NUEN 689 PROJECT:

Deep Learning Techniques to Predict Initial Enrichment of a PWR Fuel Pin

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Objective:

The objective of this project was to solve a nuclear forensics problem, determining initial U-235 enrichment based on Pu-239 produced, using different deep learning techniques. The techniques of interest were a Long Short-Term Memory (LSTM) neural network, and an Inverse Physics Informed Neural Network (IPINN).

Background:

- The quantities, enrichments, and origins of Pu-239 are of great concern in Safeguards and Nonproliferation.
- This project aims to predict the initial uranium enrichment of some burned nuclear fuel sample, based on its Pu-239 concentration.
- Pu-239 is the most abundant plutonium isotope produced through fuel transmutation, but other nuclides (U-239, Np-239) will also be considered. Figure 1 provides a graphic of the transmutation process.
- Given data from MCNP simulations, the networks predict the initial fuel enrichment of U-235 of the sample, based on all current nuclide concentrations

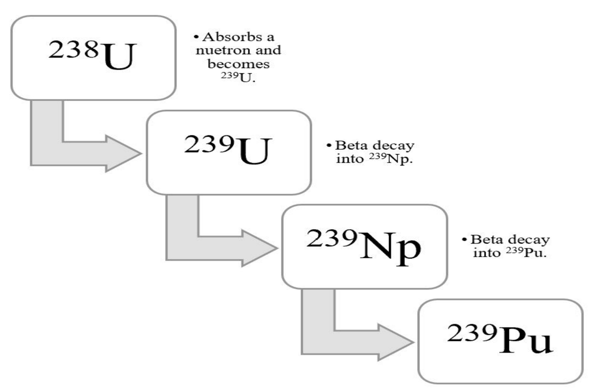


Figure 1. ^{239}Pu breeding chain.

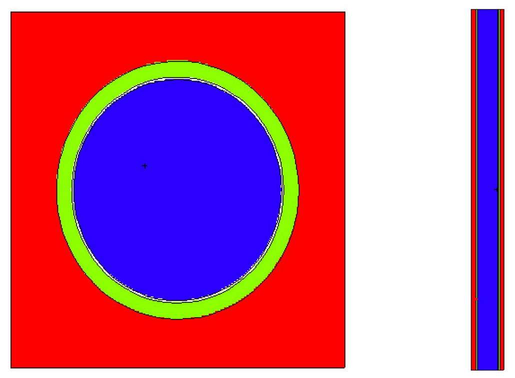
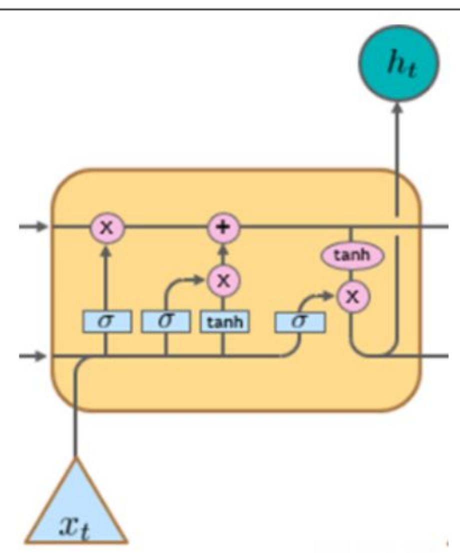
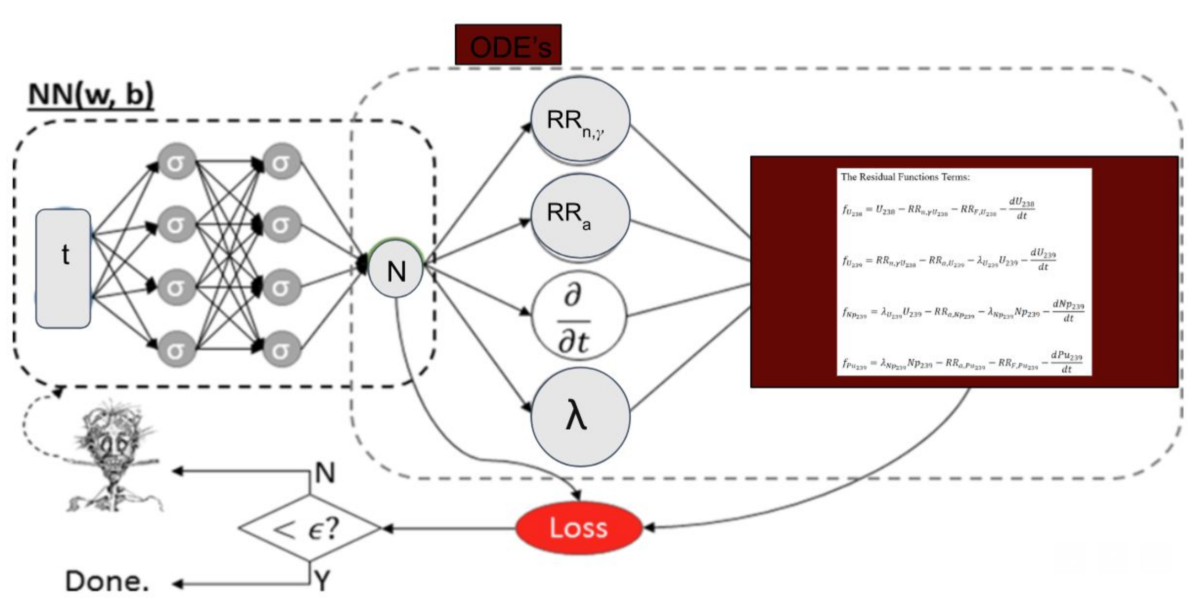


Figure 2. The fuel pin layout.

Methodology:

The LSTM NN	The IPINN
• This approach utilizes a Long-Short Term Memory (LSTM) NN, to understand the time-dependencies of the nuclide concentrations. • Inputs to the network will be the concentrations of nuclides in the current sample (U-238, U-235, U-239, Pu-239, Np-239), and the output will be the estimated concentrations of those nuclides at many timesteps throughout the sample's history. • The most significant data point in this output will be the initial U-235 enrichment.	• This approach relies on an inverse PINN (Physics Informed Neural Network) using the Bateman equations, which describe abundances and decay rates of the nuclides in time. • The Bateman equations used for the residual function terms, and the neural network will approximate the concentration of U-238, which is set as a learnable parameter. • The U-238 concentration can then be used to determine the enrichment of U-235 with some assumptions.



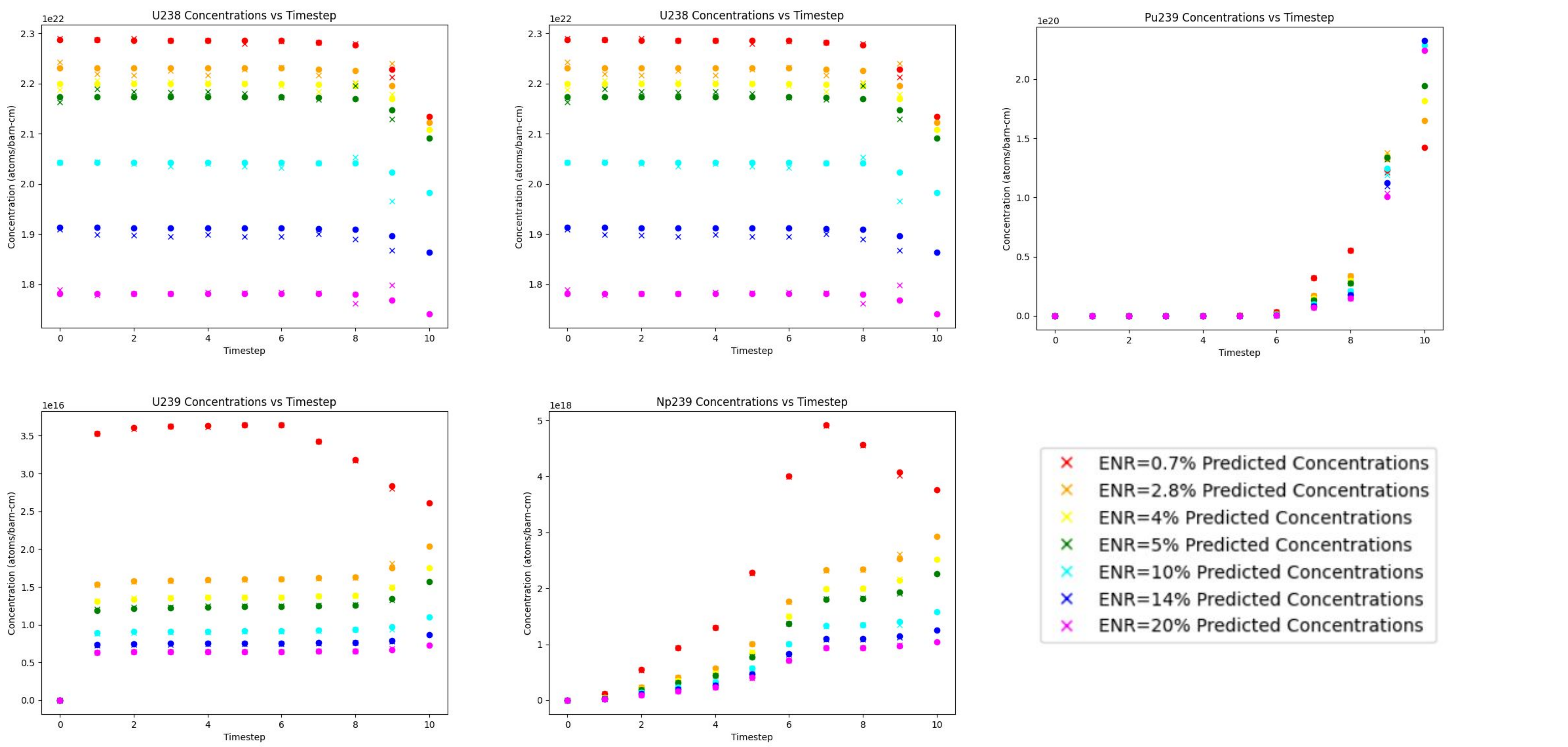


Description of Data

MCNP data was generated for burnup simulations for seven different initial U-235 enrichments: 0.7%, 2.8%, 4%, 5%, 10%, 14%, and 20%. Concentrations of five nuclides (U-238, U-235, U-239, Pu-239, and Np-239) were available at 11 non-uniform timesteps, going up to 2 years. Reaction rates were collected for the Bateman equations in the IPINN model.

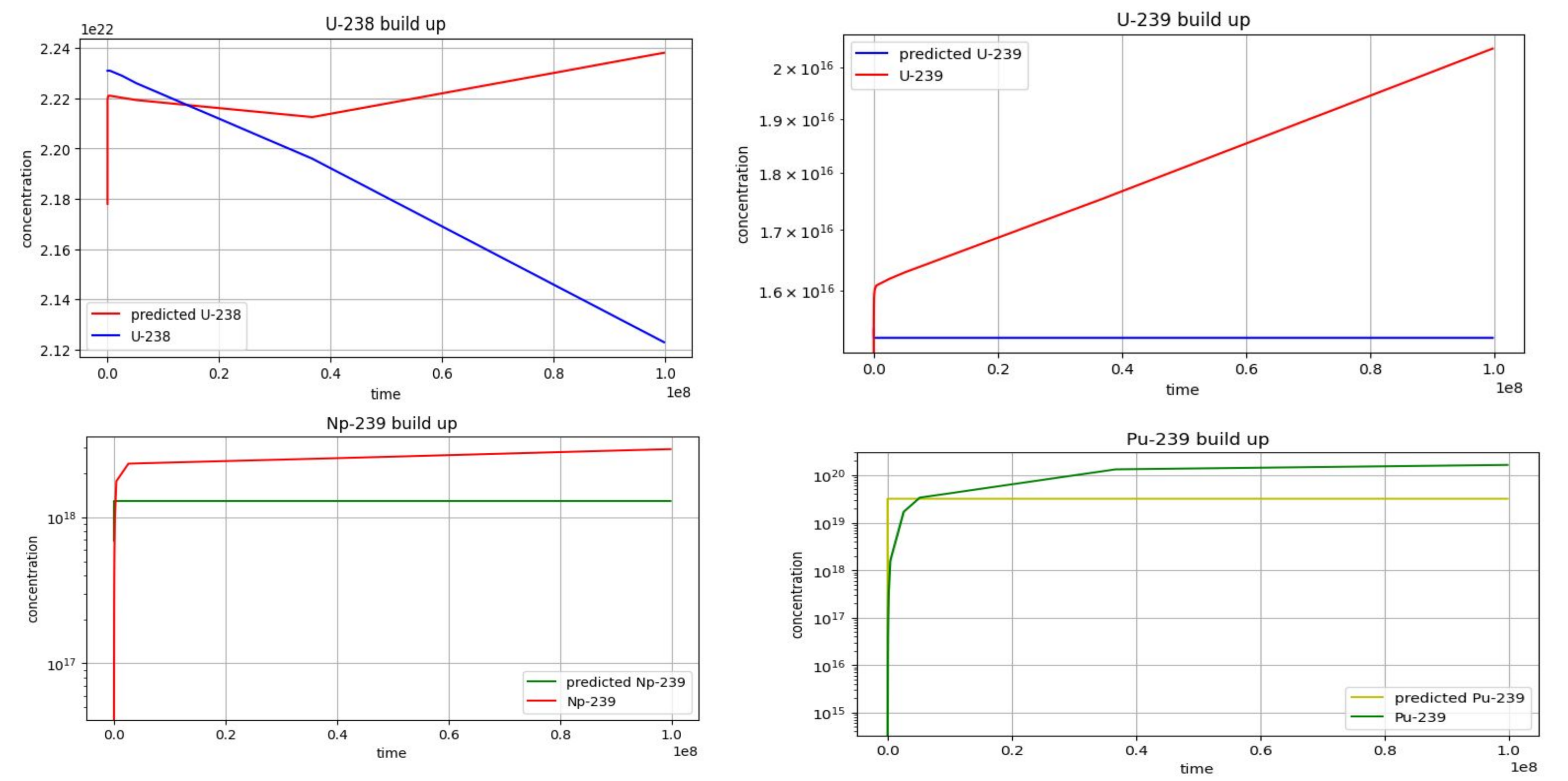
Results:

Long Short-Term Memory (LSTM) Results



The LSTM model accurately predicts initial U-235 enrichment within 2% for each simulation, including evaluation data sets. Concentration predictions across intermediate timesteps are also generally accurate.

Inverse Physics Informed Neural Network (IPINN) Results



LSTM vs IPINN Results

Nominal Simulated Enrichment (%)	True Simulated Enrichment (%)	LSTM Prediction (%) & Percent Error	IPINN Prediction (%) & Percent Error
0.7	0.8042	0.8052 (Error = 0.13%)	0.84 (Error = 20.00%)
2.8	3.241	3.245 (Error = 0.14%)	3.32 (Error = 18.57%)
4.0	4.597	4.533 (Error = 1.39%)	4.69 (Error = 17.25%)
5.0	5.741	5.698 (Error = 0.74%)	5.85 (Error = 17.00%)
10	11.48	11.68 (Error = 1.75%)	11.6 (Error = 16.00%)
14	17.20	17.42 (Error = 1.32%)	17.4 (Error = 24.29%)
20	22.92	22.76 (Error = 0.69%)	23.1 (Error = 15.50%)

The plots displayed are the results of the 2.8% enriched simulation. The IPINN predicted the enrichment with an average percent error of 18%. The percentage errors between the true and predicted enrichments for each simulation (for both the LSTM and IPINN models) are displayed in the table.

Conclusion:

The LSTM model generally outperformed the IPPIN model in predicting the initial U-235 enrichment of the fuel sample. The LSTM made prediction errors that were less than 2%, but the IPPIN made prediction errors ranging from 15-25%. The LSTM model was also more flexible than the PINN; a single LSTM was capable of considering many different enrichments, but the number of IPPIN models required was equal to the number of enrichments. Future work may include a consideration of a wider range of enrichments, as well as a greater number of simulations to train the models on.

This project was produced for the NUEN 689 course

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