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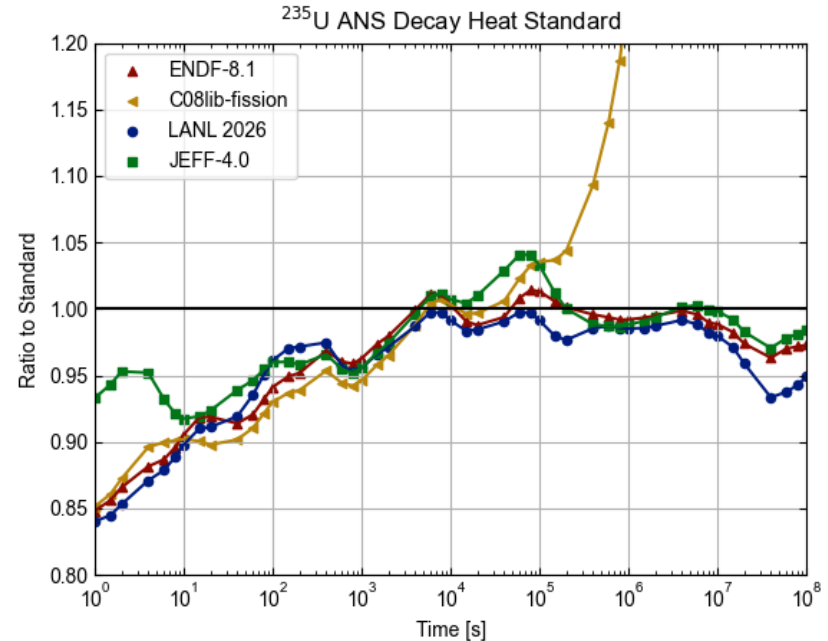
Adjustment of a New Thermal FPY Evaluation to a Decay Heat Standard

Max Guzman

August 24, 2026

Motivation

- Independent Fission Product Yield (FPY) evaluations are difficult to validate experimentally
- Decay heat power data provides an observable that can be used to validate and adjust independent FPYs
- Goal: Use Generalized Least Squares (GLS) to adjust independent FPYs and assess whether this improves simulated results



LANL U-235(n,f) Fission Product Yield ENDF Test File

- New ENDF test file containing FPY evaluations for 26 energy points
- New ENDF format MF38 proposed to store correlations for independent and cumulative FPYs
- This project strictly deals with the single evaluation of independent FPYs at thermal energy (10^{-5} eV)
- These independent FPYs were generated from model predictions combined with cumulative FPY measurements
- Availability of decay heat data at thermal energies allows for validation and adjustment of these FPYs

CINDER¹

- MCNP's depletion utility used to calculate the inventory of nuclides in an irradiated material
- Solves set of coupled differential equations that govern the atom densities of all nuclides in a material over time

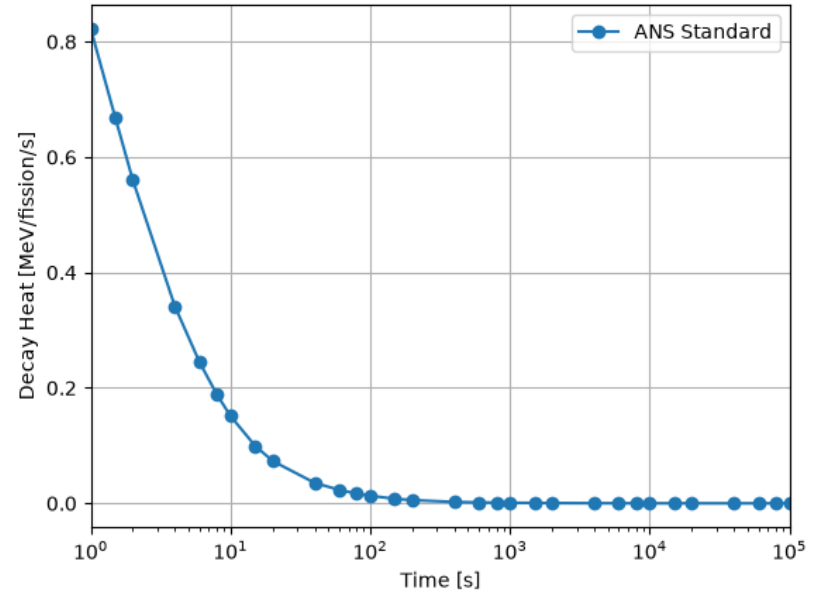
$$\frac{d\mathcal{N}_m(t)}{dt} = -\mathcal{N}_m(t)\beta_m + \overline{Y}_m + \sum_{k \neq m} \mathcal{N}_k(t)\gamma_{k \rightarrow m}$$

- Each differential equation balances probability of transmutation of nuclide m to a different nuclide with probability of all other nuclides transmuting to nuclide m
- Nuclide inventory known at each time step → Decay data can be used to calculate total decay heat rate at each time step

1. Shannon Holloway, William Wilson, Charles T. Kelsey IV, Hannah Little, Vladimir Mozin, and Tal England.
A Manual for CINDER2008 Codes and Data.
Technical Report LA-UR-11-00006, 2011.

ANS Standard

- *Decay Heat Power in Light Water Reactors* published by American Nuclear Society (ANS)²
- Provides values of decay heat power after shutdown of thermal LWR for fuel assemblies initially containing U-235 and U-238
- Excludes contributions from actinides
- Based on experimental data up to 10^5 seconds (28 hours)
- Extrapolates to 10^{10} seconds (317 years)

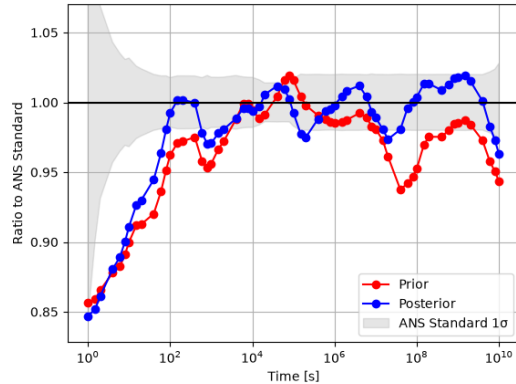


Generalized Least Squares

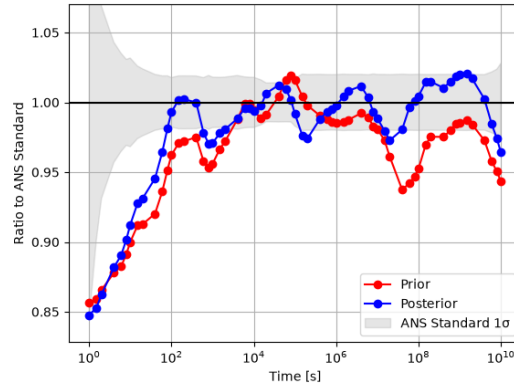
- Cost function derived from Bayes' Theorem is minimized, which maximizes the posterior probability of the adjusted FPY data
- The purpose of this is to update the prior FPY data from the ENDF evaluation given what is known from decay heat power dataset
- GLS assumes the relationship between FPYs and decay heat power is linear and the uncertainties on these datasets are Gaussian
- Iteratively Reweighted Least Squares (IRLS) was implemented to prevent relative uncertainties from biasing posterior results
- Nonlinear GLS was also implemented to account for the nonlinear relationship between FPYs and decay heat power

Adjustment to ANS Standard Across All Times

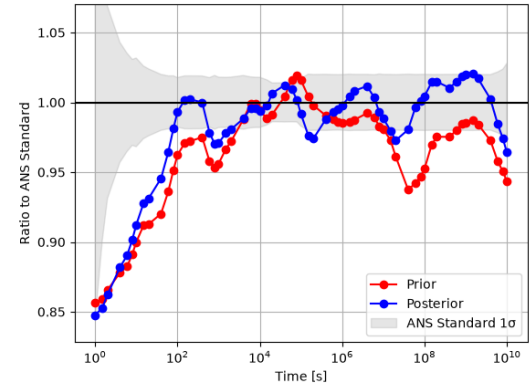
Linear GLS



IRLS



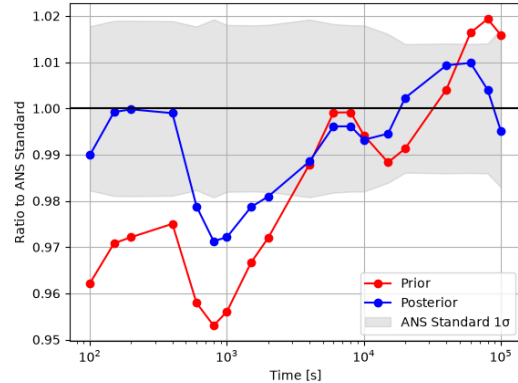
Nonlinear GLS



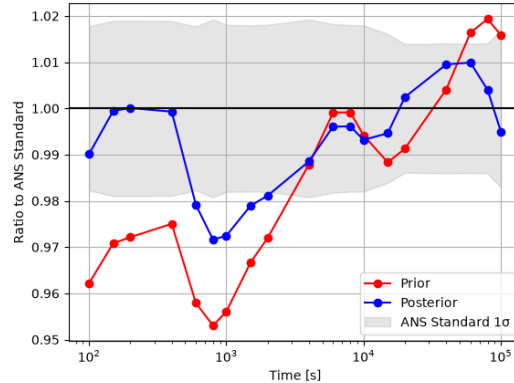
- Running linear GLS, IRLS, and nonlinear GLS gave virtually identical results
- Sensitivity matrices were also calculated via forward, backward, and central differences but results did not change
- Posterior FPYs give CINDER outputs that don't match the ANS standard much better than the prior FPYs

Adjustment to ANS Standard Across Selected Times

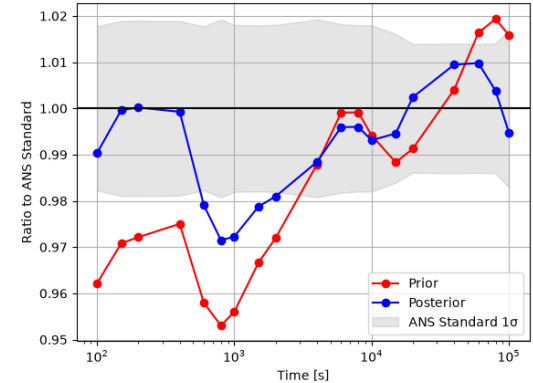
Linear GLS



IRLS

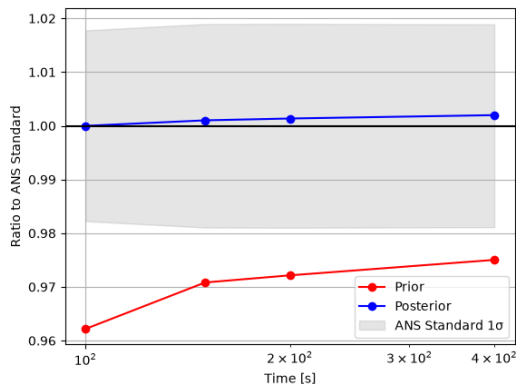


Nonlinear GLS



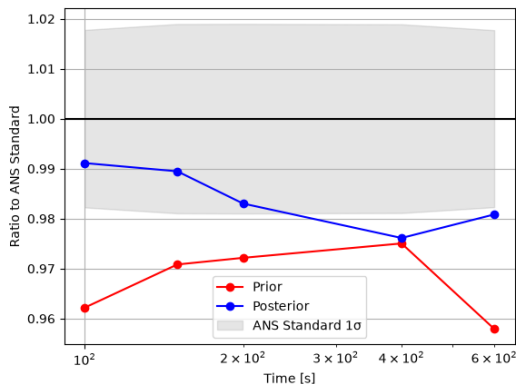
- ANS standard time points were limited between 100 and 10^5 seconds
- It was thought that the inclusion of extrapolated decay heat values after 10^5 seconds might be hindering the adjustment
- Adjustments were still unable to consistently get CINDER results within the uncertainties of the ANS standard

Forced Adjustment



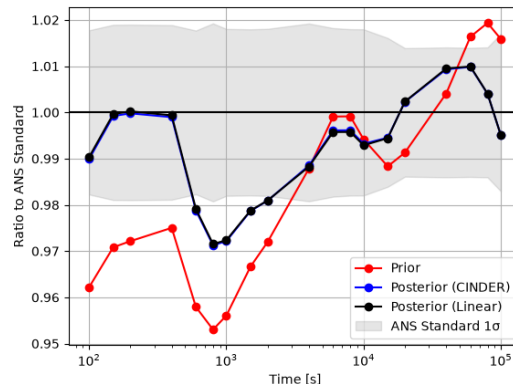
Forced Adjustment (4 Points)

- Uncertainties on decay data were limited to 10^{-5}
- GLS adjustment was limited to 4 time points
- The posterior ratio using those points went to 1 $\rightarrow$ showing the GLS algorithm is correct



Forced Adjustment (5 Points)

- 1 additional time point was included in a subsequent adjustment
- Posterior ratio no longer went 1
- Suggests incompatibility of these 5 decay heat power values with FPYs

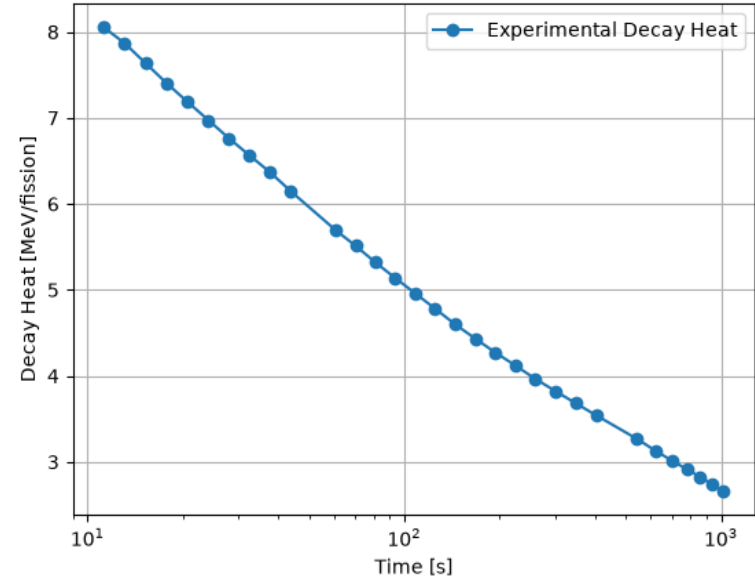


Posterior Ratio via Sensitivity

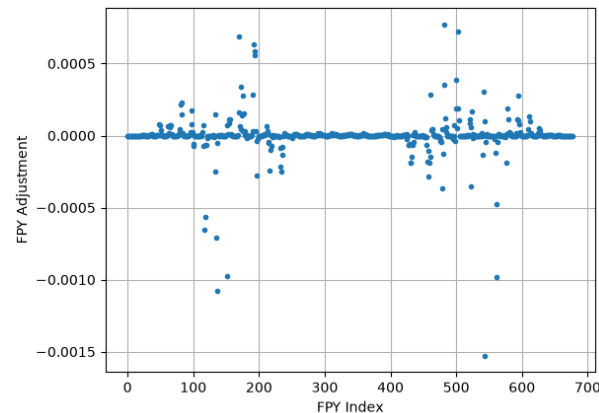
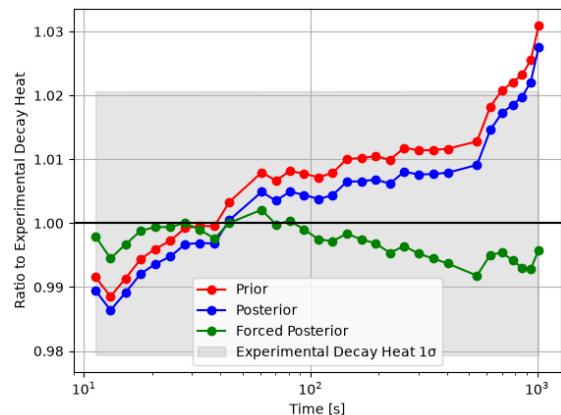
- Posterior ratio was calculated by multiplying prior FPYs by the sensitivity matrix
- Result very closely matches posterior ratio from CINDER
- Relationship more linear than expected, further suggesting data incompatibility

Adjustment to EPRI Experiment

- Since the ANS standard is derived from multiple experiments and simulations, a single self-consistent dataset was sought out
- The Electric Power Research Institute (EPRI) collected decay heat power data from 1 to 10^5 seconds after irradiating a U-235 sample for 24 hours³
- The sample was a 22.8 wt% HEU-Al alloy that was irradiated with a thermal flux of $10^8 \frac{n}{cm^2s}$



Adjustment to EPRI (1976) Experiment



Regular and Forced Adjustments

- Posterior ratio shown in blue did not change much from the prior
- Forced adjustment shown by the green line closely matches the experimental data, which shows this dataset is compatible with the thermal FPYs

Range of FPY Adjustments

- Some FPYs were adjusted by about 0.001 while most stayed close to their original value
- Nuclides most sensitive to decay heat were Cs-141, Rb-93, Ba-142, Sr-94, and Te-134
- No nuclide was adjusted by more than 0.8σ

Conclusion

- Unable to get desired compatibility between ANS standard decay heat power data and thermal FPYs for U-235 that would've allowed for a closer match with CINDER simulations
- Experimental decay heat power data from irradiation of U-235 alloy was compatible enough to achieve a close match with CINDER
- Future Work:
 - Apply GLS workflow to other decay heat power benchmarks
 - Adjust other quantities in tandem with FPYs
 - Apply other methods besides GLS