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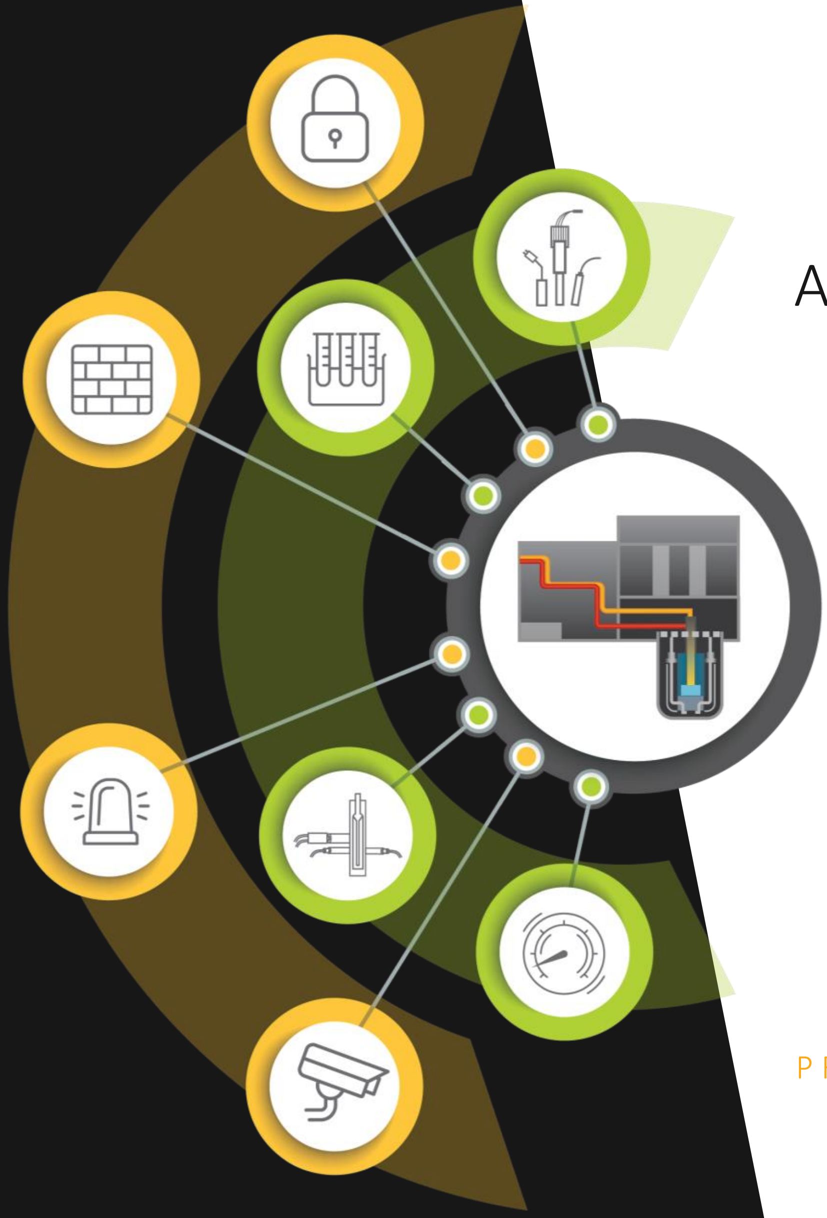

ADVANCED REACTOR SAFEGUARDS

Using Machine Learning to Improve Efficiency and Accuracy of Burnup Measurements at PBR Reactors

PRESENTED BY

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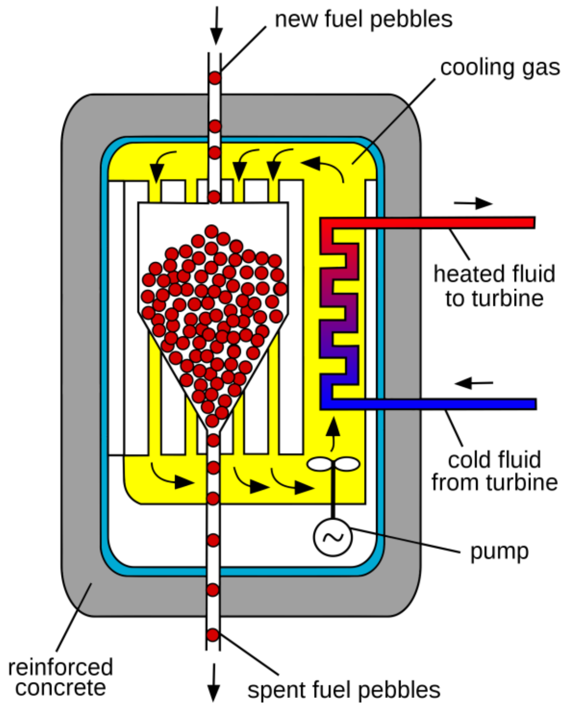
Brookhaven National Laboratory | U.S. DEPARTMENT OF ENERGY

Motivations of the Work

- Burnup measurement is the key to deciding if the pebble should be discharged or recycled during the operation of a PBR reactor
- Burnup measurement faces two challenges:
  - High throughput
  - High accuracy
- Objectives
  - Create and validate a workflow for modeling and simulation of both burnup and gamma-ray detection
  - Build ML models
  - Study performance of ML models

Pebble bed reactor scheme



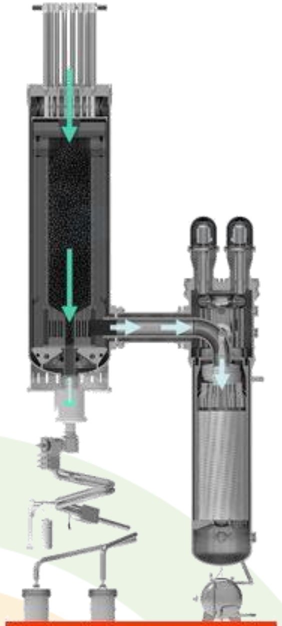
[Pebble-bed reactor - Wikipedia]

FY23 Technical Tasks

- Modeling and simulation
  - Add collimator to the workflow to reduce the flux
  - Validation of the simulation workflow
    - Develop full PBMR model
    - Automate result generation
    - *Validate the Serpent simulation results with the ones generated in Oak Ridge Isotope GENeration (ORIGEN)*
- Explore the explainability of the ML model

Modeling and Simulation

Modeling and Simulation Workflow

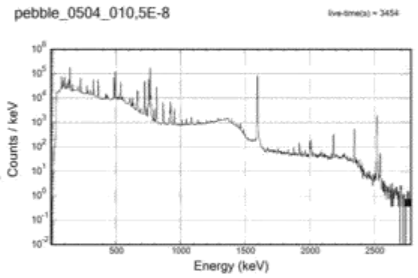


SERPENT SIMULATION

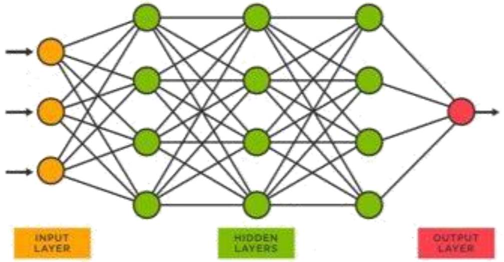
Include burnup model and collimation

GAMMA SOURCE

GADRAS SOFTWARE



GAMMA SPECTRA

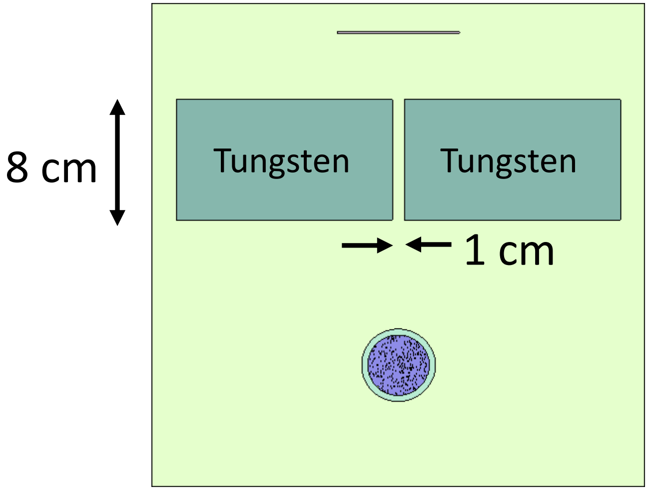


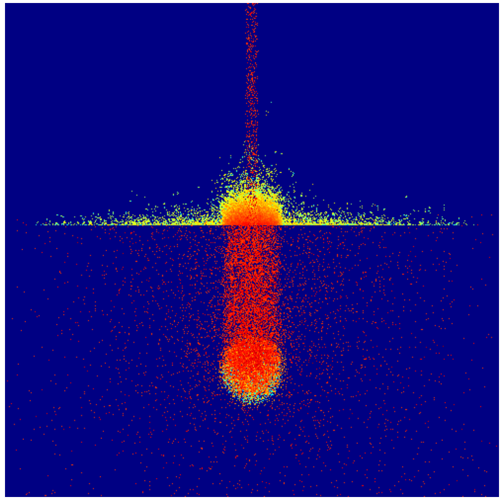
ML ALGORITHM

PREDICTION

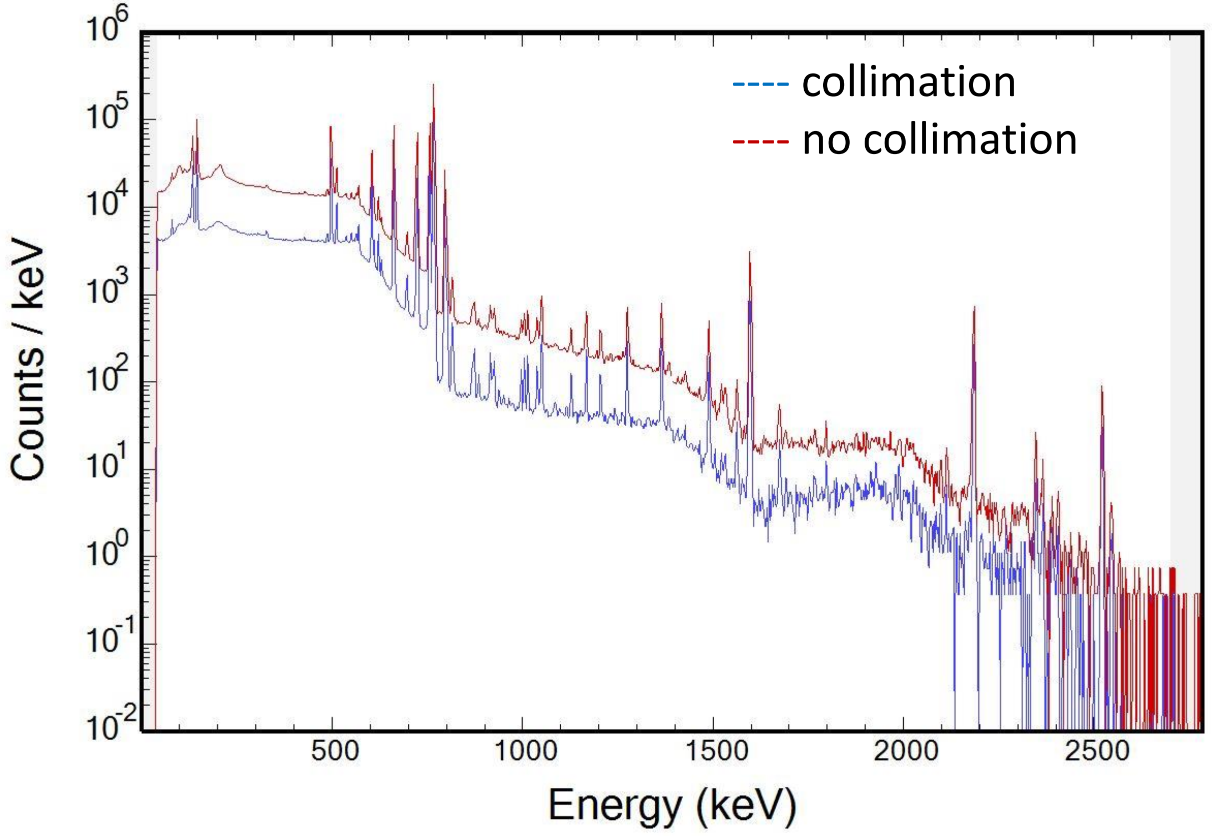
Collimation Analysis

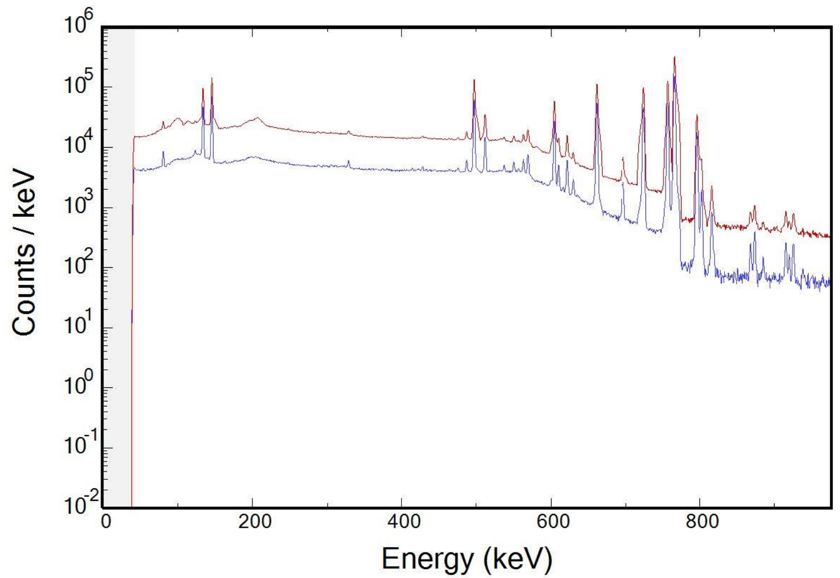
- Ejected pebbles from the core are highly radioactive, so collimator is needed to reduce the flux seen by the detector.
- A few options (MCNP, Geant4, Serpent) were considered based on ease of implementation, efficiency of simulation and accuracy.
- We decided to model the collimator directly into the source model in Serpent, eliminating the need to validate data translation to/from an external code.

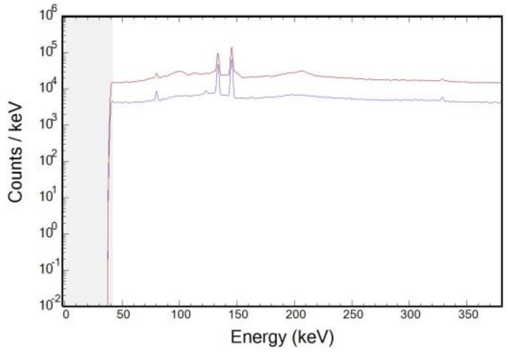


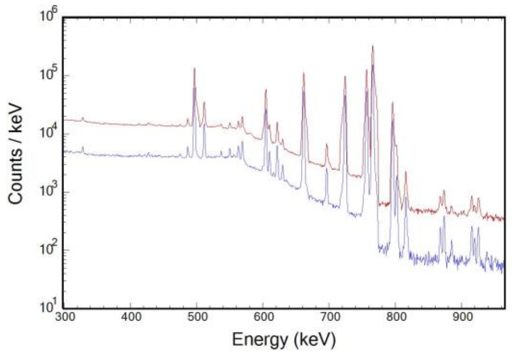


Collimation Analysis (Cont'd)







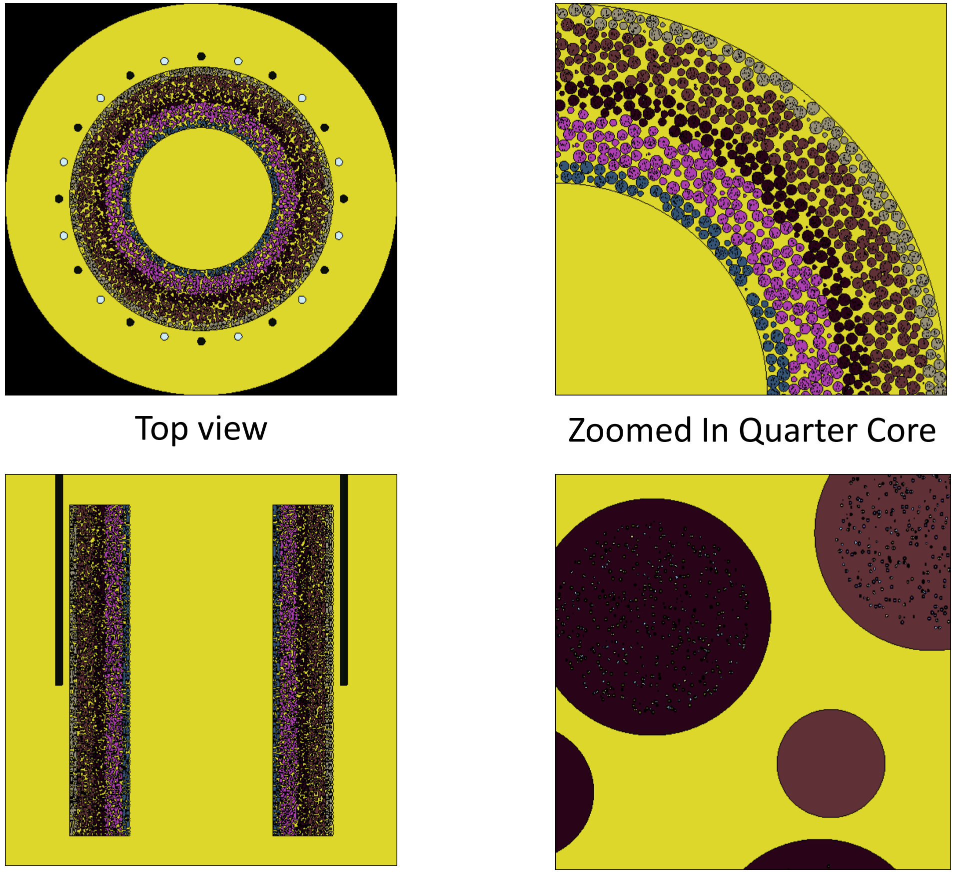


Full spectra with and without collimation

Collimation effect on specific energy ranges

Full Core Model for Burnup Validation

- Compared to the lattice model, a full-core model allows
  - More realistic flux and power distribution, hence resulting in more accurate burnup on a pebble per its location.
  - Full core modeling generates a potential to describe the effects of pebble flow path on the overall burnup
  - More accurate simulation to validate or compare to experimental data
  - The effect of control and burnup poisons are better described in a full core model



Top view

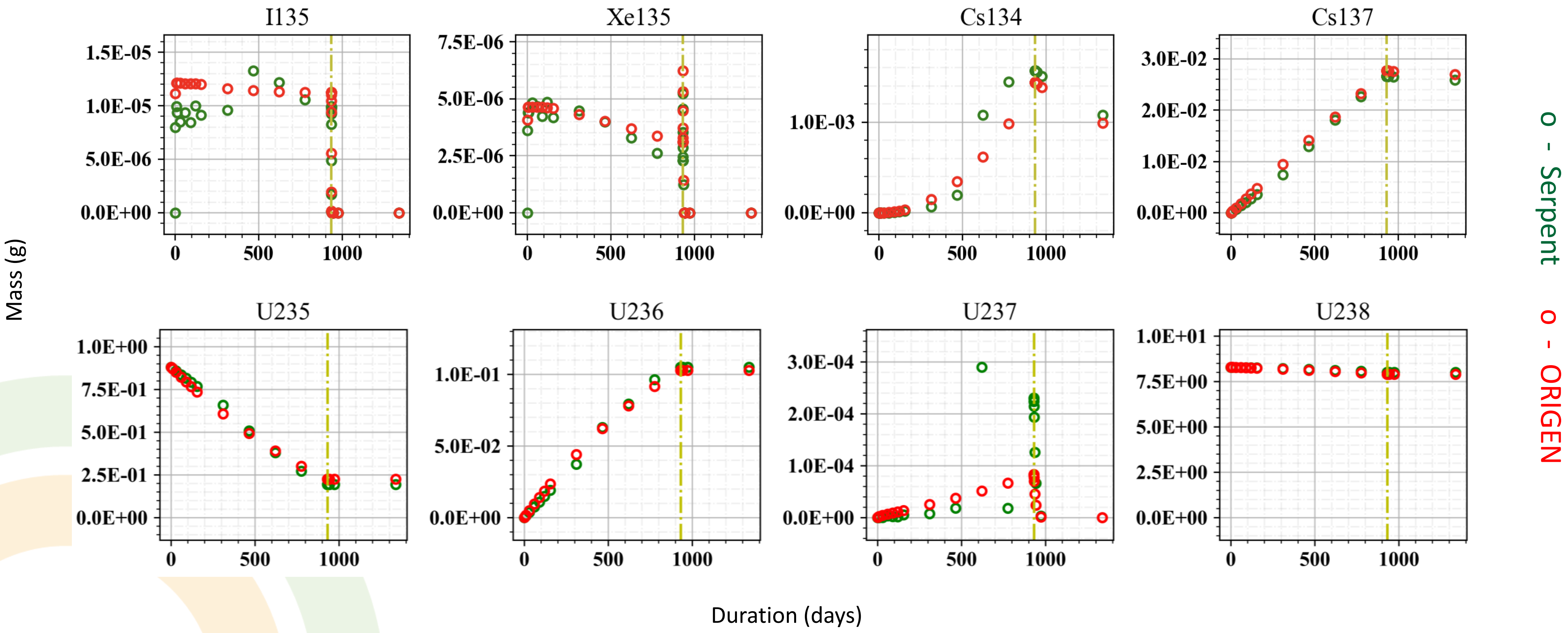
Zoomed In Quarter Core

Cut through Side View

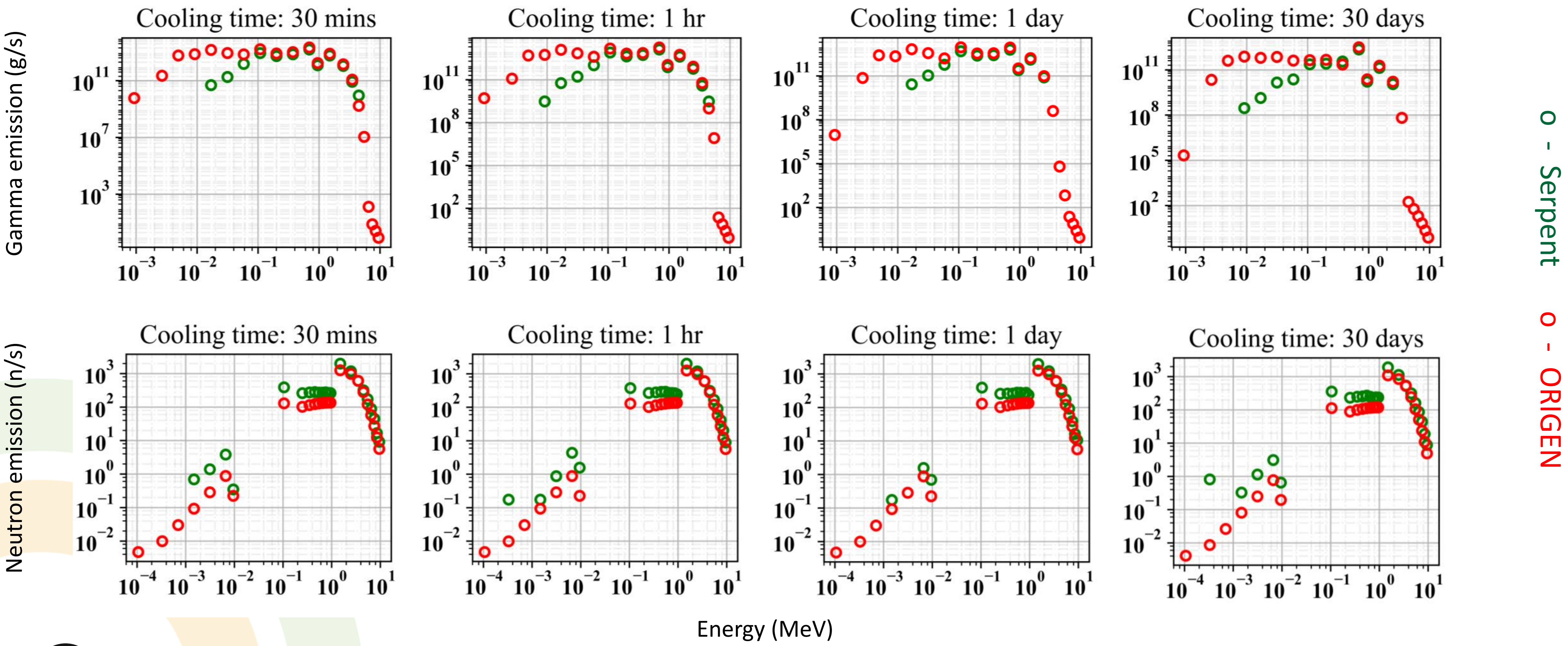
Pebble in Core

Full core model of a PBMR design

Simulation Results – (isotope verification)



Simulation Results – (emission verification)

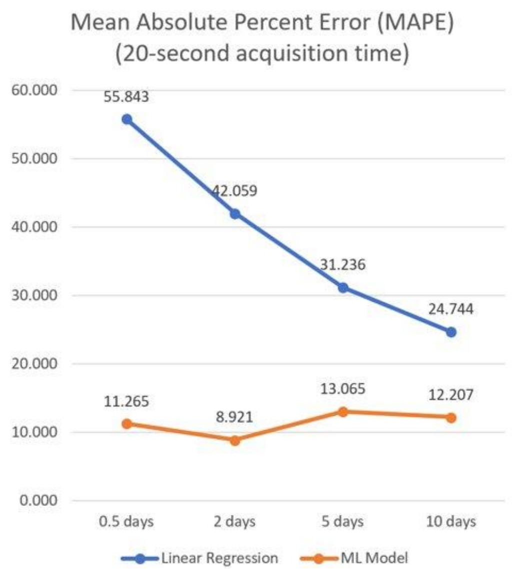


Explainability of ML Model

Machine Learning for Burnup Measurement

- We have demonstrated promising results with our ML models
  - Significantly outperforming linear regression method
  - Specifically, high performance at short cooling
- Results accepted for publication

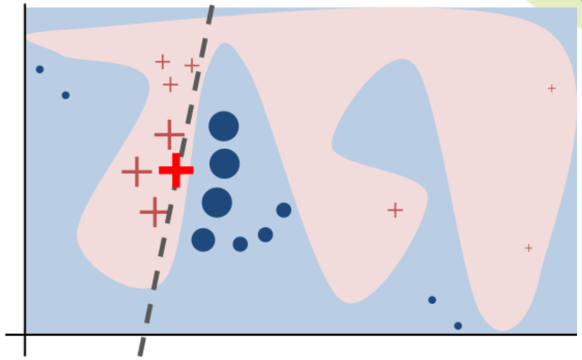
C. X. Soto et al. "A Better Method to Calculate Fuel Burnup in Pebble Bed Reactors Using Machine Learning," *Nuclear Technology*, DOI 10.1080/00295450.2023.2200573



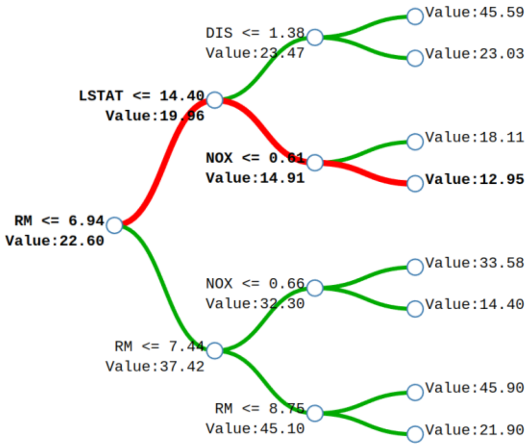
- However, Neural Network-based **ML models are inherently opaque**
  - Learned feature representations are not easily interpretable
  - Therefore, confidence and downstream impact of this work may be limited in its present state
  - Also, short-cooling performance merits deeper investigation

Approaches to ML Explainability/Interpretation

- Criteria of tool selection
  - *Support the data and models*
  - *Output explainability insights – identifying simple features related to gamma spectra that are most responsible for the ML predictions*
- Two selected tools
  - **LIME**: Linear Interpretable Model-agnostic Explanations
  - **SHAP**: SHapley Additive exPlanations

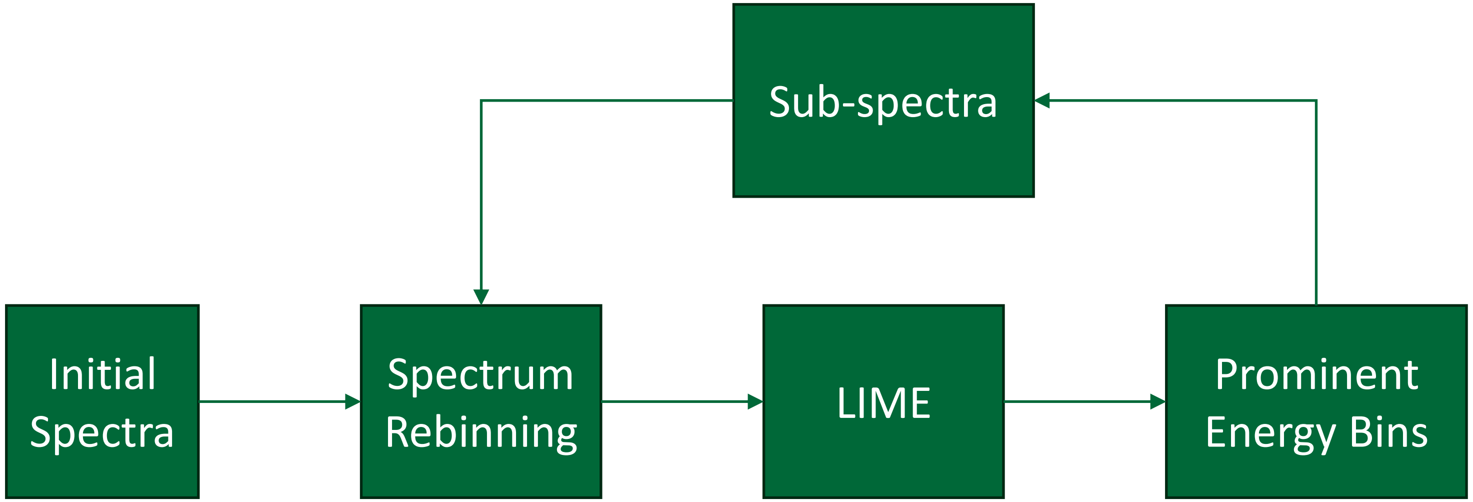


LIME works by creating linear decision boundaries using perturbed feature values



SHAP works by creating an ensemble of tree models based on Shapley-value estimations for feature contributions

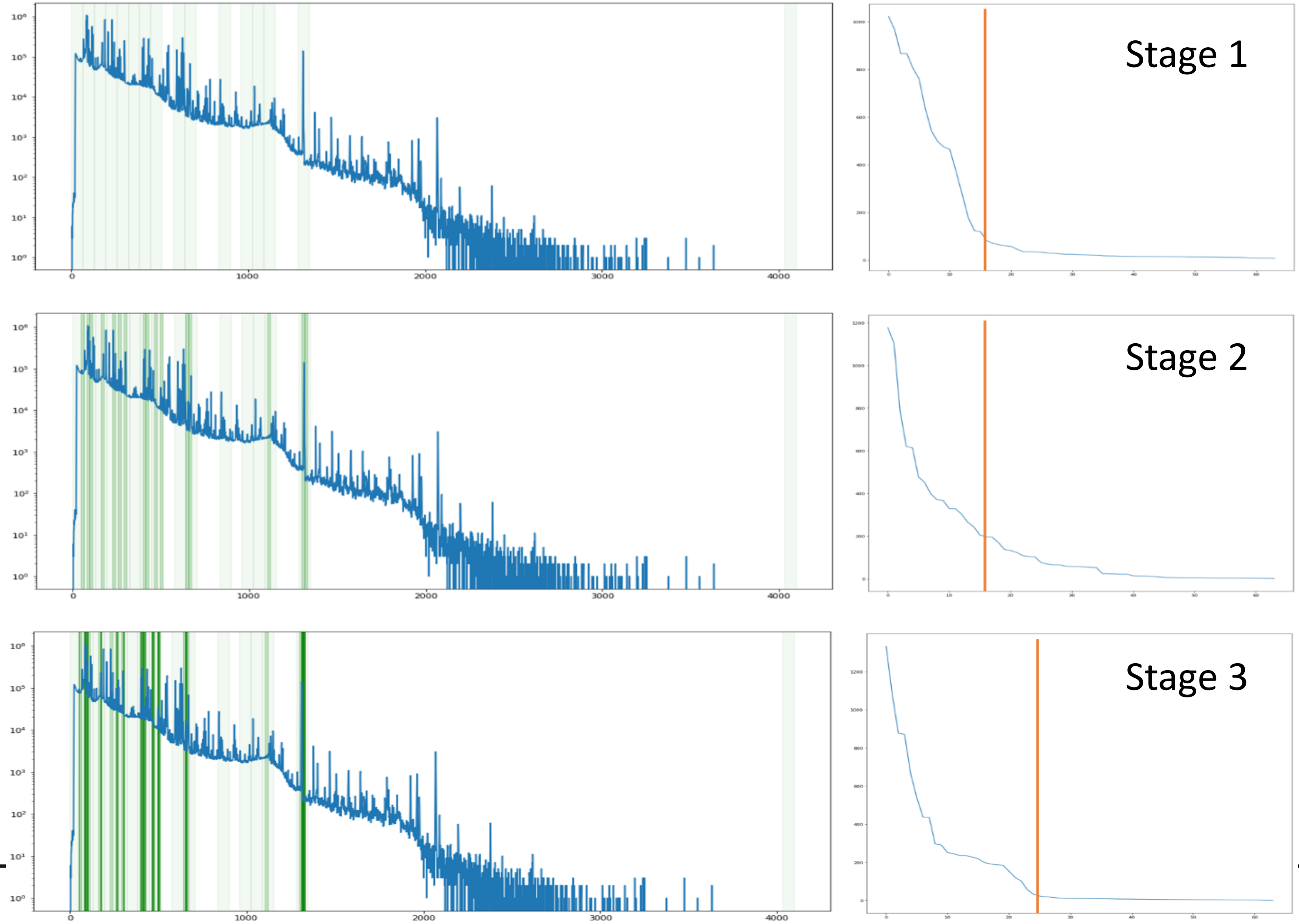
An Iterative Approach to Explore Explainability



LIME Results

- 12-hour cooling time and 1-hour measurement time

Stage	Narrow down threshold	Explainability
1	25%	88.74%
2	25%	78.95%
3	37.5%	96.71%



LIME Results

Top 24 energies identified by our LIME-based explainability analysis, for the 12-hour and 120-hour cooling condition dataset

Rank	Energy (keV)	Energy (keV)	Rank	Energy (keV)	Energy (keV)
1	891.153	2740.737	13	61.281	389.433
2	446.385	2754.297	14	318.921	348.753
3	443.673	888.441	15	58.569	584.697
4	337.905	308.073	16	340.617	354.177
5	118.233	118.233	17	280.953	421.977
6	278.241	2735.313	18	893.865	66.705
7	180.609	337.905	19	205.017	2770.569
8	286.377	58.569	20	899.289	405.705
9	36.873	446.385	21	272.817	61.281
10	55.857	443.673	22	888.441	351.465
11	896.577	2751.585	23	316.209	69.417
12	66.705	55.857	24	69.417	454.521

LIME Results

Validation of LIME-selected features with new MLP and LR models. Arrows indicate direction of better performance per metric: RMSE (root mean square error), MAPE (mean absolute percent error), R^2 (correlation coefficient)

		↓ RMSE	↓ MAPE (%)	↑ R^2
MLP	Original spectra	0.66	2.04	0.9995
	Stage 1 features	0.37	1.61	0.9998
	Stage 2 features	0.27	1.33	0.9999
	Stage 3 features	0.28	1.07	0.9999
Linear Regression	Original spectra	0.74	7.93	0.9992
	Stage 3 features	0.53	5.16	0.9996

Linear regression on top-N LIME features (all features ~3 keV wide)

	↓ RMSE	↓ MAPE (%)	↑ R^2
Top-24 (all)	0.528	5.16	0.9996
Top-8	0.698	6.81	0.9994
Top-4	3.424	20.99	0.9848
Top-2	6.113	58.74	0.9533

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Next Steps

- Improve burnup model towards realistic operational conditions by varying
  - Transient time
  - Cooling time
  - Measurement time
- Study the performance of the ML models with the new datasets
- Validate the burnup model with measured spectra as new burnup experiments go through and gamma spectra of newly burned TRISO particles become available

Acknowledgement

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