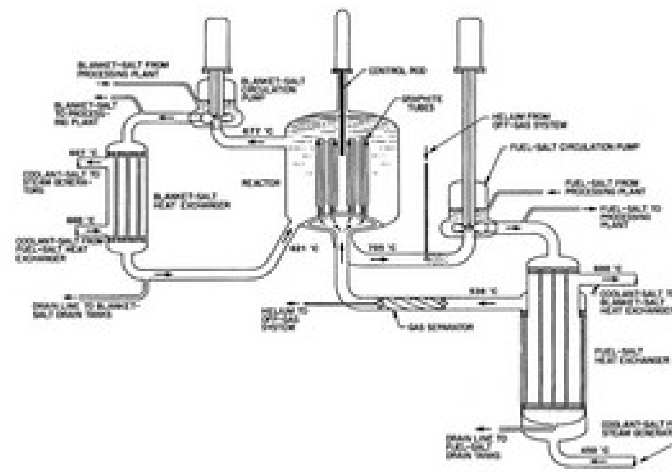


MSR dynamics models developed

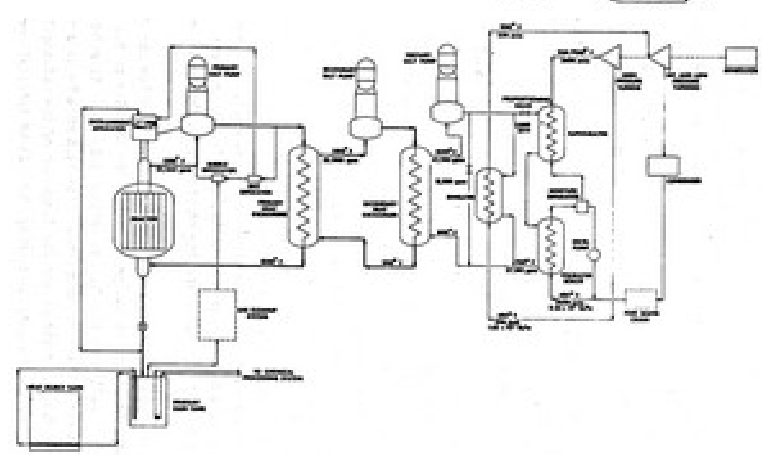
- Molten Salt Reactor Experiment
  - Modified PKE for core; PHX; radiator.
  - Validated with MSRE data.



- Molten Salt Breeder Reactor
  - Two-fluid modular MSBR, 1000MWe/4
  - ORNL-4528, 1970

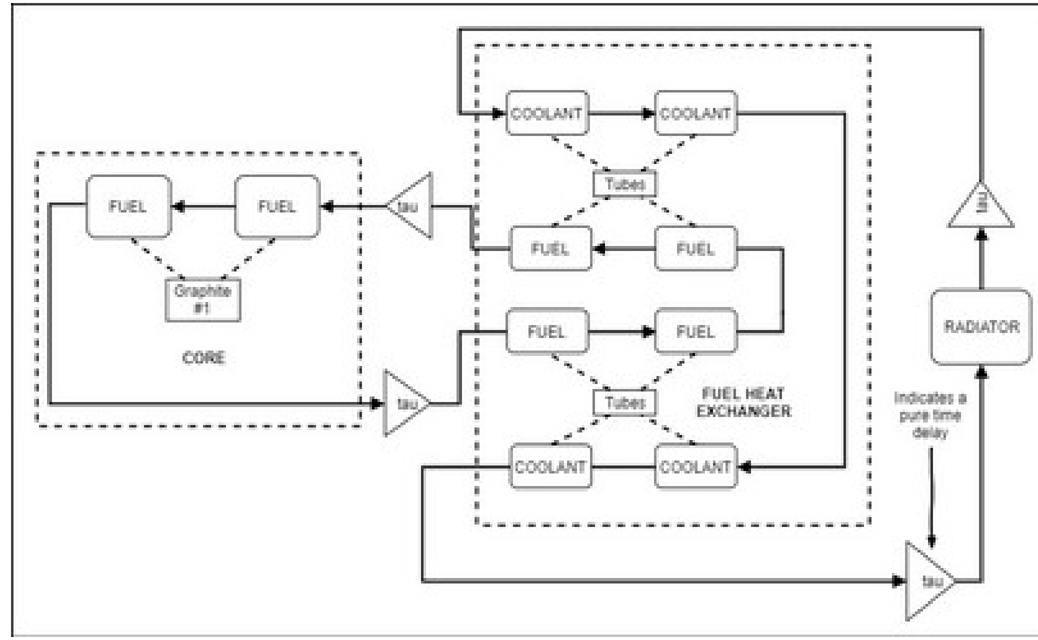


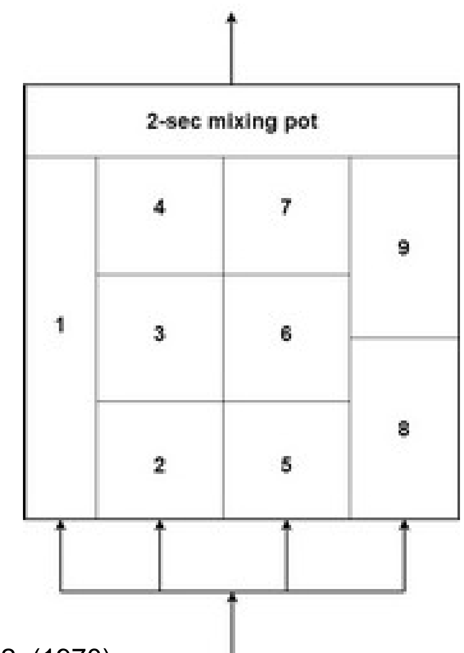
- Molten Salt Demonstration Reactor
  - Single fluid MSDR, 350MWe
  - ORNL-TM-3832, 1972



MSRE modeling approach

- Methodology inspired by earlier work at ORNL*
- Lumped-parameter model
- Modified point kinetics
- Two liquid lumps for every solid lump
- Model developed in MATLABT-Simulink
- Core: 1-region and 9-region
  - 9-region distributes temperature feedbacks and power production spatially using importance-weighted factors.



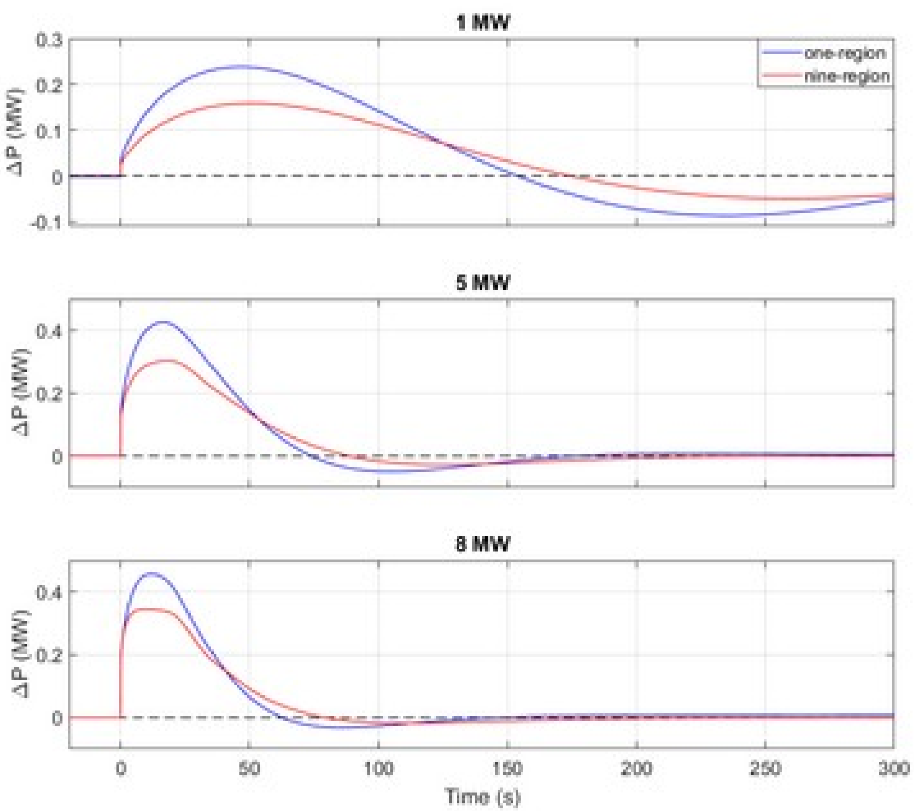


*T. W. Kerlin, et al. “Theoretical Dynamics Analysis of the Molten-Salt Reactor Experiment,” *Nuclear Technology*, 10, 118-132, (1970).

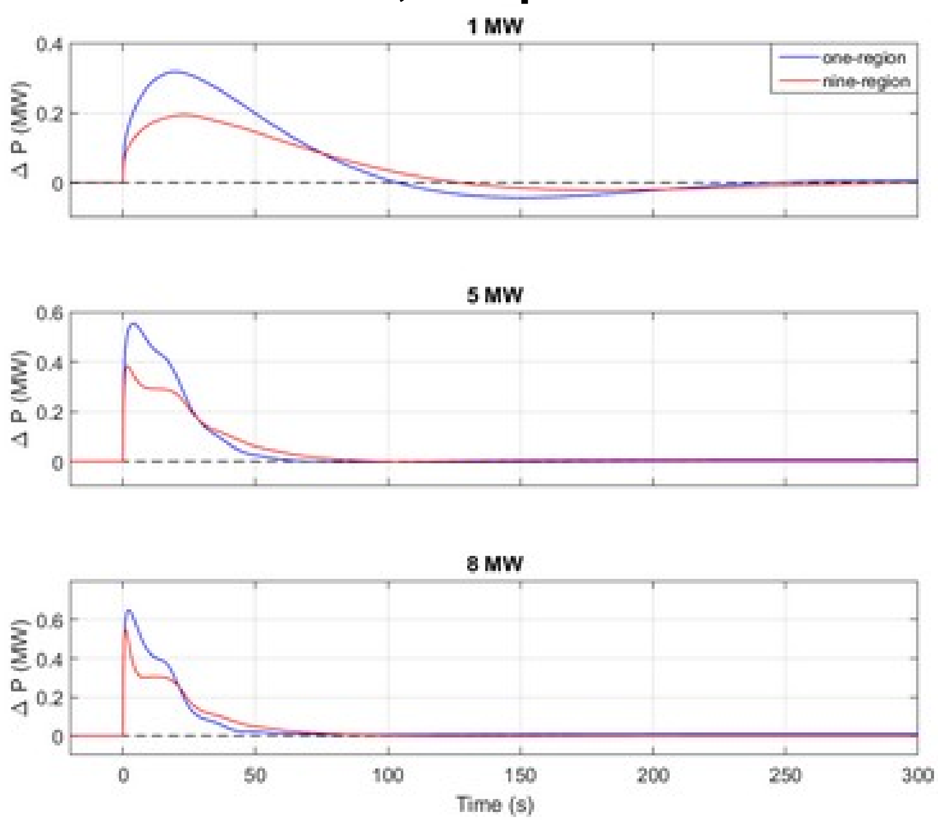
MSRE model results

- System power response to +10 pcm reactivity insertion at 1, 5, and 8 MWth power.
- 9-region model better resolves initial power rise.

U-235, +10 pcm

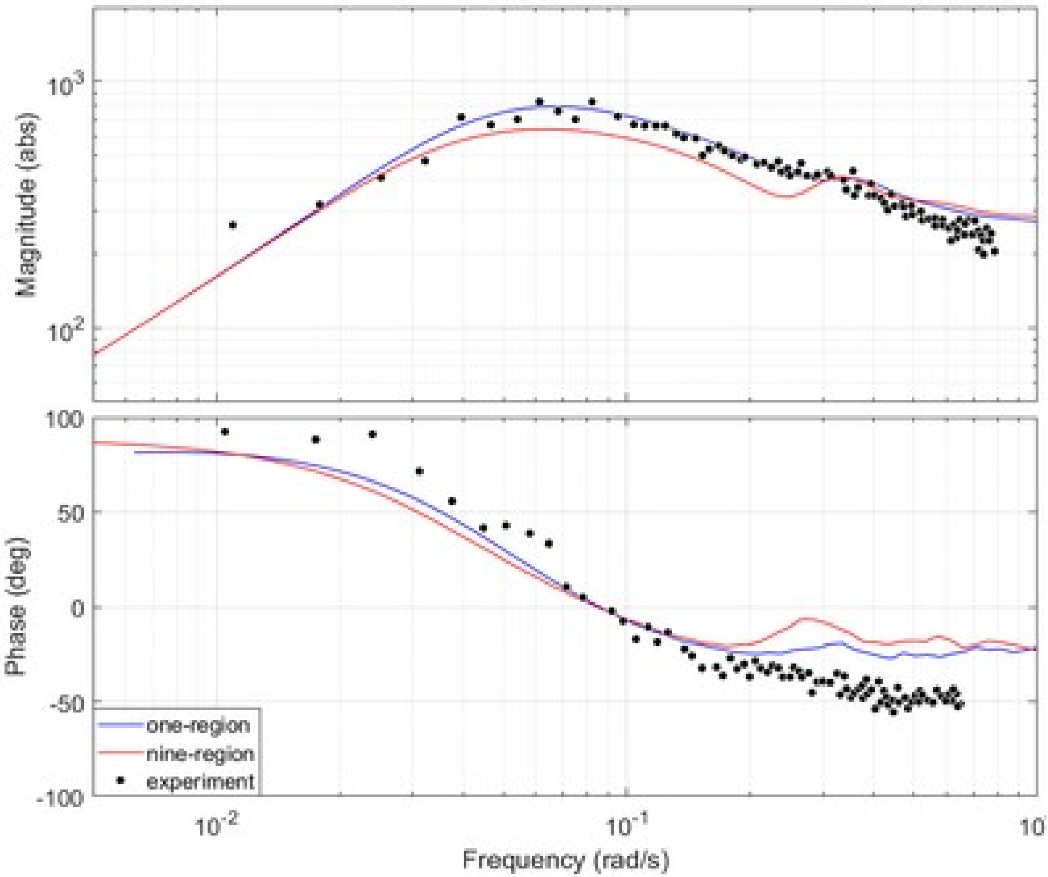


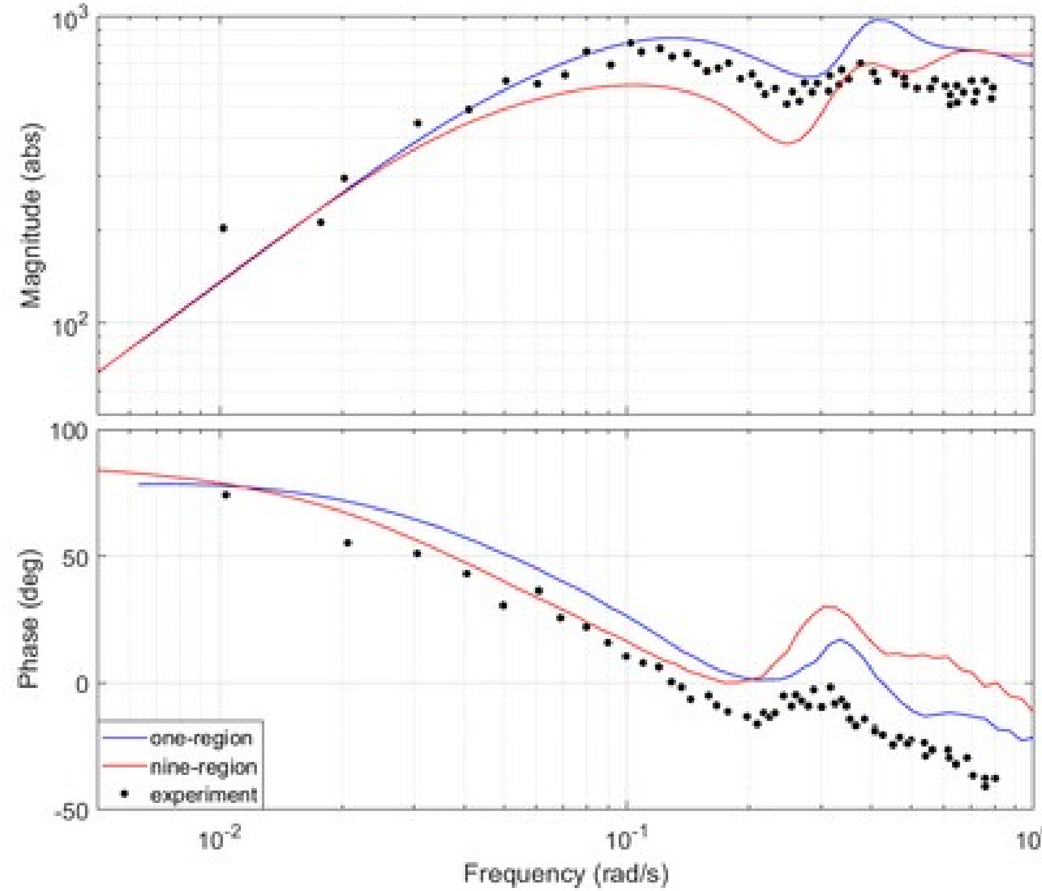
U-233, +10 pcm



Frequency characteristics

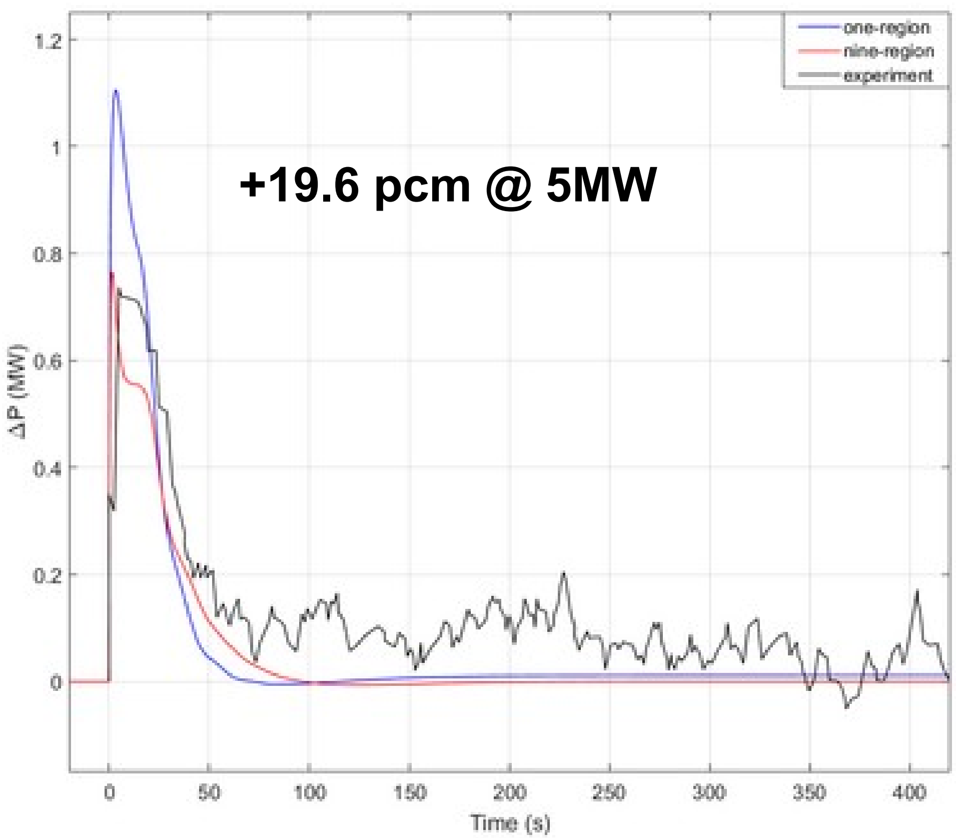
- Both core models describe the measured data equally well.
- Note lack of error bars on data.

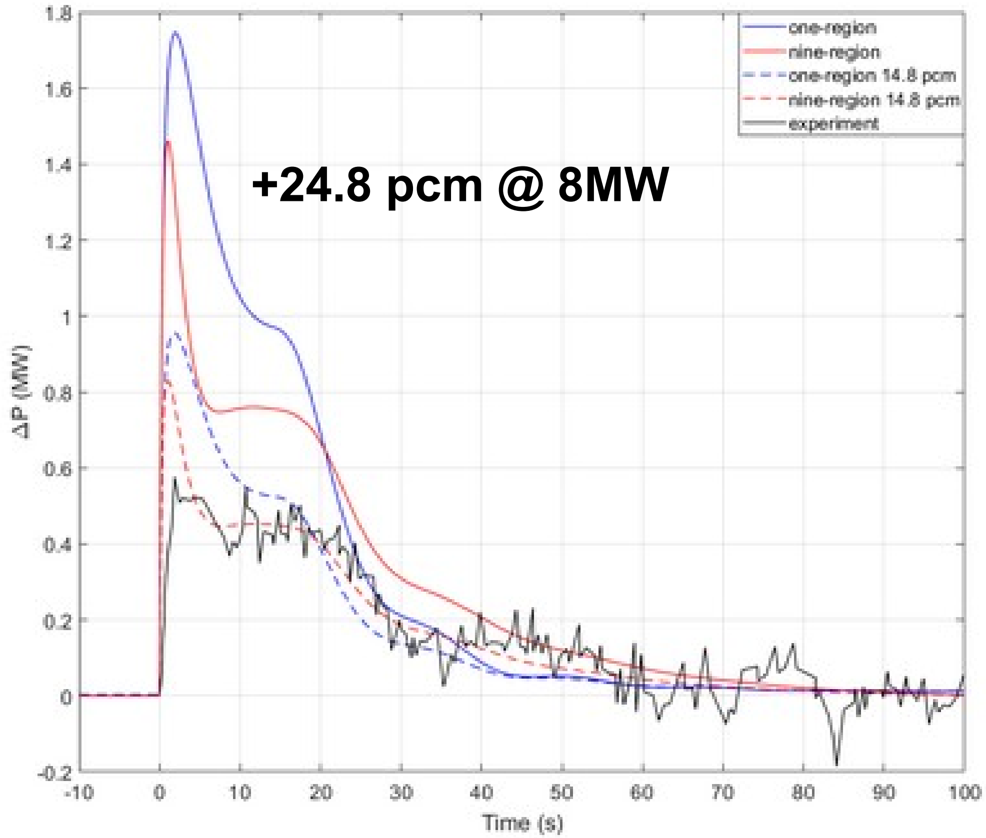




MSRE data shortcomings

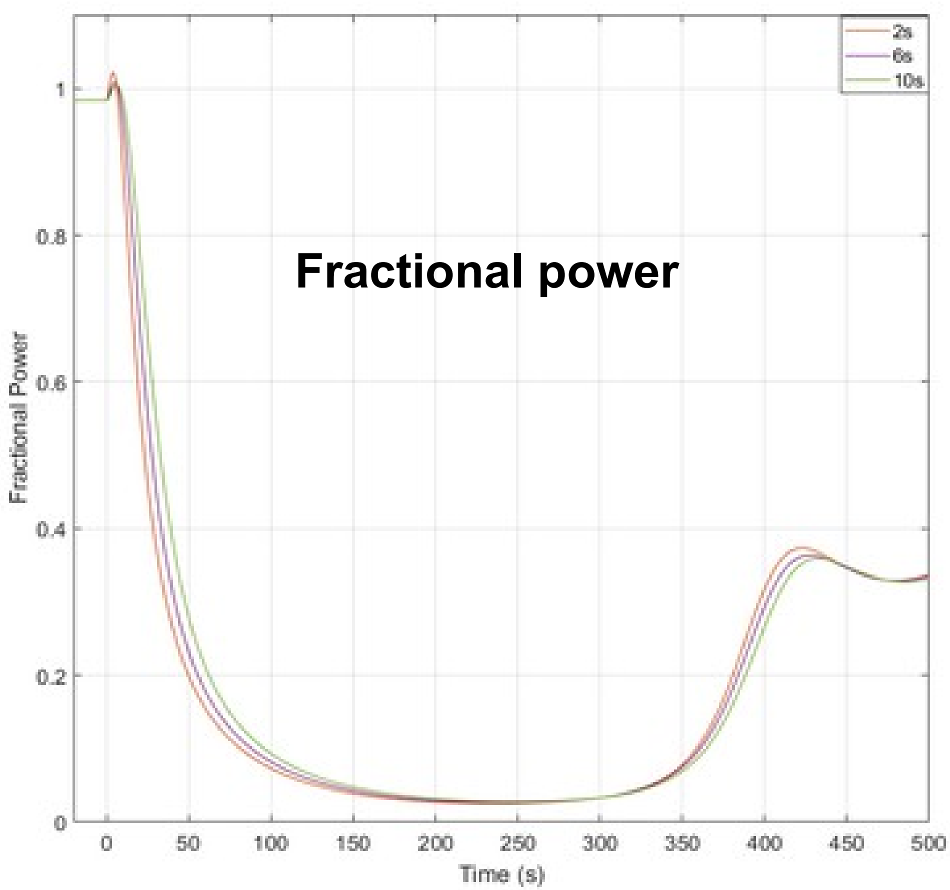
- Reactivity insertion data at full power cannot be reconciled with the model.
- Note the lack of error bars in the data.

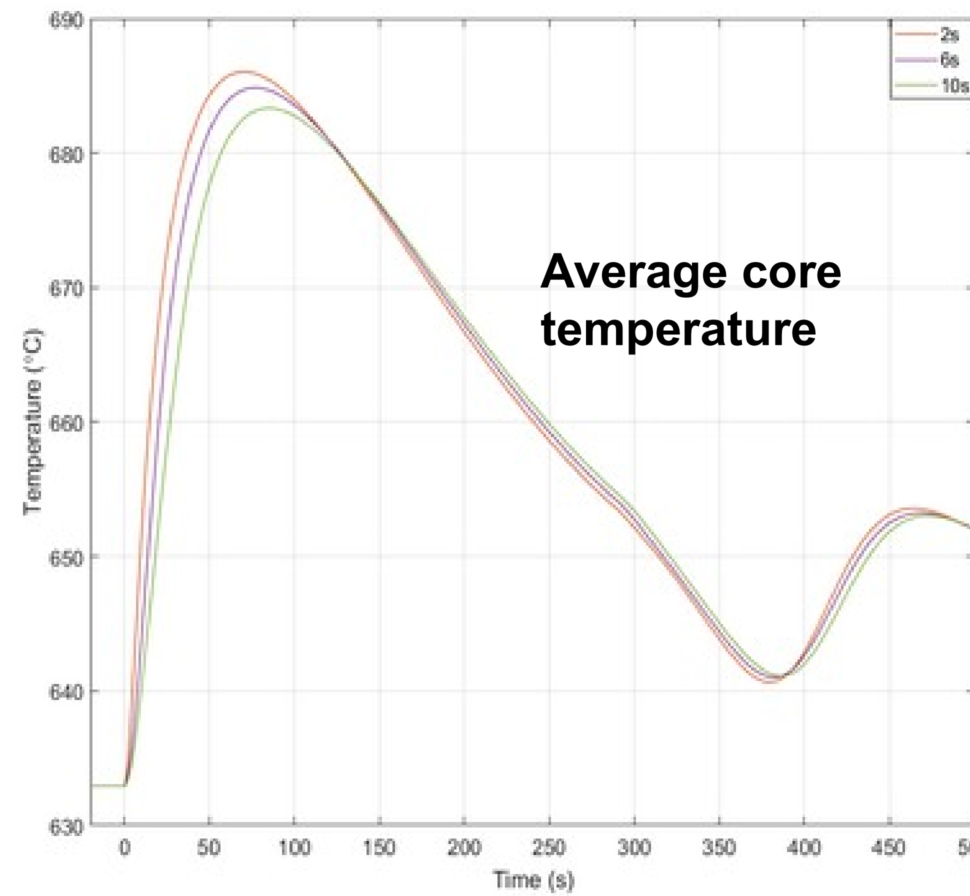




Modeling operational anomalies

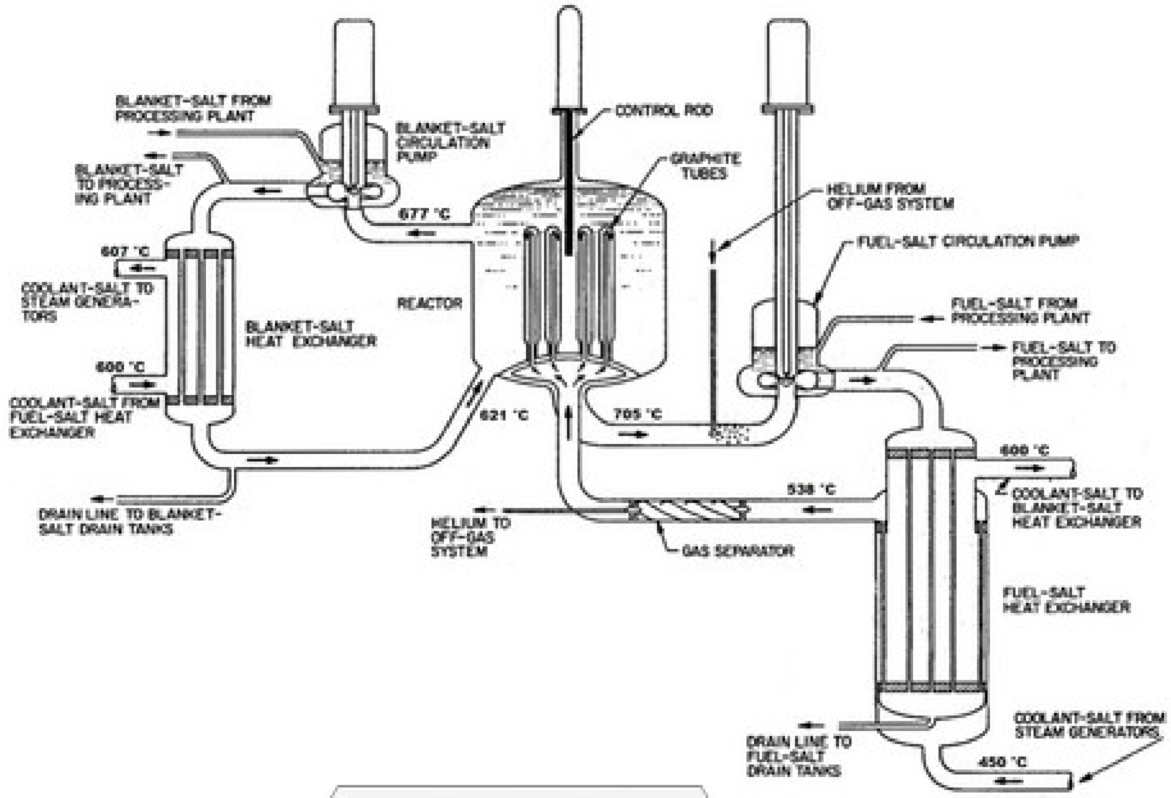
- Loss of flow in both primary loop.
- Starts at full nominal power (8MWth), no corrective action (control rods, salt heaters, etc.).
- No decay heat in this model.

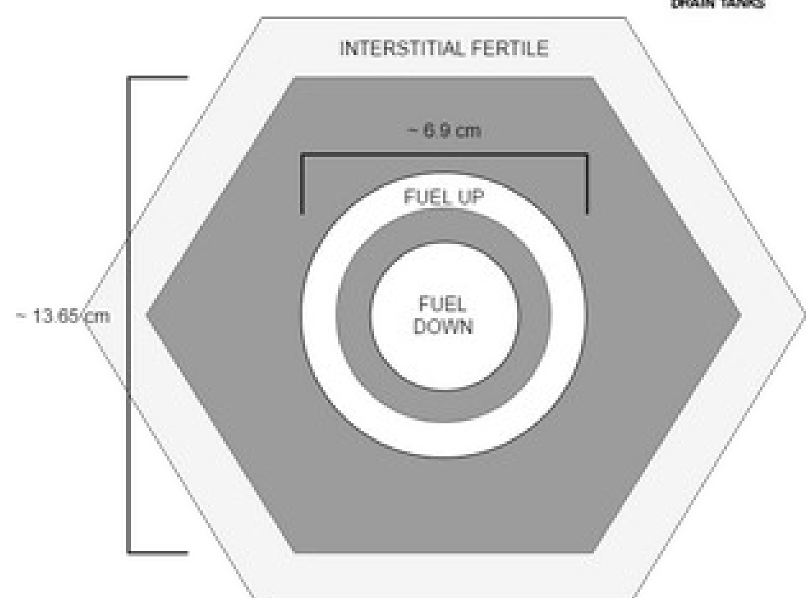




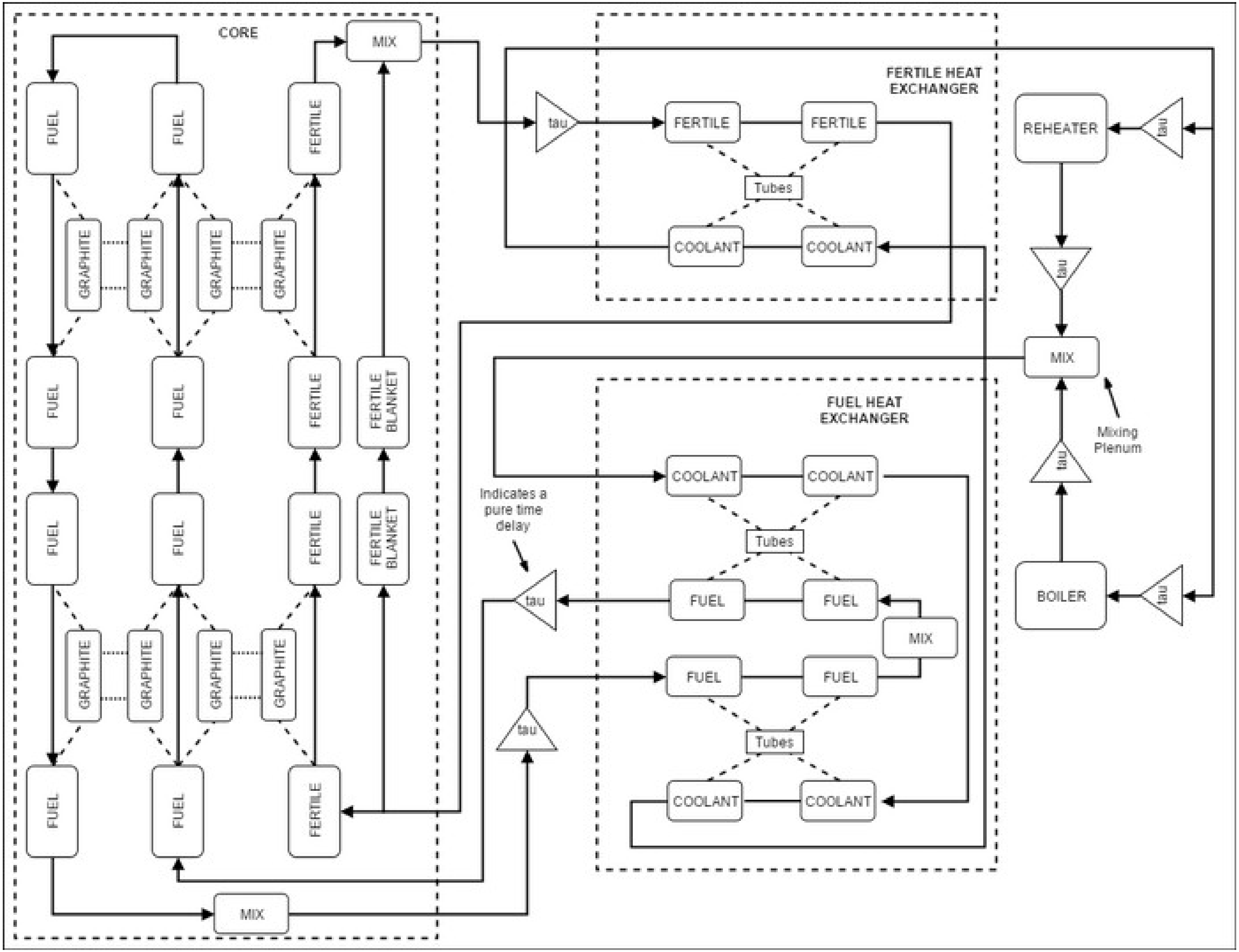
Two-fluid Molten Salt Breeder Reactor

- ORNL-4528
- 4 reactor modules 556 MWTh each, powering one 1000MWe turbine.
- Modeled up to boiler and reheater.
- $^{7}LiF\text{-}BeF_2\text{-}UF_4$ fuel salt, $^{7}LiF\text{-}BeF_2\text{-}UF_4$blanket salt in separate flow channels.
- Thorium breeder, LFTR



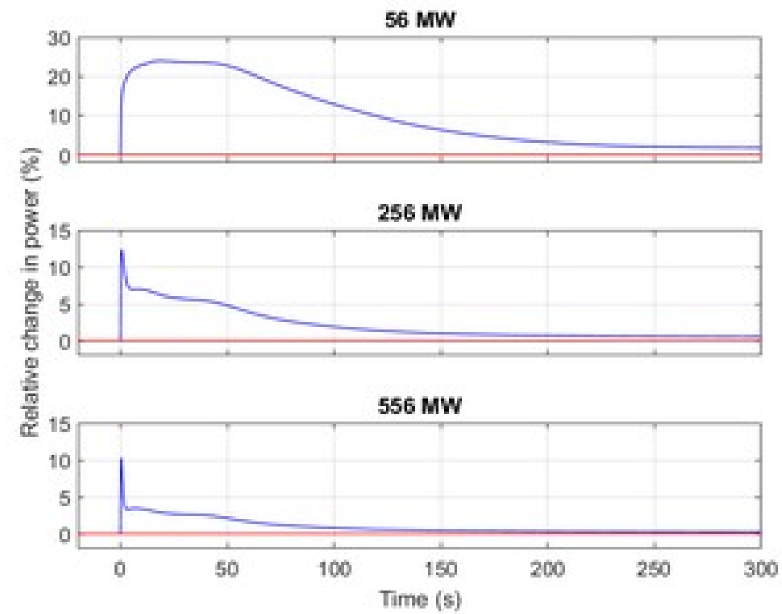


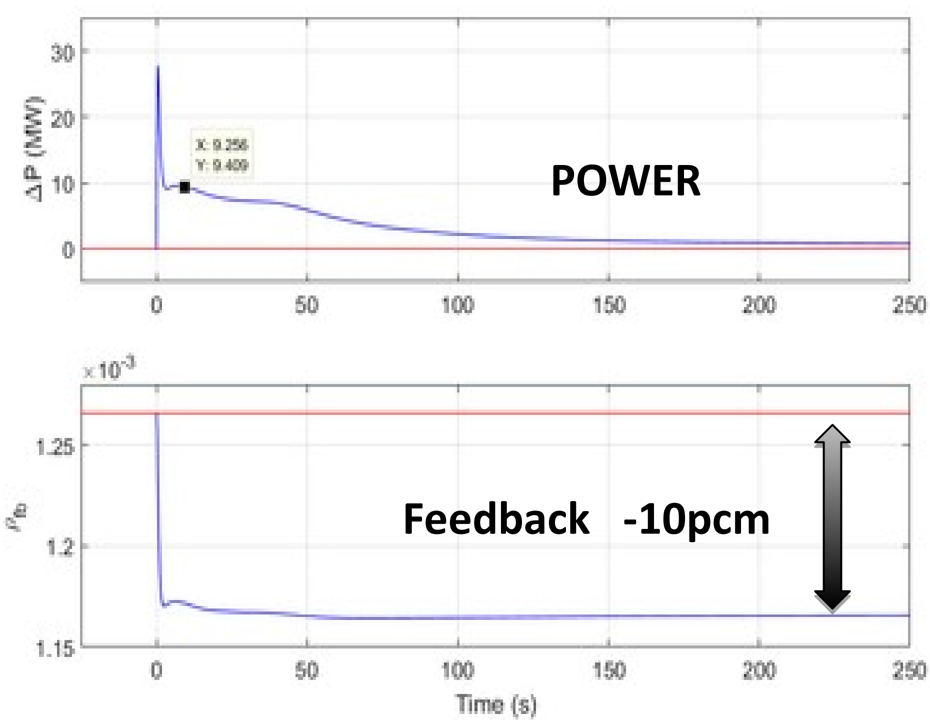
Lumped-parameter representation of MSBR

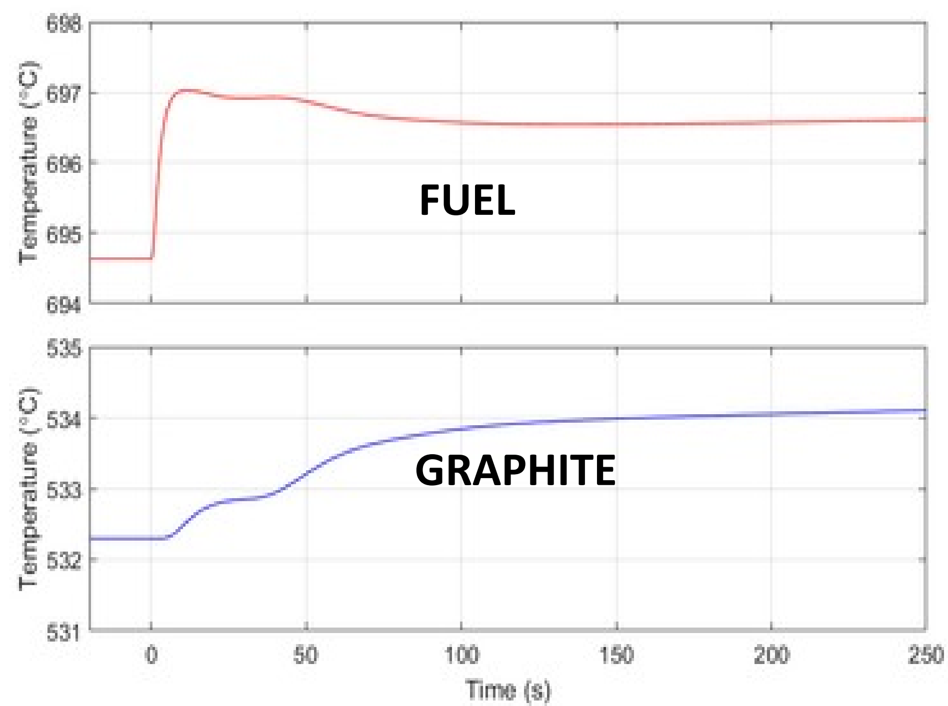


Response to +10 pcm step reactivity

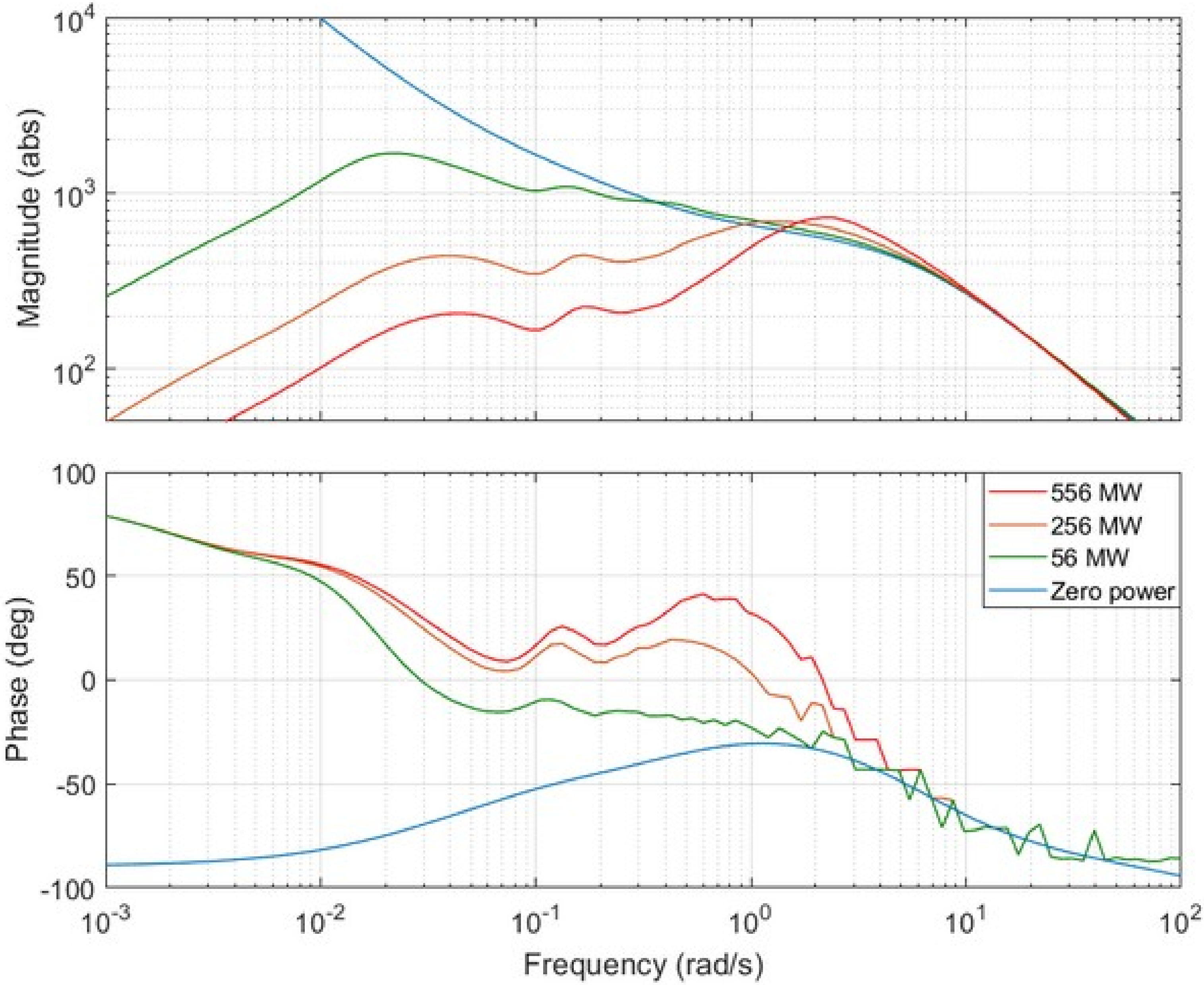
- Stable behavior, the higher operational power the faster damped by feedbacks.
- Fuel and moderator temperature rise.







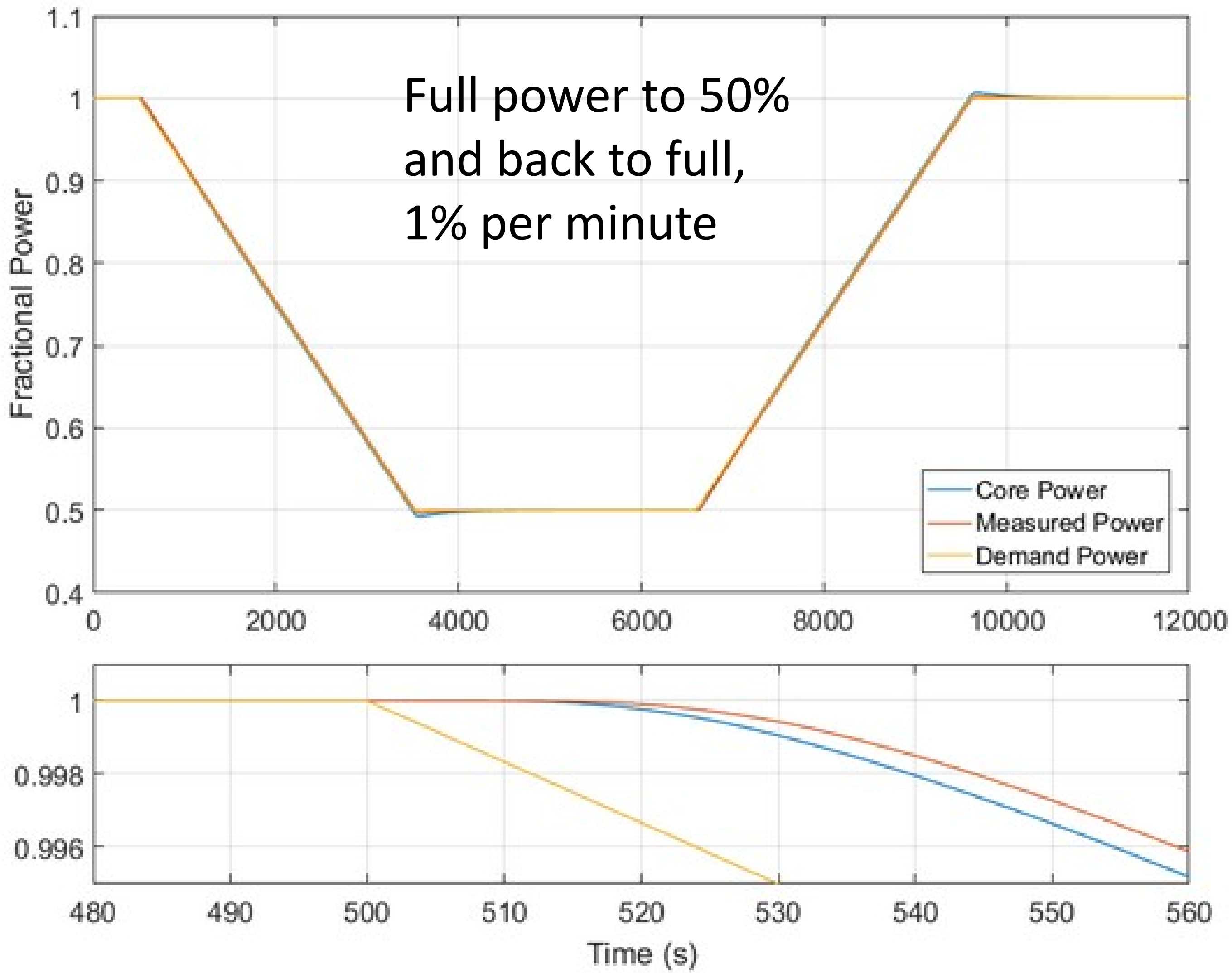
MSBR frequency characteristics



Load-following via reactivity feedback

- Demand driven core power with no other action.
- MSRs – low pressure, constant flow rate.

- Change in power corresponds to change of temperature difference across the core and the heat exchangers.



Load-following via reactivity feedback II

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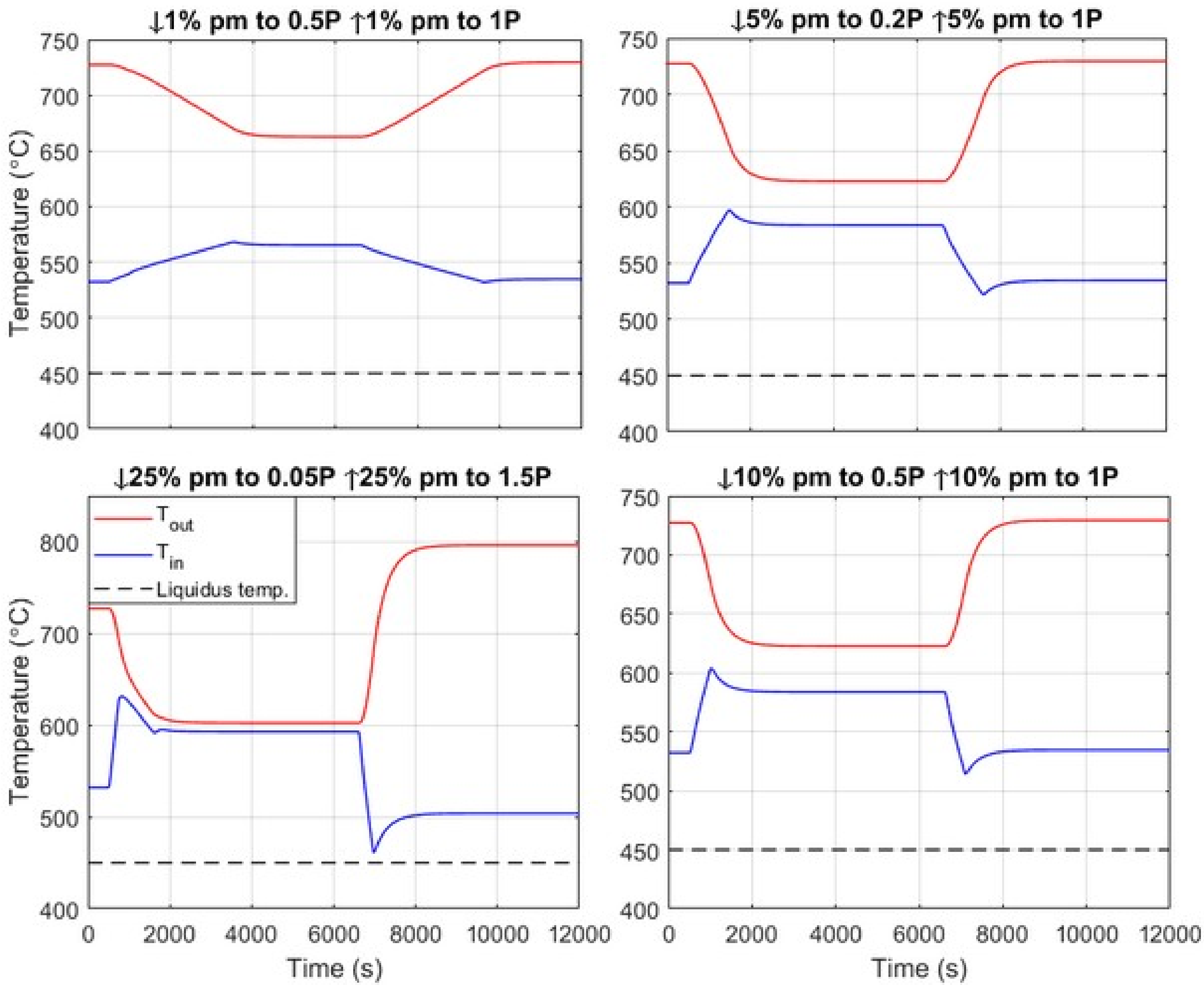
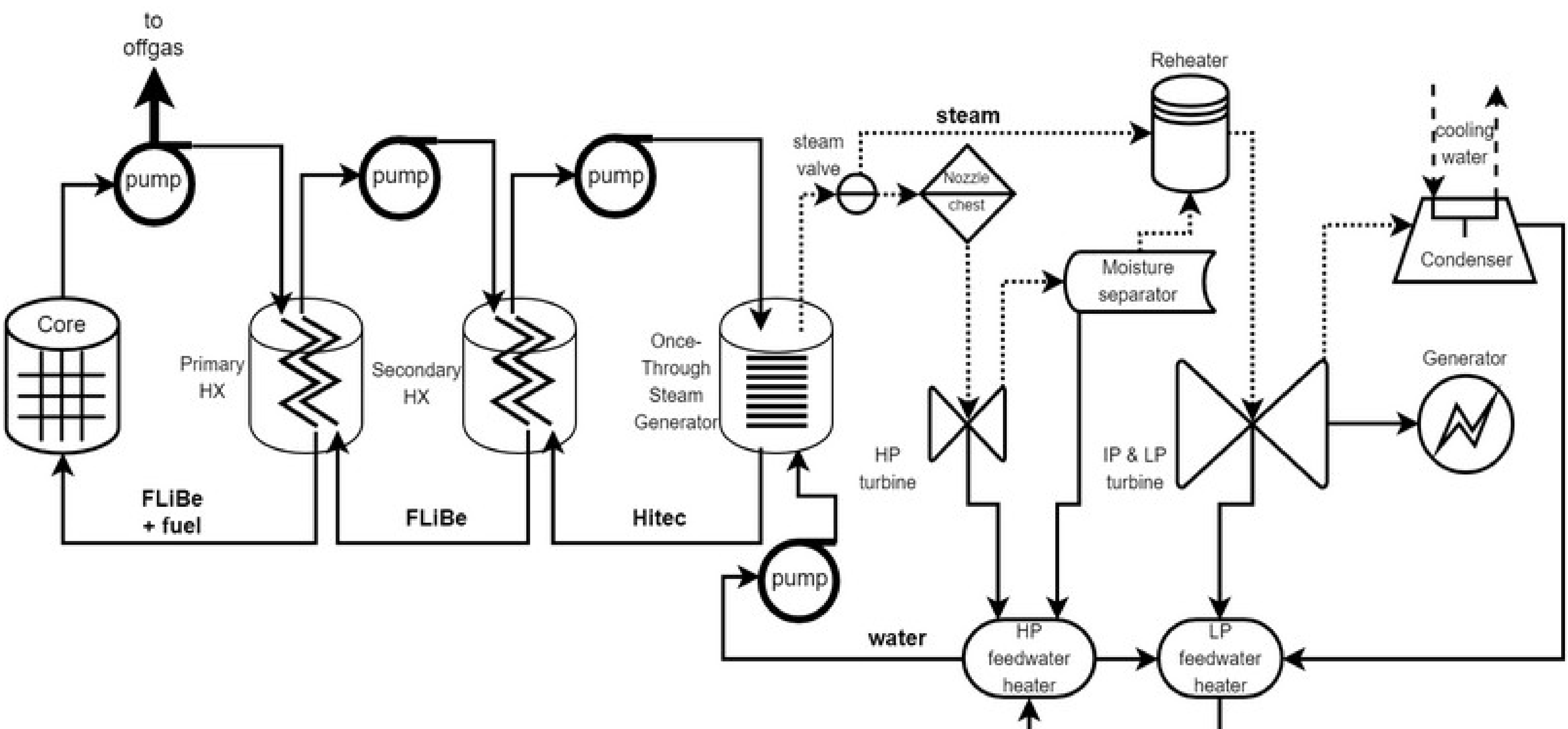
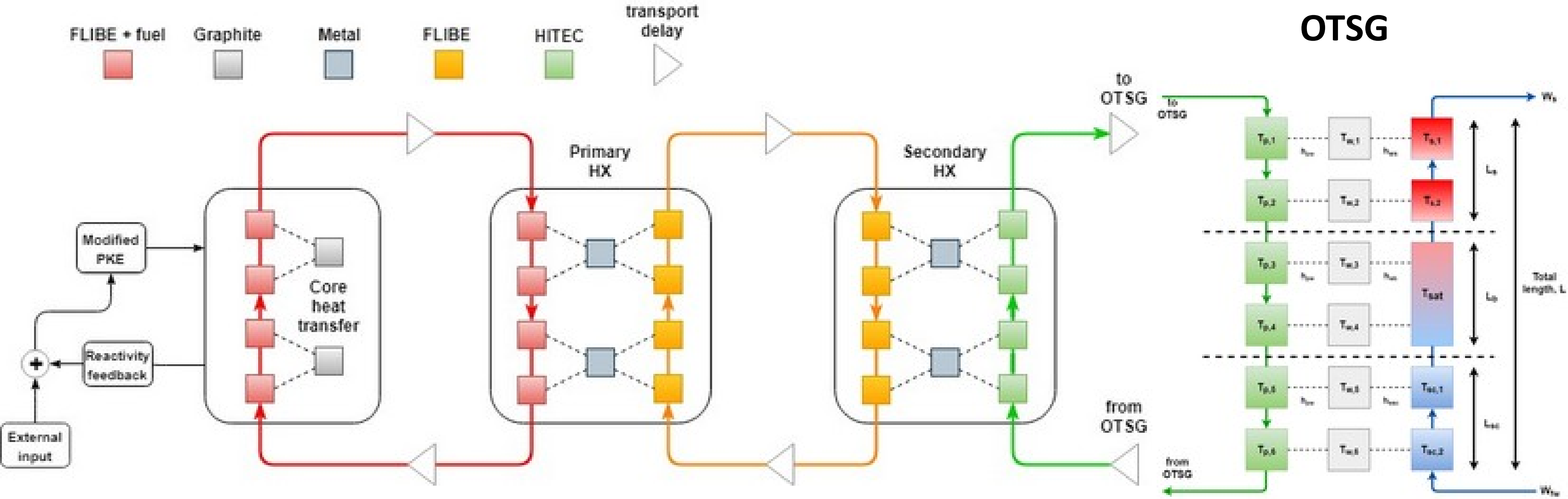


Full power plant modeling: MSDR, ORNL-TM-3832

- 750 MWth/350 MWe reactor fueled with LiF-BeF_2-ThF_4-UF_4
- Semi-commercial test-bed reactor, bridge to MSR breeders
- 3 primary loops, each with a secondary and tertiary loop
- Hitec (KNO_3-$NaNO_2$-$NaNO_3$) salt loop to capture tritium



Lumped parameter model



Neutronics

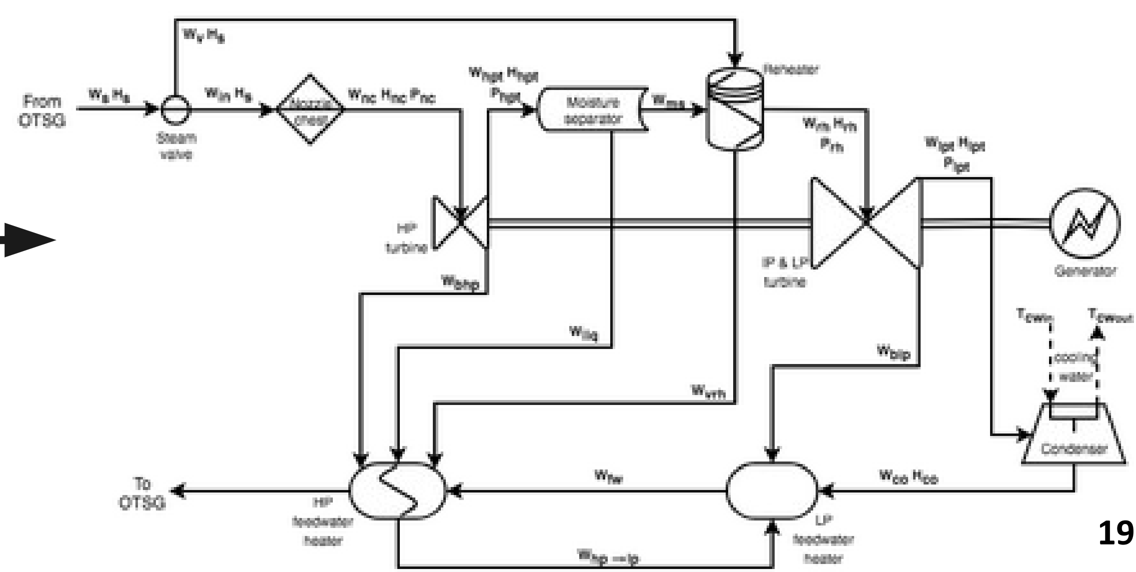
Primary loop

Secondary loop

Tertiary loop

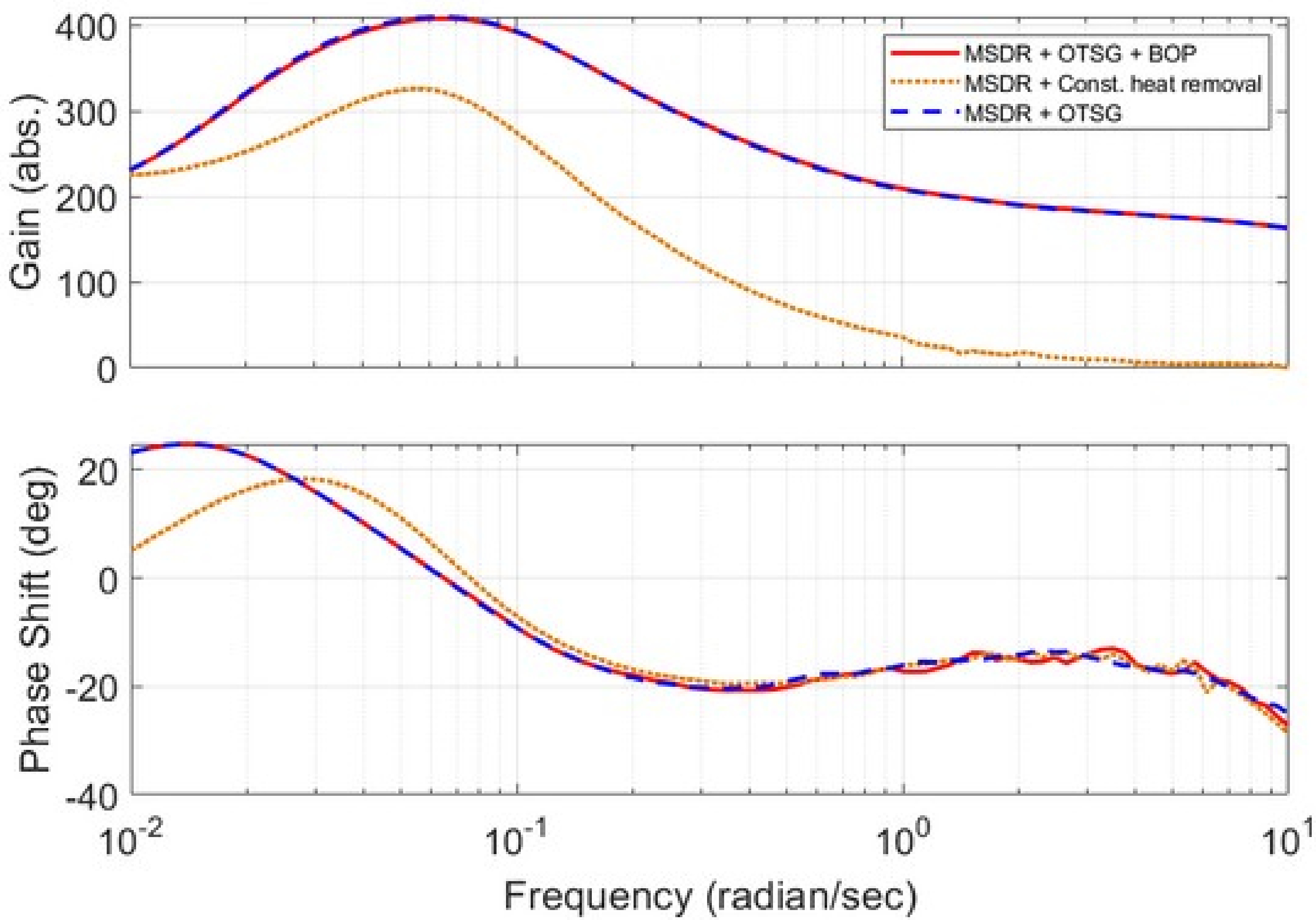
Steam

Reheated regenerative Rankine cycle balance of the plant



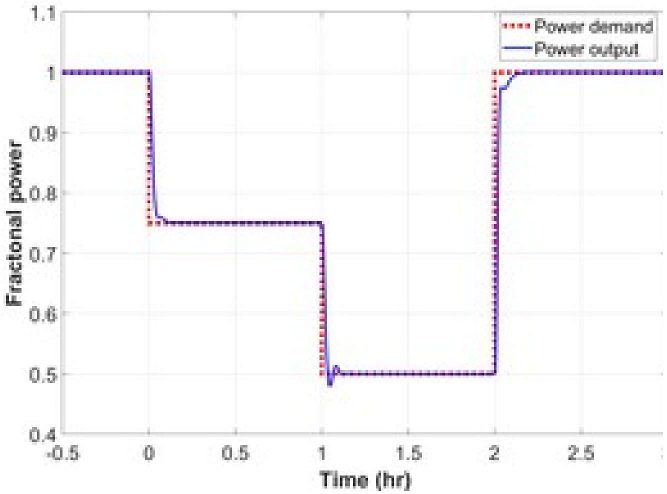
Full-plant frequency response

- Rankine BOP is complex. Does frequency behavior depend on its details?
- Steam generator matters, BOP does not.

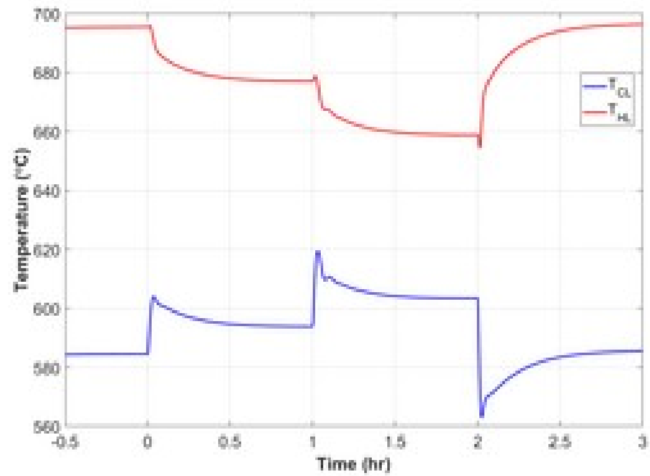


MSBR demand load following

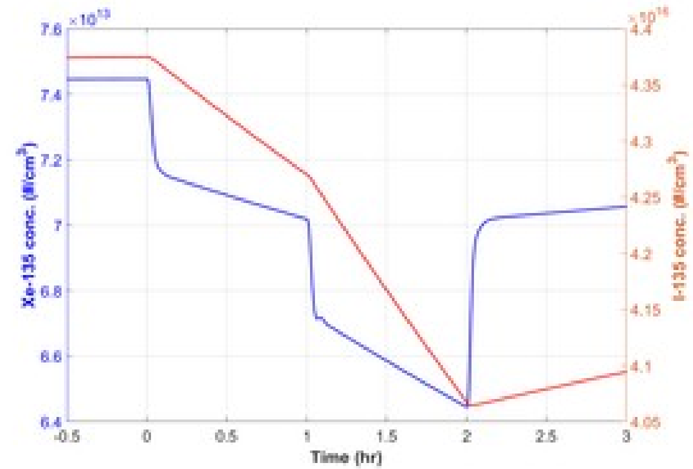
Power: core and demand



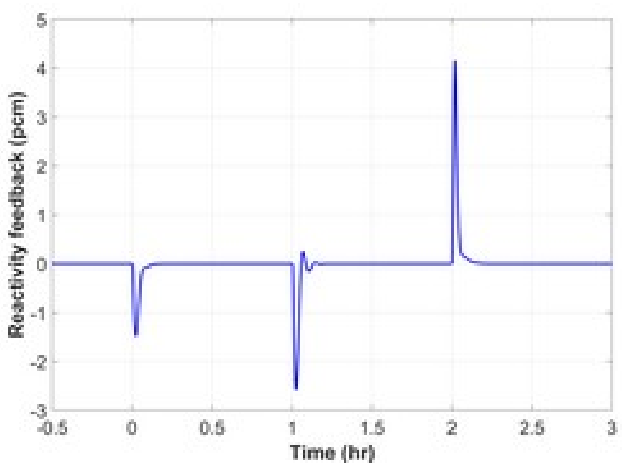
Temperatures: core in and out



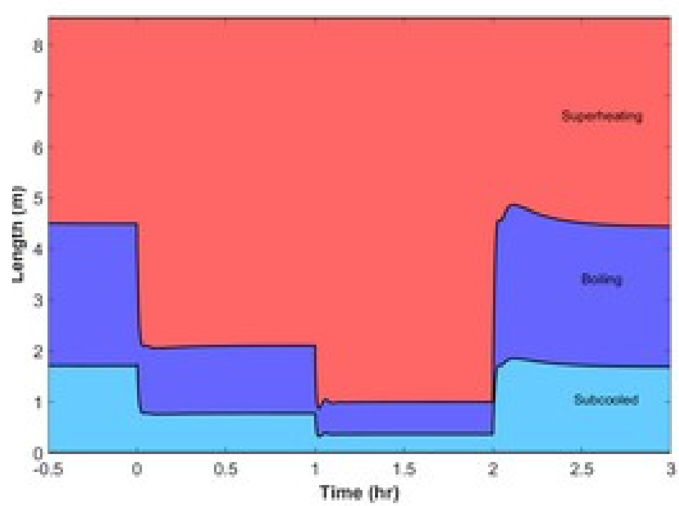
Concentrations of Xe-135 and I-135



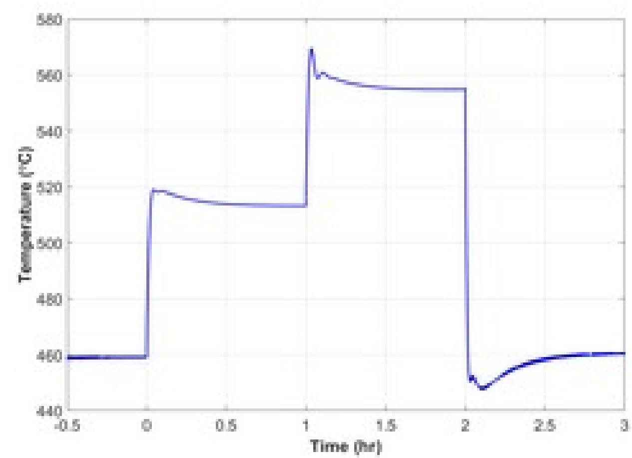
Reactivity feedback



Levels of OTSG regions



Steam temperature

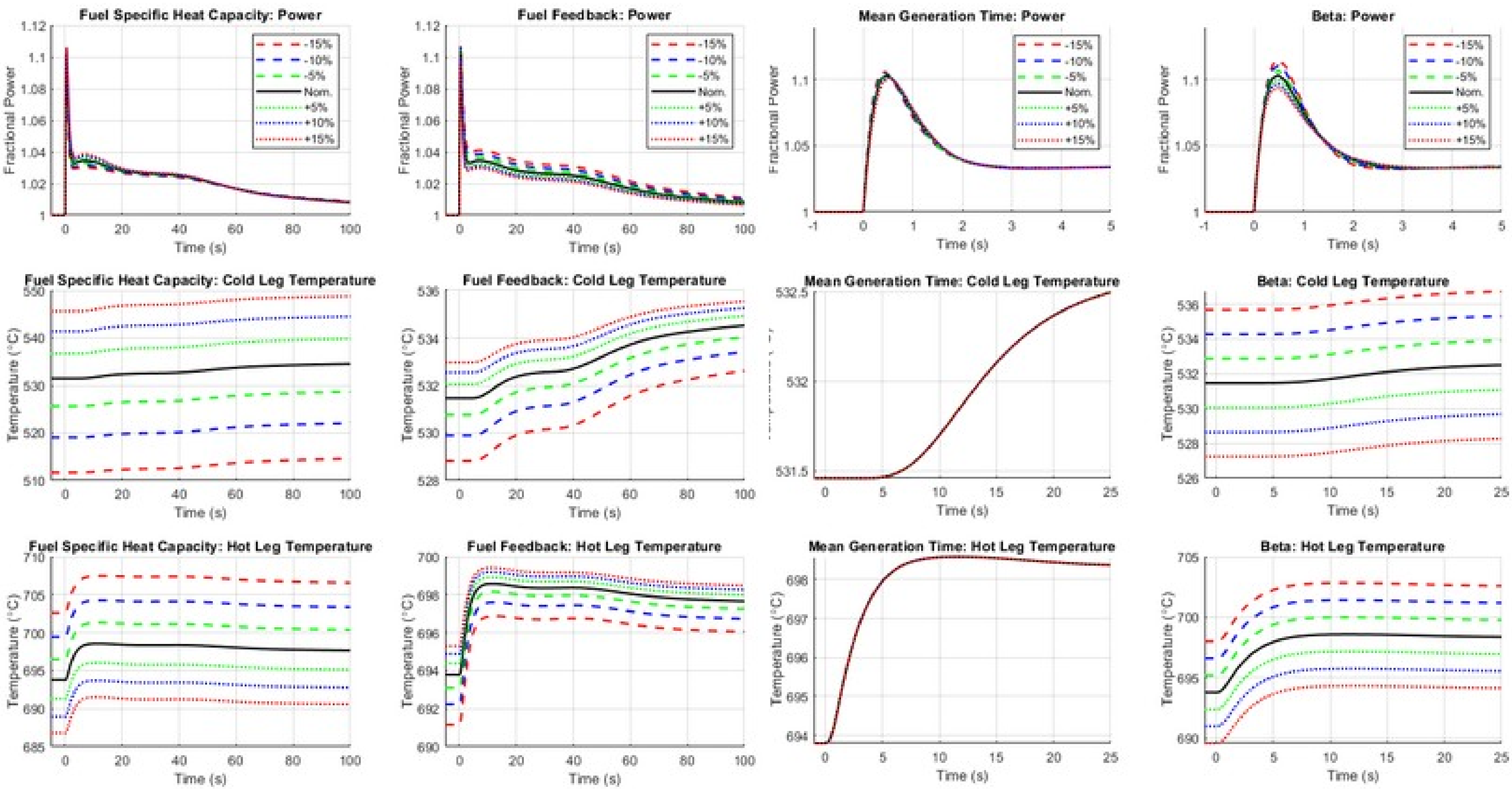


Sensitivity analysis

- MSR models have hundreds of parameters, many evolve with fuel depletion.
- Measuring these is expensive and time consuming
- Parameter sensitivity → research priorities.
  - Sensitivity analysis is a mathematical technique to determine how input changes affect output.
  - One-at-a-time approach used (other techniques exist).
  - Behavior can be explored in time and frequency domains.
  - Inform design and maintenance decisions.
  - Help establish safety margins.

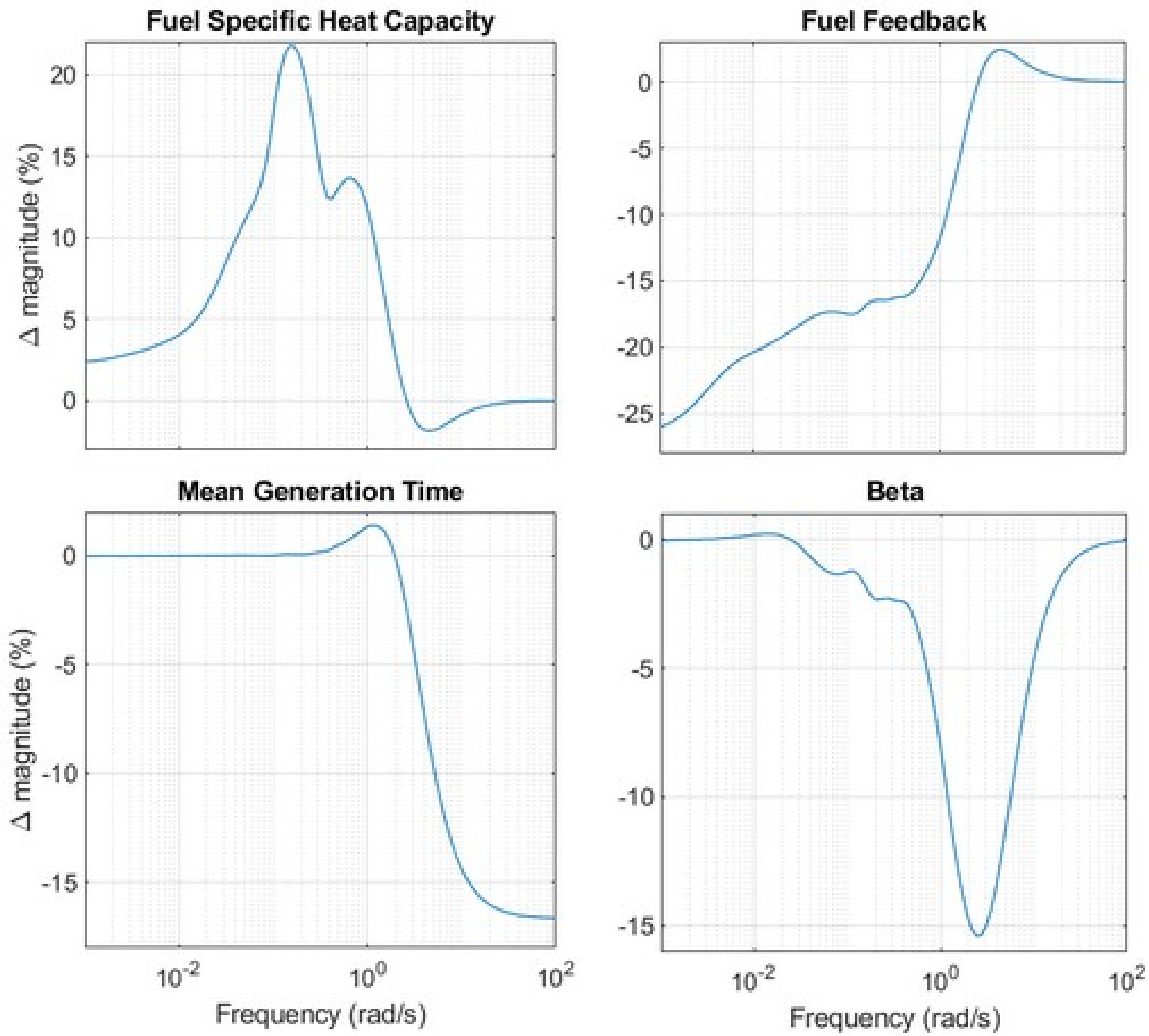
Time domain sensitivity

- Select parameters perturbed by -15% to +15%
- Response to +20pcm reactivity insertion is shown.



Frequency domain sensitivity

- Change in amplitude for +20% change in parameters.
- MSDR power response change is sensitive at different frequencies.
- Characteristic features present an opportunity to determine changes in reactor parameters by measuring power response.

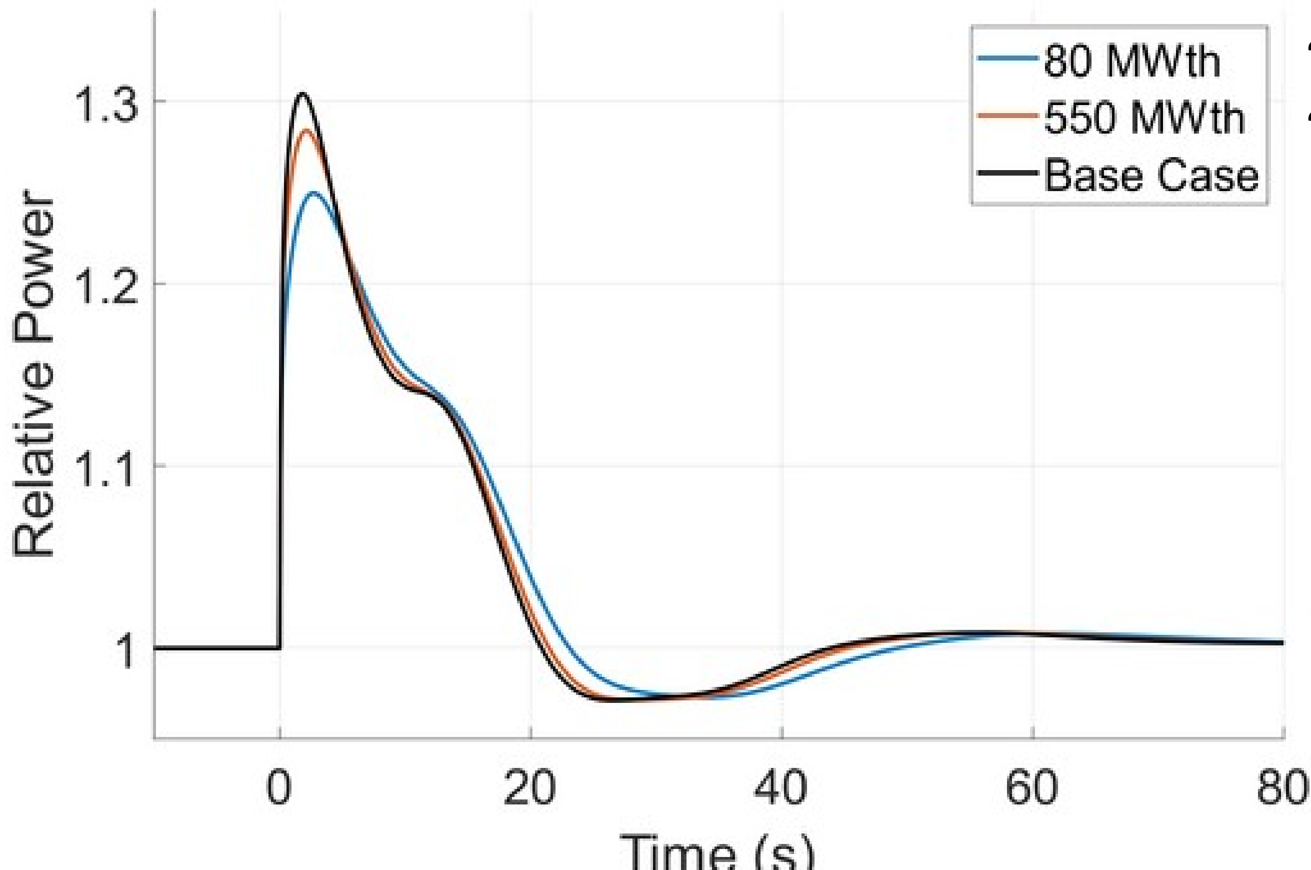


Safeguards: Detecting Plutonium Diversion

- International Safeguards are required for global deployment of any reactor design.
  - IAEA significant quantity (SQ) of Plutonium: 8kg.
- MSRs have no agreed upon method for safeguarding.
- Traditional item counting does not apply for MSRs.
- In a loss of the continuum of knowledge, there needs to be a means of material accountancy in the fuel salt.
- Liquid (mixed) fuel: unique opportunity for new ideas.
  - Fuel sampling. Time capsules of fuel depletion history.
  - Liquid fuel level measurements.
  - Characteristic changes in frequency response.
- Can frequency analysis detect 1SQ diversion of Pu?

Response to 50 pcm step insertion

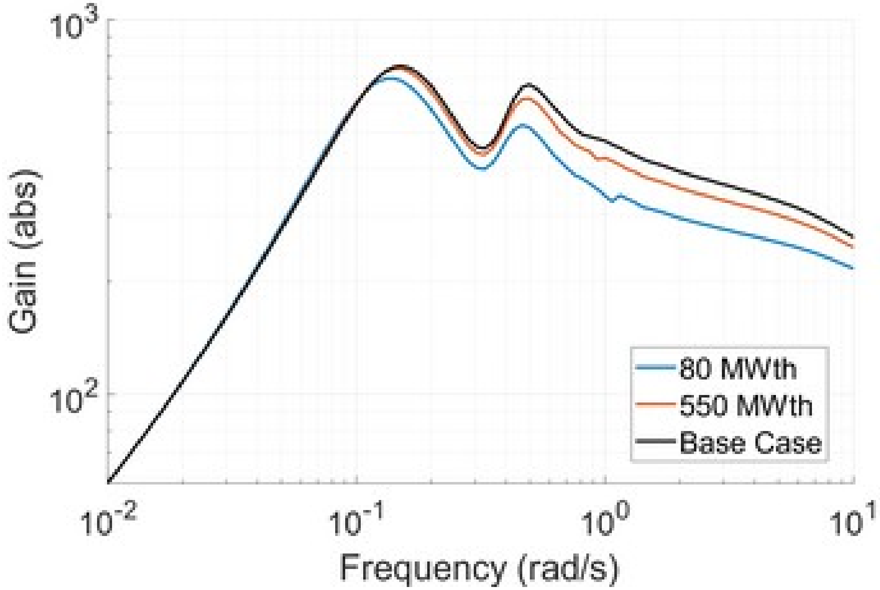
- Removal of plutonium changes delayed neutron fraction.
- Time response to reactivity insertion after 1 SQ removal is hard to resolve even for small reactors



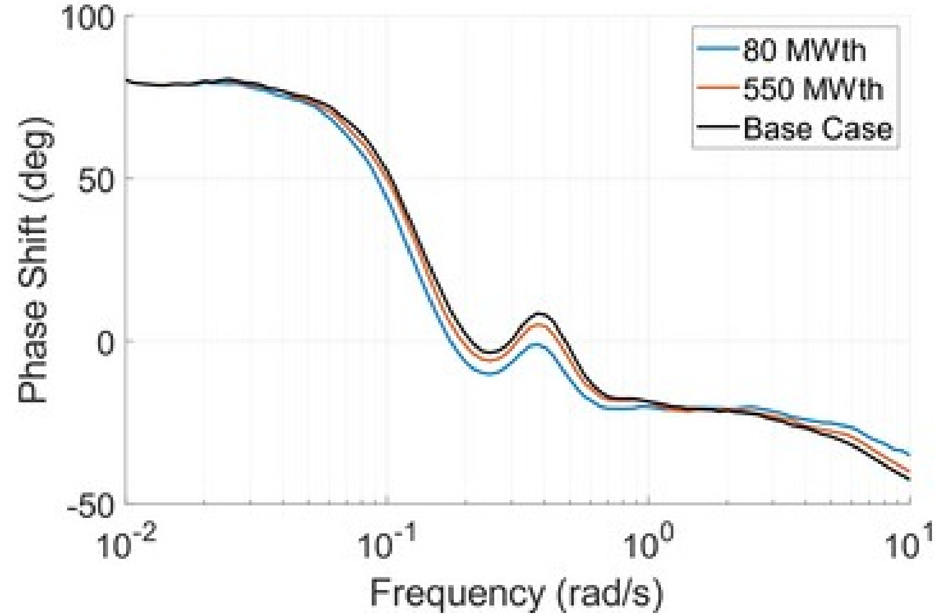
% Pu removed
~100%
~15%

1SQ out: Frequency characteristics and its change

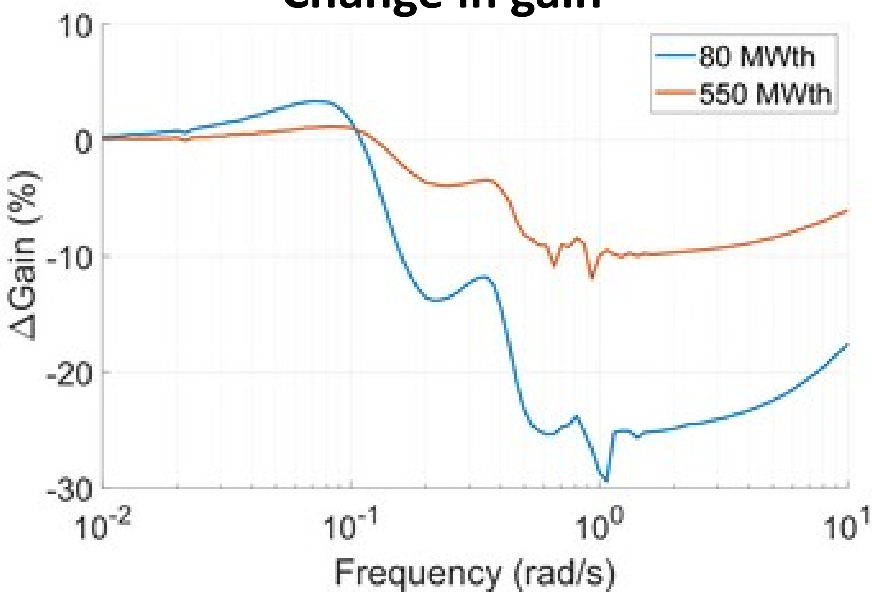
Gain



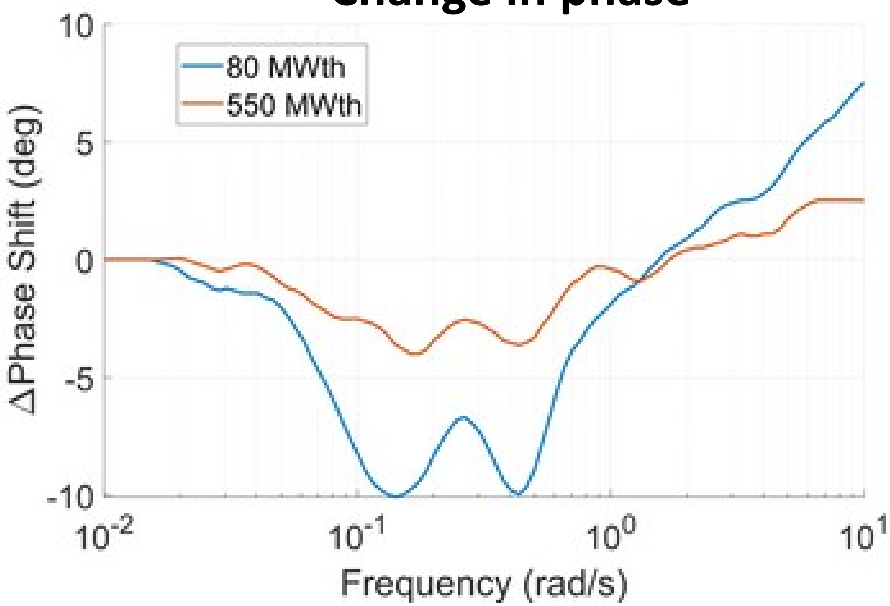
Phase



Change in gain



Change in phase



Decay heat production and removal

- Removal: generic decay heat removal system (DHRS)
  - Logistic curve:

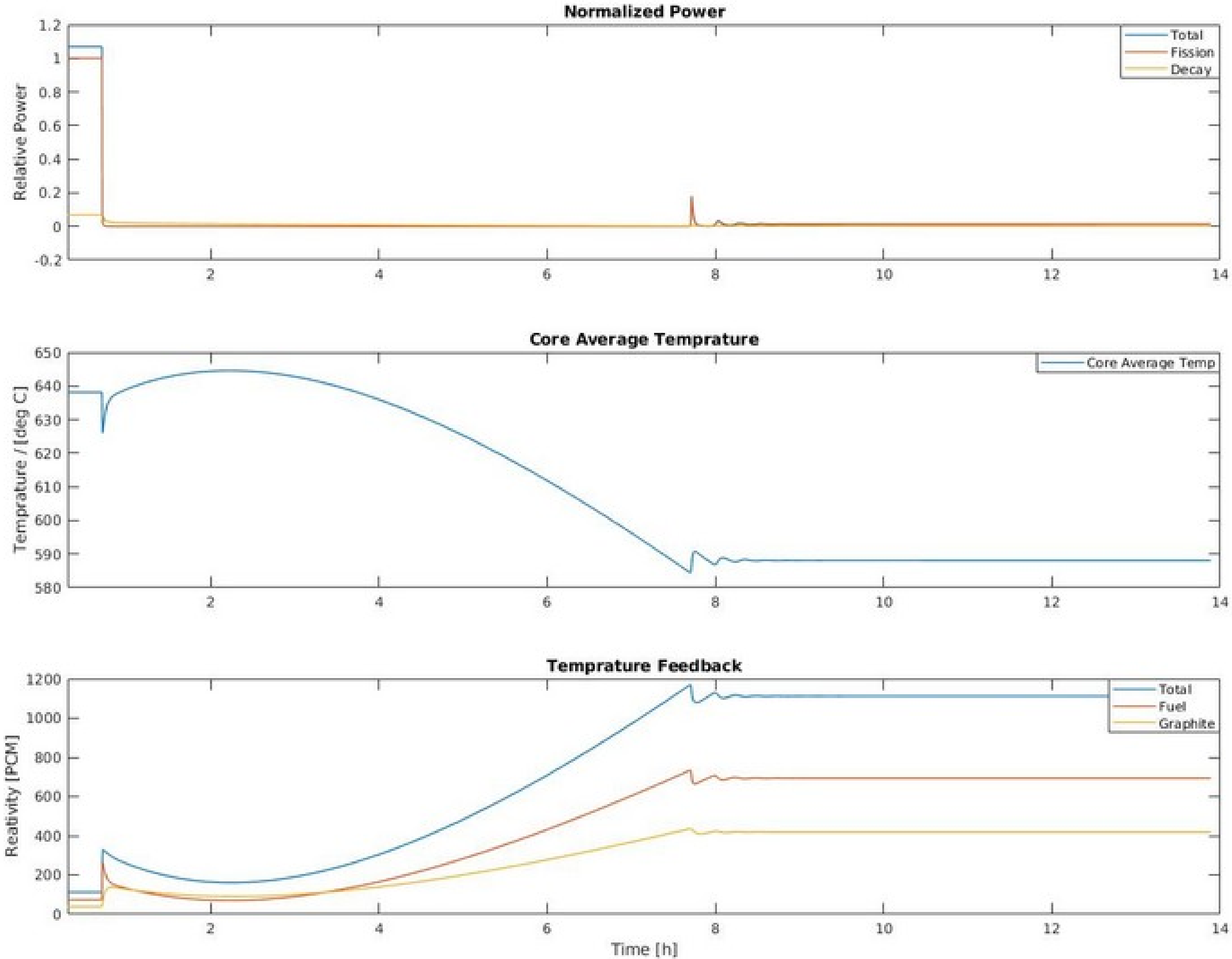
$$P_{DHRS}(t) = \frac{P_{max} - P_{min}}{1 + \exp[(1 - \frac{t - t_0}{t_{DHRS}}) + \ln(1/\epsilon - 1)]} + P_{min}$$

    - Parasitic and max heat removal, time to half power, start time.
  - Scope out functional requirements for a real DHRS.
- Dynamic decay heat production

$$\frac{P_d}{dt} = \sum_{i=1}^{i=N} \frac{dn}{dt} \delta \gamma_i - \lambda_i P_d(t)$$

  - rate of change = rate of production - rate of decay
- Example (next slide) of an off-normal transient:
  - Heat sink is blocked
  - Rods drop inserting 1000 pcm of negative reactivity
  - DHRS opens
-

BOP trip, rod drop, DHRS action



Conclusions

- MSRs: tremendous progress in the last 10 years!
- Dynamic modeling characterizes system behavior in time.
  - Useful for instrumentation and control.
  - Accident scenarios, parameter sensitivity to guide research.
  - Novel methods of safeguards.
  - Functional requirements for a decay heat removal system.
- Well designed MSRs are stable and can rapidly follow demand load.
  - Low pressure system with constant flow rates.
- Thank you for your attention. Questions?