MIT NSE Overview

Benoit Forget

Assistant Professor
Massachusetts Institute of Technology
Department of Nuclear Science and Engineering

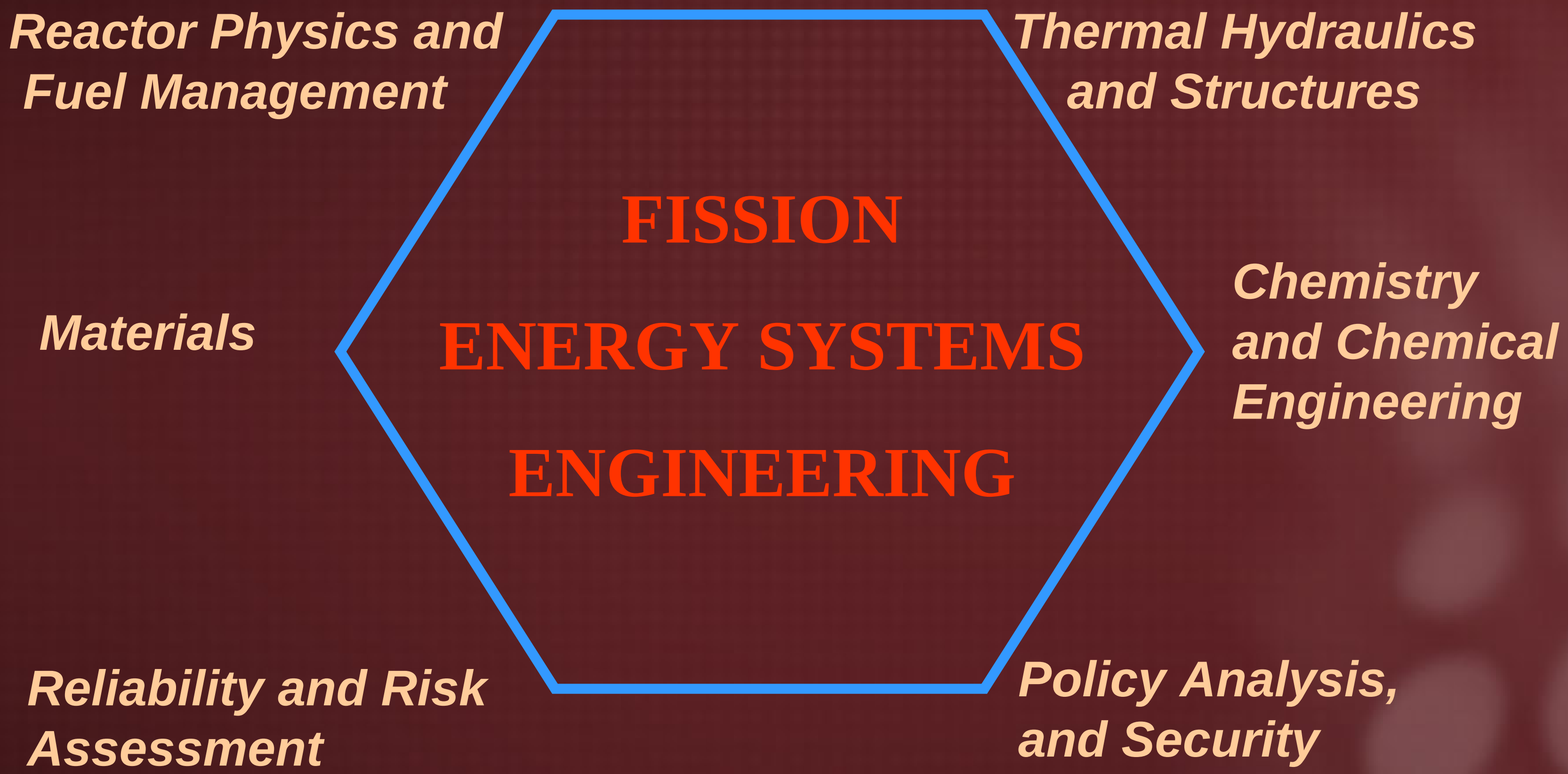
Nuclear Science and Engineering Department

- Three main programs
  - Fission engineering and nuclear energy
  - Fusion and plasma physics
  - Nuclear science and technology
- By the numbers
  - 17 faculty members
  - Approximately 100 graduate students
  - Approximately 50 undergraduate students

Fission area

- Center for Advanced Energy Studies (CANES) aims at development of innovative concepts and analysis methods for advanced nuclear energy systems technology and operations
  - Home to most of the fission faculty and a few permanent research staff
- Four main research programs
  - Advanced power reactors
    - Annular fuel, Supercritical CO2 power cycle, nanofluids, …
  - Nuclear fuel cycle
    - Charles Forsberg is the director of a NEI/EPRI project on the future of the nuclear fuel cycle
  - Enhanced system performance
  - Nuclear energy and sustainability

Disciplines of Fission Energy Engineering



Faculty and staff

Forget, Driscoll, Bernard, Newton, Pilat

Buongiorno, Hu, Kazimi, Todreas,

Ballinger, Yildiz, McKrell Hobbs, Yip

FISSION ENERGY SYSTEMS ENGINEERING

Forsberg, Kohse, Regalbuto, Barton

Apostolakis, Golay

Kadak, Lester, Moniz

* Full Time * Part Time * Emeritus Professor

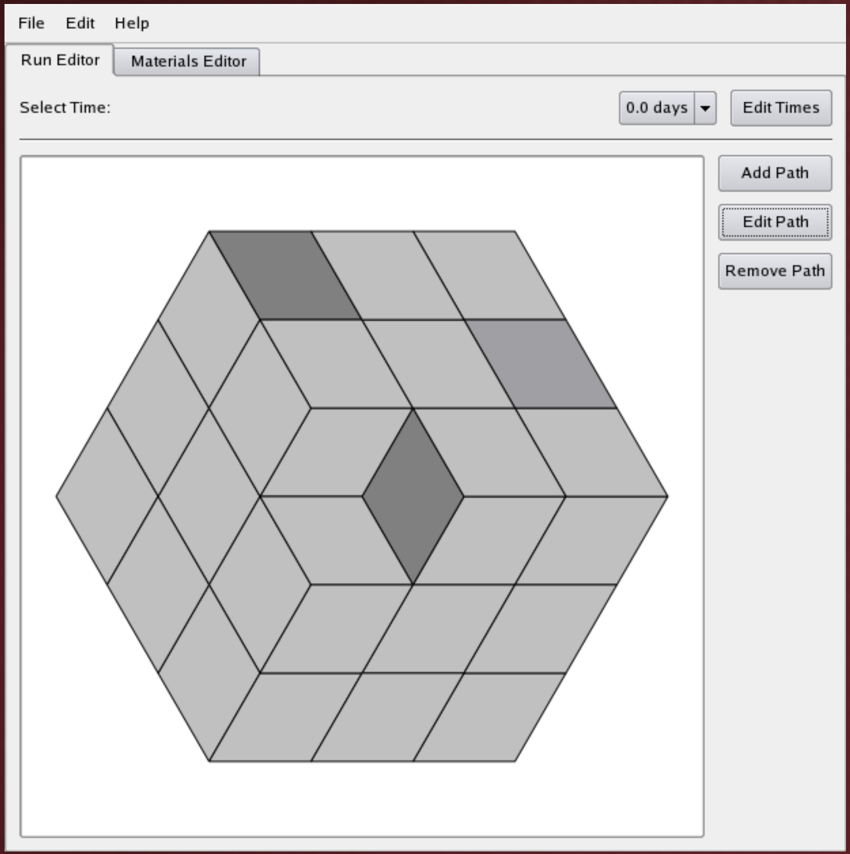
My research group

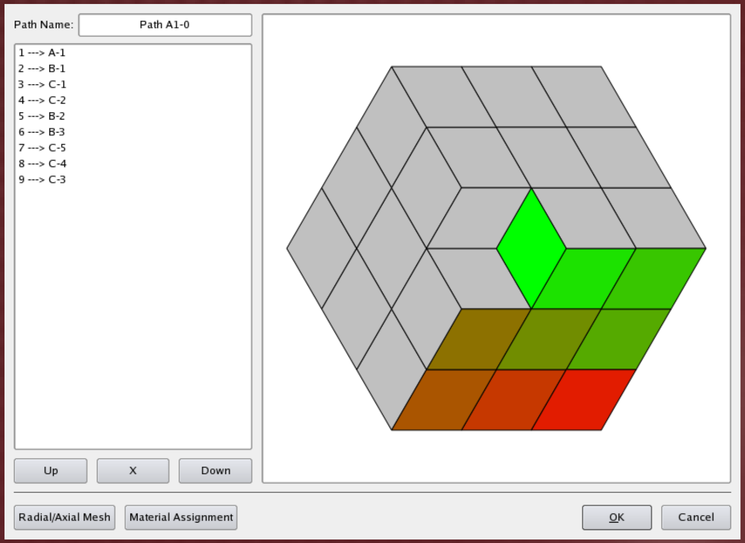
- PhD candidates
  - Paul Romano (Stochastic methods)
  - Stephanie McKee (Salt cooled reactors)
  - Matt Everson (r-adaption coupled to neutron transport)
- Master’s students
  - Lei Zhu (generalized multigroup theory)
  - Mark Massie (spectral optimization)
  - Eugeny Sosnovsky (multiphysics coupling using bond graph theory)
  - Guillaume DeRoo (economics of MOX recycling)
- Visiting students
  - Nicolas Stauff (fast reactor blanket design)
  - Cyril Dolymnyj (validation and development of MCODE)

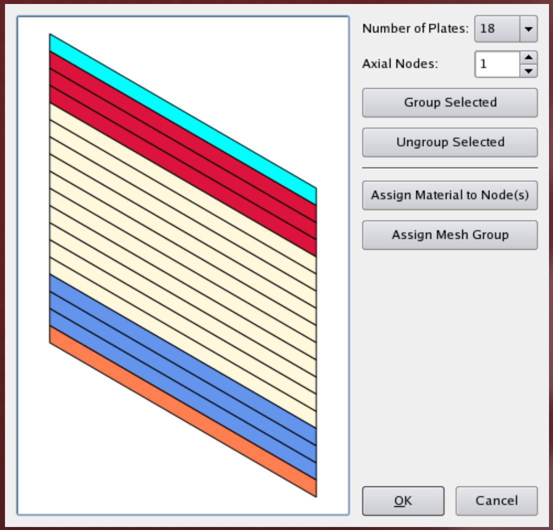
MITR conversion project

- Must convert to LEU fuel under RERTR Program by 2014
  - Reduce enrichment for research and test reactors
  - Using current qualified LEU fuel would significantly reduce the neutron flux for experiments
  - Requires high density LEU fuels to keep current performance capabilities
    - High density monolithic fuel composed of Molybdenum and Uranium
    - Density of about 17 g/cc (current LEU fuel has density of 4.8 g/cc)
- Two students (Romano and Zhu) are providing neutronic simulation support
  - Automated the fuel management scheme for MCNP/MCODE/ORIGEN simulations
  - Developed GUI interface
  - Designing fuel plate irradiation experiment

MITR Conversion Project



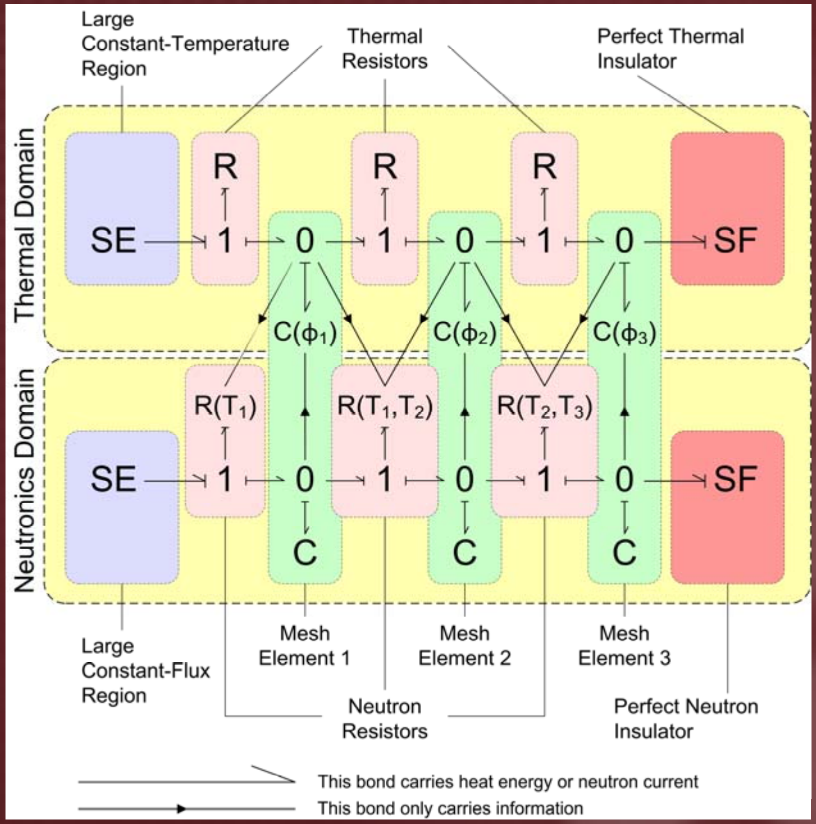




- Written in Python/Qt
- Can easily be extended to other core geometries

Bond graph modeling for tightly coupled nuclear simulations

- Bond graph formalism relies on using several basic elements to describe the energy flow of the system by dividing any power flow between two ports into two components: *effort* and *flow*.
- Graphical representation of a dynamic system where each junction or element is governed by specific equations that can be used to formulate an equation system.
- Proof of concept will couple neutron diffusion and simple thermal-hydraulics using the bond graph formalism.



Spectral Optimization for Nuclear Fuel Transmutation

Mark Massie and Benoit Forget

Background

- The use of transmutation in the nuclear fuel cycle has been extensively studied
  - They compared the effectiveness of various transmutation-based recycling programs
  - These studies are usually constrained to current reactor technologies
  - Assembly designs and materials are selected on a trial-and-error approach
- Most studies concluded that fast reactors were better suited for actinide transmutation
  - Better transmutation rate of actinides
- While others leaned toward light water reactors
  - Better consumption of Am-241
  - Alternative studies have looked into moderated targets in fast reactors to try to combine both effects
- Careful analysis suggests that the best system is relative to our objectives
  - Idea came to identify which spectrum is best suited for given objectives instead of the other way around

Objective

- To provide a quantitative optimization of transmutation of used nuclear fuel based on the physics of depletion by identifying optimal flux spectra for various fuel cycle applications
  - We suggest to look at the problem from the reverse direction
- Instead of arbitrarily choosing a recycling strategy and analyzing its effectiveness, this work aims to identify a desired result of transmutation and use optimization to find the best way to reach that goal
  - Optimize the flux for the objectives of the analysis

Methodology

- Find optimal flux spectra for various fuel cycle applications
  - Storage of SNF
    - Minimize decay heat
    - Minimize mobile isotope production
    - Minimize radiotoxicity
  - Handling of SNF
    - Reduce neutron emission
    - Reduce photon emission
    - Reduce decay heat
  - Nonproliferation
    - Reduce Pu-239 and/or increase Pu-238, Pu-240 content
- Cost functions are defined and minimized by varying the flux
  - Cost functions can be a mix of various weighted objectives
  - Future studies will also look into constrained optimization

Methodology

- Starting point is a LWR SNF vector
  - 50 GWd/MTHM from ORIGEN-S calculation
- The fuel is irradiated for a given period of time
  - In this study we irradiated the fuel for 1000 days
    - Future studies will look at the impact of the irradiation time
  - No constraint on the total flux
    - but we do have constraints in the individual group fluxes
- Simulated Annealing is used to optimize flux spectrum
  - It's simple and effective
  - Allows the possibility to move upward in the solution and get out of local minimum
  - Simulates the annealing process in metallurgy

Simulated Annealing Optimization

- At high temperatures, molecules have high internal energy, can move around freely
  - Random combination of solution elements
- When cooled quickly, atoms form crystal structure with many defects, high internal energy
  - Local minimum
- When cooled slowly, atoms have time to rearrange themselves to find structures that have fewest defects, lowest internal energy
  - Global minimum

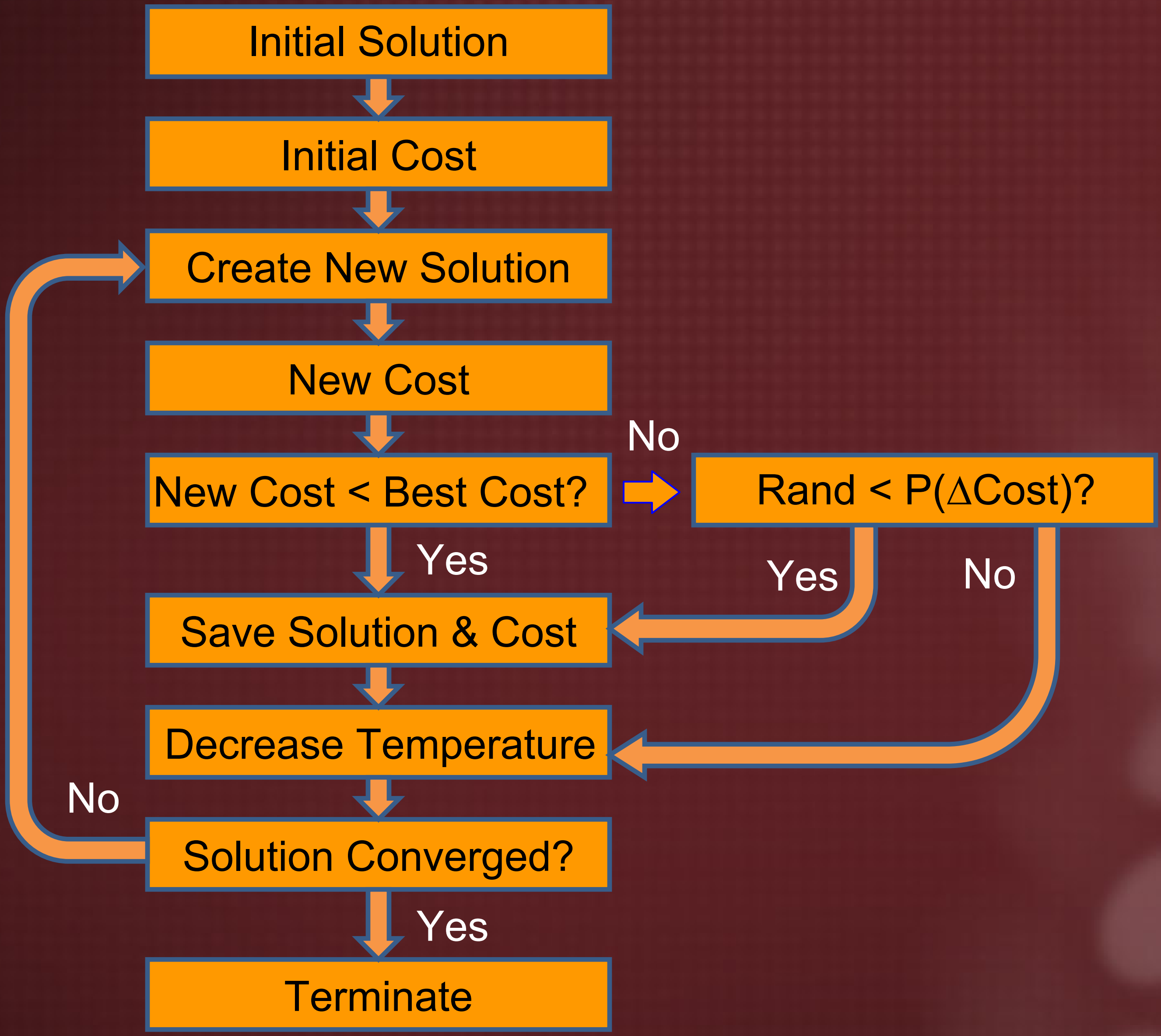
Acceptance Criteria

- At temperature *T*, the probability of an increase in energy of the system *ΔE* is given by

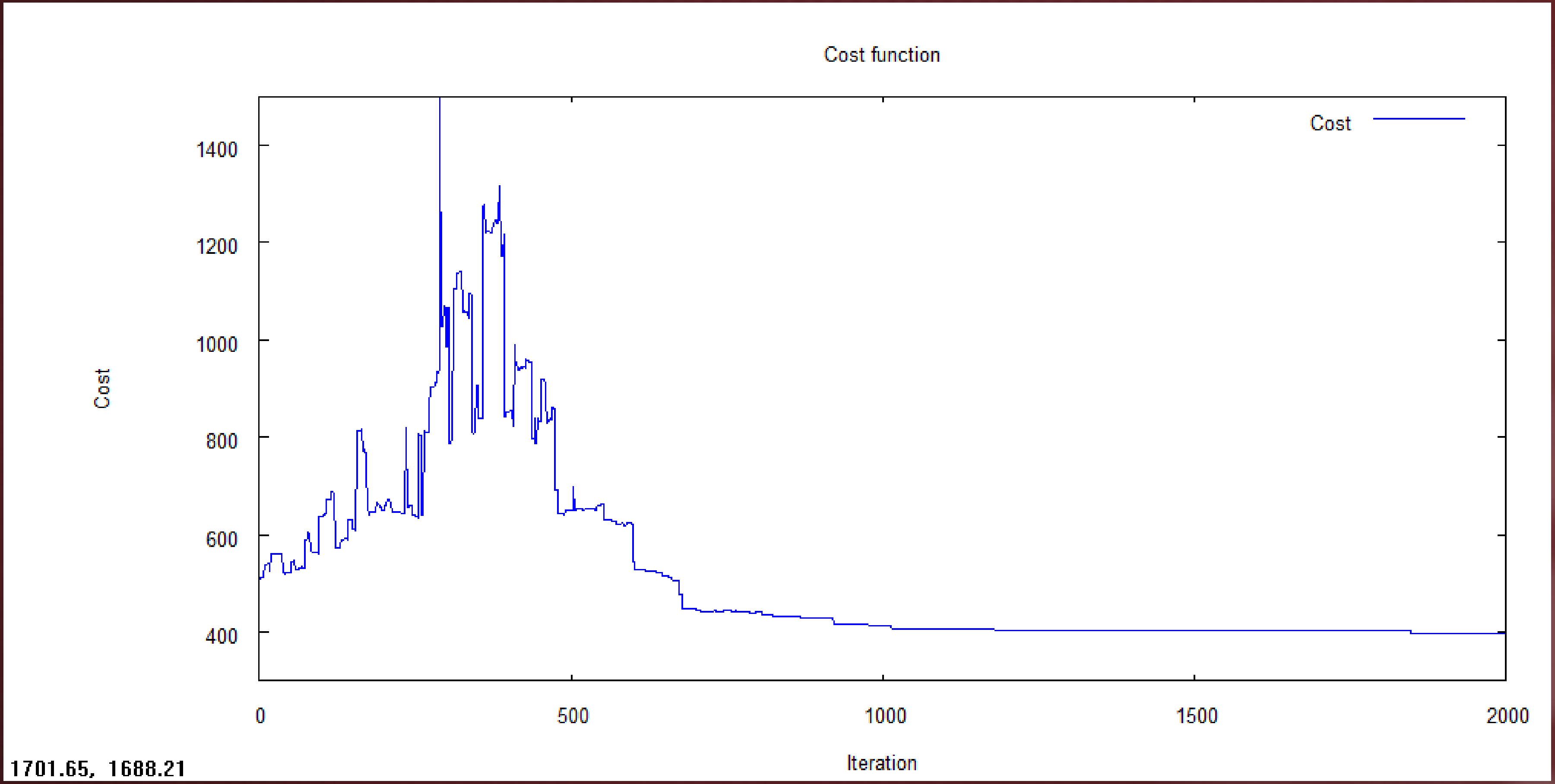
$$P(\Delta E) = e^{-\Delta E / kT}$$

  - When *T* is relatively large, the search space is very broad
- If new cost is better than previous best cost, new solution is automatically accepted
- If new cost is not better than previous best cost, the probability that it is accepted is

$$P(\Delta Cost) = e^{-\Delta Cost / T}$$


Initial Solution
Initial Cost
Create New Solution
New Cost
New Cost < Best Cost?
No
Rand < P(ΔCost)?
Yes
Yes
No
Save Solution & Cost
Decrease Temperature
No
Solution Converged?
Yes
Terminate

Cost function convergence

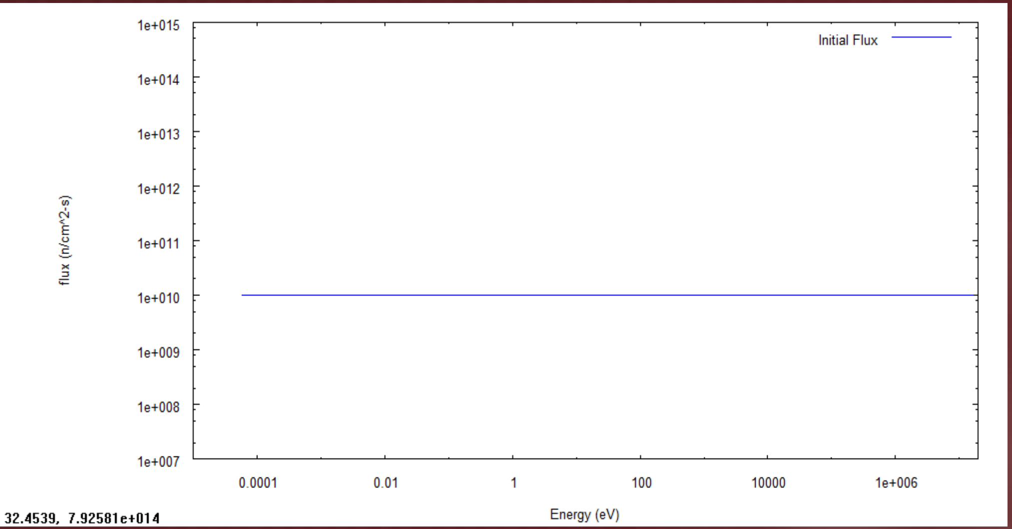


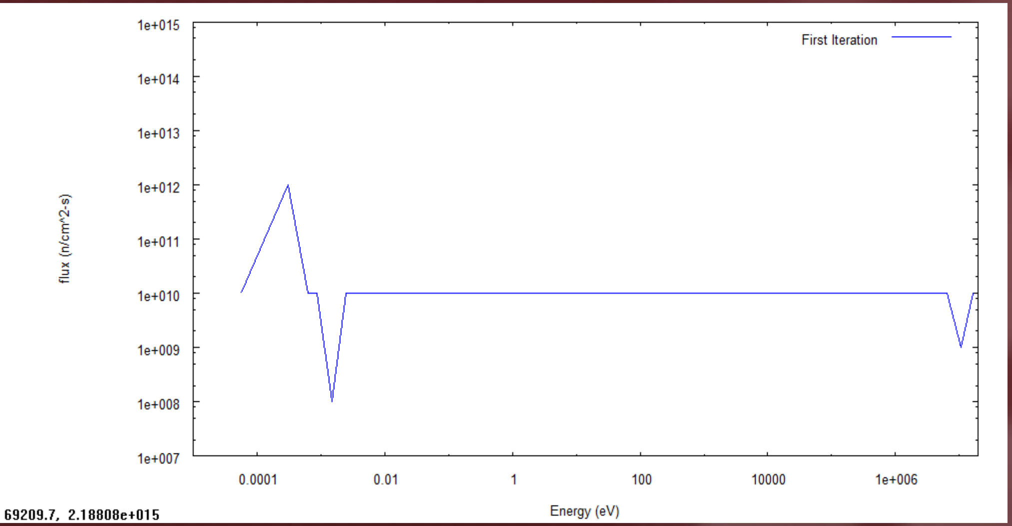
Simulation

- 54 Energy Groups
  - Infinite medium calculation was performed using CENTRM
  - Initially were aiming for 60 groups with equal lethargy
- Initial guess is a flat spectrum (1E9)
  - Maximum group flux is 1E14
    - Maximum total flux 5.4E15
  - Minimum group flux is 1E8
    - Minimum total flux 5.4E9
- Depletion code was written for the higher actinides
  - U-234 to Es-253
  - Exponential matrix method
- Flux is modified by a neighboring function

Neighboring function

- Randomly select the number of energy group to change
  - Between 1 and 3
- The flux is varied randomly by a factor of 10 or 100
  - Only the exponent of the flux is changed



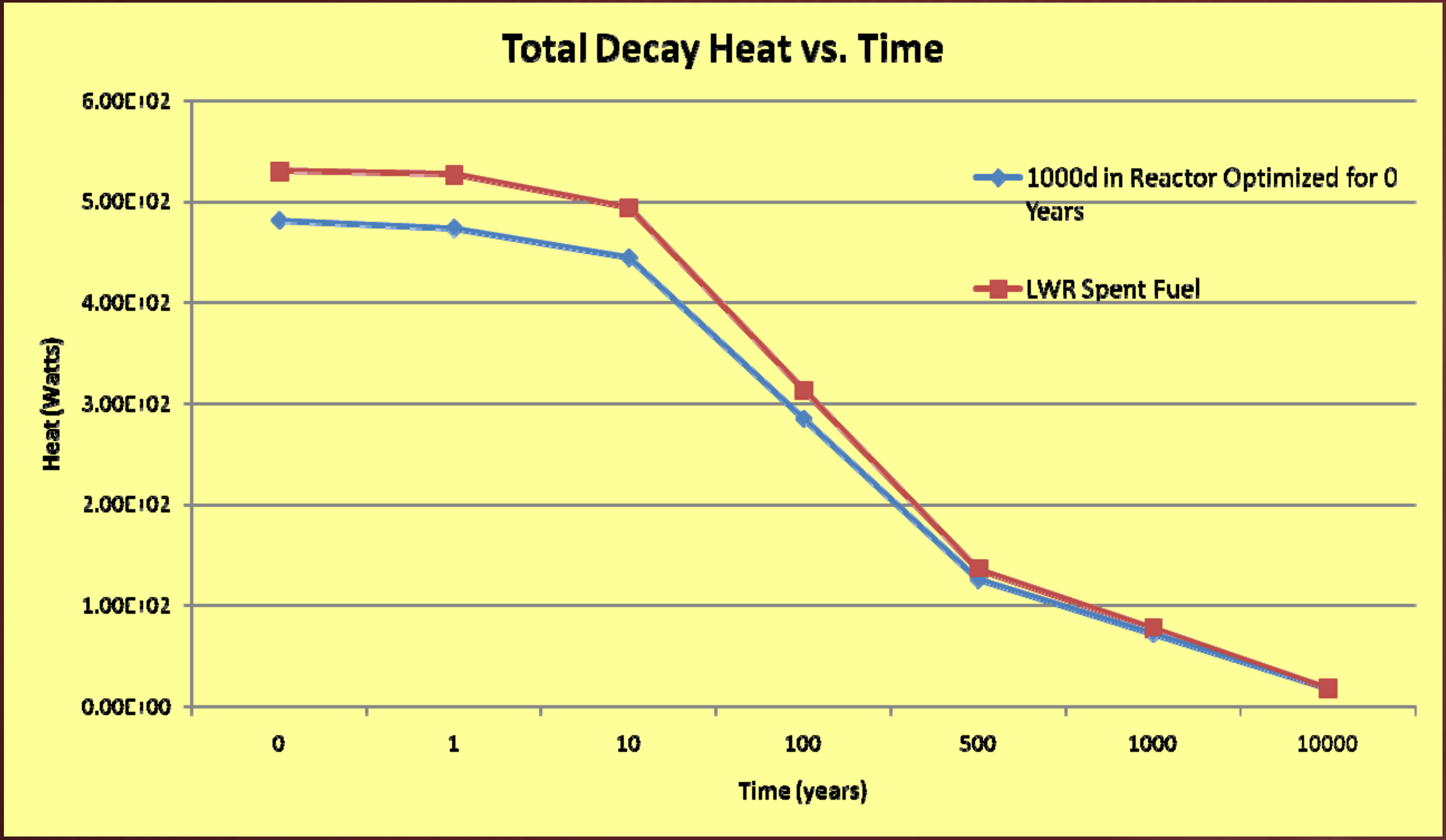


Cost Function

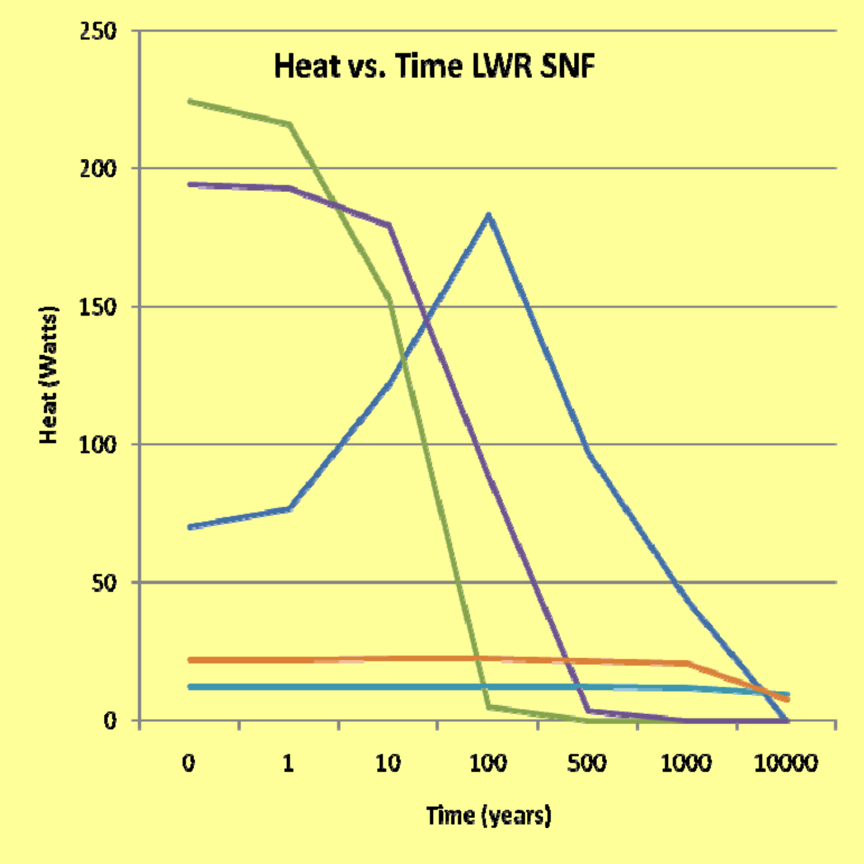
- Cost in this study is defined by the total decay heat
  - Sum of decay heat produced by all actinides
- Begin with 1MT of LWR SNF
- Irradiate for 1000 days in a reactor followed by a decay period of 10000 years
  - Simulates once-through recycle with disposal
  - Comparisons are made with LWR SNF decayed for 10000 years
  - Study minimizes decay heat at 0, 100 and 1000 years after irradiation
  - Study also minimizes total decay heat integrated over 10000 years

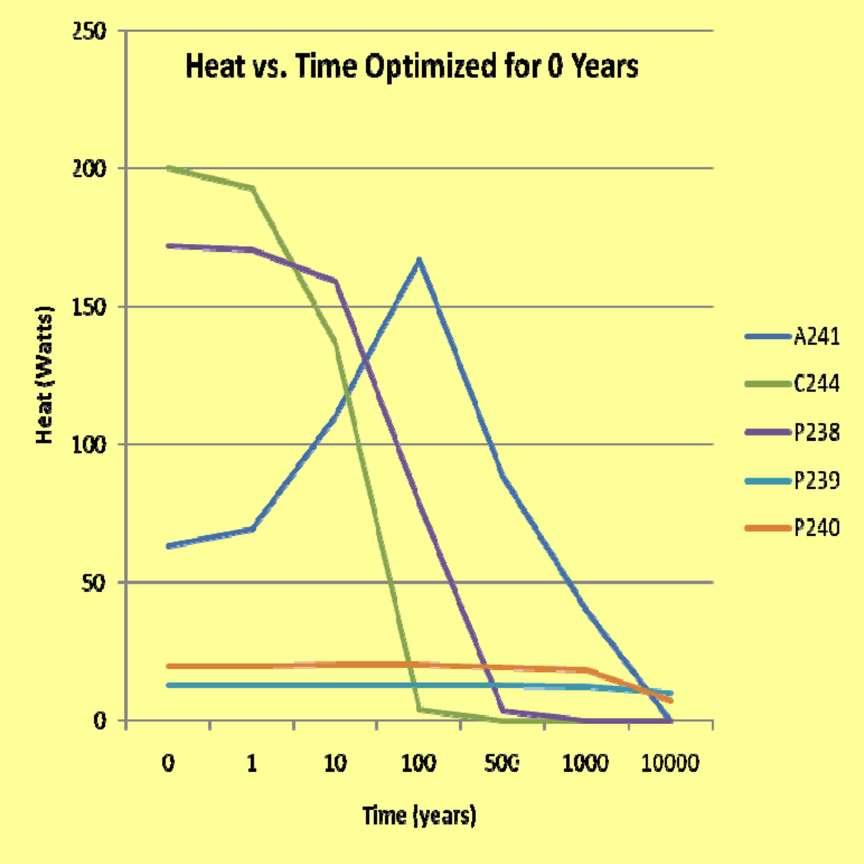
No Transmutation

Optimized for 0 Years

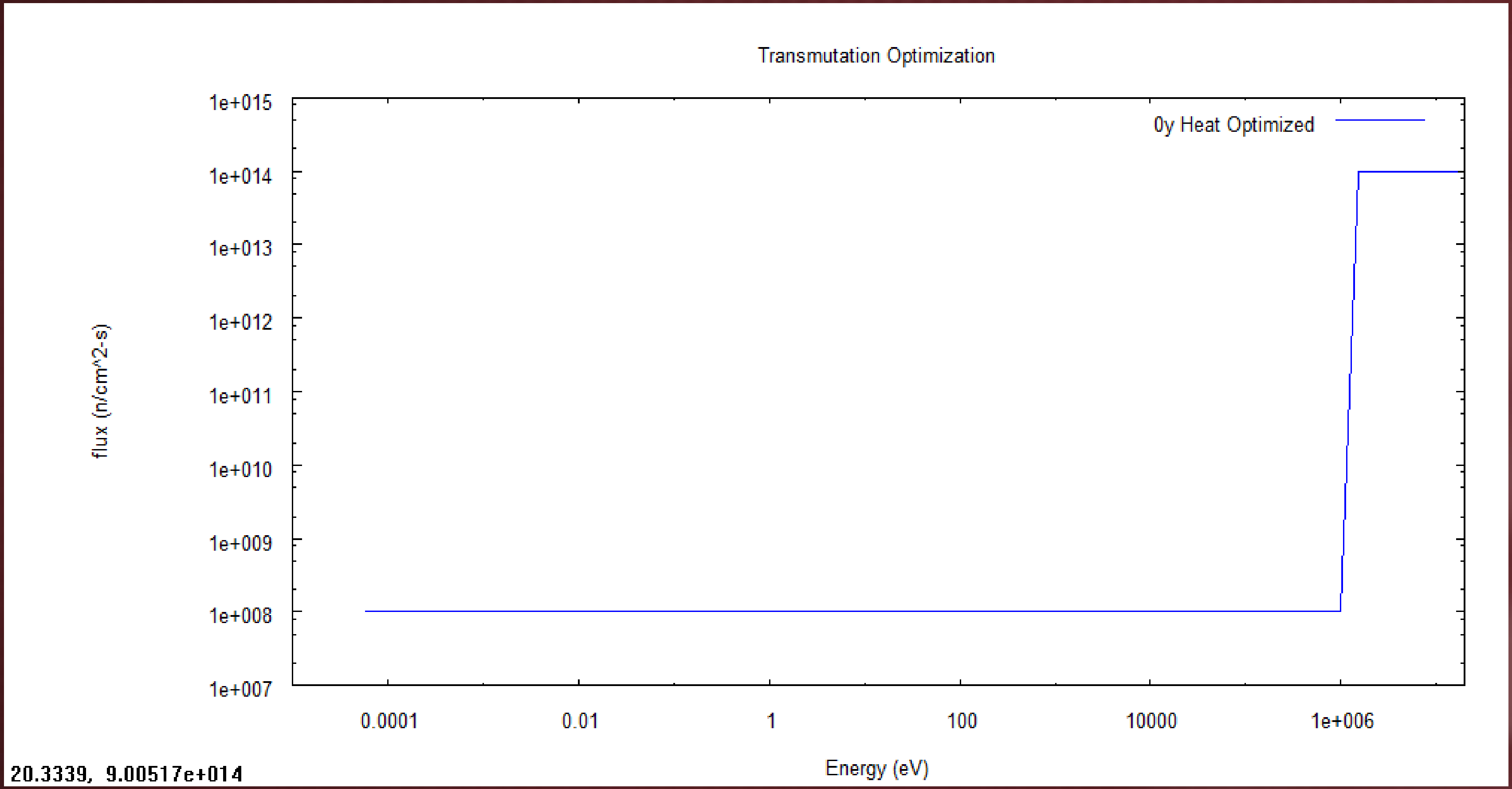


Optimized for 0 Years

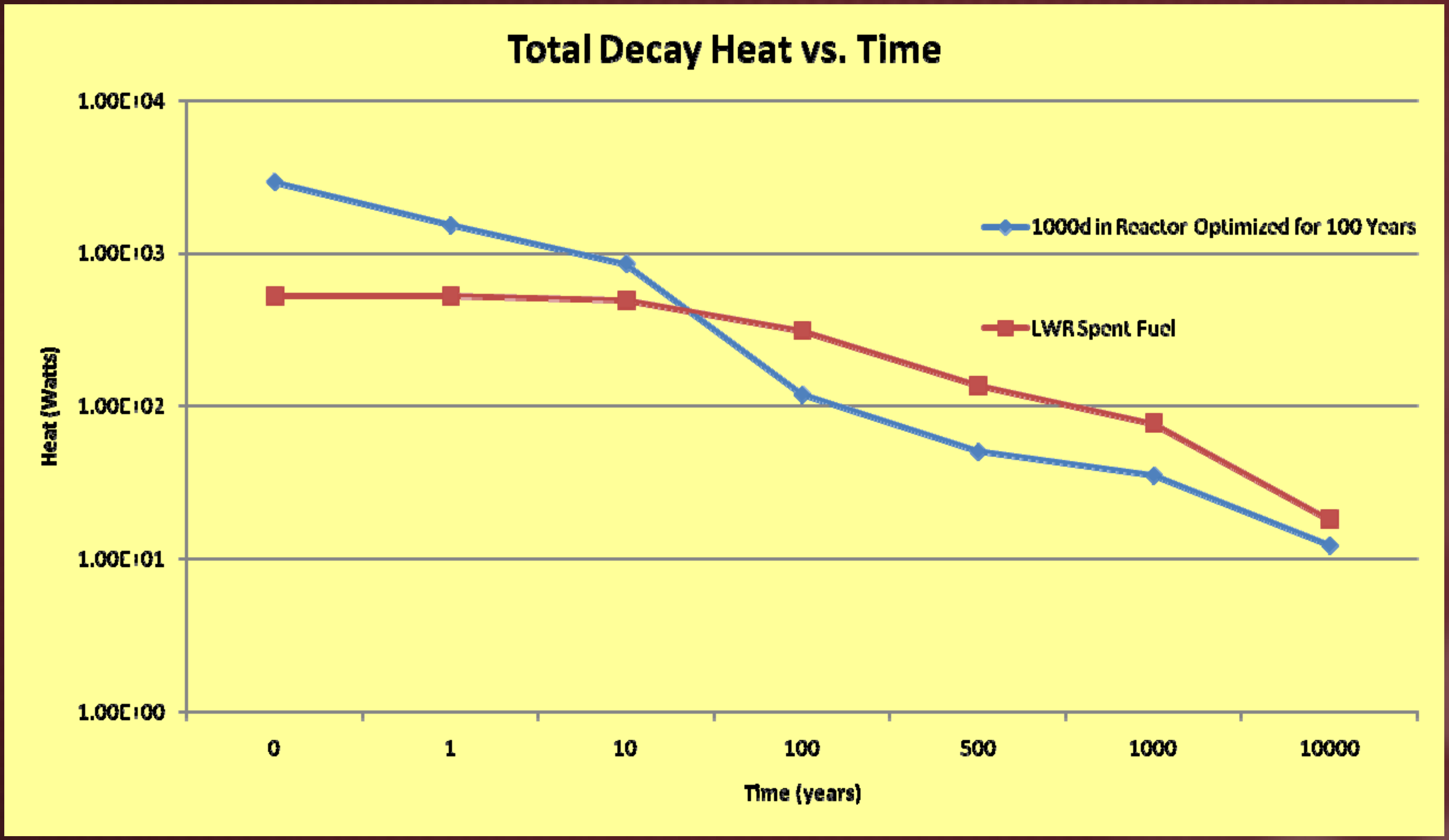




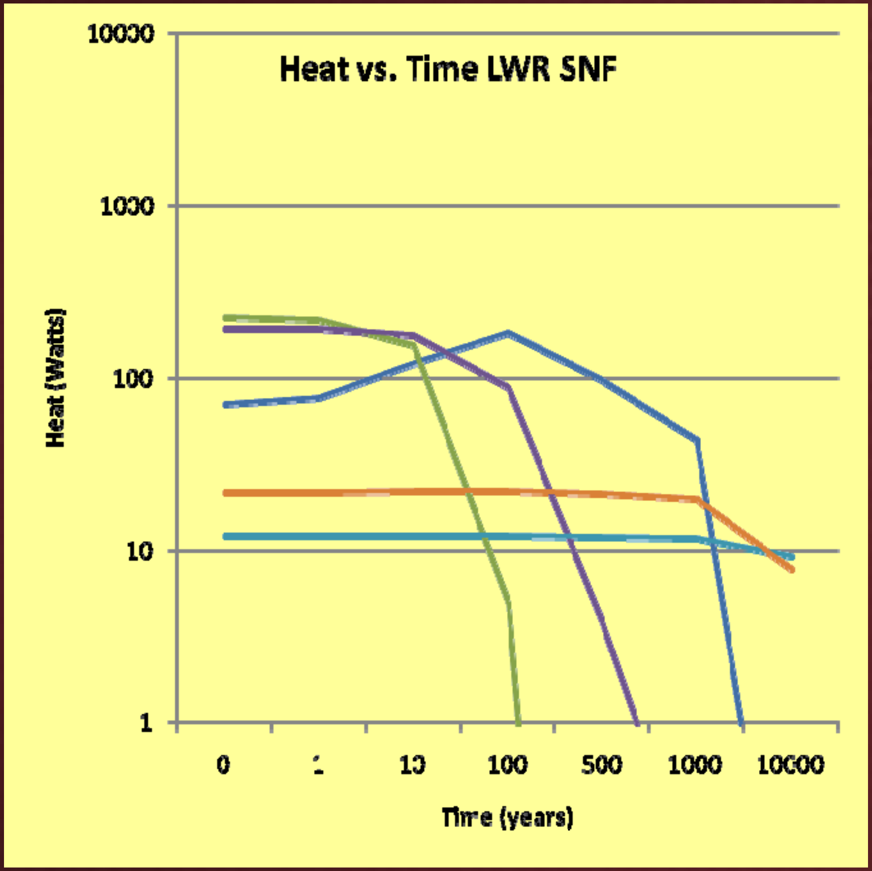
Optimized for 0 Years

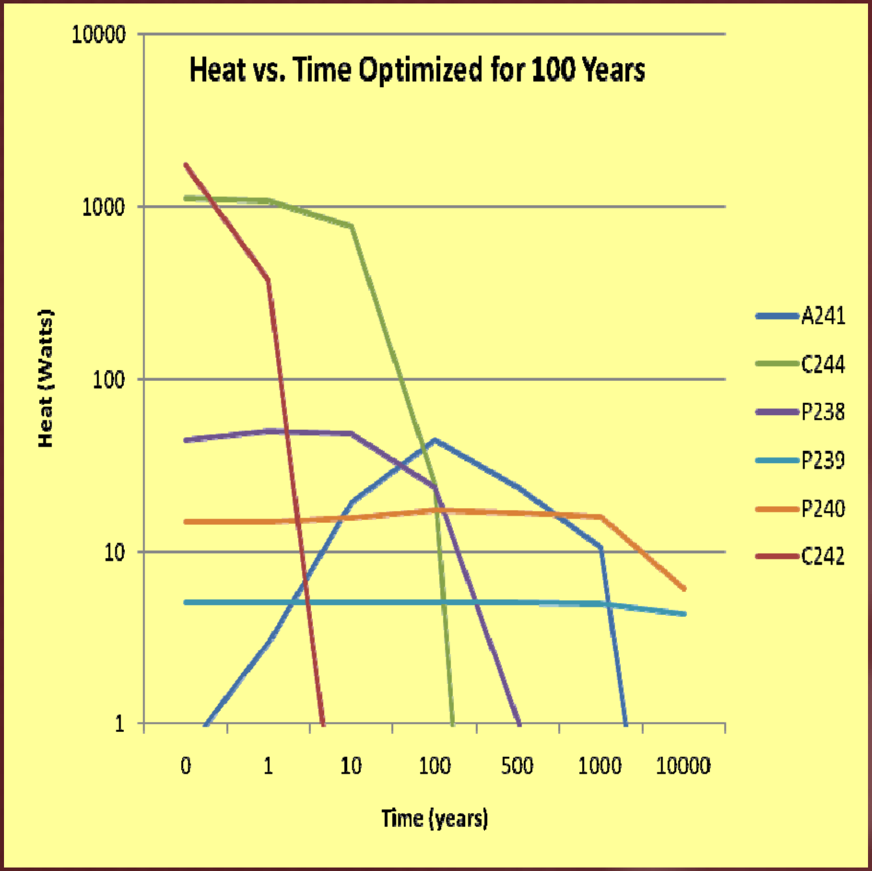


Optimized for 100 Years



Optimized for 100 Years





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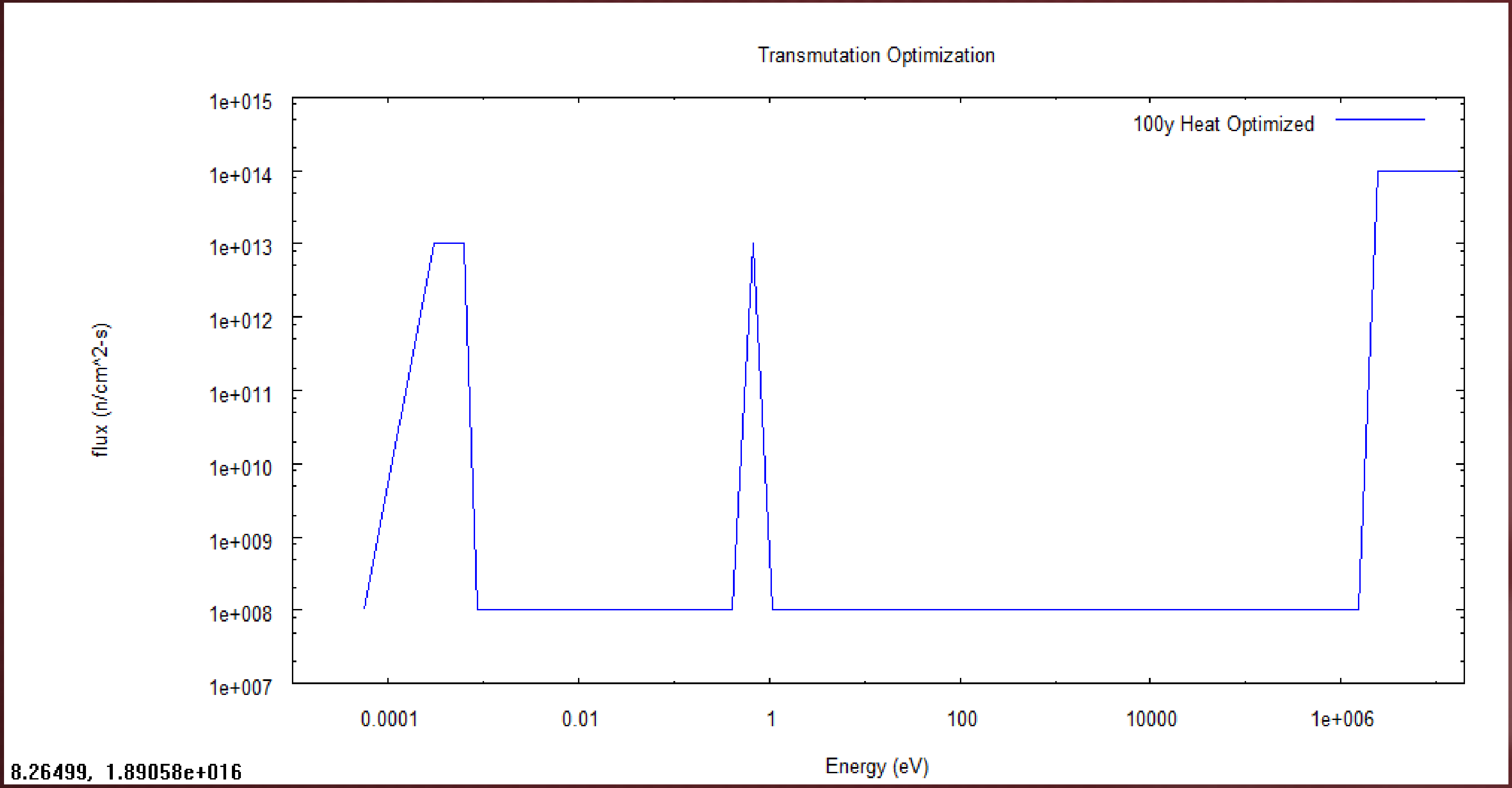
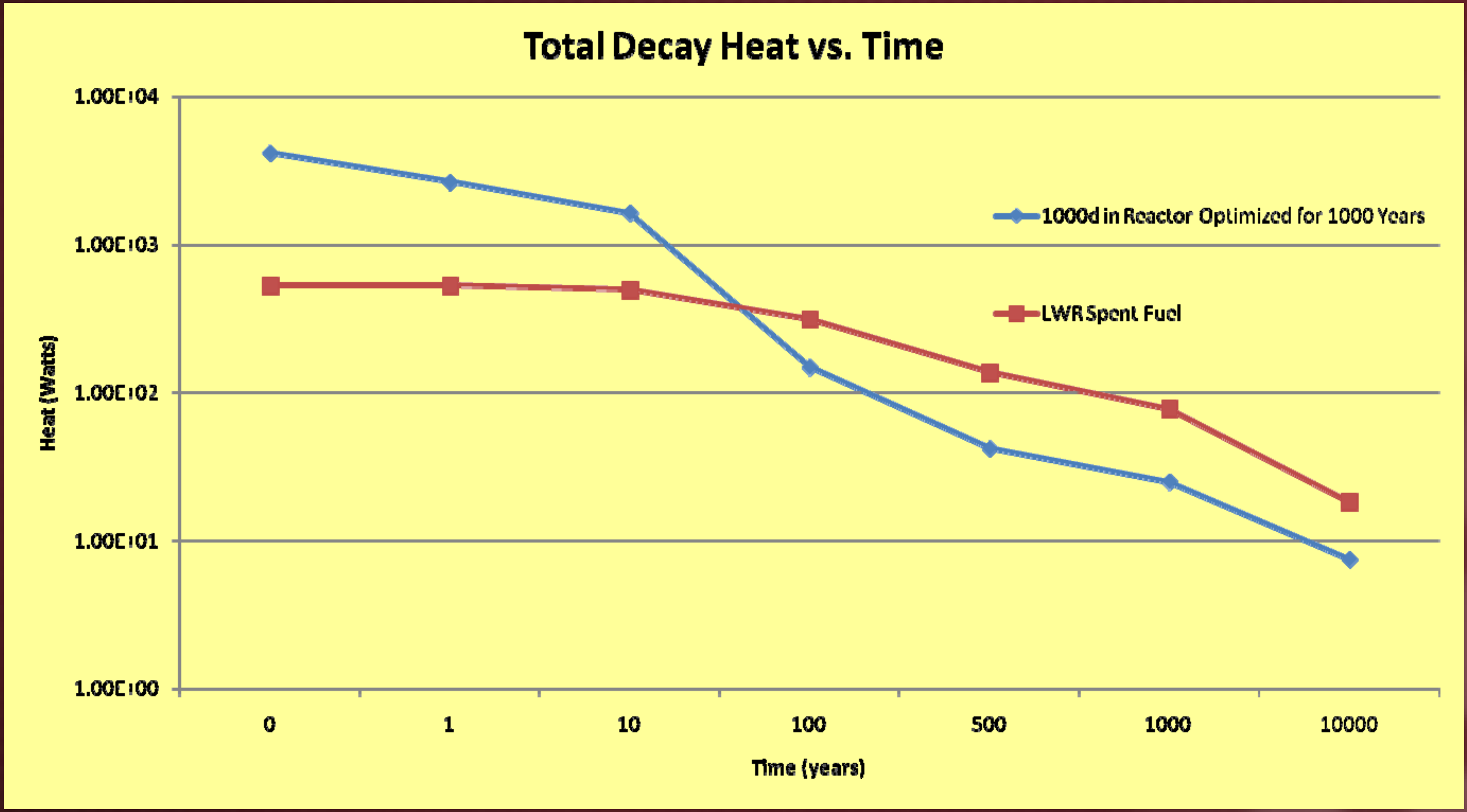
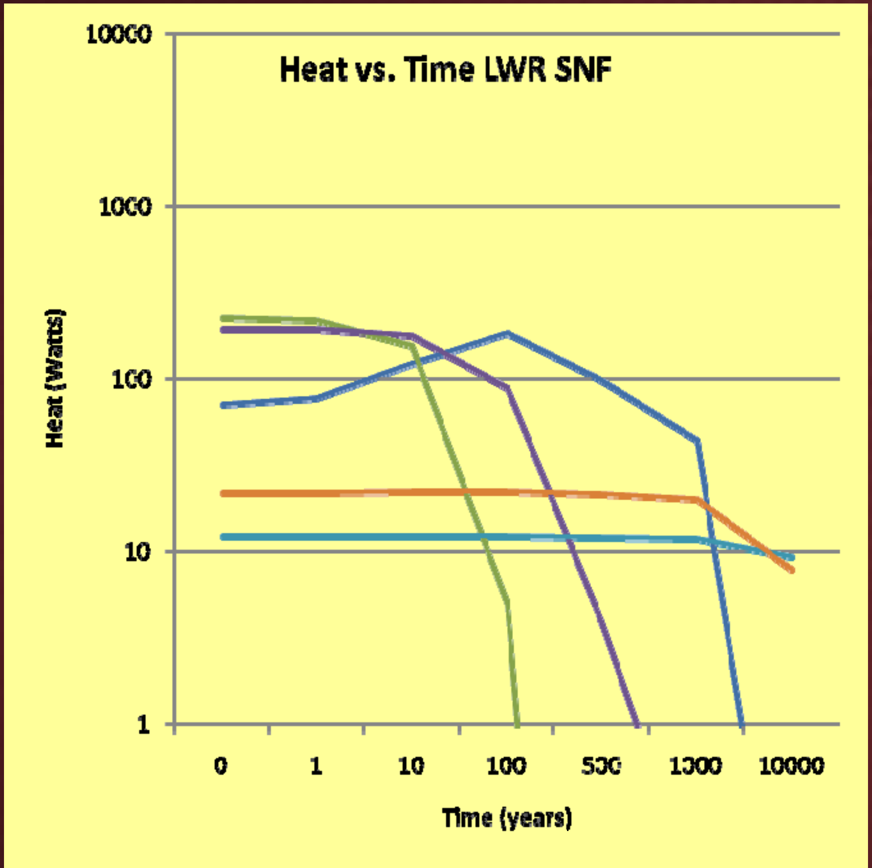
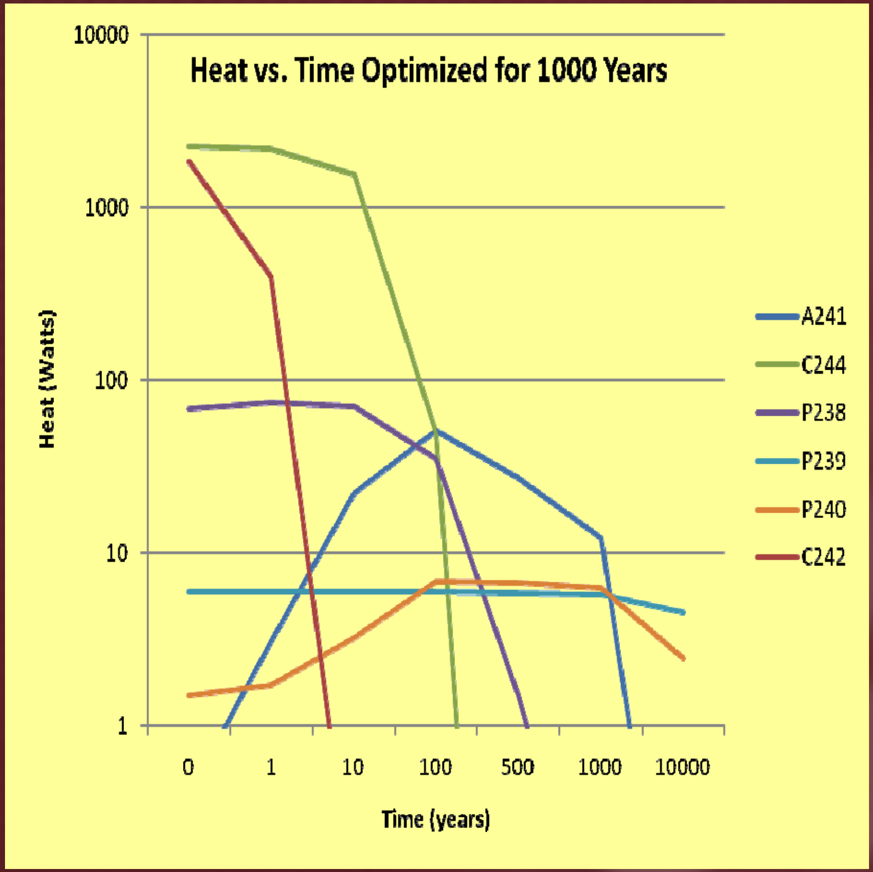


Optimized for 1000 Years

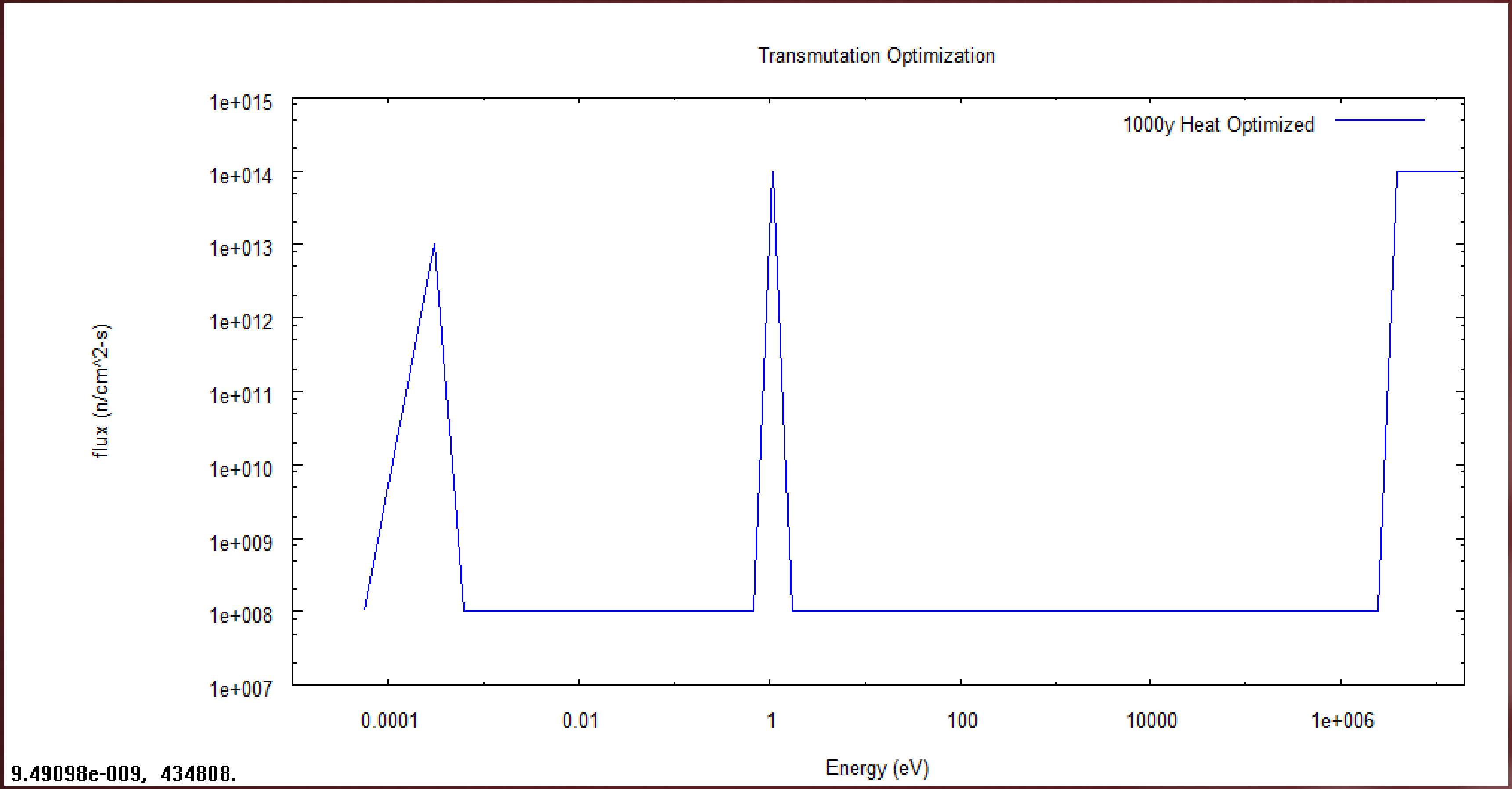


Optimized for 1000 Years

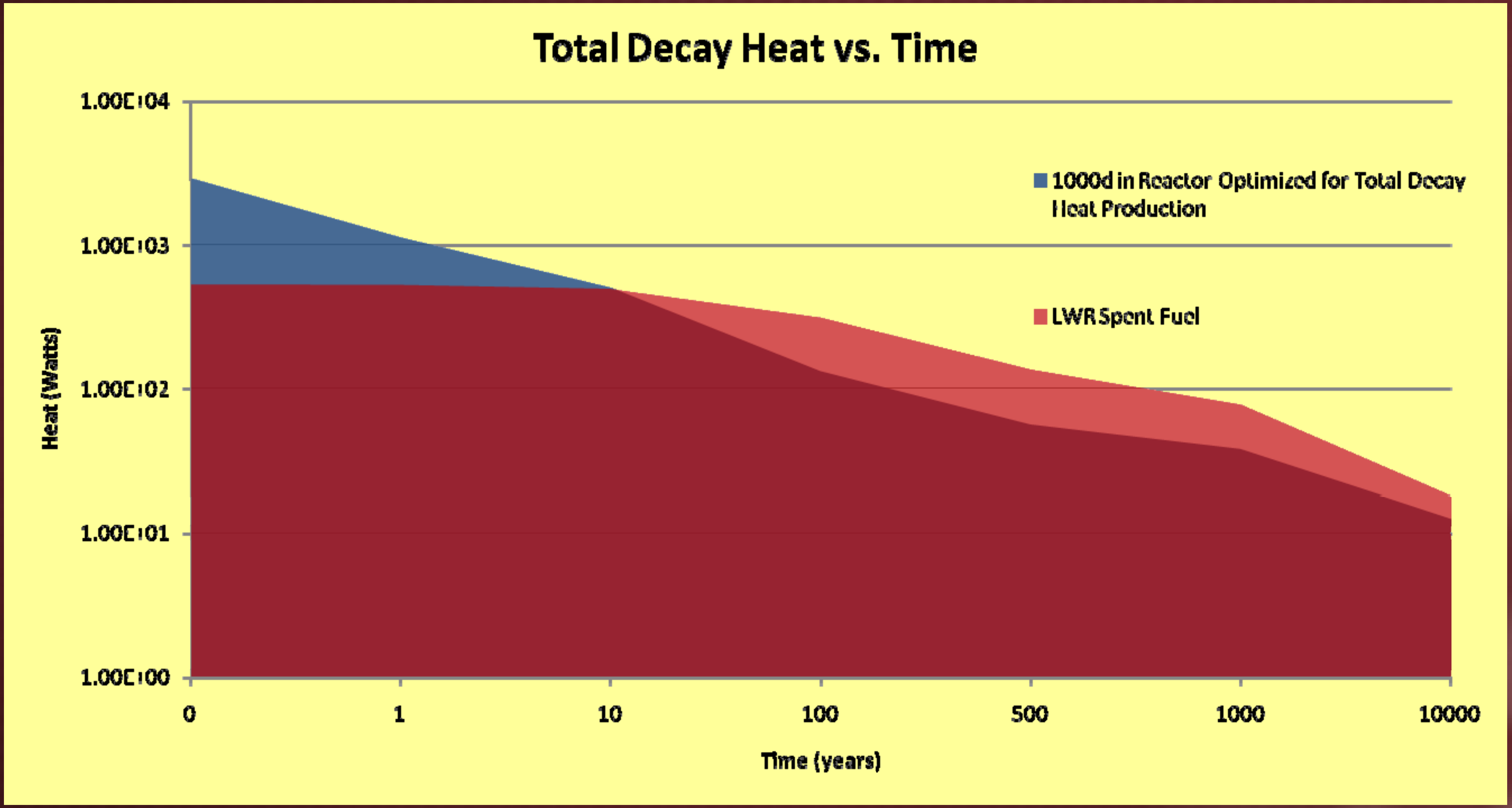




Optimized for 1000 Years



Optimized for Total Decay Heat Production



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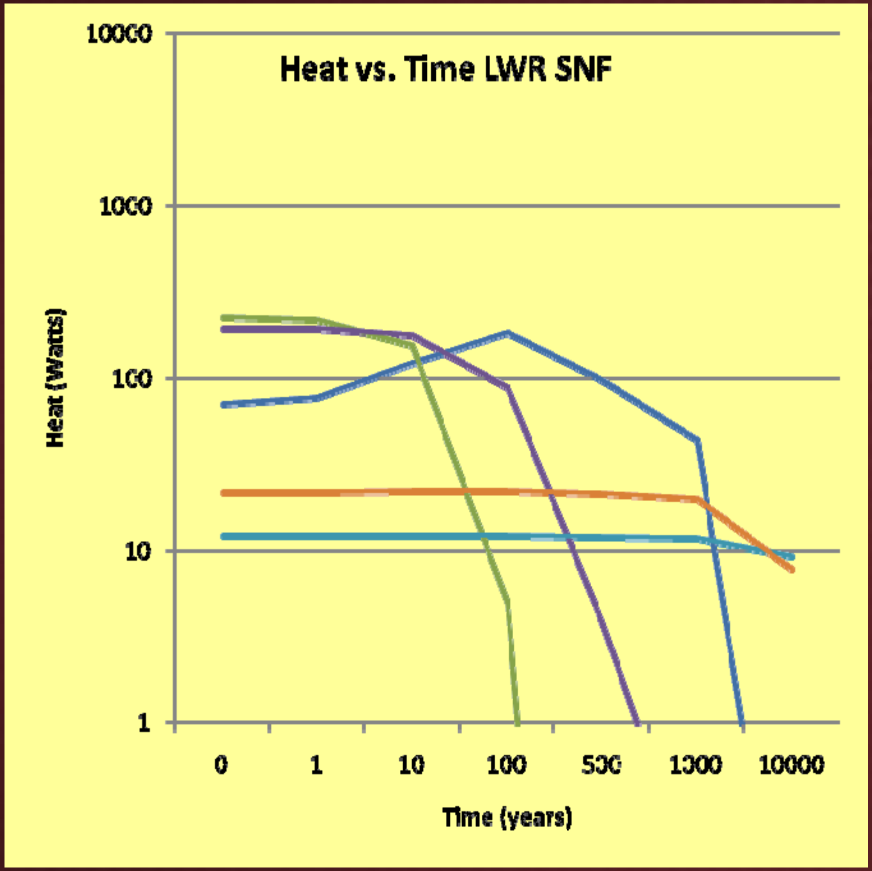
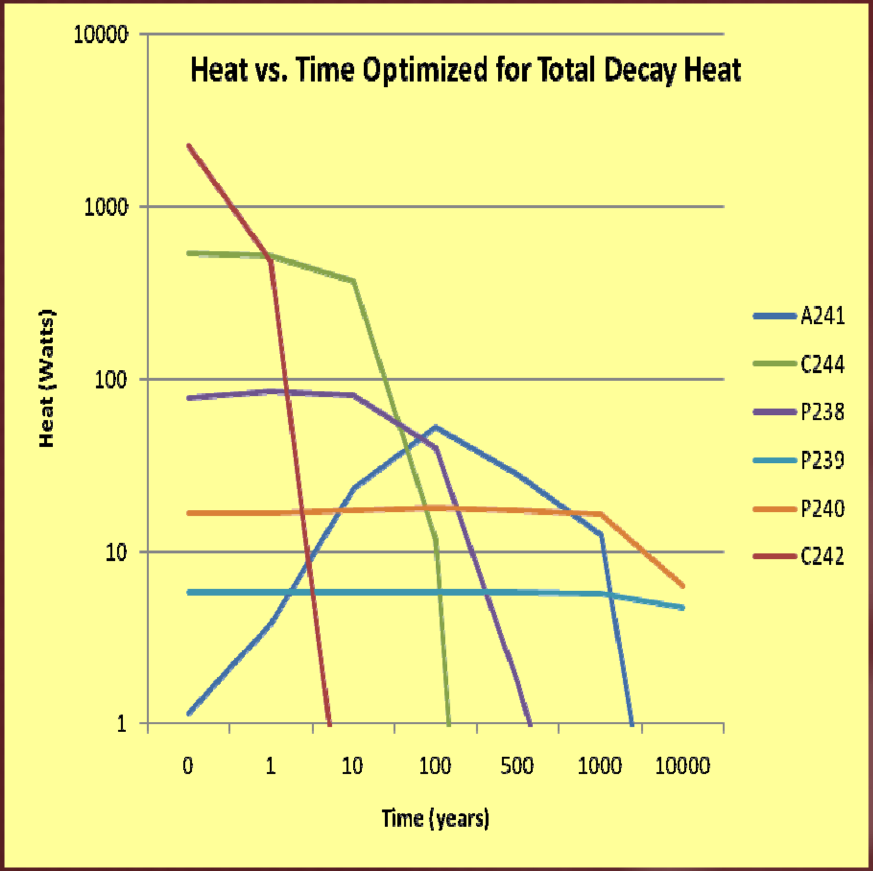
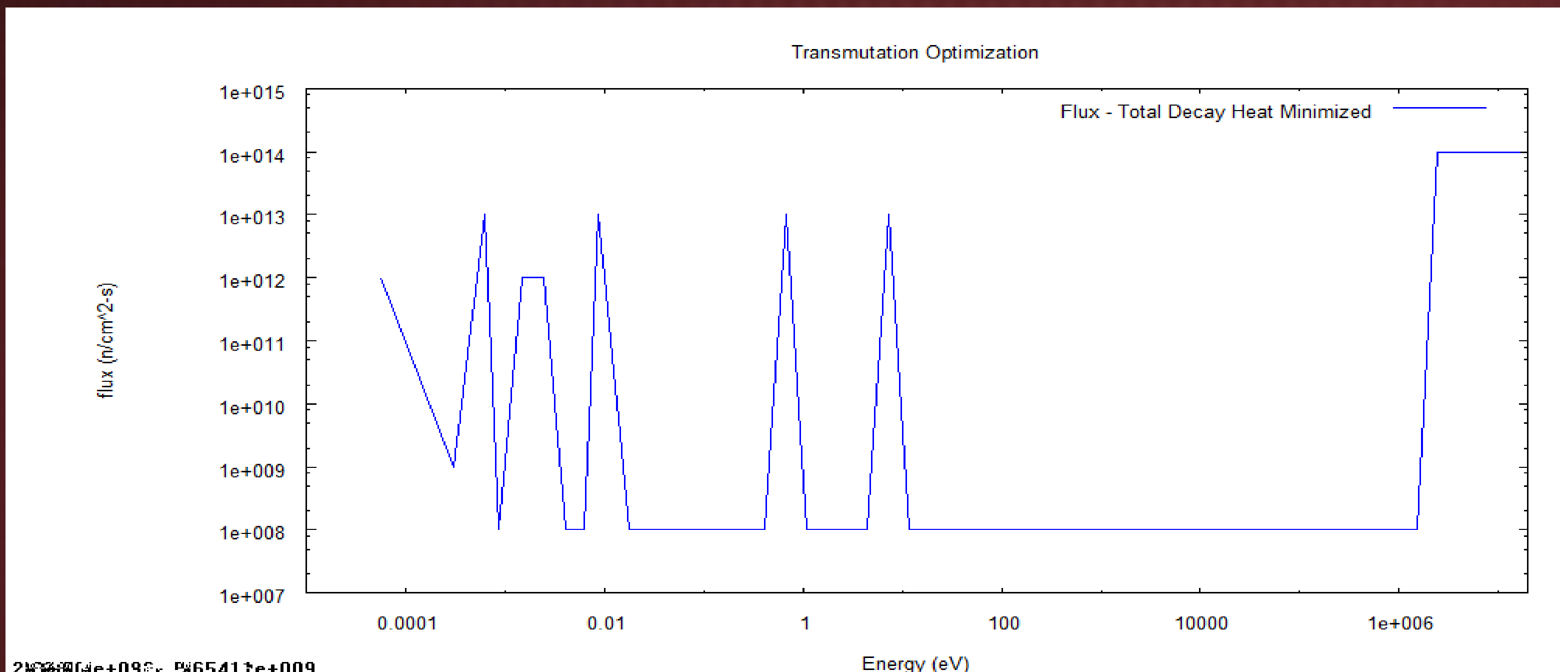


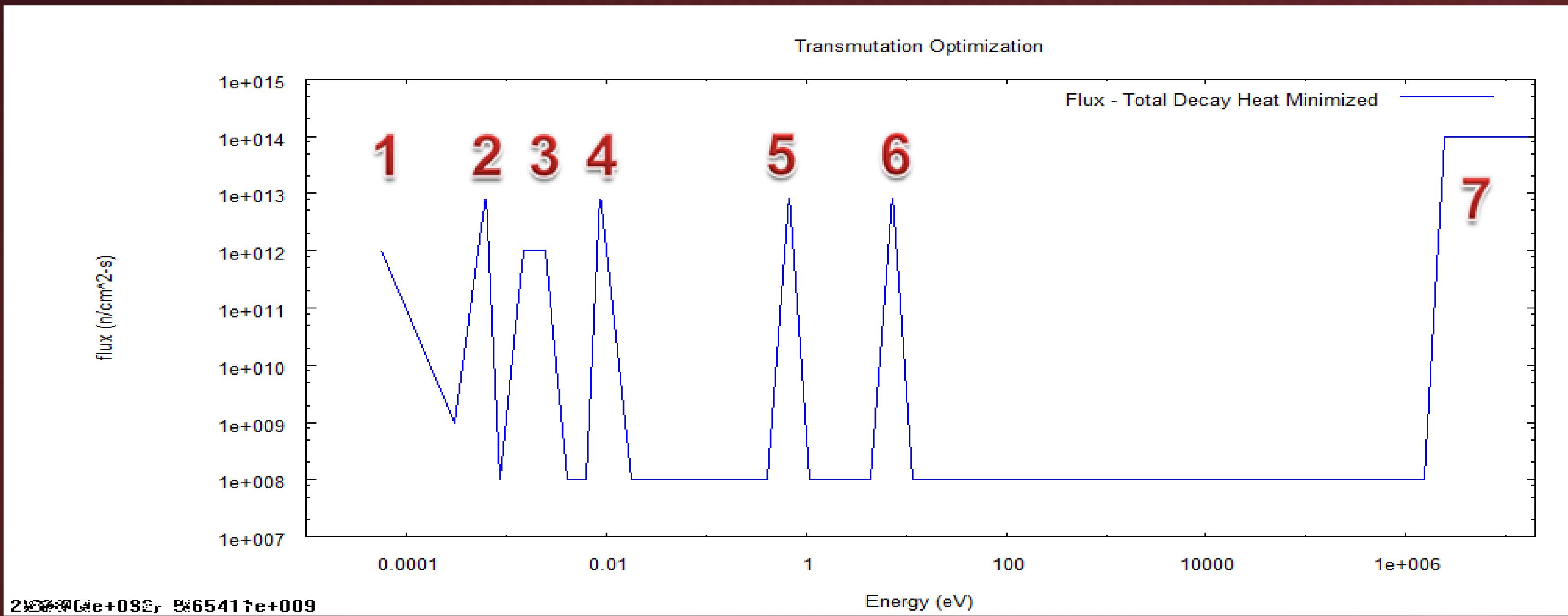


Optimized for Total Decay Heat Production



	LWR SNF	Optimized
W-Years	1.85E+05	9.87E+04
% Change		-46.7

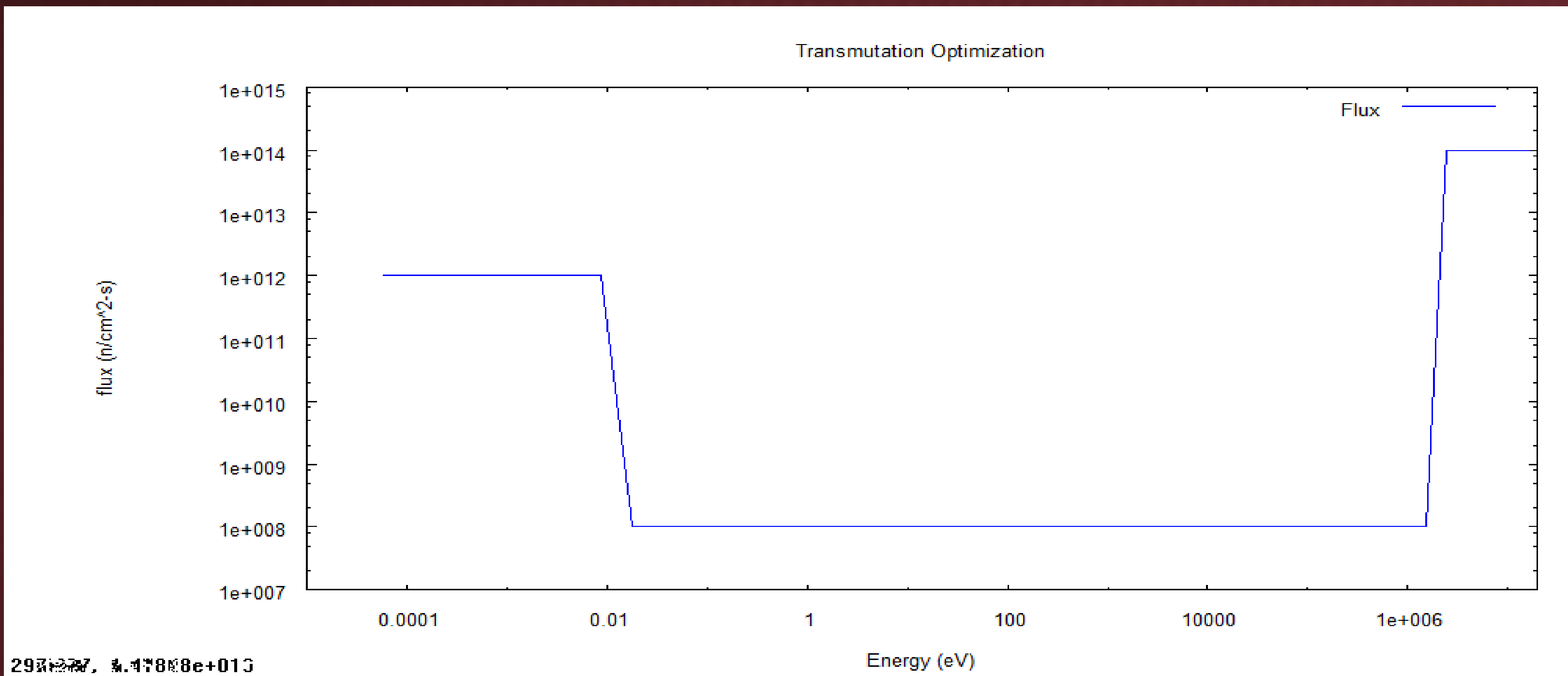
Optimized for Total Decay Heat Production



	Flat 1E8	Peak 1	Peak 2	Peak 3	Peak 4	Peak 5	Peak 6	Peak 7
W-Years	1.85E+05	1.43E+05	1.14E+05	1.63E+05	1.50E+05	2.64E+05	1.82E+05	1.71E+05
% Change	-	-23.0	-38.6	-11.8	-19.0	42.7	-1.6	-7.8

- Peaks 1-4 reduce considerably Am-241 and Pu-239
  - Increases Cm substantially (Cm-242 with half-life of 163 days)
- Peak 5 reduces Am-241 and Pu-240
  - Increase in Pu-238 significantly
- Peak 6 reduces considerably Cm-244
  - Increases Pu-238 and Pu-239
- Peak 7 reduces slightly most isotopes
  - Energy above fission threshold

Basic Shape for Minimizing Total Decay Heat Production

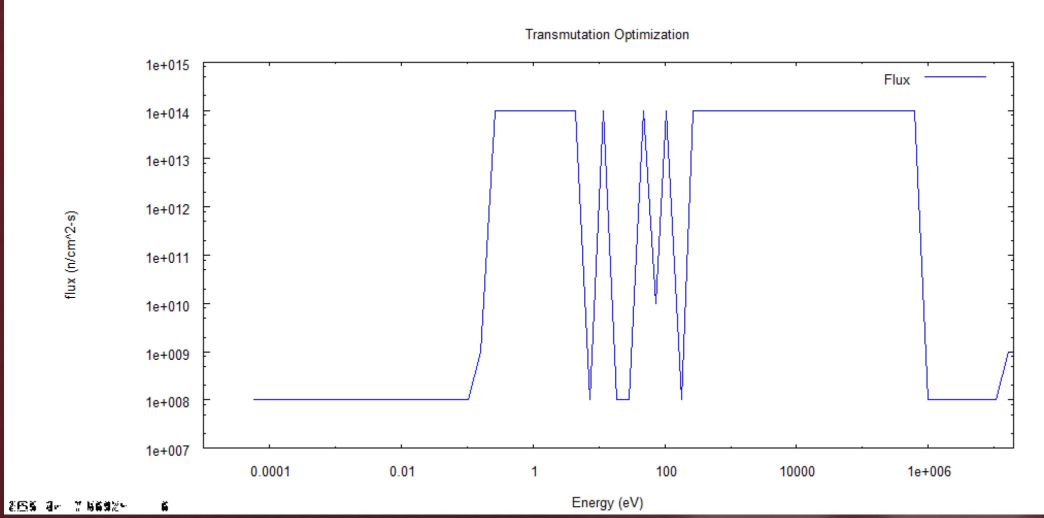


	LWR SNF	Optimized	Basic "Thermal" Shape
W-Years	1.85E+05	9.87E+04	1.09E+05
% Change		-46.7	-40.9

Maximizing decay heat

- Cost function can be redefined as to maximize the decay heat
  - Cost = 1 / Integral of decay heat
  - Indicates which flux to avoid
  - Can also be used if one is interested in optimizing flux for the production of certain isotopes

	W-Years	% Change
No Irradiation	1.85E+05	---
Max Heat	1662645	798.4

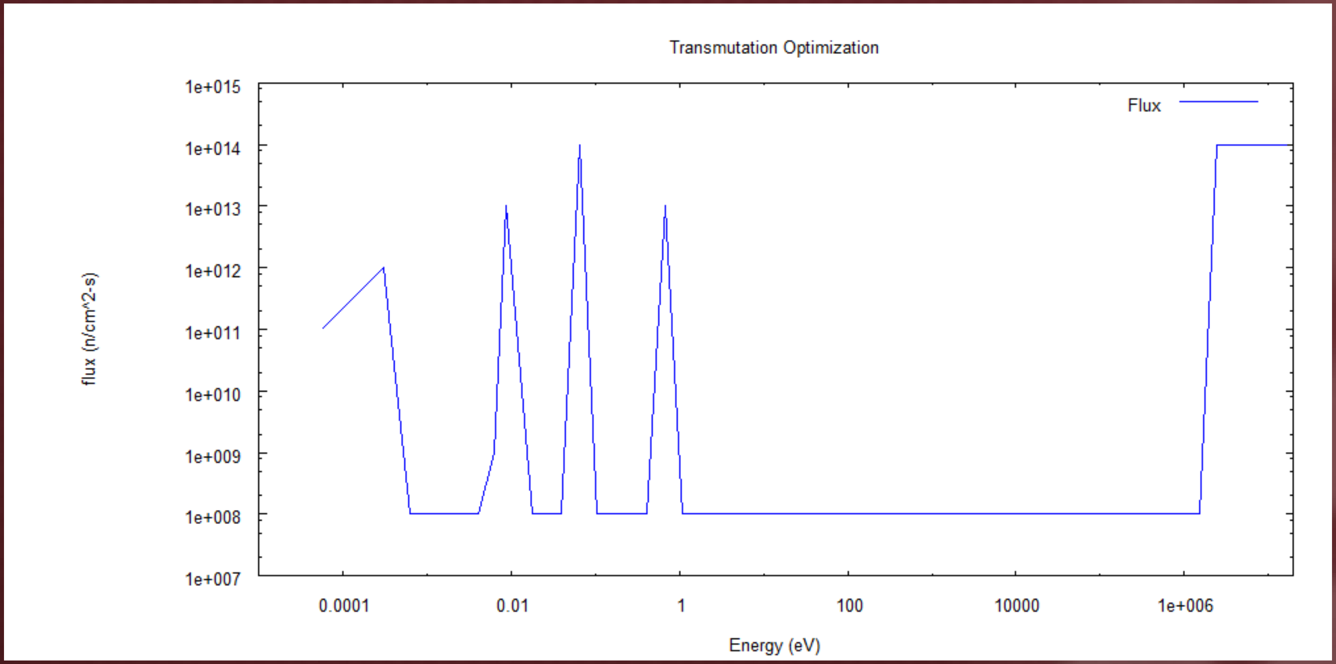


Recycling of selected isotopes

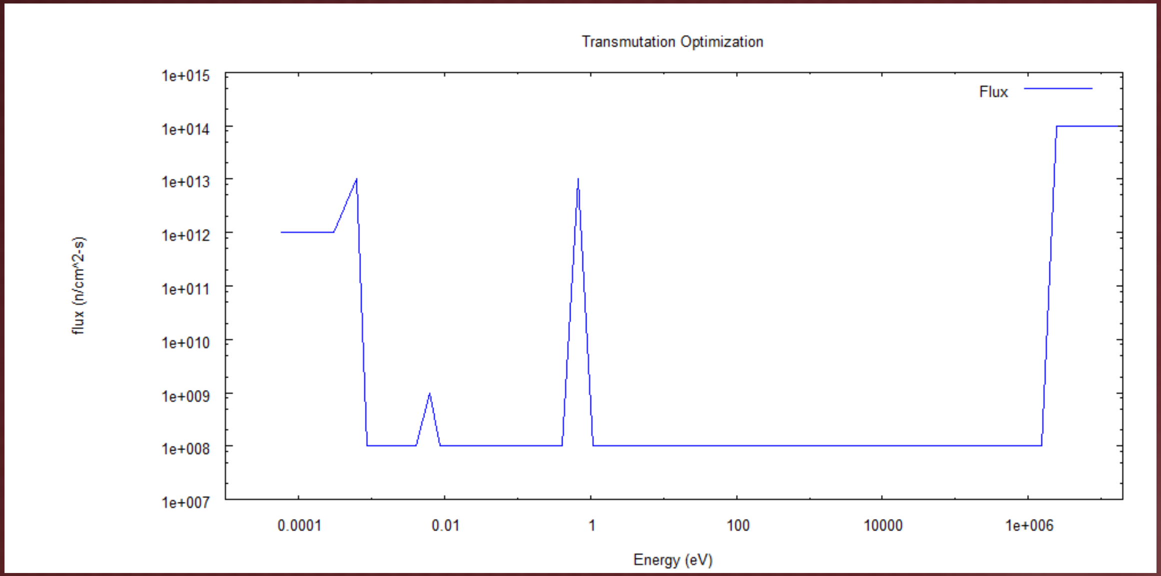
- Study of separation processes
  - PUREX, UREX, …
- Separated different actinides before irradiation
  - Separated actinides are recombined afterwards
  - All TRU
  - Np, Pu, Am
  - Np, Pu
  - Pu only

	W-Years	% Change
No Transmutation	1.85E+05	---
All TRU	9.87E+04	-46.7
Np Pu Am	1.04E+05	-44.0
Np Pu	1.11E+05	-40.0
Pu	1.12E+05	-39.4

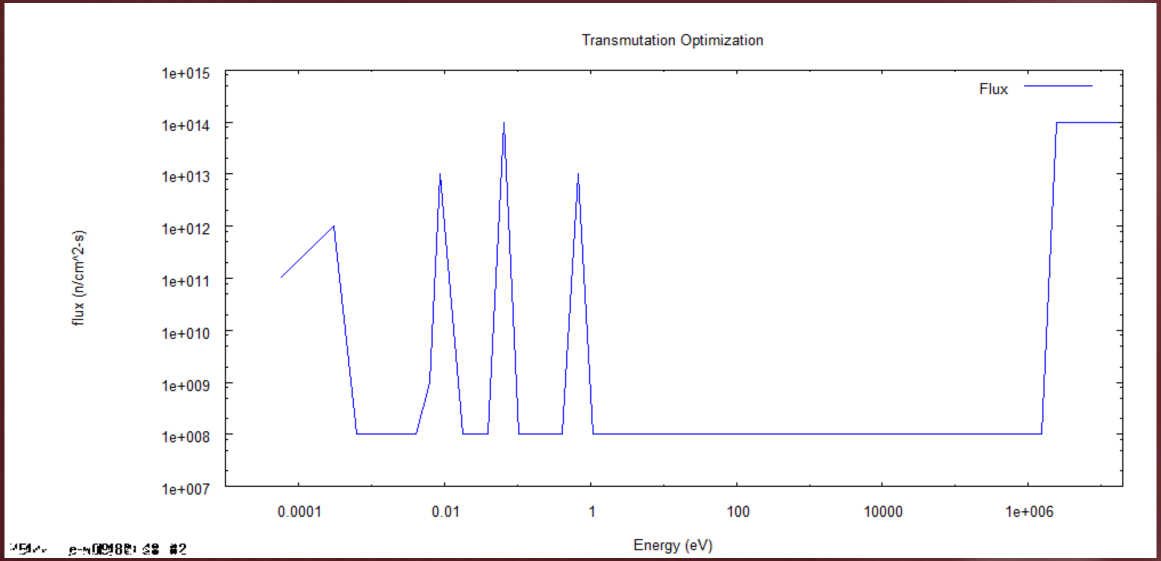
Np, Pu, Am



Np, Pu


Transmutation Optimization
Flux
flux (n/cm^2-s)
1e+015
1e+014
1e+013
1e+012
1e+011
1e+010
1e+009
1e+008
1e+007
0.0001
0.01
1
100
10000
1e+006
Energy (eV)

Pu only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1e+007
0.0001
0.01
1
100
10000
1e+006
Energy (eV)

Conclusions

- Recycling can minimize decay heat in the long run
  - Separating actinides doesn't seem to help
    - Might not be the case with a more realistic flux
- Fast flux will reduce the immediate decay heat after irradiation
- Thermal spectrums seem more suited when considering long term decay heat
  - Decay heat can potentially be reduced by more than 40%
  - Such decay heat reduction can influence repository design
    - Reduce spacing between drifts
    - Increase capacity in volume limited repositories

Future Work

- Irradiation time study
- Cost functions
  - Transmutation rate
  - Isotope production (e.g. Pu-238)
  - Proliferation studies (minimize Pu-239 or maximize Pu-238 and Pu-240)
  - Combine multiple objectives in a weighted cost function
- Constrained optimization
  - Optimize decay with constraints on neutron emission, …
- Couple optimization code with transport code for design optimization
  - More realistic flux shape
  - Optimal material selection for specific purposes