THE UNIVERSITY OF
TENNESSEE
KNOXVILLE

DEPARTMENT OF
NUCLEAR ENGINEERING

Fast Neutron Source at UTK for Cross Section Measurements in Support of Advanced Reactor Development

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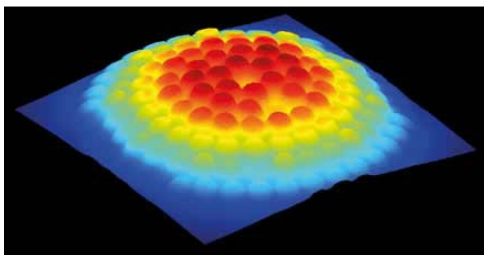
New UT Nuclear Engineering Building

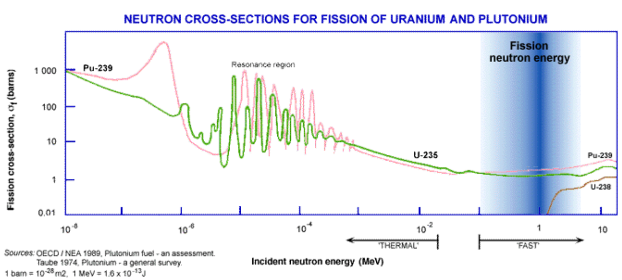
Completion in summer of 2021

Fast Reactor Cross Section Data Needs

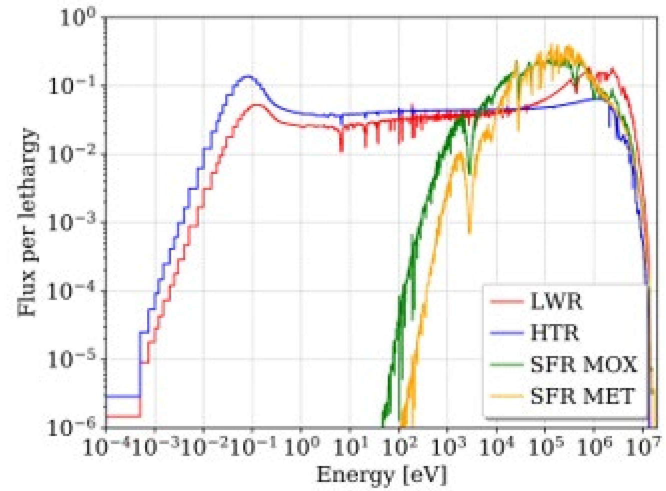
Next generation (fast reactor) reactor design is strongly dependent on modeling & simulation

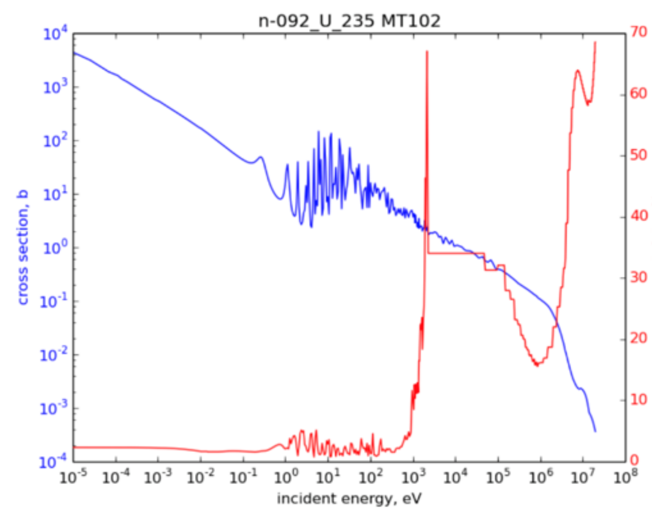


Modeling & simulation depends on nuclear data



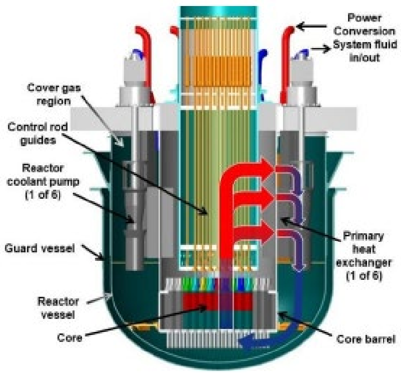
Higher uncertainty in nuclear data will result in more conservative design which will make the plants more expensive and less competitive





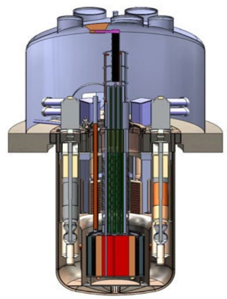
Fast Reactor Developers

Westinghouse



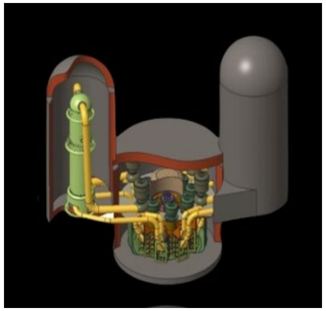
Lead Fast Reactor

TerraPower



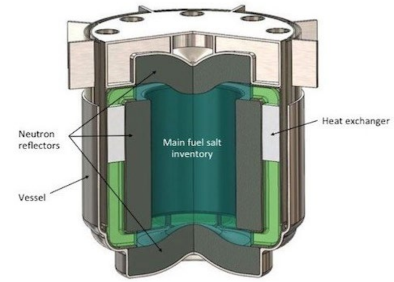
Sodium Fast Reactor

ELYSIUM INDUSTRIES INC



Molten Chloride Salt Fast Reactor

TerraPower

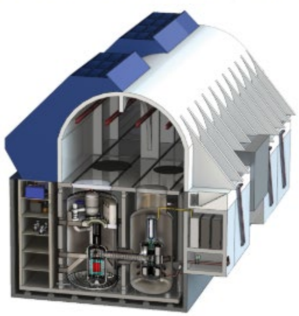


Molten Chloride Salt Fast Reactor

GE HITACHI

Sodium Fast Reactor

GENERAL ATOMICS



Gas Cooled Fast Reactor

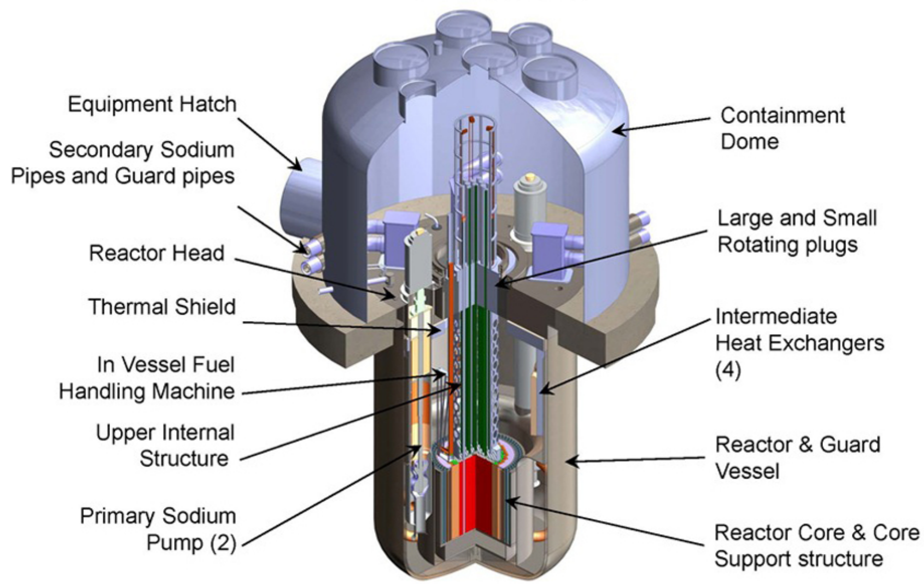
NuGen

Gas Cooled Fast Reactor

Nuclear Data Affecting Reactor Design

- Beginning-of-Life (BOL) k_{eff} +/- 2.2%
- Coolant temperature feedback coefficient +/- 138%
- Void worth +/- 147%
- “Uncertainties in key design parameters due to nuclear data have been computed that may be used to set design margins during the TWR development program. The **uncertainties of many parameters are higher than is desired**, **motivating additional efforts in cross section measurements**, improved data evaluations, and data assimilations.” – N. Touran, et al.

Traveling Wave Reactor (TWR)



TerraPower

Source: N. Touran and J. Yang, "Sensitivities and Uncertainties Due to Nuclear Data in a Traveling Wave Reactor," Proceedings of the PHYSOR 2016 Meeting in Sun Valley, ID, May 2016.

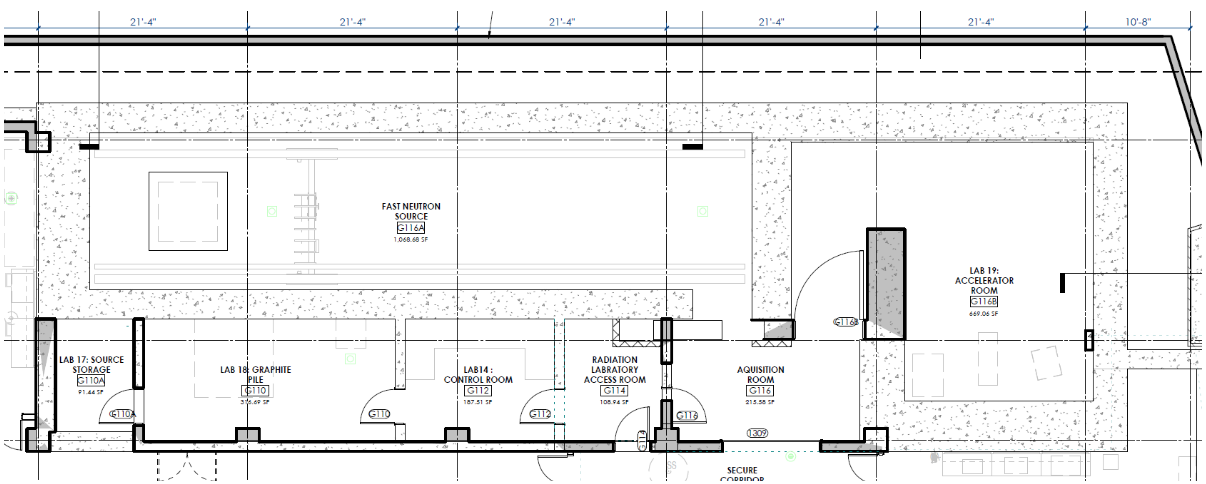
UTK Fast Neutron Source (FNS)

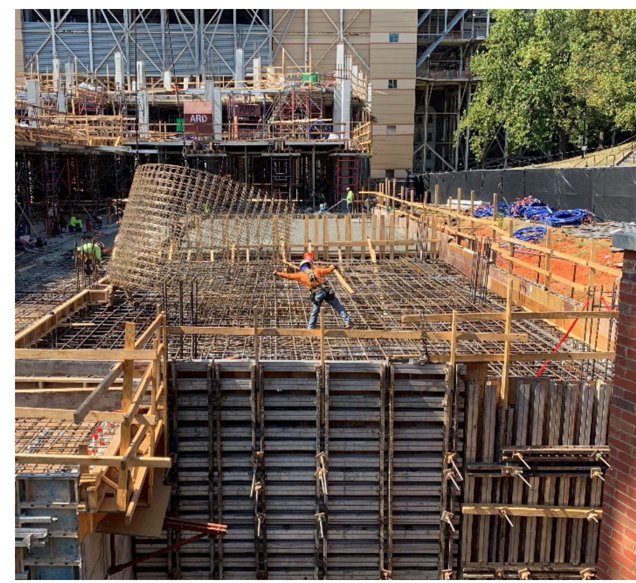
FNS Facility Design:

- 16’x70’ Heavily shielded vault and adjacent control room
- Physical security systems
- 18’ ceilings and Bridge Crane for moving shielding and core components

FNS Core and Design:

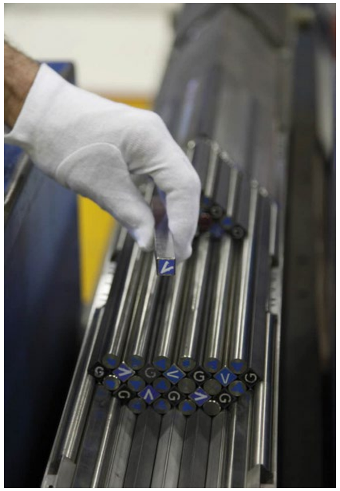
- Neutron Generator driven subcritical system (.95-.98 Keff)
- Oscillator, Transfer System, and Beam Line for both integral and differential cross section measurements
- Highly flexible and reconfigurable design

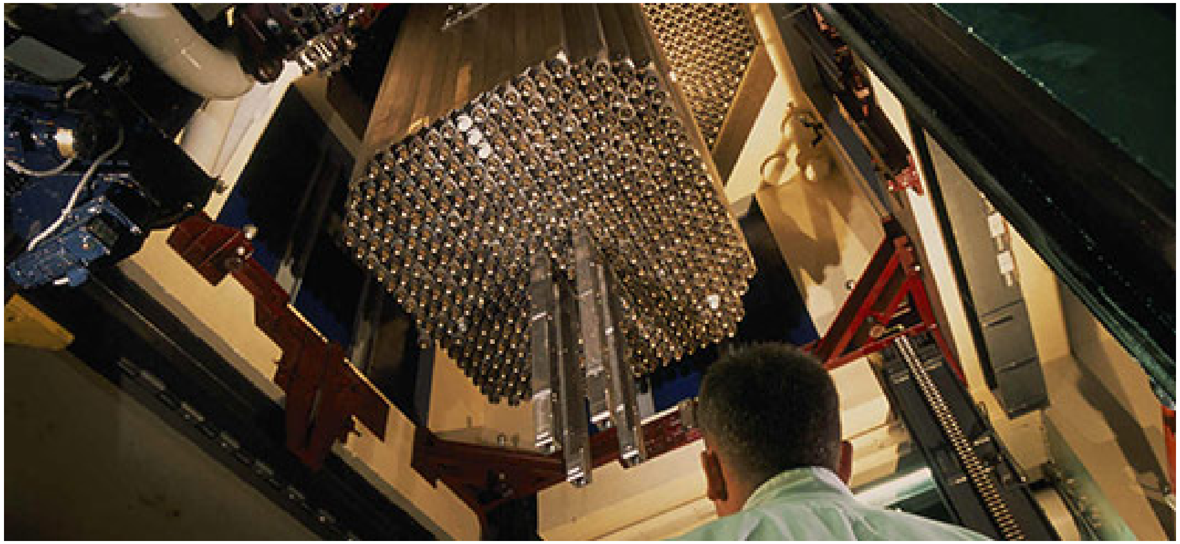




Flexibility Concept

- MASURCA Facility (Cadarache, Fr.)
  - Neutronics studies of fast lattices (1966)
  - Air cooled fast reactor operating at
    - maximum of 5kW th
    - flux level up to 10^9 n/cm2/s
  - Reconfigured into subcritical ADS: MUSE



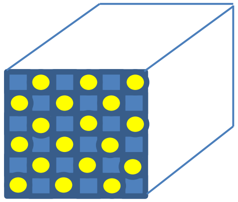


Flexible Design:

- Core of wrapper tubes 4”x4”x 1m long
  - cylinder rodlets
  - square platelets
- Flexible loadings

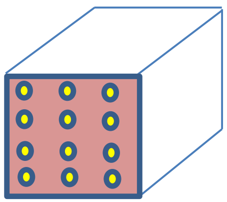
Soule, R, W. Assal, P. Chaussonnet, C. Destouches, C. Domergue, G. Imel, G.M. Thomas, “Neutronic Studies in Support of ADS : The MUSE Experiments in the MASURCA Facility”, 2002

Fast/Thermal Coupled Design Concept



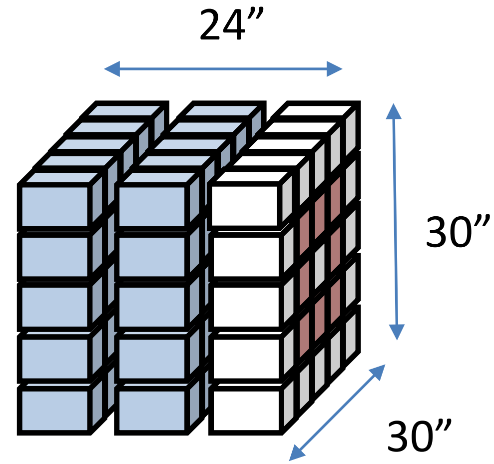
1” diameter Uranium rod (8” long)
1” square ended rectangle
Pb, Na, or Salt (8” long)

Fast Cassette

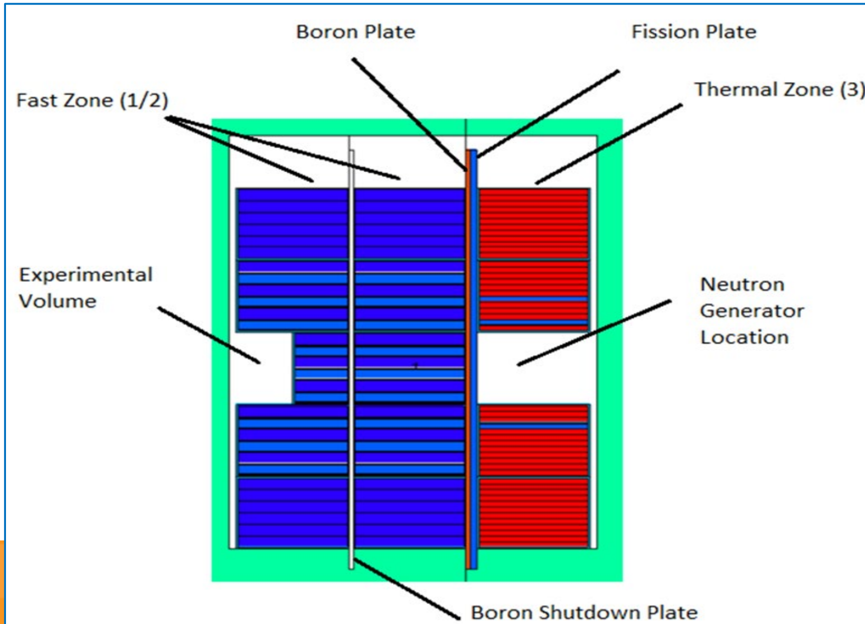


0.5 ” diameter Uranium rod (8” long)
High Density Poly Block

Thermal Cassette



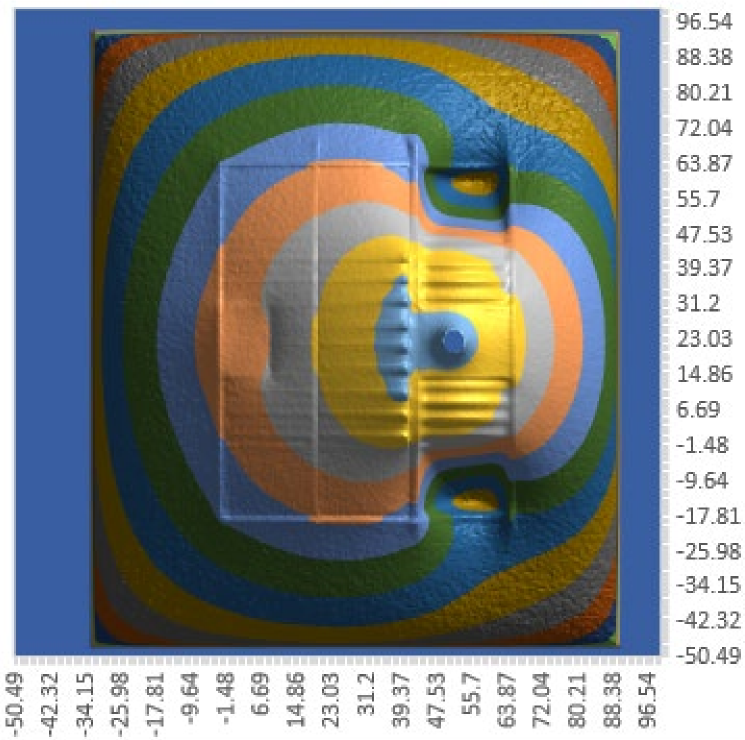
Flexible Core Design



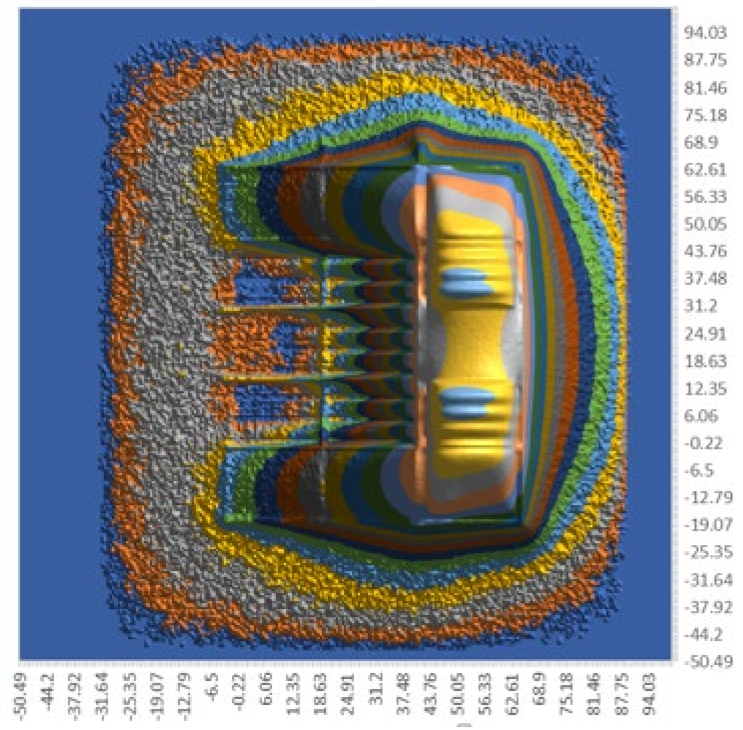
Experimental Volume
Flux 2.23E+06
w/ 3x10^9 n-Generator

Thermal Keff = 0.88
Fast Keff = 0.60
Coupled Keff = 0.95

Simulation Results



Fast Flux



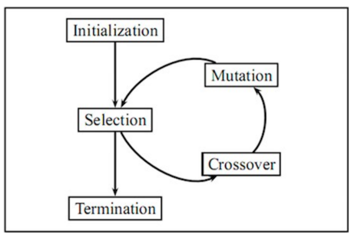
Thermal Flux

Reflector: 10” steel
Shielding: 4” borated poly and 6” steel

Extremely Flexible AI Design

AI Design Optimization

Human Design



AI Design

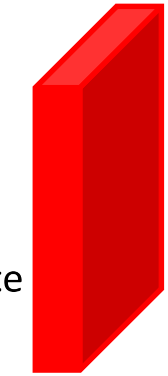
Plate Design

0.5 ” thick Uranium plate

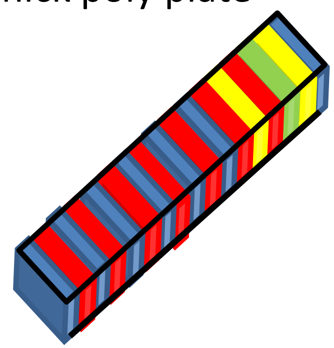
0.5 ” thick Lead plate

0.05 ” thick Cadmium plate

0.5 ” thick poly plate



6”x6” x.5”



Initial Genetics Algorithm Design:

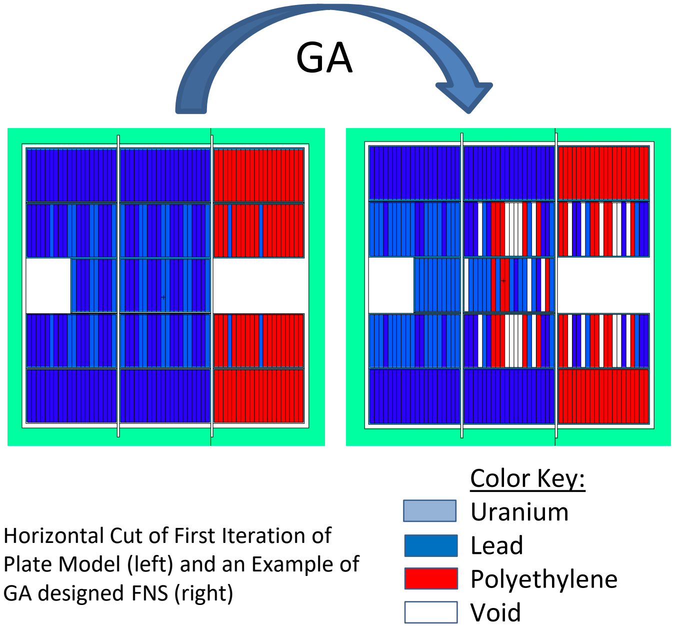
- Reduced Uranium Mass by 3X
- Improved Performance by 3X

Expert-Designed vs. AI Designs

Goal:
For a specific desired neutron spectrum and materials (advanced reactor design), optimize the distributions of the materials throughout the core.

	Fast Flux	F/NF Ratio	Uranium Mass (lbs.)
GA A	2.29E+06	62.4	1788
GA B	2.72+06	42.8	1677
Cyl. Model	1.16+06	40.0	1709
Plate Model	1.24E+06	32.5	1739

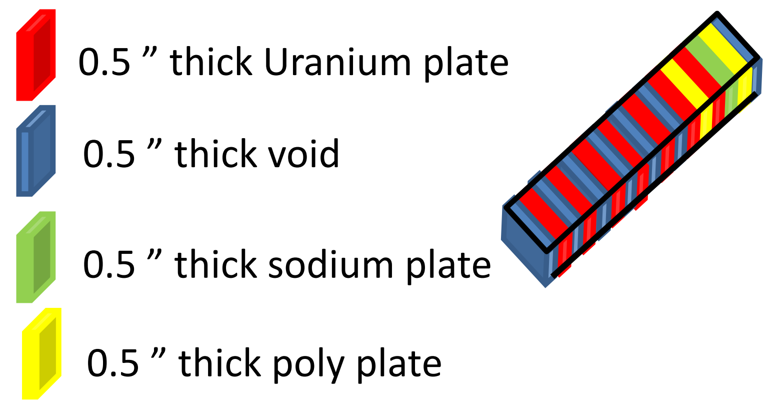
- When constraints were removed:
  - Loaded more fuel around the experiment volume
  - Increased "thermal" booster size by moving polyethylene into center zone
  - Added lead (reflector) behind neutron source
  - Cadmium (thermal neutron poison) near experiment volume
- Performance Metric Results
  - 92% higher Fast/Non-Fast Flux Ratio
    - Matches neutron spectrum better
  - 119% higher fast flux per source neutron
    - Leads to quicker experiments



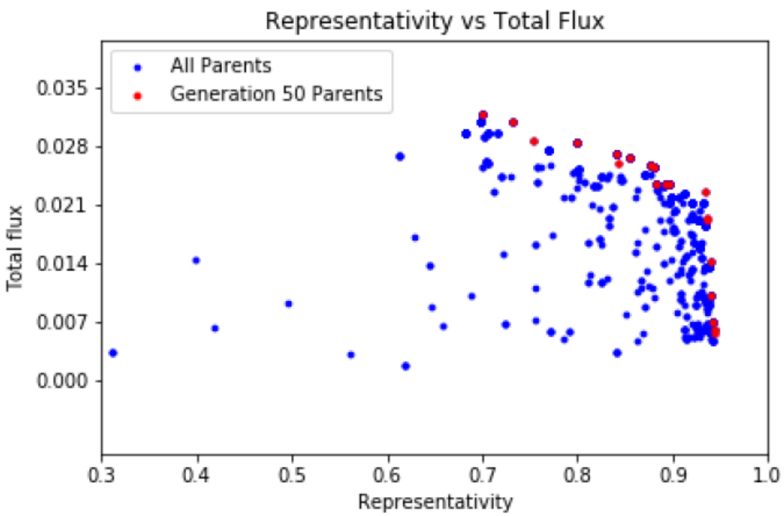
Horizontal Cut of First Iteration of Plate Model (left) and an Example of GA designed FNS (right)

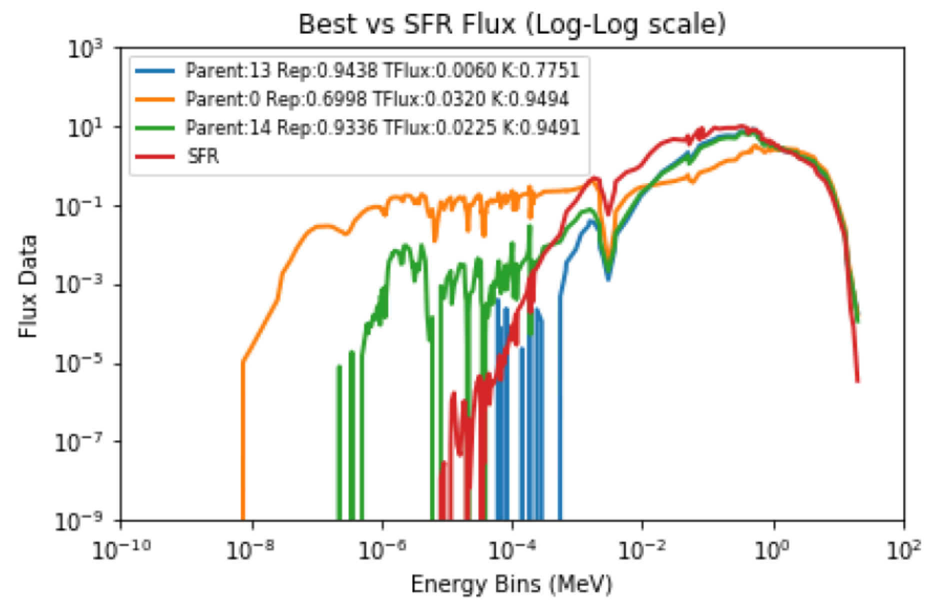
AI-Design Spectrum Matching

- Multi-objective Genetic Algorithm applied to optimize 3D FNS core
- Dual performance objectives to maximize:
  1. Spectrum Representativity
  2. Experimental Flux Level
- Result: Pareto front of solutions



Example cassette





Representativity values up to 0.99 attained for 3D AI-based design.

Simplified Path Forward

- DOE NEUP Infrastructure Grant Proposal
  - Past DOE reviewers considered FNS as a long timeline and high risk facility that required close to a ton of 9.75% enriched Uranium.
  - Revised FNS development into a stepwise design which will significantly reduce project risk through the initial utilization of several tons of natural Uranium which we currently possess.
    - Flux matching proof of principal still valid
    - Flux level reduced by an order of magnitude (longer experiment times)
  - Natural Uranium design reduces project risk through:
    - Reduced licensing requirements (NRC Part 70 license not needed)
    - Lowered safeguards and material accountability requirements
    - Removed necessity for engineered safety and shutdown systems
    - Removed need for criticality safety review and controls
    - Removed SNM security requirements

FNS Stepwise Phases

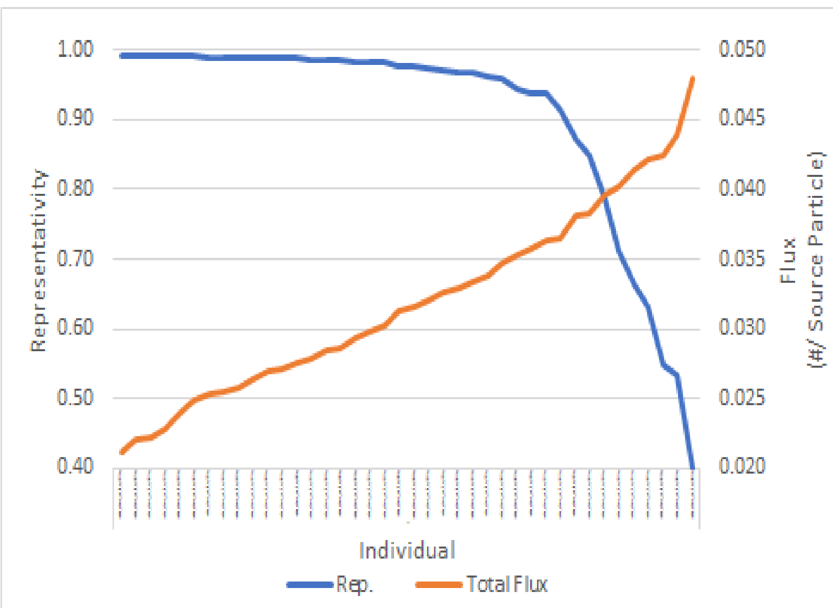
The staged design, licensing, construction, and operational plan is straight forward and well thought out:

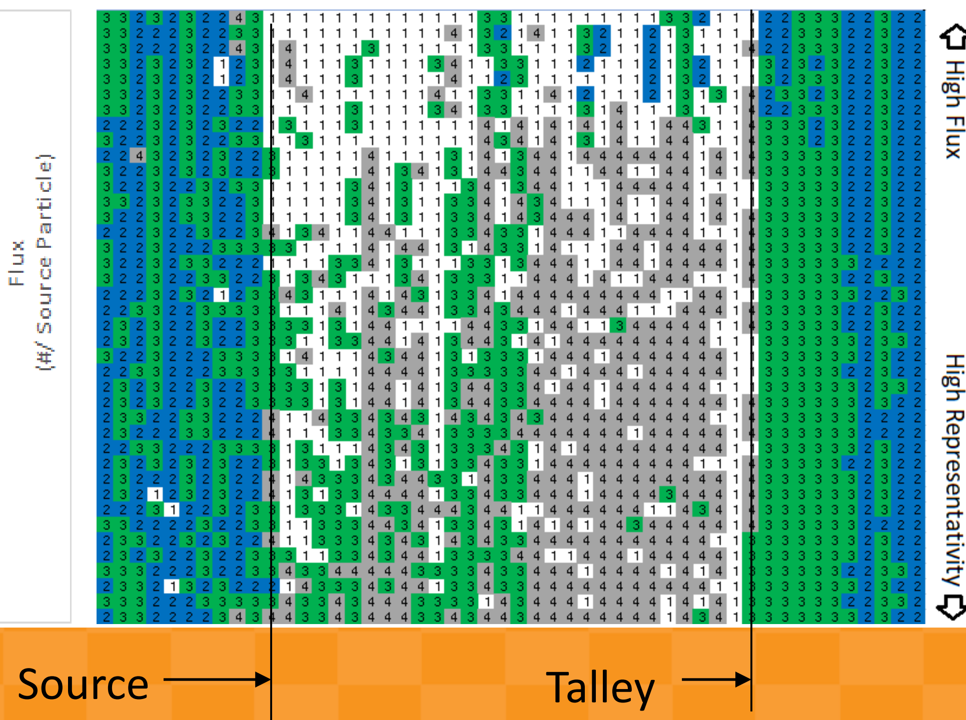
1. Acquire custom DD-109.4DD neutron generator from Adelphi Technologies Inc. (ordered) and utilize it with our new Approach Towards Criticality (ATC) facility to develop procedures, procure state license, and gain operational experience (ordered with expected April 2021 delivery).
2. Purchase instrumentation, core structural components, and shielding necessary to construct the natural Uranium based FNS. (Fall 2021 through Spring 2022).
3. Operate the FNS to meet initial DOE NE and NNSA research and student educational goals with the intent to upgrade to enriched Uranium. (Summer 2022 ->)

Natural Uranium FNS

- Natural uranium provides similar spectra matching capability when compared to 9.75% enriched fuel but at a 1/10th of the neutron flux
- 1D results point to two variants:
  - Less material between experiment volume and source (High Flux)
  - More fuel/moderator between experiment volume and source (High Rep.)
- 3D results have shown similar designs and similar flux reductions from 3D enriched to natural uranium optimization

Key	Void	Poly	Fuel	Sodium
	1	2	3	4





Natural Uranium Spectrum Matching

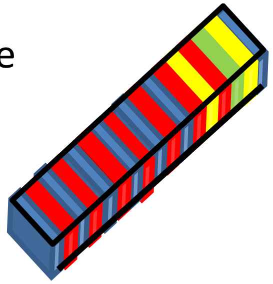
- Multi-objective Genetic Algorithm applied to optimize 1D FNS core
- Dual performance objectives to maximize:
  1. Spectrum Representativity
  2. Experimental Flux Level
- Result: Pareto front of solutions
  - ~0.99 representativity

0.5 ” thick Uranium plate

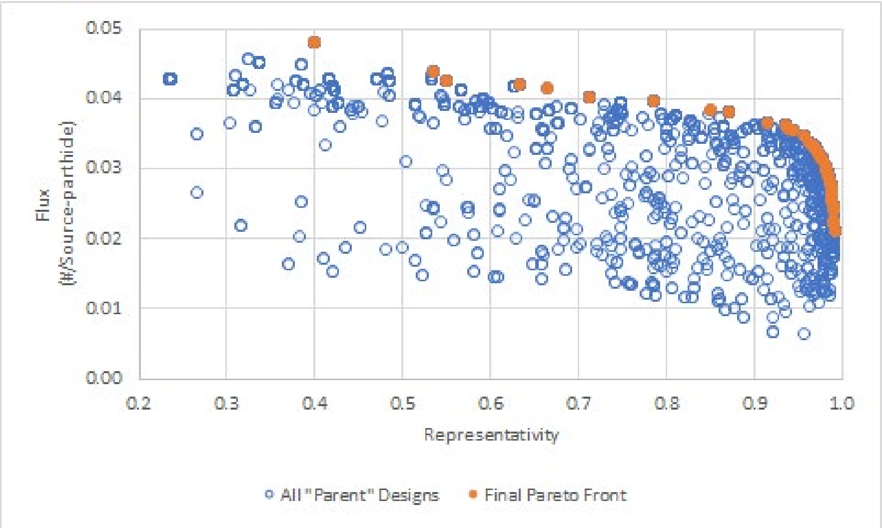
0.5 ” thick void

0.5 ” thick sodium plate

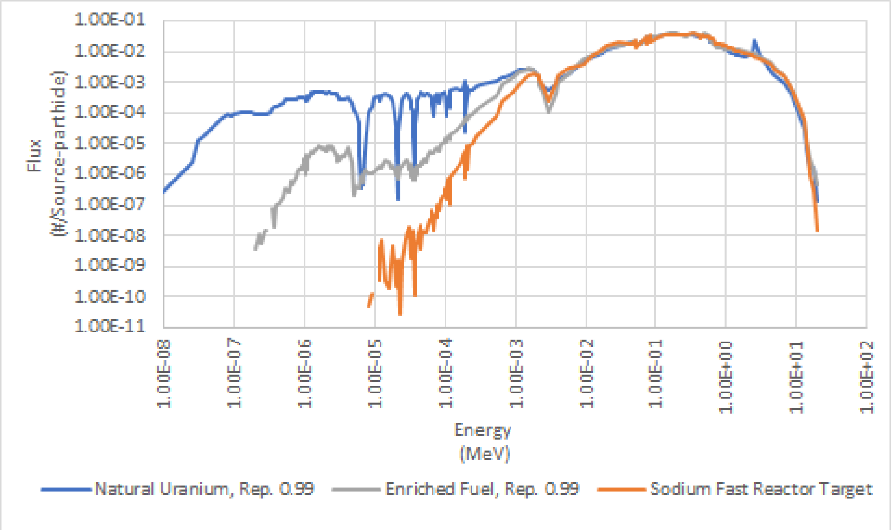
0.5 ” thick poly plate



Example cassette



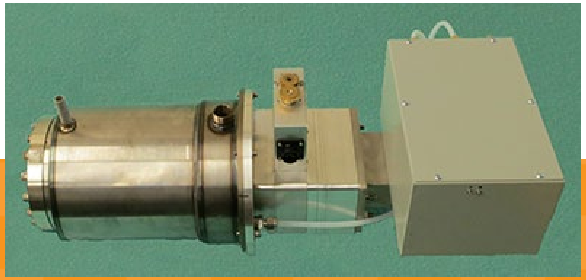
Natural Uranium Optimization Parents



Comparison of Neutron Spectra

Further Enhancements

- The facility can be used to match spectra of other high energy devices (above a fission spectrum) such as detonation and fusion.
  - Requires a DT generator and will follow the same principles.
    - The DT generator also has an order of magnitude higher source strength. With an optimized core, it may produce higher fluxes in the fission space too.
  - Requires slightly different core structural components and instrumentation.
- Measurements at temperature can be attained with an oscillator heating element.
- A proposal to NUCLEAR DATA INTERAGENCY WORKING GROUP (NDIAWG) RESEARCH PROGRAM FOA will be submitted.



Summary

- UTNE has designed a Fast Neutron Source to meet national needs
  - Neutron Fast Cross Section Uncertainty Minimization
  - Future Nuclear Criticality Safety Training
- New Building is under construction with shielded vault, security, and safety focus to open in August 2021
- AI based design optimization brings significant performance improvements and increased flexibility .