Ian Kolaja PhD Exit Talk

Advanced Fuel Measurement and Operation Modeling for Pebble Bed Reactors

November 2025

Overview

Pebble bed reactors (PBRs) present unique challenges in burnup measurement and operational modeling.

My work explores a novel method for measuring discharged fuel pebbles and a ML framework for predicting the complex, time-dependent reactivity behavior of PBRs.

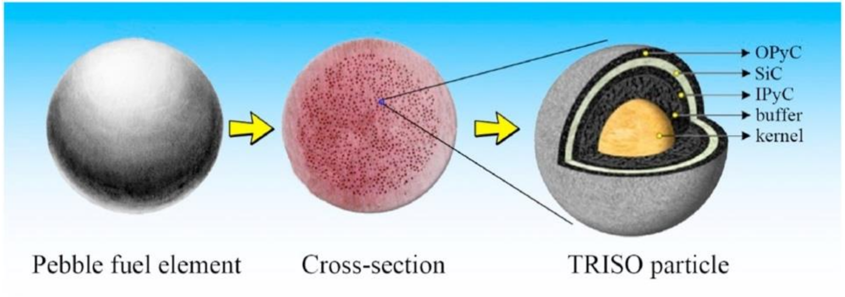
Outline

1. Introduction
2. Pebble Assessment with Bent Crystal Diffraction Spectrometers
3. Core State Prediction with a LSTM

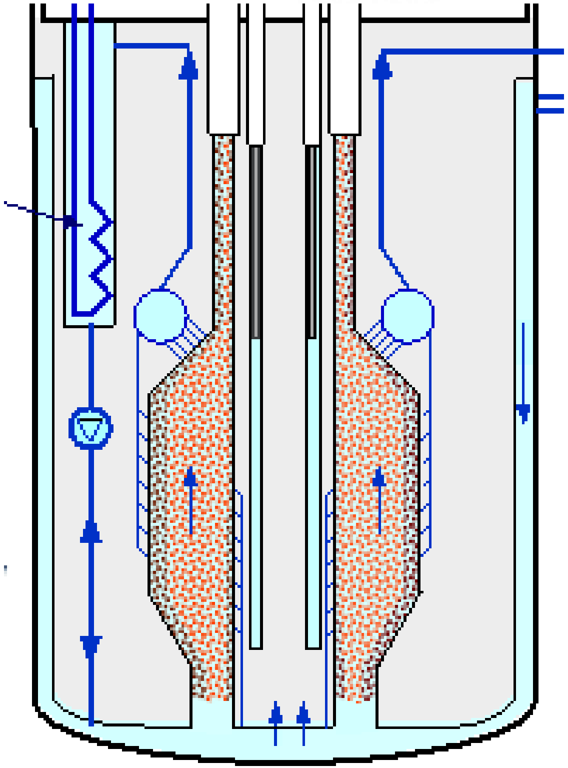
1) Introduction

Pebble Bed Reactor (PBR) Overview

- Use fuel "pebbles" instead of fuel rods
  - 10^4–10^5 pebbles in the core
  - Constant fuel circulation
- Features coolants other than water
  - Nonreactive gas (i.e. Helium)
  - Molten Salt (i.e. FLiBe)



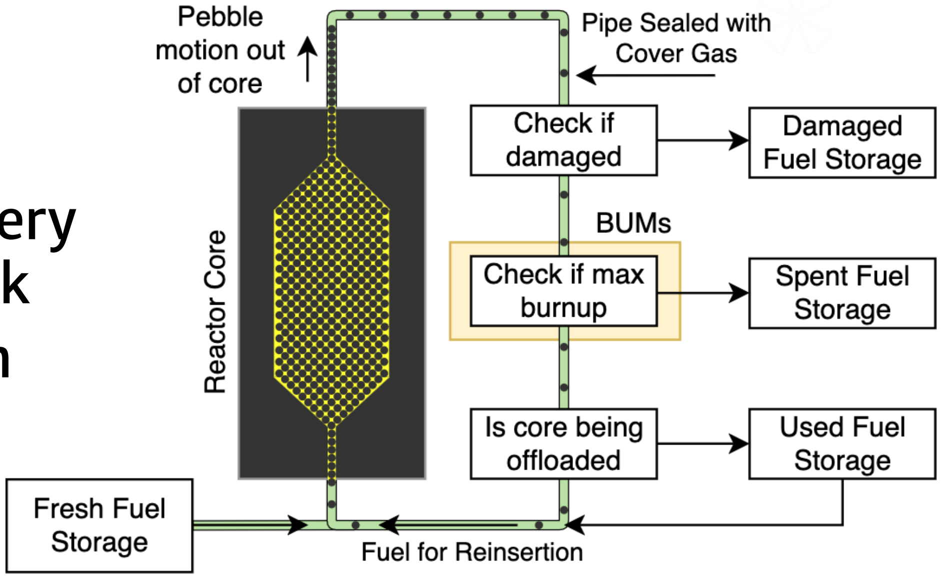
Schematic diagram of the pebble fuel, TRISO particle, and their relationship, Maolong Liu [1]



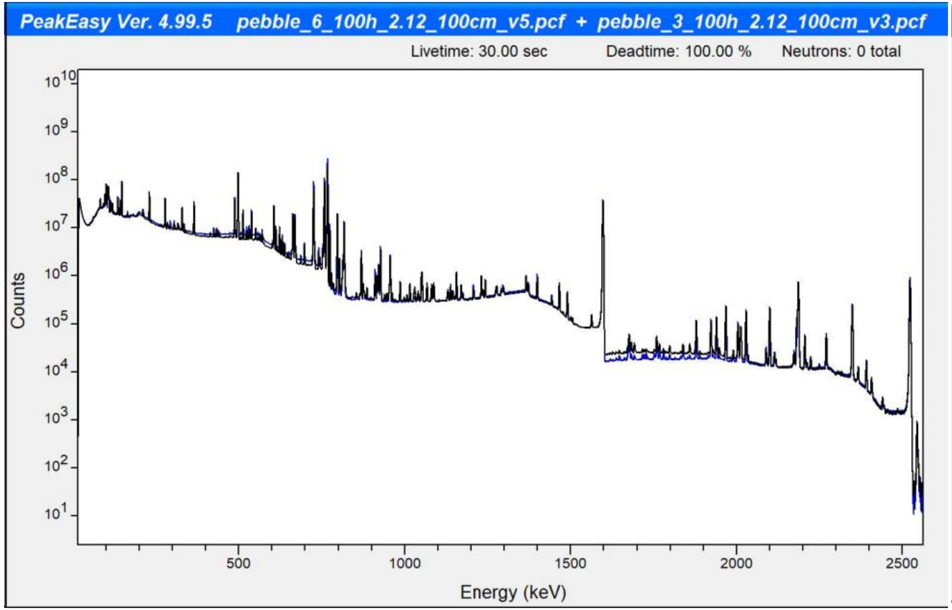
Mk1 PB-FHR schematic [2]

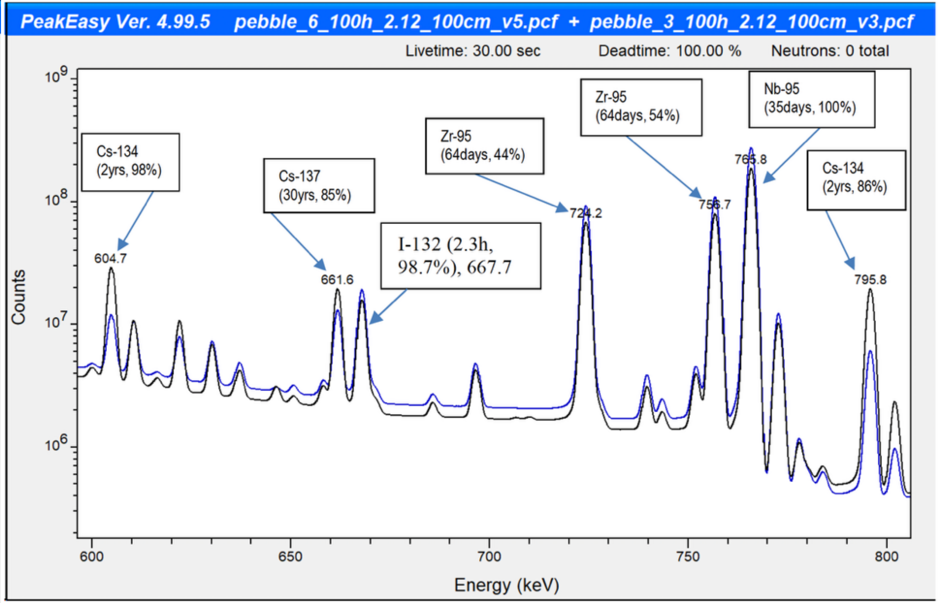
Burnup Measurement in PBRs

- ^{137}Cs is good burnup marker (661 keV gamma via ^{137m}Ba)
- Measuring burnup for PBR pebbles is hard
  - Pebbles leave the core every ~20s in Kairos benchmark
  - High activity (10^{13} Bq) can cause dead time in many detectors
  - Compton scattering and spectrum crowding can mask 661 keV peak



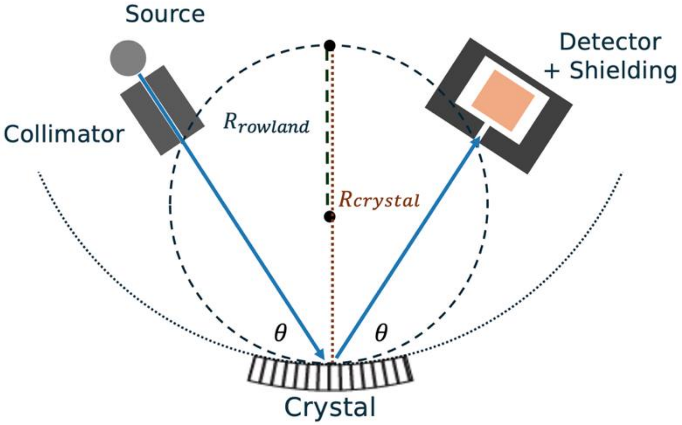
Example Gamma Spectra from discharged PBR fuel





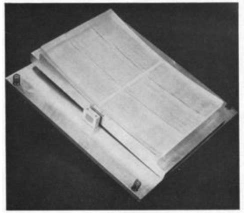
Synthetic HPGe spectrum generated with GADRAS by Don Kovacic [3]. The wide spectrum is shown (a) and the region around the 137Cs peak (b). Note the 30 second measurement time, 100% deadtime, and bin counts ranging from 10^6 to 10^8.

2) Pebble Assessment with Bent Crystal Diffraction Spectrometers

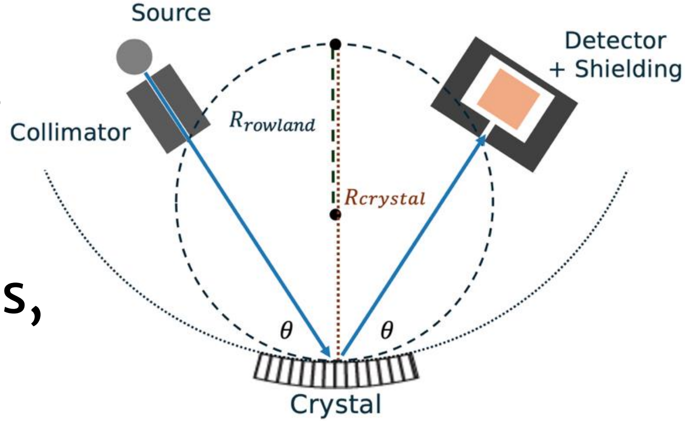


Bent Crystal Diffraction Spectrometers

- BCD Spectrometers offer a potential solution by acting as an energy filter
  - Uses perfect or mosaic crystal lattice as a diffraction grating
  - Constructively diffracts and focuses gammas entering the crystal at a certain angle and energy
  - Used in nuclear physics, astrophysics, synchrotrons, and nuclear forensics



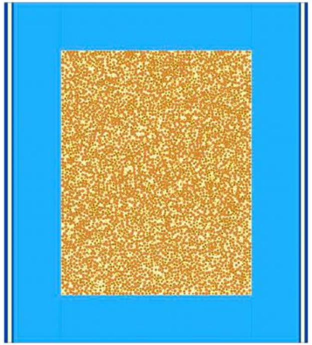
Picture of crystal [4]



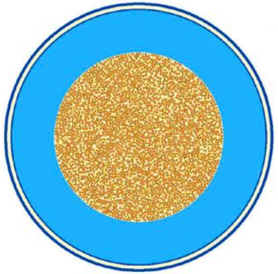
Schematic of BCD spectrometer for PBR

Pebble Data Generation

- Pebble-wise depletion performed with HxF
  - Kairos gFHR model
  - 250,000 pebbles in core, average 8 passes
- History, parameters of interest, and nuclide inventory predicted for each pebble
- Serpent used to generate emitted gamma spectra for each pebble
  - 1.5 day decay time assumed

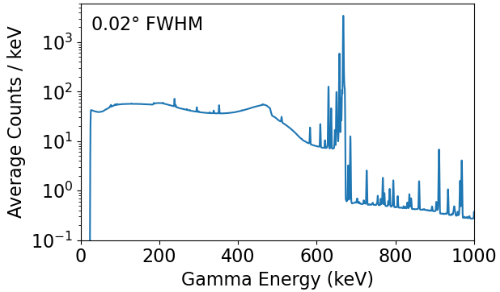


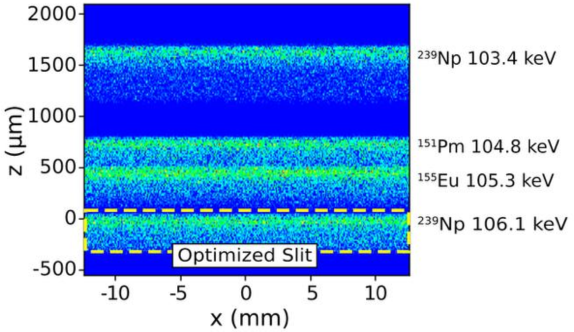
gFHR benchmark diagram



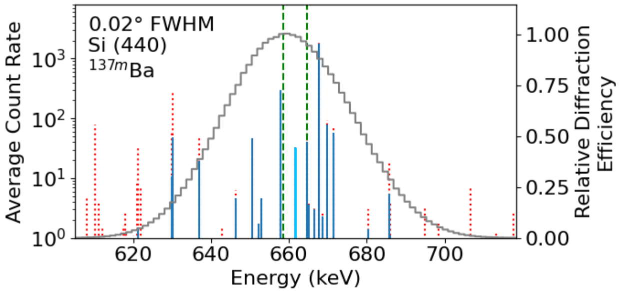
Generating Synthetic Measured Spectra

- SHADOW and GADRAS used
- Selected gammas: **661keV from ^{137m}Ba, 106 keV from ^{239}Np**, 133 keV from ^{144}Ce, 414 keV from ^{148m}Pm, 1596 keV from ^{140}La

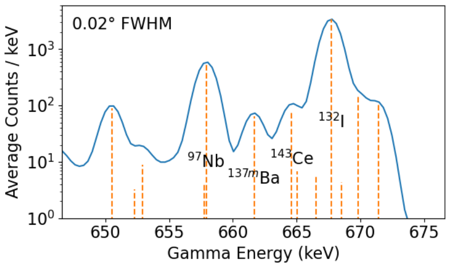




Example diffraction pattern incident on detector with slit shielding

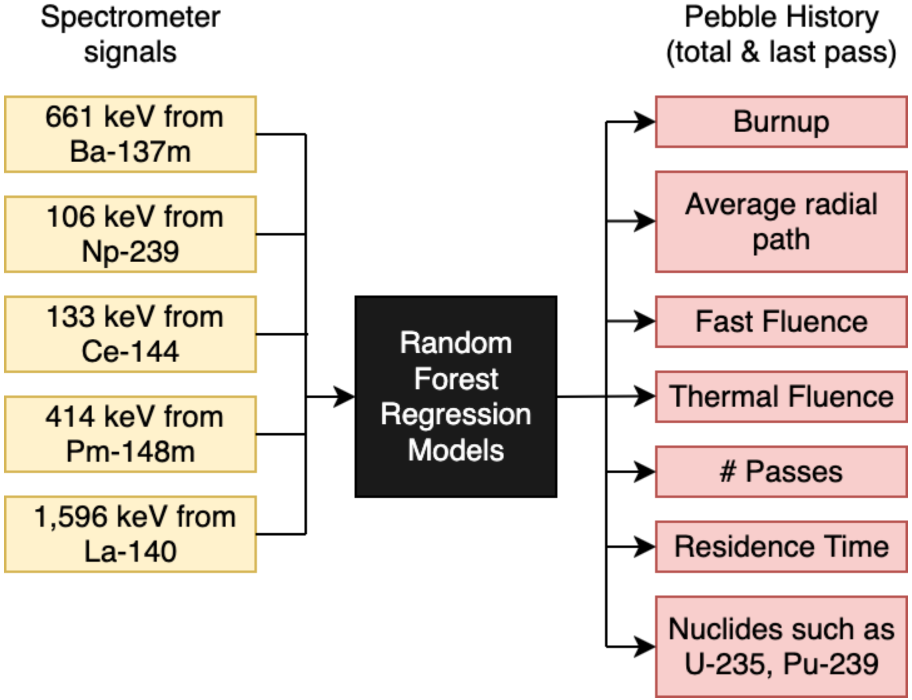


Pebble emission spectra with spectrometer filter overlay



GADRAS simulation from incident ^{137m}Ba spectrum

Regression for Pebble Assessment



Regression scores for regression performance

Parameter (cumulative)	Synthetic Spectrometer MAPE	Synthetic Spectrometer R^2	“Ideal” R^2
Burnup	2.28%	0.9953	1
# of Passes	2.27%	0.9880	0.9994
Residence Time	2.57%	0.9882	0.9994
^{239}Pu Content	5.11%	0.8862	0.8883

Parameter (last pass)	Synthetic Spectrometer MAPE	Synthetic Spectrometer R^2	“Ideal” R^2
Burnup	1.59%	0.9944	0.9948
Avg. Radial Path	10.84%	0.8793	0.8814
Thermal Fluence	3.51%	0.7425	0.8164
Fast Fluence	4.03%	0.9191	0.9270

Conclusions and Future Work

- BCD spectrometers are a powerful tool for rapid fuel pebble assessment
- ML-powered regression enables accurate prediction of many pebble properties and history parameters
- Future design optimization based on footprint or cost constraints recommended
- Experiments verifying the BCD spectrometer properties and performance in relevant environments needed

Core State Prediction with a LSTM

PBR Operation Challenges

- In-core measurements limited
  - High temperature/flux causes thermocouple drift
  - Dynamic bed leaves little room for flux detectors
- Reactivity management more complex
  - Fuel handling and operation affect reactivity on multiple time scales
  - Excess reactivity kept low and nearly constant
  - "Running-in" to equilibrium can be achieved in various ways

Factors that affect reactivity in PBRs

Short Term — **Long Term**

Control rod movement

Pebble circulation rate change

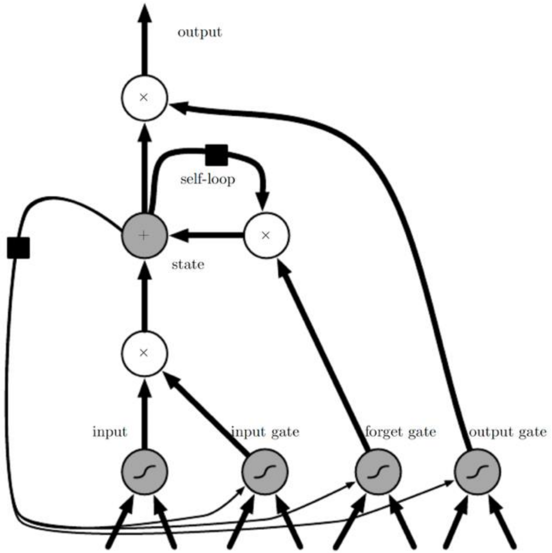
Change to fuel insertion pattern

Power change

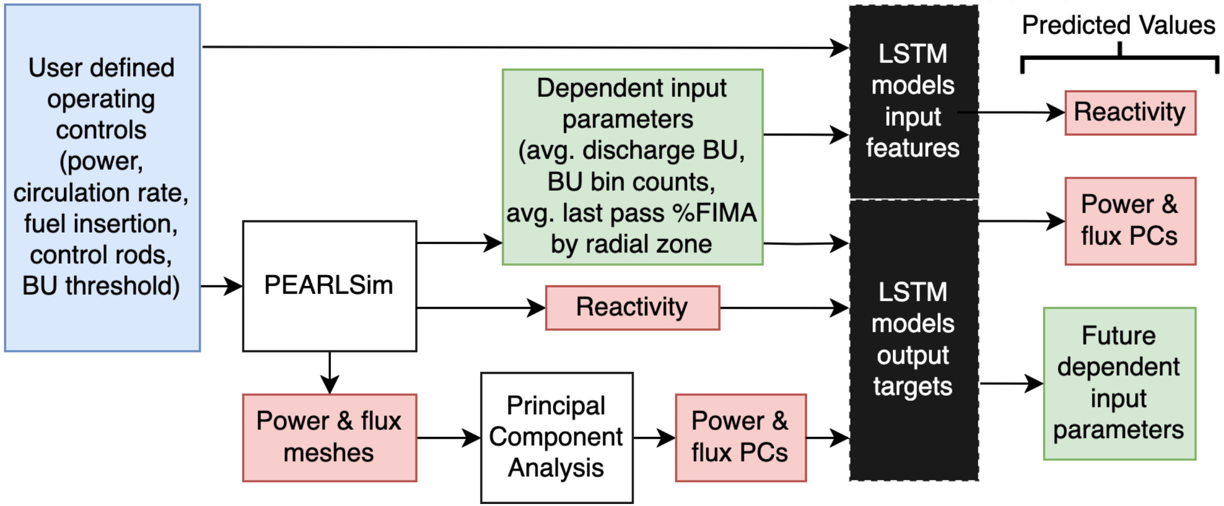
Change to burnup limit

Fuel depletion, or burnup

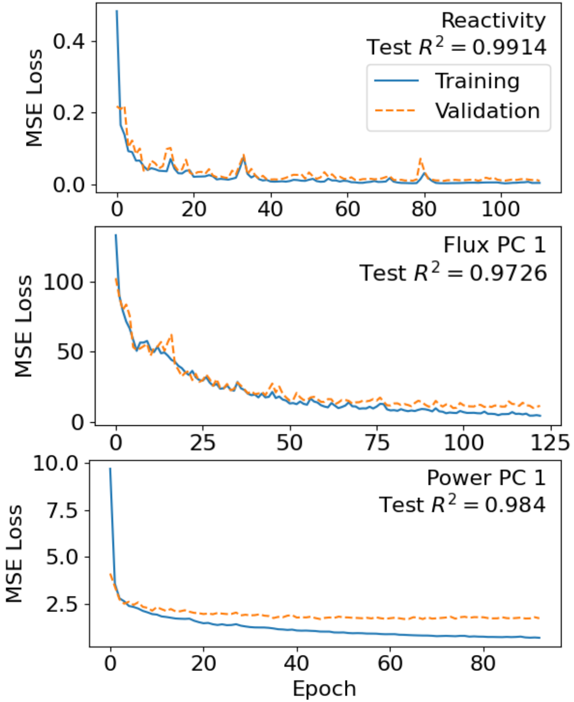
Long-Short Term Memory (LSTM) Network



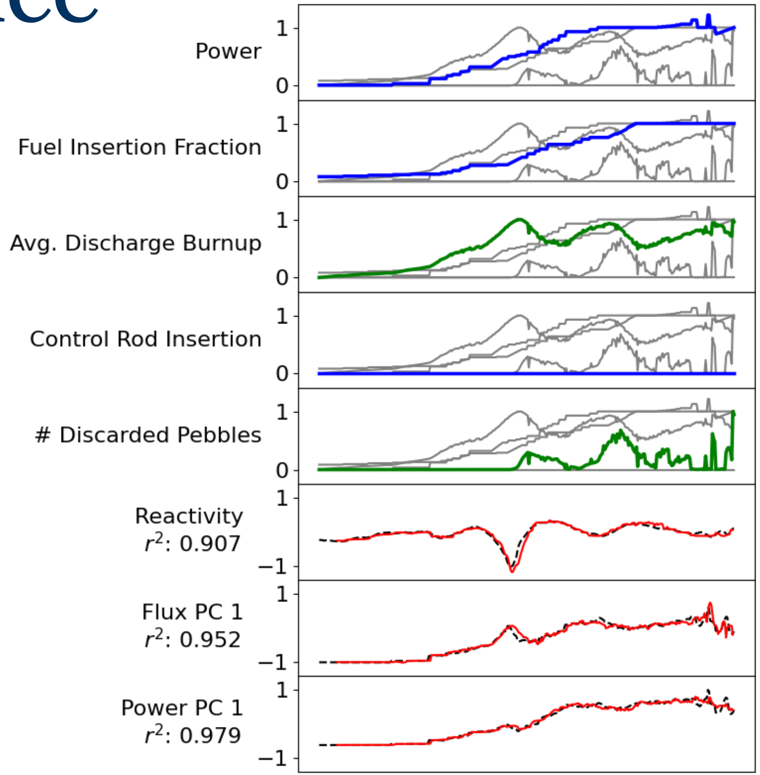
This block diagram shows the structure of an LSTM recurrent network "cell," illustrated by Ian Goodfellow et al. [5]



Model Performance



Performance on unseen sequence



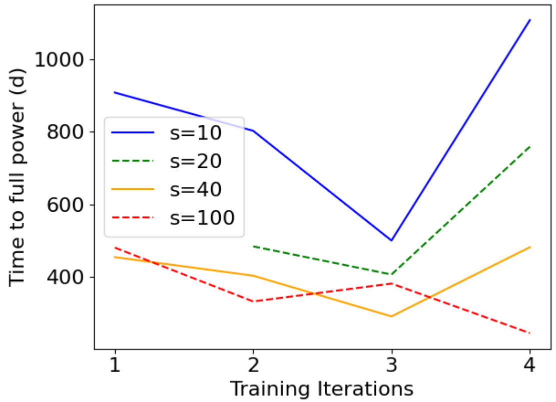
Input Controls

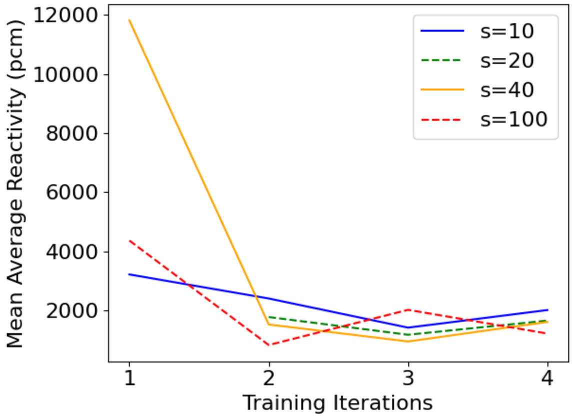
Dependent Inputs

Outputs

Running-In Optimization

- LSTM used to control core simulator
- Controls moved towards "goal" state (i.e. 100% power, 0% graphite pebbles, rods fully withdrawn)
- Impact on reactivity predicted
- Controls selected so reactor is critical
- Different minimum number of adjustments, s, used
- Model retrained each time





Conclusions and Future Work

- LSTMs offer a strong tool for predicting reactivity
- Coupling core model with thermal hydraulics
- Running-in with multiple enrichments needed
- Feature engineering can be expanded
  - Reduced order models (i.e. infinite lattice k_∞)
- Other ML model options (i.e. autoencoder)

Acknowledgements

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My friends from undergrad My friends from Civ/EnvE

The senior members of NucE Berkeley Hope Scholars

Engineering Student Services My chosen family

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Thank You

References

[1] M. Liu, C. Zeng, Z. Luo, H. Gu, and J. Deng, ‘Optimization of the TRISO fuel particle distribution based on octahedral and icosahedral-based segmentation methods in the pebble-bed nuclear core’, *International Journal of Advanced Nuclear Reactor Design and Technology*, vol. 2, pp. 103–110, 2020.

[2] C. Andreades *et al.*, ‘Design Summary of the Mark-I Pebble-Bed, Fluoride Salt–Cooled, High-Temperature Reactor Commercial Power Plant’, *Nuclear Technology*, vol. 195, no. 3, pp. 223–238, 2016.

[3] D. N. Kovacic *et al.*, ‘Nuclear Material Control & Accounting for Pebble Bed Reactors (FY 2023 Summary Report)’, Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (United States), 11 2023.

[4] B. W. Wehring and M. E. Wyman, ‘A bent-crystal spectrometer for the measurement of K X-rays coincident with fission’, *Nuclear Instruments and Methods*, vol. 61, no. 2, pp. 189–197, 1968.

[5] I. Goodfellow, Y. Bengio, and A. Courville, Deep Learning. MIT Press, 2016.