EUCLID Project Summary

Prepared by Jesson Hutchinson, Denise Neudecker, and Bob Little

EUCLID team: J. Alwin, B.W. Bell, A. Clark, T. Cutler, M. Grosskopf, W. Haeck, M. Herman, J. Hutchinson, N. Kleedtke, J. Lamproe, R.C. Little, I. Michaud, D. Neudecker, M. Rising, T. Smith, N. Thompson, S. Vander Wiel, N. Wynne

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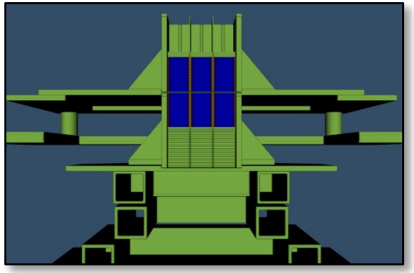
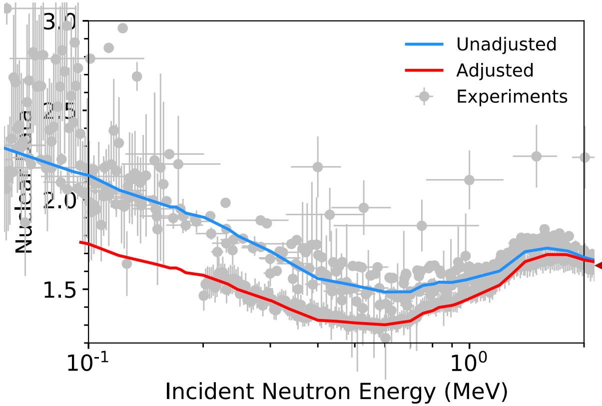
LA-UR-24-21103

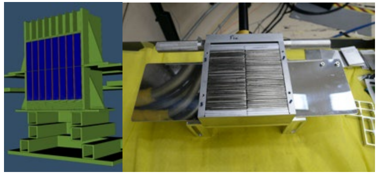
EUCLID designed validation experiments optimized to reduce ^{239}Pu compensating errors & adjusted nuclear data to experiments

Neutron Transport Simulation (MCNP)



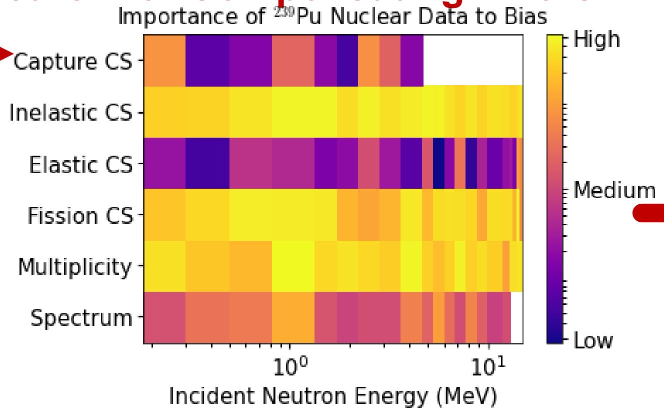


Experiment Refines Nuclear Data to Improve Simulations

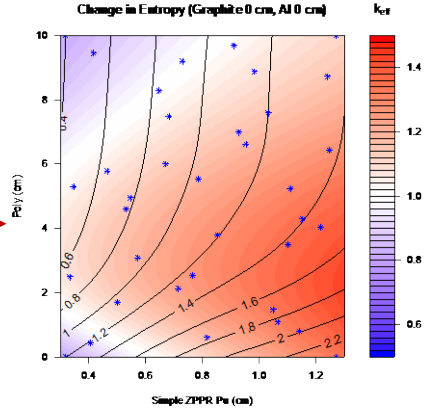


Validation Experiments

ML-Augmented Search for Compensating Errors



ML-Optimally Designed Experiment to Resolve Compensating Errors



There is a symbiotic relationship between NCSP and LANL LDRD through the EUCLID project

- A big part of the success of the EUCLID proposal was due to previous work supported by NCSP (MCNP, nuclear data, and NCERC capabilities).
- And the work performed under EUCLID has / will similarly benefit the NCSP mission:
  - New MCNP capabilities
  - Improved nuclear data (e.g., reduced errors in fast Pu-239) and nuclear data capabilities
  - New methodology, tools, and equipment will impact on future NCERC experiments
    - Current example – Thales project aimed at increased throughput at LANL PF-4
  - Closer collaboration across AM / IE / ND program elements & statistical scientists / ML
  - Training opportunities for crew members and fissionable material handlers

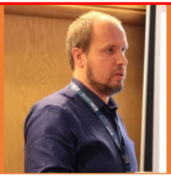
Team

Experiments Underpinned by Computational Learning for Improvements in nuclear Data

Personnel that have work on NCSP projects

Nuclear Data


Noah Kleedtke

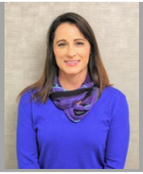

Wim Haeck


Michal Herman

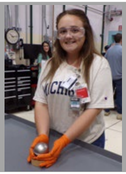

Robert Little


Denise Neudecker

Simulations


Jennifer Alwin


Alexander Clark

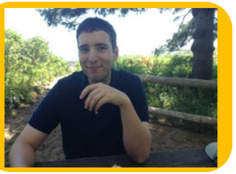

Juliann Lamproe


Michael Rising

Machine Learning


Brian Bell

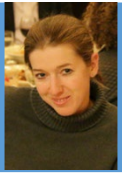

Michael Grosskopf


Isaac Michaud

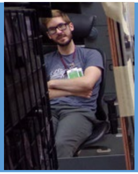

Scott Vander Wiel

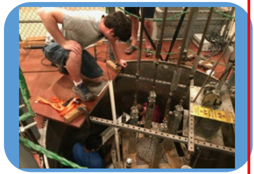
Experiments


Nick Wynne


Theresa Cutler

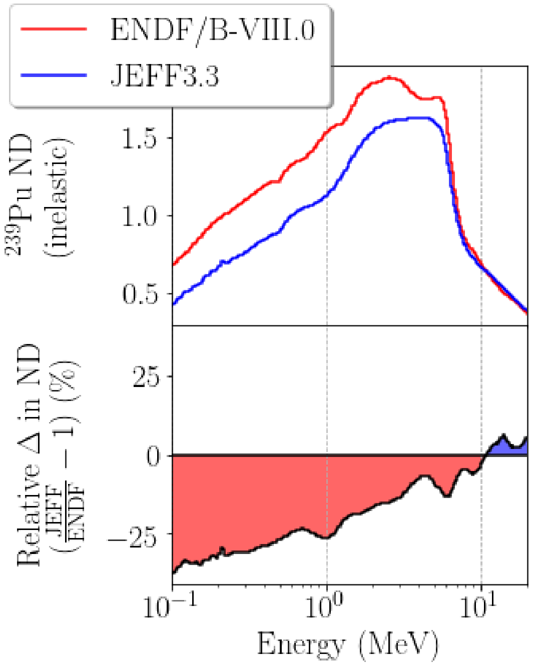

Jesson Hutchinson

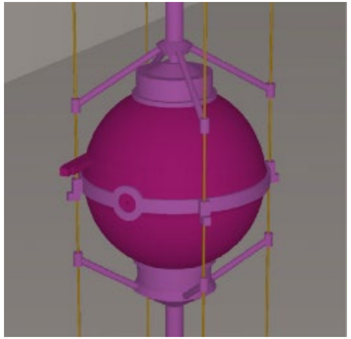

Travis Smith


Nicholas Thompson

Unresolved compensating errors for Pu-239 fast nuclear data lead to widely different data.

Differences in ENDF/B-VIII.0 and JEFF3.3 nuclear data represent uncertainty in the differential information.



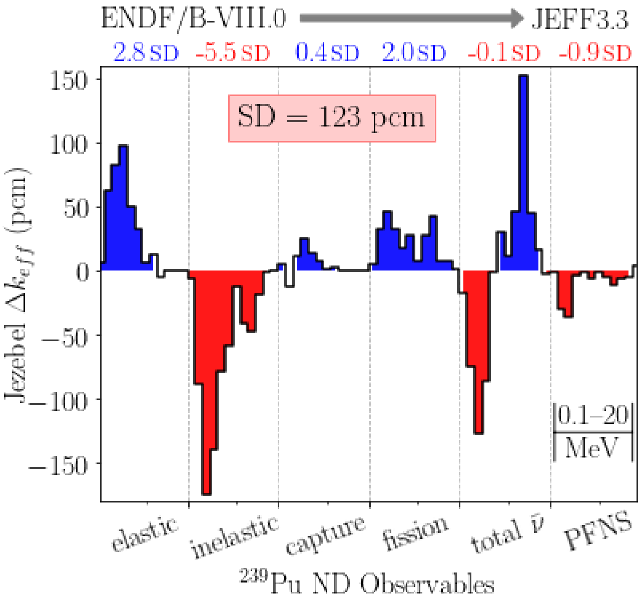


```
@@@ PU-MET-FAST-001-001 @@@
1 1 -15.61 -1          imp:n=1
2 0          1         imp:n=0

1    so    6.3849

c material 1: Plutonium
m1      94239.00c 3.7047E-02
        94240.00c 1.7512E-03
        94241.00c 1.1674E-04
        31069.00c 8.2661E-04
        31071.00c 5.4859E-04
kcode 1000000 1.0 200 4200
ksrc 0 0 0
```

Both ENDF/B-VIII.0 and JEFF3.3 compute Jezebel k_{eff} equally well using MCNP6 but contributions per reaction differ drastically



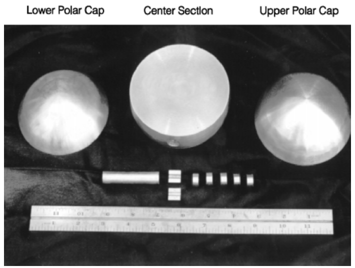
Optimal Criteria and Experimental Design

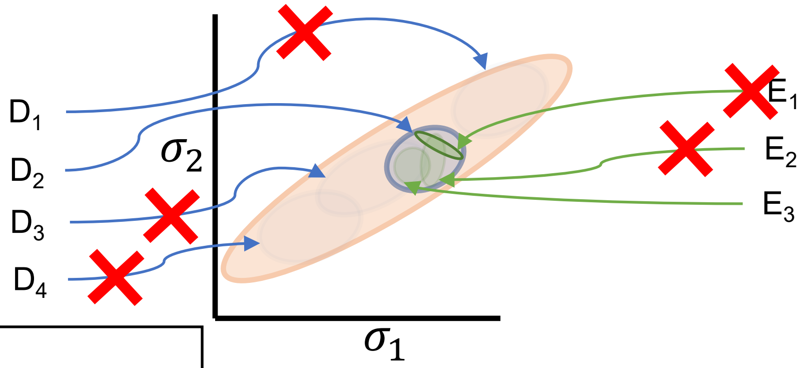
- For sensitivity matrix S of proposed experiments, the adjusted ND covariance is

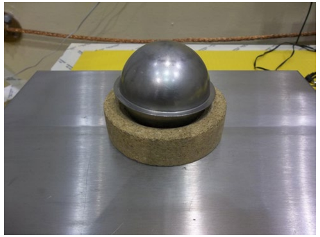
$$\Sigma' = \Sigma - (\Sigma S)(S^T \Sigma S + \Sigma_c + \Sigma_e)^{-1}(\Sigma S)^T$$

D-optimality: Maximize the reduction in log-determinant of the covariance matrix

- Minimizes the volume of the ND credible region ⇒ constrains compensating errors
- Ranks the quality of the potential experiments (higher D-opt is better)







Λ_2

Considered Measurements

1. k_{eff}
2. Reactivity Coefficients
3. Reaction rate ratios
4. Subcritical measurements
5. Rossi-alpha

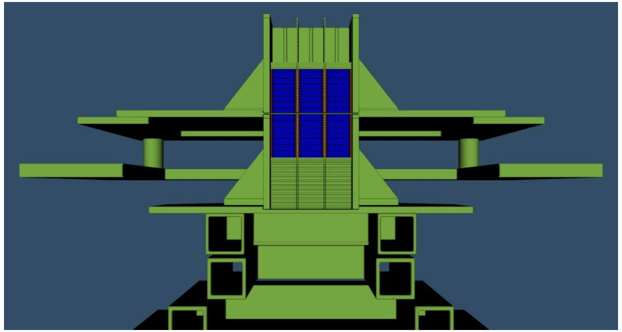
A similar approach could be used for future NCSP experiments.

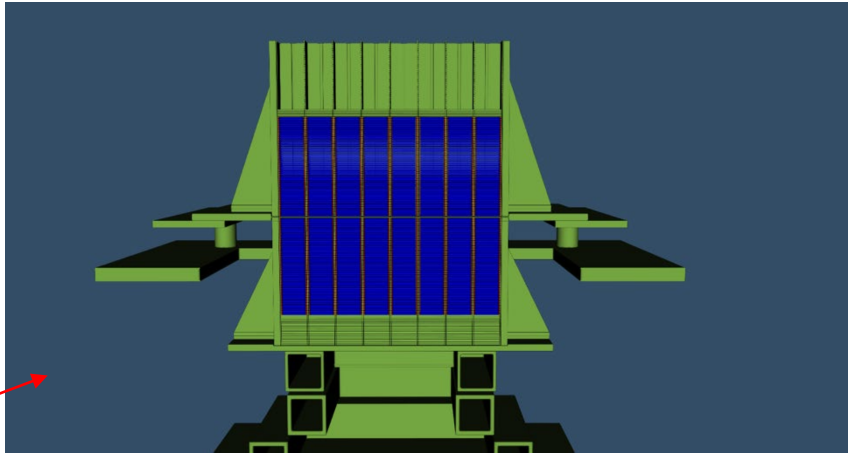
Experiment Optimization

- Results of the D-Optimality analysis led us to two configurations:

3 X 2 (Low Mass/Cube)
Critical with 384 ZPPR plates (41 kg Pu)

8 X 1 (High Mass/Slab reactor)
Critical with 1033 ZPPR plates (109 kg Pu)



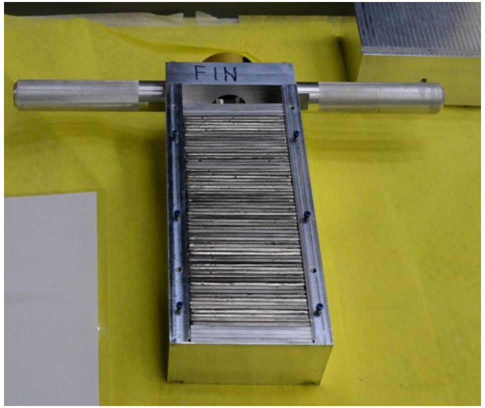


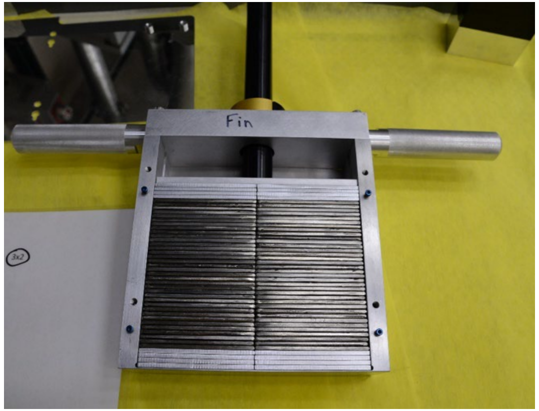
8x1 H/"D" ratio is 5.4

- Both utilize WG Plutonium-Aluminum No-Nickel (PANN) ZPPR plates as fuel
- Non-nuclear components can be used for future experiments as well

Experiment execution

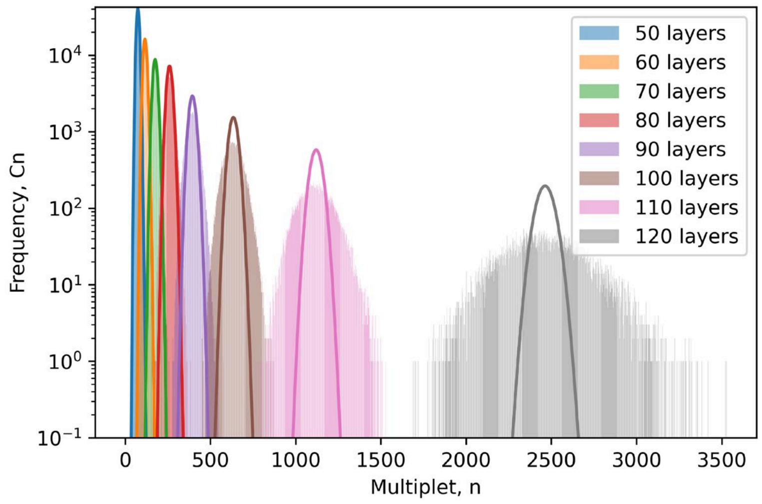
- 7 weeks at NCERC: Nov 28 2022 - Jan 26 2023
- The most Plutonium ever used in an NCERC Experiment

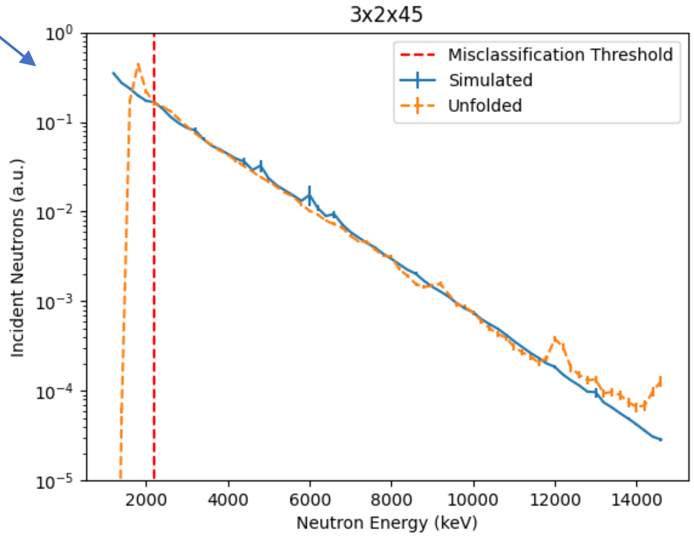




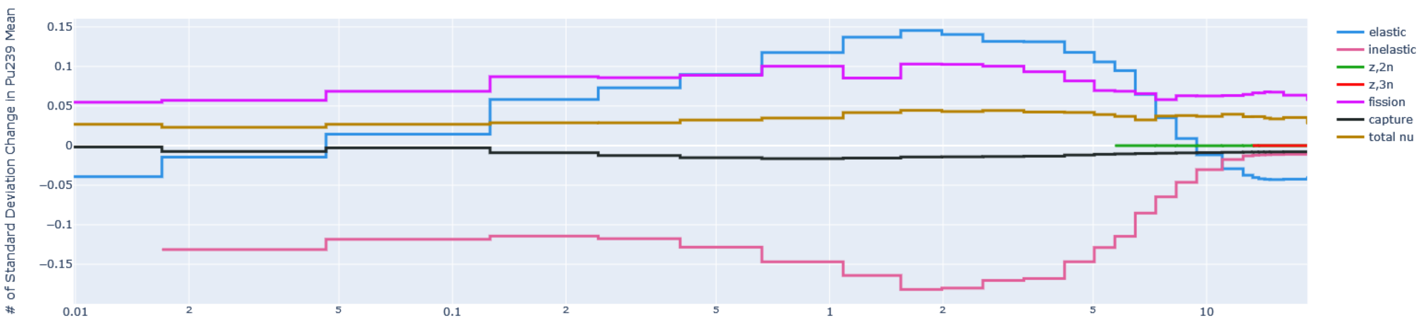
Measurement Responses

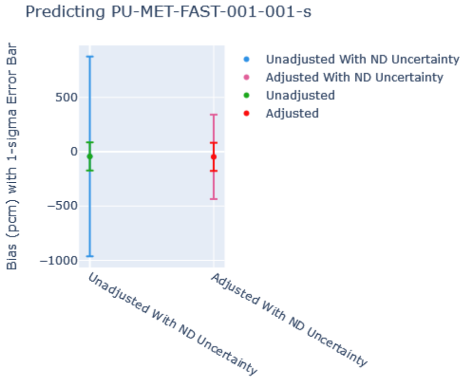
- Six responses were measured for each configuration:
  - Critical: ICNC 2023
  - Subcritical (neutron noise): ANE
  - Neutron leakage spectra: APS 2023 and upcoming journal submission
  - Rossi-α: future work
  - Reactivity coefficients: ICNC 2023
  - Reaction rate ratios: submitted for journal publication
- Measured values, simulated values, simulated sensitivities, and covariances utilized for nuclear data adjustment

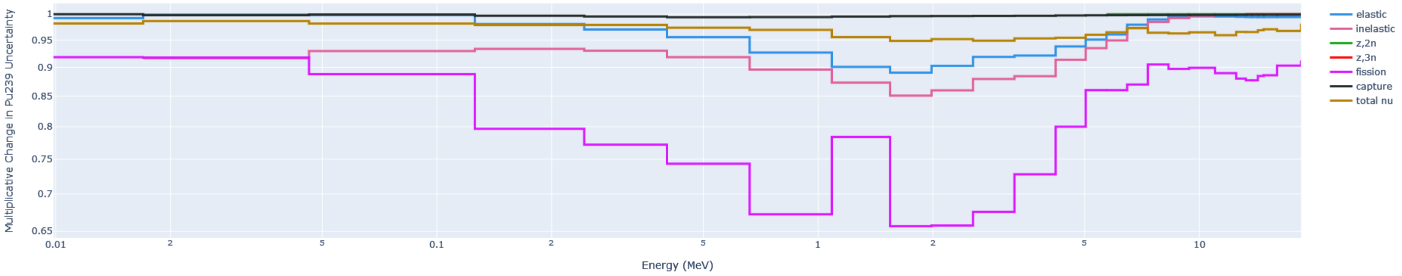




Nuclear Data adjustment using EUCLID k_{eff}'s





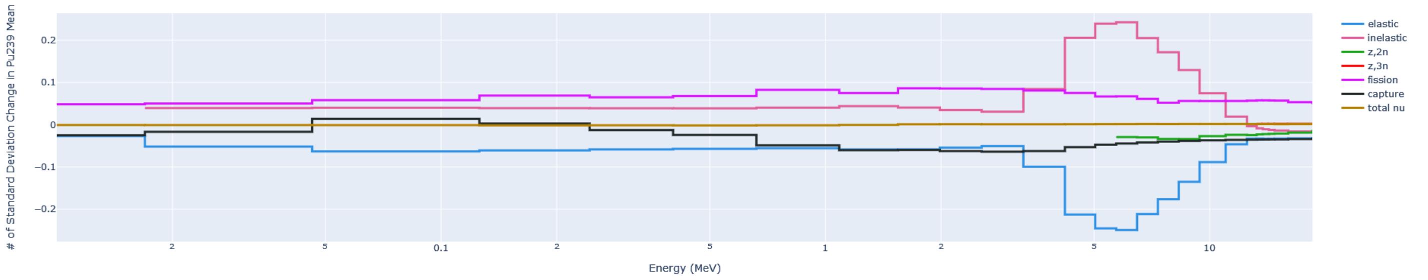


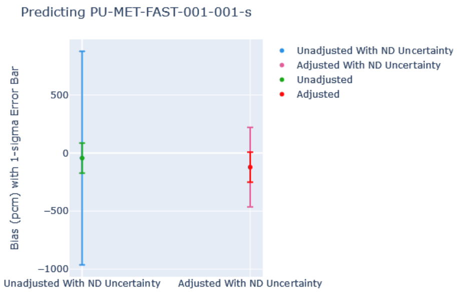
Jezebel impact (pcm)

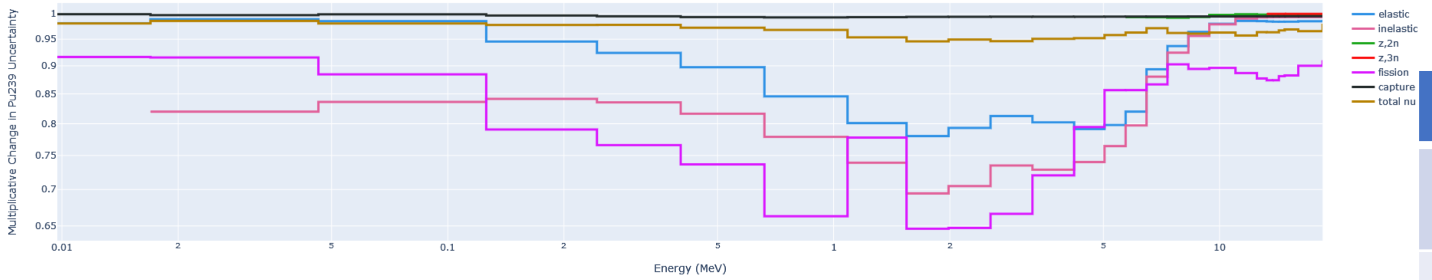
	Prior	Posterior
PMF001 Bias	-44	-48
PMF001 ND unc	919	388

- ND adjustment performed using the EUCLID Adjustment Tool (EAT)
- ND changes on the order of 0.15σ
- Large uncertainty reduction, primarily because of fission

ND adjustment using EUCLID k_{eff}'s, neutron leakage spectra, and reaction rate ratios





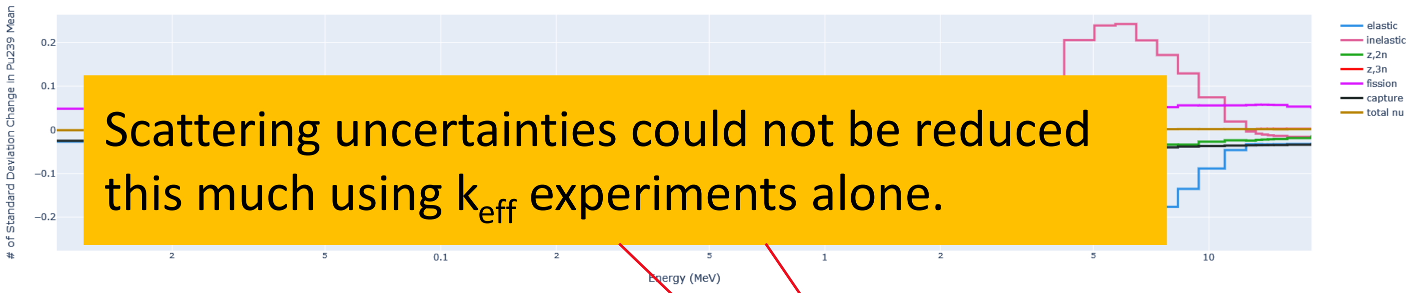


Jezebel impact (pcm)

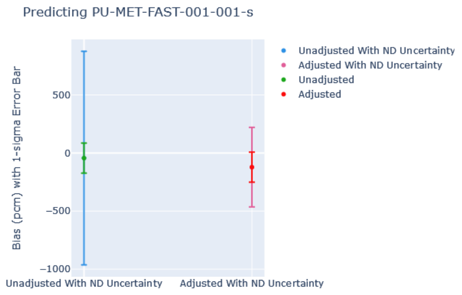
	Prior	Posterior
PMF001 Bias	-44	-121
PMF001 ND unc	919	342

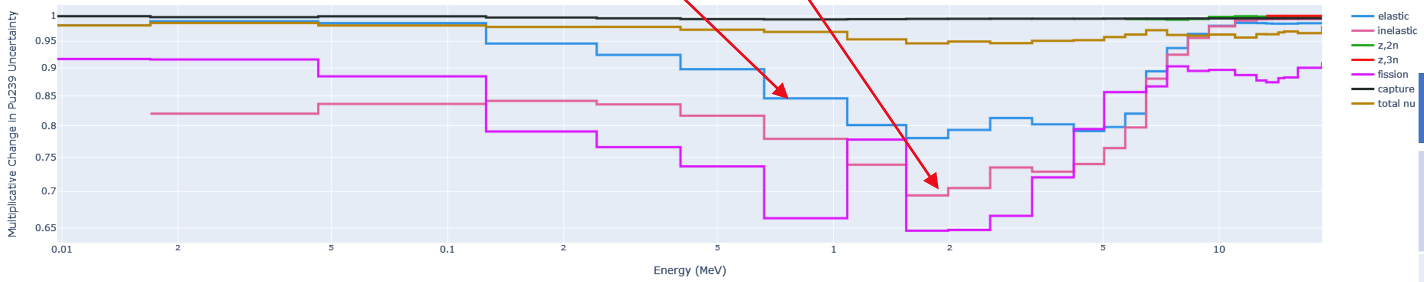
- ND changes on the order of 0.2σ (<0.1σ for non-scattering)
- k_{eff}'s greatly help reduce fission uncertainty and neutron leakage spectra greatly helps reduce scattering uncertainty

ND adjustment using EUCLID k_{eff}'s, neutron leakage spectra, and reaction rate ratios



Scattering uncertainties could not be reduced this much using k_{eff} experiments alone.





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- k_{eff}'s greatly help reduce fission uncertainty and neutron leakage spectra greatly help reduce scattering uncertainty

Different Configurations and Responses Contribute Differently to Reductions in Nuclear Data Uncertainties

k_{eff}'s are good for fission cross section

8x1 has very little impact on scattering

3x2 leakage spectra has large impact on scattering

	Fission	nu	Elastic	Inelastic	Capture
3x2 k_{eff}	**31.4%**	4.8%	4.8%	5.2%	0.5%
8x1 k_{eff}	**31.8%**	4.9%	**0.6%**	**0.4%**	0.6%
3x2 NLS	14.1%	2.2%	**14.0%**	**15.6%**	0.3%
8x1 NLS	13.6%	2.3%	1.9%	2.0%	0.3%
3x2 RRR	0.3%	0.0%	2.0%	2.0%	0.3%
8x1 RRR	0.1%	0.0%	2.9%	3.5%	0.1%
All	35.3%	5.4%	20.7%	30.6%	0.7%

Maximum reduction in nuclear data uncertainty

EUCLID Crew Member and FMH Training Opportunities

- Training of new crew members and Fissionable Material Handlers was a major focus.
- Ten crew/FMH trainees were able to participate in the experiment, getting invaluable hands-on experience.
- Included many aspects of experiment execution:
  - Approach-to-critical, reactivity coefficients, Rossi-alpha measurements, irradiation, etc.
- Several conversions from student to staff positions during the EUCLID project – and these individuals are continuing to contribute to NCSP tasks.

Conclusions and future work

- The EUCLID LDRD DR project ended in Sept 2023.
- Multiple EUCLID responses strongly reduce Pu239 ND uncertainty AND help our understanding of elastic and inelastic scattering where differential experiments and theory cannot constrain the data sufficiently.
- Many advancements will be useful for NCSP:
  - EUCLID Adjustment Tool (EAT)
  - MCNP FSEN
  - FAUST-tk/ACE-tk advancements
  - New experiment data
  - New experiment design capabilities
  - Connections across different disciplines
- More work is still needed:
  - Publications
  - Benchmark(s)

Type	Number	Highlights
Journal publications	15	ANE, Nuclear Data Sheets, Statistical Analysis and Data Mining, NSE, American Statistician, Physical Review Research, Phys Rev C, Frontiers in Physics, and Frontiers in Nuclear Energy
Conferences	20	ND 2022, CoDA 2023, ICNC 2023
Workshops/ meetings	Many	CSEWG, OECD/NEA SG 46+47, IAEA, WANDA, NDUQWM, NCERC Futures, TPR

Acknowledgments

- Research reported in this publication was supported by the U.S. Department of Energy LDRD program at Los Alamos National Laboratory.
- NCERC is supported by the DOE Nuclear Criticality Safety Program, funded and managed by the National Nuclear Security Administration for the Department of Energy.
- Los Alamos National Laboratory is operated by Triad National Security, LLC, for the National Nuclear Security Administration of the US Department of Energy under Contract No. 89233218CNA000001.

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

NCSP NUCLEAR CRITICALITY SAFETY PROGRAM

NCERC NATIONAL CRITICALITY EXPERIMENTS RESEARCH CENTER

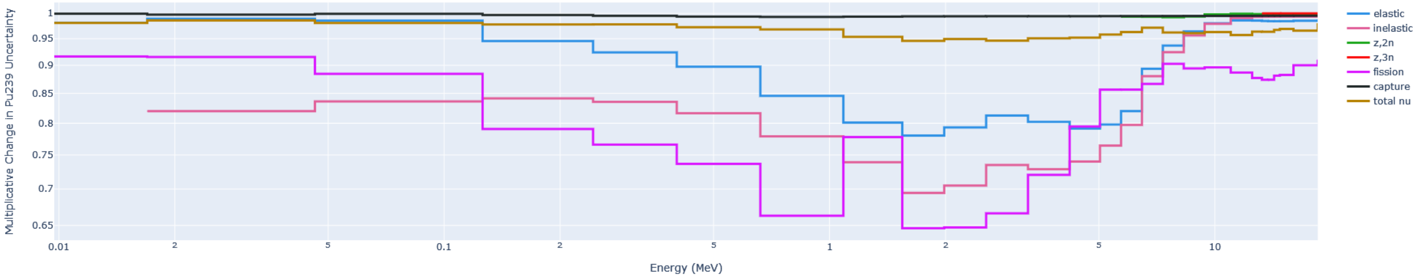
MCNP6

LDRD

Backup slides

EUCLID designed validation experiments optimized to reduce ^{239}Pu compensating errors

- EUCLID resulted in many advancements useful to NSCP:
  - EUCLID Adjustment Tool (EAT)
  - MCNP FSEN
  - FAUST-tk/ACE-tk advancements
  - New experiment data
  - New analysis capabilities
- Two configurations built at NCERC and 6 responses were measured
- Combined use of responses shown to be useful to constrain nuclear data and help in understanding of Pu239 scattering
- The EUCLID results will be useful to the ND community

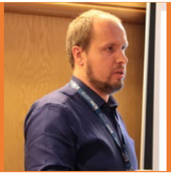


Team

Experiments Underpinned by Computational Learning for Improvements in nuclear Data

Nuclear Data

Noah Kleedtke



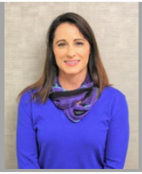
Wim Haeck

Michal Herman

Robert Little

Denise Neudecker

Simulations



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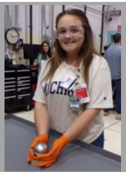

Juliann Lamproe

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Experiments

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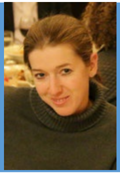

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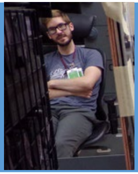

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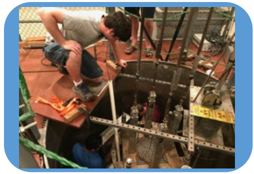
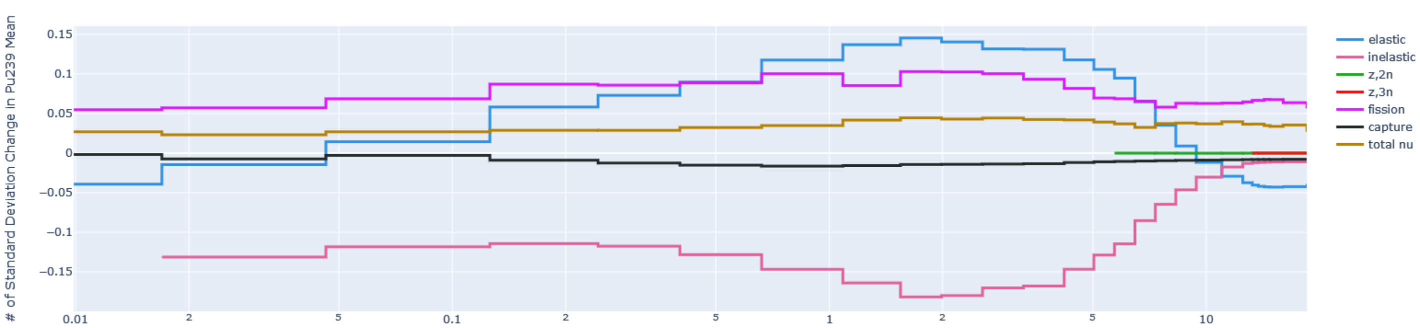
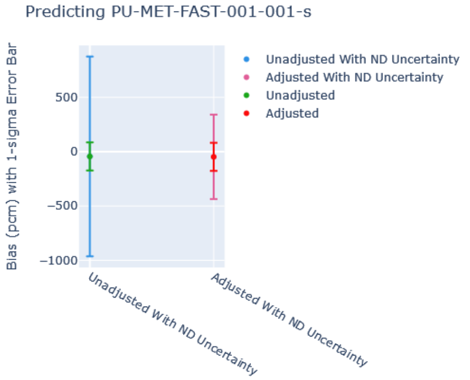


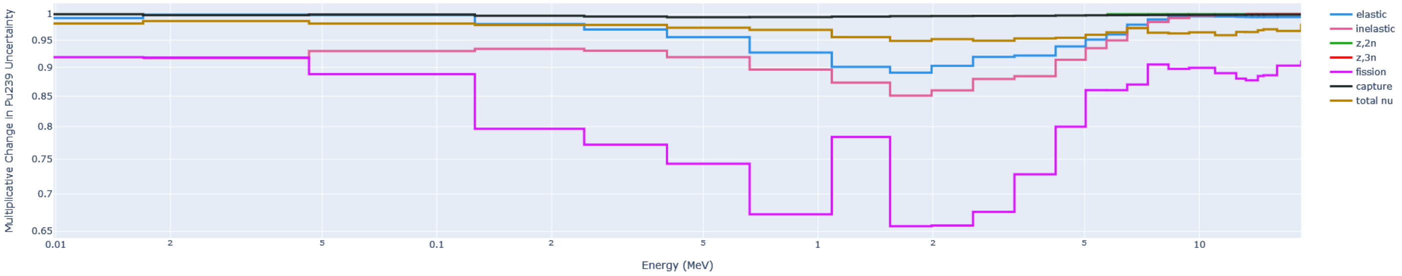
Nicholas Thompson

LDRD

ND adjustment using EUCLID crits







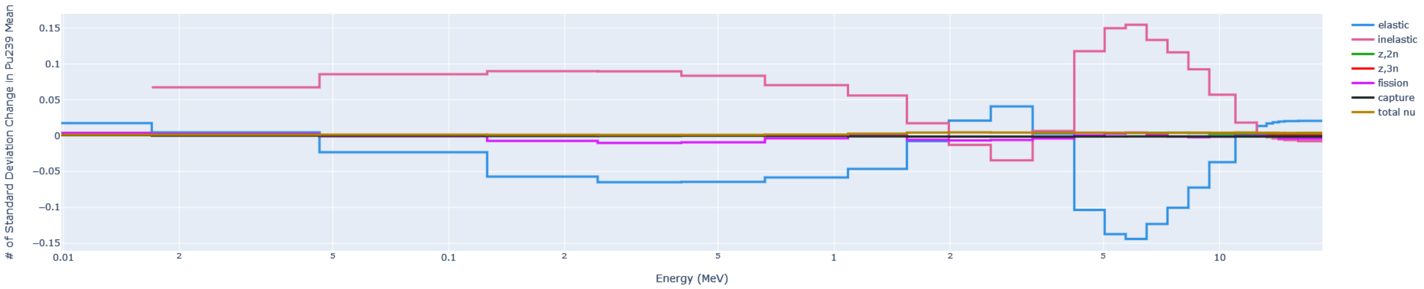
Jezebel impact (pcm)

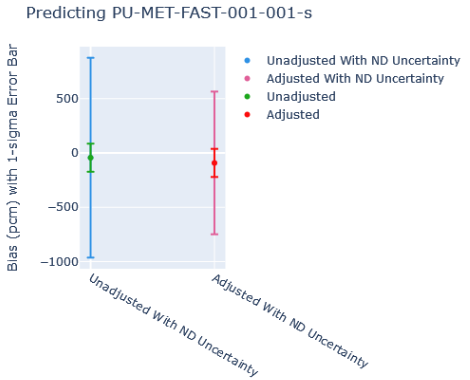
	Prior	Posterior
PMF001 Bias	-44	-48
PMF001 ND unc	919	388

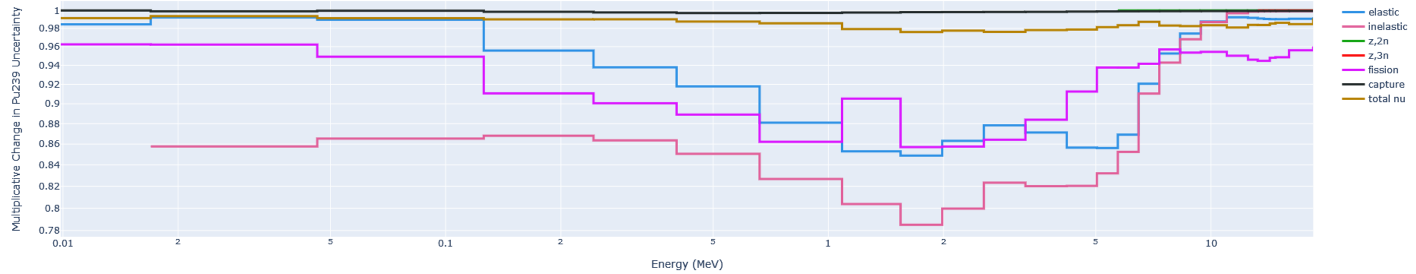
- ND adjustment performed using the EUCLID Adjustment Tool (EAT)
- ND changes on the order of 0.15σ
- Large uncertainty reduction, primarily because of fission

LDRD

ND Adjustment using EUCLID neutron leakage spectra





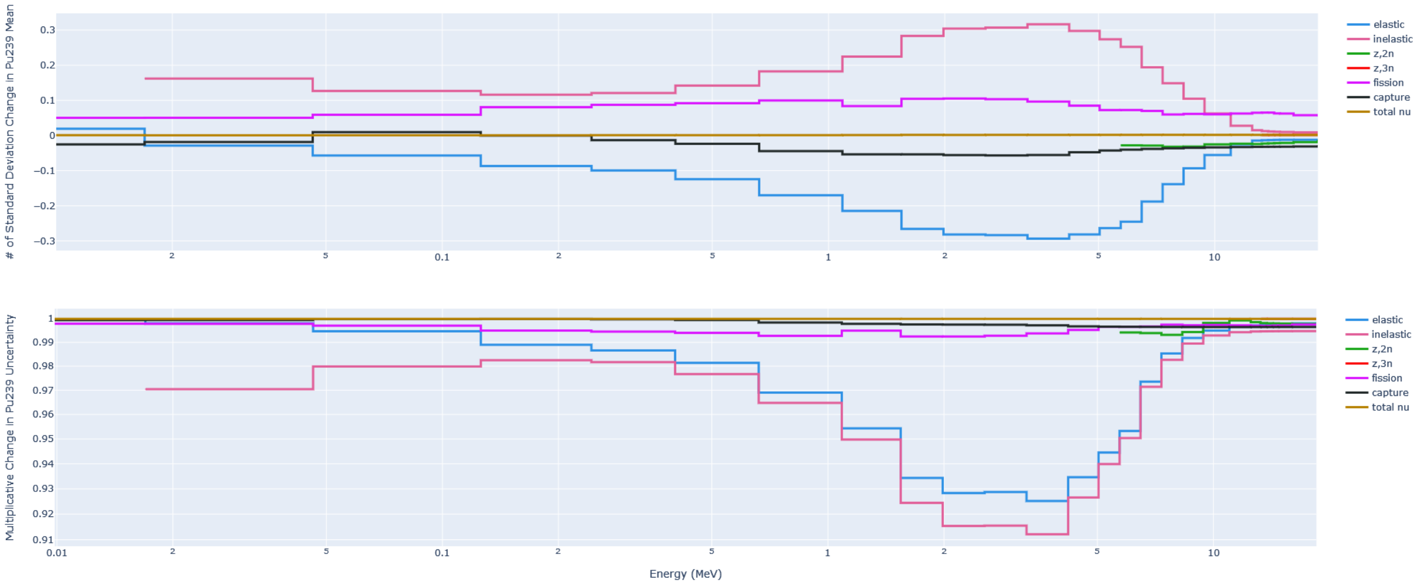


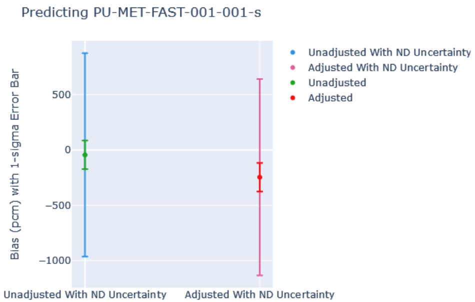
Jezebel impact (pcm)

	Prior	Posterior
PMF001 Bias	-44	-57
PMF001 ND unc	919	601

- ND changes on the order of 0.15σ
- Decent uncertainty reduction, due to inelastic, elastic, and fission

ND adjustment using EUCLID RRR





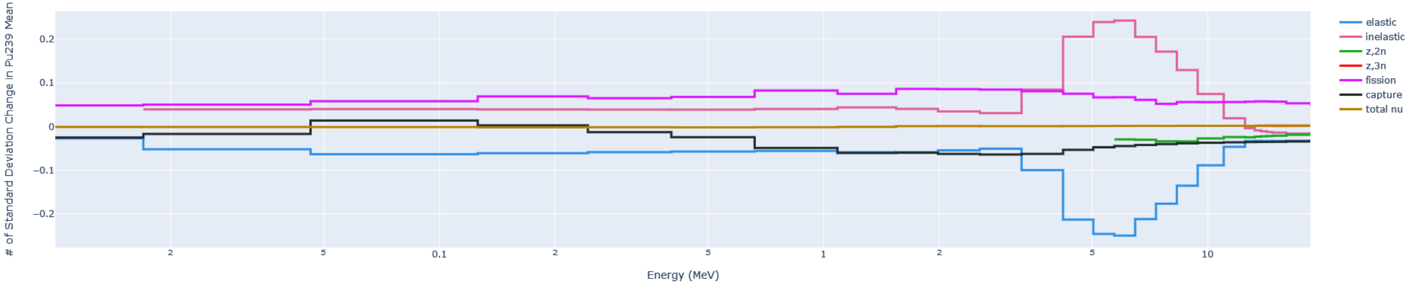
Jezebel impact (pcm)

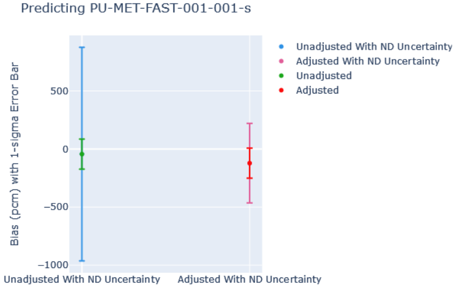
	Prior	Posterior
PMF001 Bias	-44	-246
PMF001 ND unc	919	888

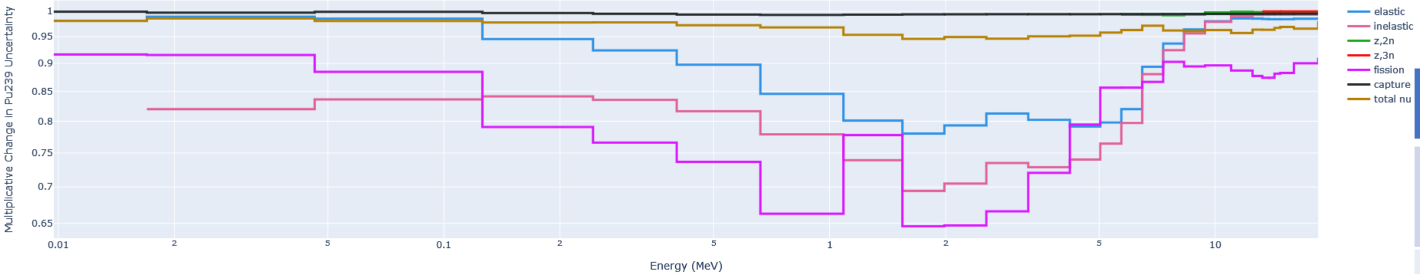
- ND changes on the order of 0.3σ
- Small uncertainty reduction, but driven by elastic and inelastic
- Somewhat large bias in Jezebel

LDRD

ND adjustment using EUCLID crits, NLS, and RRR







Jezebel impact (pcm)

	Prior	Posterior
PMF001 Bias	-44	-121
PMF001 ND unc	919	342

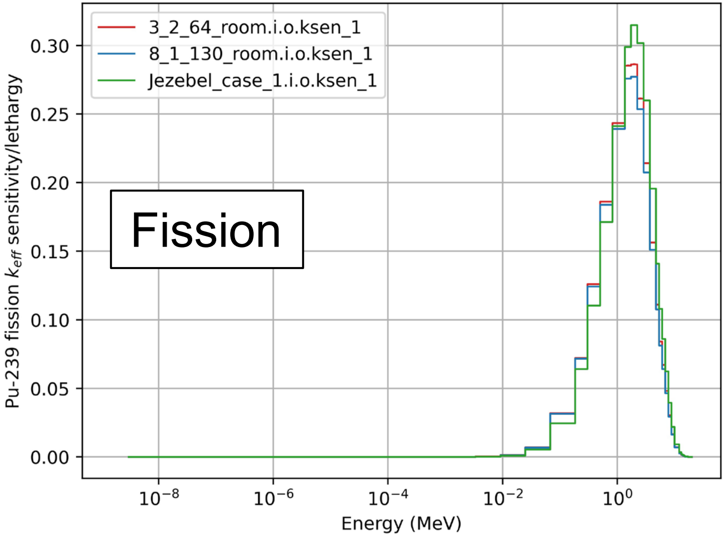
- ND changes on the order of 0.2σ (<0.1σ for non-scattering)
- Crits greatly helps reduce fission uncertainty and NLS greatly helps reduce scattering uncertainty

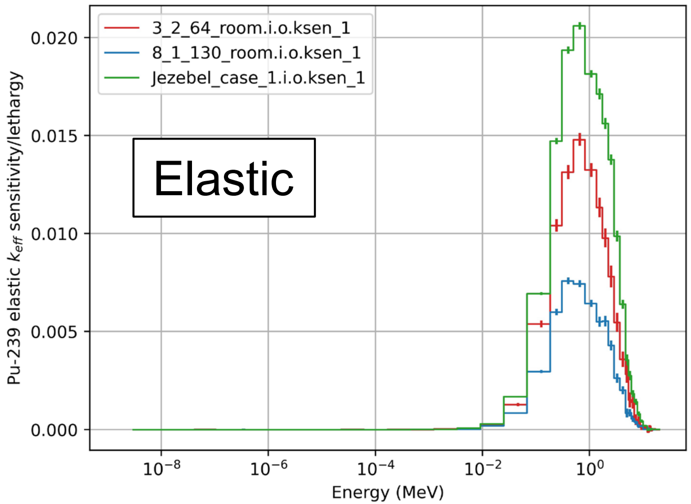
LDRD

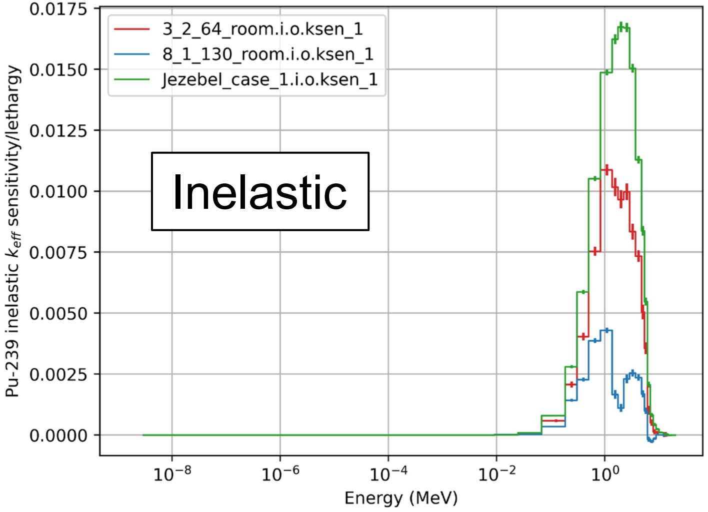
This is a large team effort

k_{eff} Sensitivities (From MCNP)

- Jezebel – detailed benchmark, case 1
- 3 X 2 X 64
- 8 X 1 X 130





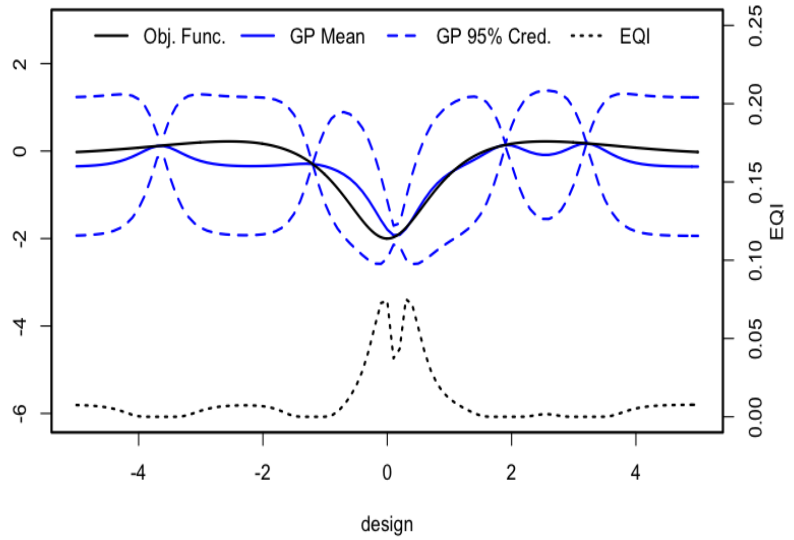


LDRD

Machine Learning and Optimization

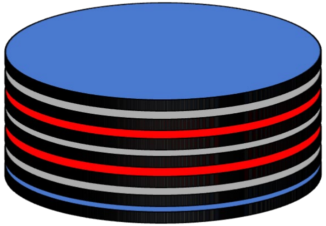
- Gaussian process (GP) optimization uses ML surrogates to guide optimization
- Converts a “hard” optimization problem (D-opt + MCNP) to a sequence of “easier” problem (GP + acquisition function)
- Two GP models used: D-opt (obj. function) and k_{eff} (constraint)
- Optimization was performed with experts in-the-loop

Example optimization after 5 objective function evaluations

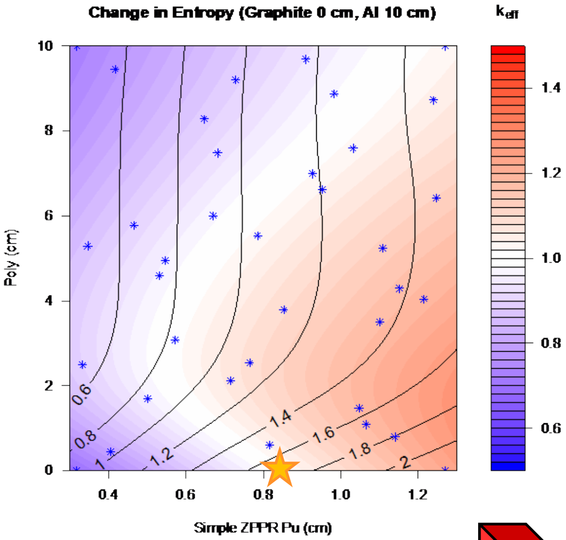


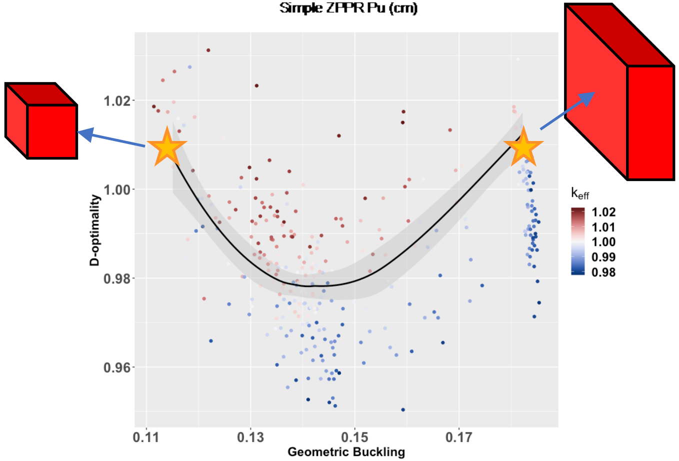
Approach: Prioritized k_{eff} measurements to identify bulk characteristics and then optimized auxiliary measurements

EUCLID Design Steps and Decision points



- Cylindrical Prototype
  - Eliminated moderators and decouple systems
- Parallelepiped Prototype
  - Optimized geometry (high and low neutron leakage) and selected reflector
- Critical Configurations and Measurements
  - Minimized configurations and prioritized measurements by expected D-optimality





Primary Measurements
1. k_{eff}
2. 2 RC (two positions)
3. 2 SC batches (two levels of crit)
4. 1 RR batch (one location)

Secondary Measurements
1. 1 Rossi-alpha
2. 1 RC(at other level)

Experiment Constraints

- System must be able to go critical (k_{eff} = 1.0)
- Excess reactivity limit of 80 cents
- Maximum temperature of 100°C
- Pu mass limit = 150 kg PuE
- Two general purpose critical assemblies:

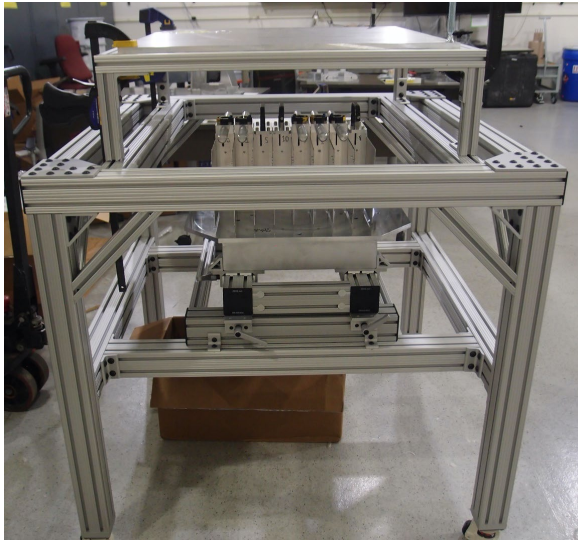
Mass was not an issue, but the size of the opening on Planet allowed for bigger experiments

	Planet	Comet
Total weight limit	2,000 lbs	**20,000 lbs**
Moveable platen weight limit	1,000 lbs	**2,000 lbs**
Horizontal opening size	**29” X 29” (square hole)**	21” diameter (circular hole)
Travel Distance	4” – 26”	**5” - 28”**

LDRD PLANET

Experiment Components

- Nearly 1,000 components were specially made for EUCLID
  - Aluminum plates, Aluminum spacers, 8 X 1 and 3 X 2 buckets, fins for heat dissipation, etc.
  - All components were measured and test fit
  - Also procured elevators to lift detectors and experiment components
- These components can be used for future experiments as well
- Also used existing stock materials and reused existing components



Radiation dose

- Due to the large amount of plutonium (especially for the 8 X 1 configuration), there are high dose rates near the assembly, and potentially large dose to workers.
- Simulations were done beforehand and compared to measurements of ZPPR plates to estimate dose.
- Additional simulations were performed to identify ways to minimize dose to workers during the experiment.
- In the end, all doses were below those analyzed and documented.